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Unmanned Aircraft Systems – ATM Collision Avoidance Requirements

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Abstract

A major goal in the development of Unmanned Aircraft Systems operations is access to non-segregated airspace. In order to achieve this, UAS must have a Sense & Avoid function analogous to the See & Avoid function of manned aircraft.

In order to determine the ATM Collision Avoidance Requirements for UAS operating in non-segregated airspace EUROCONTROL have commissioned the CAUSE study, Phase 1 of which is reported here.

The study uses results from previous EUROCONTROL safety studies of ACAS to demonstrate that there is a need for UAS to have a collision avoidance capability comparable to that delivered by ACAS on manned aircraft.

The required performance capability is derived for a range of airspace regimes.

The study also investigates to what extent carriage of ACAS by UAS might deliver this capability and the issues involved.

Keywords

UAS	UA	collision avoidance	Sense and Avoid
See and Avoid	ACAS	TCAS	

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1.3	2010-05-17	comments incorporated from EUROCAE WG73 SG1 and RTCA SC203

CONTENTS

1. INTRODUCTION

1.1 Background

1.1.1 Unmanned Aircraft Systems

Unmanned Aircraft (UA) as part of Unmanned Aircraft Systems (UAS) are widely used in military operations. The number of UAS, both military and civil is expected to increase significantly in future years as technology matures and appropriate regulations evolve.

Currently UAS operate in specifically reserved areas of segregated airspace. However, in recent years considerable interest and effort has been expended world-wide into the development of technologies, procedures, and standards that will allow UAS to become fully integrated into the Air Traffic Management (ATM) environment.

A major goal for the participants in this field is that of enabling UAS operation in non-segregated airspace. Aviation is, justifiably, a risk-averse and safety-conscious domain. The introduction of a new form of aviation into this domain is slow and difficult since it must be introduced in such a way as to have no detrimental impact on the overall safety of the ATM system, and this must be proved before vehicles are allowed unrestricted access to the civil ATM environment.

1.1.2 Conflict management

The majority of General Air Traffic (GAT) is reliant on Air Traffic Services to provide Air Traffic Management.

The provision of civil Air Traffic Services in non-segregated airspace is laid out in ICAO's Global ATM Operational Concept Document [1] which describes the current implementation and provides a template for developments over the next 30 years.

Conflict Management, as part of the Operational Concept, has the function "to limit, to an acceptable level, the risk of collision between aircraft and hazards." Conflict Management is applied in three layers:

- strategic conflict management;
- separation provision; and
- collision avoidance.

To be integrated into non-segregated airspace UAS functions which facilitate compliance with separation provision and a collision avoidance capability must fit into this layered approach. Strategic conflict management is achieved through the design of the airspace and the Air Traffic Control (ATC) procedures employed within it, and UAS must be able to follow, cooperate and participate with separation provision. When separation provision fails (for whatever reason) UAS must be able to employ a collision avoidance function providing an acceptable level of safety.

1.1.3 Collision avoidance

The pilot of an aircraft has ultimate responsibility for ensuring that *"An aircraft shall not be operated in such proximity to other aircraft as to create a collision hazard"* as described in ICAO Annex 2 "Rules of the Air" [5]. Furthermore the Rules of Air state that *"Nothing in these rules shall relieve the pilot-in-command of an aircraft from the responsibility of taking such action … as will best avert collision."*

To help the pilot discharge this responsibility the pilot should exercise the See & Avoid procedure. However, See & Avoid has known limitations (see, *e.g.* [6]) and to aid the collision avoidance process the Airborne Collision Avoidance System (ACAS) safety net has been developed.

The Airborne Collision Avoidance System (ACAS) II is currently mandated for carriage in European airspace by all civil turbine-engined fixed-wing aircraft with a maximum take-off mass over 5,700 kg or maximum approved passenger seating configuration over 19.[1]

Various EUROCONTROL studies have demonstrated the continuing safety benefit (in terms of the reduction of the risk of mid-air collision) that has resulted from the ACAS mandate.

The current safety benefit is achieved through a population of aircraft that cooperate at two levels:

- aircraft cooperate in being detectable by the collision avoidance systems on other aircraft; and
- when a resolution to a conflict is required between two equipped aircraft, compatible resolution manoeuvres are produced.

It is assumed that UAS operating in non-segregated airspace will possess a Sense & Avoid capability and in addition a specific collision avoidance function, either as part of the sense-and-avoid capability or as a separate dedicated system.

Inevitably UAS in non-segregated airspace will encounter other aircraft and airborne objects. It will be essential that the presence of a proportion of UAS does not unacceptably erode the safety benefit provided by ACAS in the airspace as a whole, nor to individual aircraft.

A number of issues immediately present themselves when the integration of UAS into non-segregated airspace is contemplated. Among these are:

- the ability of UAS to detect other aircraft regardless of the other aircraft's collision avoidance capability (*i.e.*, in the case of manned aircraft, whether fitted with ACAS or not);
- the ability of UAS to detect and perform collision avoidance on other airborne objects that present a hazard to flight safety;
- the ability of ACAS on manned aircraft to detect UAS;
- the interoperability of UAS collision avoidance and ACAS;

[1] *N.B.* The ICAO ACAS Manual [20] paragraph 7.3.3 states: "There is no basis for interpreting the ICAO requirement to fit ACAS as a requirement for UAVs."

- the extent to which UAS Sense & Avoid can provide an adequate collision avoidance capability when Sense & Avoid is also used as a means of complying with separation provision; and
- the differences in the performance of UAS collision avoidance when implemented with a remote pilot in the control-loop to when implemented as an automated response.

1.1.4 EUROCONTROL studies

The role of EUROCONTROL (the European Organisation for the Safety of Air Navigation) covers the management of the pan-European ATM network in the context of SESAR and beyond.

Since the advent of TCAS EUROCONTROL's Mode S & ACAS Programme Office has been proactive in monitoring and studying the operational and safety implications of ACAS equipage.

EUROCONTROL has instigated an ongoing series of studies to investigate the potential safety benefits resulting from the carriage of ACAS. These studies confirmed the safety benefit delivered by the initial European ACAS mandate and were instrumental in extending the mandate (to cover smaller aircraft) to its current level.

1.1.5 CAUSE study

1.1.5.1 Objective

Continuing its remit to anticipate developments in aviation well ahead of their implementation (so as to enable appropriate, coordinated, and timely policy decisions to be taken), EUROCONTROL has commissioned QinetiQ to conduct the current study (known as CAUSE – Collision Avoidance Requirements for Unmanned Aircraft Systems) to assess various aspects of potential UAS equipage with a collision avoidance system as part of the UAS's Sense & Avoid functionality.

The outputs of this study will be used to inform both EUROCONTROL and other regulatory bodies (*e.g.* EASA, ICAO) on how best to incorporate UAS into non-segregated airspace.

1.1.5.2 Scope

The continuing advances in UAS technology mean that there will naturally be inevitable pressure from UAS operators and manufacturers to allow UAS operations in non-segregated airspace. Equally naturally there will be a cautious attitude adopted by other airspace users, regulators, and ANSPs. EUROCONTROL must balance these competing pressures and ensure that the integration of UAS into the ATM environment is orderly and conducted only after due consideration of the safety issues.

The CAUSE study considers the collision avoidance requirements of UAS in two phases:

- this, the first phase, focuses on:
  - the identification of potential safety issues;
  - the determination, in high-level terms, of the collision avoidance equipage requirements of UAS.
- a second (optional) phase will focus on:
  - developing a methodology to quantify UAS collision avoidance performance;
  - developing metrics and targets for UAS collision avoidance performance; and
  - the promulgation of results and conclusions to ICAO, accompanied by any necessary recommendations for changes to Annex material.

1.1.5.3 Work Packages

Phase 1 of the CAUSE study was comprised of six work packages (WPs) broadly in line with the areas of study laid out in EUROCONTROL's Call for Tender [2]. Following the kick-off meeting WP 1.6 was redefined to consider UAS Collision Avoidance Function requirements on the basis of performance requirements for a range of non-segregated airspace regimes rather than on the basis of UAS characteristics and aerodynamic performance. The WPs are specified in the CAUSE Project Management Plan [3] and are outlined below:

- WP 1.1 – Potential safety benefits and disbenefits
  - Determine and quantify, based on the data and traffic forecast available today, if there is: a safety benefit and need to equip UAS with an airborne collision avoidance system; a safety disbenefit to other airspace users if UAS enter into the airspace without a compatible collision avoidance system.
  - Work carried out in this work package is reported in Section 2.
- WP 1.2 – Interoperability with ACAS
  - Define interoperability requirements between any future UAS dedicated collision avoidance system and the existing ACAS II.
  - Work carried out in this work package is reported in Appendix C.
- WP 1.3 – Sense & Avoid
  - Identify issues posed by the potential employment of Sense & Avoid for UAS collision avoidance as well as for other functions.
  - Work carried out in this work package is reported in Sections 4.2.2.1 and Section 4.2.2.2.
- WP 1.4 – UAS performance and ACAS II
  - Consider whether UAS performance would allow them to respond correctly to the ACAS RAs (*e.g.* rate of climb restrictions), if equipped.

  - o Work carried out in this work package is reported in Appendix D.3.
- WP 1.5 – Automated response to ACAS II
  - o If UAS are to be ACAS equipped, quantify advantages and disadvantages of UAS automated responses to RAs.
  - o Work carried out in this work package is reported in Appendix D.4.
- WP 1.6 – Equipage requirements
  - o Determine and define, in broad terms, the collision avoidance equipage requirements for UAS.
  - o Work carried out in this work package is reported in Section 5.

1.1.5.4 SESAR

The work in this study aligns with and supports the SESAR ATM Master Plan [4] in the following areas:

- En-route (SESAR WP 4);
- Aircraft (SESAR WP 9);
- En-route and Approach ATC Systems (SESAR WP 10); and
- Ground CNS systems (SESAR WP 15).

1.1.6 Structure of the report

This report is structured as follows:

1.1.6.1 Section 1 – Introduction

This introductory section provides: background to the current study; the structure of the work carried out; and basic definitions.

1.1.6.2 Section 2 – Potential Benefits and Disbenefits

Section 2 quantitatively explores the potential benefits and disbenefits (in terms of the risk of mid-air collision) to UAS and to other airspace users when UAS are allowed to operate in non-segregated airspace with various levels of effectiveness of a collision avoidance function.

The use of certain broad assumptions enables the results of previous EUROCONTROL safety studies of the efficacy of ACAS II to be used to give indicative results. The results demonstrate the desirability and necessity of ensuring that UAS have a collision avoidance capability at least as good as that of manned aircraft.

1.1.6.3 Section 3 – Collision Avoidance Fundamentals

Section 3 summarises the fundamental principles behind a collision avoidance function (as laid out in ICAO documents) and its place within the ATM system of conflict management.

1.1.6.4 *Section 4 – UAS Collision Avoidance*

Section 4 takes the general principles explored in Section 3 and considers how they apply specifically to collision avoidance performed by UAS.

1.1.6.5 *Section 5 – Requirements for UAS Collision Avoidance*

Section 5 uses the principles established in Section 4, together with the attributes of the range of airborne objects that UAS might encounter and need to avoid, to establish functional and capability requirements for a UAS collision avoidance function.

The categories of objects that can reasonably be expected to be encountered in different airspace regimes are considered, and UAS collision avoidance function requirements for specific types of non-segregated airspace are developed.

1.1.6.6 *Section 6 – Conclusions and Recommendations*

Section 6 draws conclusions based on the results presented in the previous sections and makes a series of recommendations concerning UAS collision avoidance requirements, the evaluation of UAS collision avoidance performance, and further work.

1.1.6.7 *Section 1.6 – References*

Section 1.6 provides references to the other documents cited in this report.

1.1.6.8 *Appendix A – Acronyms and Abbreviations*

Appendix A provides a list of the acronyms and abbreviations used in this report.

1.1.6.9 *Appendix B – Relevant ICAO Annex 2 Provisions*

Appendix B provides the text of ICAO Annex 2 provision relevant to the current work, and a commentary of their applicability to UAS and the CAUSE study.

1.1.6.10 *Appendix C – Interoperability of UAS Collision Avoidance with ACAS*

Appendix C takes account of the fact that any UAS (and its collision avoidance function) will encounter other aircraft in non-segregated airspace equipped with the current ACAS II collision avoidance system.

Interoperability requirements for UAS collision avoidance, to ensure that the proven benefit of ACAS II equipage is not adversely affected, are described.

1.1.6.11 *Appendix D – Issues with ACAS Equipage of UAS*

Appendix D explores the issues that arise if UAS are equipped with the current ACAS II collision avoidance system (that is mandated for carriage by medium and large manned commercial air traffic).

1.1.6.12 Appendix E – Performance of See & Avoid

Appendix E gives some observations about the quantification of the performance of See & Avoid by the flight-crew of manned aircraft, with which the performance of Sense & Avoid on UAS needs to be compared.

1.2 Definitions

A number of specific terms are extensively used in this report and are defined here.

1.2.1 Unmanned Aircraft

For the purpose of this study an Unmanned Aircraft (UA) is a reusable, powered, uncrewed aircraft capable of controlled, sustained, level flight. Also known as Unmanned Aerial Vehicle (UAV) or Remotely Operated Aircraft (ROA).

1.2.2 Unmanned Aircraft System

An Unmanned Aircraft System (UAS) comprises an Unmanned Aircraft and all of the associated support equipment, ground control station, data links, telemetry, communications and navigation equipment, *etc.*, necessary to operate the UA.

The UA is the flying portion of the system (flown by a pilot via a ground-based control system[2]).

1.2.3 See & Avoid

ICAO Annex 2 [5] lays out 'The Rules of the Air', contained within which is the requirement that:

> "An aircraft shall not be operated in such proximity to other aircraft as to create a collision hazard and the statement that It is important that vigilance for the purpose of detecting potential collisions be exercised on board an aircraft, regardless of the type of flight or the class of airspace in which the aircraft is operating…".

The exercise of this vigilance, for the purpose of avoiding hazards, is generally referred to as the 'See & Avoid principle'.

The terms 'see' and 'avoid' are habitually mentioned together. The implication being that the former leads inevitably to the latter: that a threat once seen will be successfully avoided. However, it should be noted that this is not necessarily the case: visually acquiring a threat (seeing it and recognising that it is a threat) does not guarantee that the threat will be, or even can be, avoided.

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[2] Some military UAS operate completely autonomously through the use of an on-board computer, but EUROCONTROL advise that such systems will not be permitted to operate in autonomous mode in non-segregated airspace in the foreseeable future.

1.2.4 Sense & Avoid

See & Avoid is exercised by the flight-crew of manned aircraft. The corresponding function in UAS is the analogous principle of 'Sense & Avoid'.

The term Sense & Avoid is employed by many interested parties with precise meanings that depend on the context. However, it should be noted that the term has no formal definition. Beyond the high-level requirement implied by the statements quoted above no particular method, technology, functionality, nor performance is required of the Sense & Avoid principle.

In manned aircraft See & Avoid, as exercised by the pilot, is inherently independent of avionics systems providing separation provision and collision avoidance. This need not be the case for Sense & Avoid in UAS which might be independent of these systems, but could equally be an integral part of these systems (provided appropriate levels of safety were assured).

1.2.5 ACAS and TCAS

Airborne Collision Avoidance System (ACAS) is the ICAO term for on-board avionics systems that operate independently of ATC and mitigate the risk of mid-air collision.

ACAS exploits the equipage of aircraft with standard ATC SSR transponders to detect and track nearby aircraft ('intruders'). On the basis of these tracks ACAS can display the relative positions of other aircraft on a traffic display and can also issue alerts to the flight-crew when a risk of impending collision is diagnosed.

ACAS issues alerts when the system diagnoses that there is a risk of impending collision with a Mode C or Mode S transponder equipped aircraft.

There are three levels of ACAS capability:

- ACAS I – provides '**Traffic Advisories**' (TAs) only. These alert the pilot to the presence of an intruder that may become a threat to his own aircraft and are accompanied by a display to aid visual acquisition. No international implementation of ACAS I is planned at the ICAO level.
- ACAS II – provides TAs and also provides '**Resolution Advisories**' (RAs) in the vertical plane. ACAS II TAs are intended as precursors to RAs, which provide the pilot with advice on how to regulate or adjust his vertical speed so as to avoid a collision. The sense of RAs against other ACAS II equipped aircraft are coordinated so that the two aircraft choose complementary manoeuvres.
- ACAS III – provides TAs, and RAs in the vertical and horizontal planes. No ACAS III equipment currently exists, and none is likely to appear in the near future, because of technical and operational difficulties.

ACAS II[3] is specified in ICAO SARPs [7] and is mandatory equipage in ECAC states for all civil fixed-wing turbine-engined aircraft with a maximum take-off mass (MTOM) over 5,700 kg, or authorised to carry more than 19 passengers.[4]

Currently the only system that is fully compliant with the ICAO SARPs is the Traffic alert and Collision Avoidance System (TCAS) II Version 7 (as specified in the RTCA MOPS [8]). Consequently the terms ACAS and TCAS are effectively synonyms.

An excellent guide to the use of ACAS, and its functionality, can be found in the EUROCONTROL ACAS training brochure [9].

1.2.6 UCAF

The acronym UCAF (UAS Collision Avoidance Function) is coined here to represent a generic UAS collision avoidance function that can comprise airborne and ground-based, human and procedural, elements as well as equipment.

It is not envisaged that a single specific system (or combination of systems) would deliver the collision avoidance function for all UAS. Rather the collision avoidance capability on a particular UAS could depend on the characteristics of that UAS and the airspace in which it wished to fly.

UCAF might share any of technology, sensors, hardware, and data with on-board systems providing airborne separation, but is ultimately distinct since collision avoidance must still provide protection when separation provision has failed.

The possibility that the existing ACAS system might form a component of UCAF is not discounted.

[3] The term ‘ACAS’ is used from hereon for convenience and should be understood to mean ‘ACAS II’ unless otherwise stated.

[4] *N.B.* The ICAO ACAS Manual [20] paragraph 7.3.3 states: “There is no basis for interpreting the ICAO requirement to fit ACAS as a requirement for UAVs.”

2. POTENTIAL BENEFITS AND DISBENEFITS

2.1 Introduction

2.1.1 EUROCONTROL Studies

A series of EUROCONTROL studies have investigated the continuing safety benefit resulting from the widespread equipage of manned aircraft with ACAS:

- Work Package 1 of the ACASA study [10] developed tools and a methodology which was used to demonstrate the safety benefit of the ACAS mandate in Europe.
- The ASARP study [11] updated the tools and applied them to the continental RVSM environment to demonstrate the continuing safety benefit resulting from ACAS equipage.
- The AVAL study [12] adapted the tools further and applied them to a future environment which includes a significant level of operations by Light Jets and Very Light Jets (which are currently outside of the ACAS mandate), so as to assess their effect on the performance of ACAS.

2.1.2 Encounter model and Logic risk ratio

The methodology involves generating a large set of representative aircraft encounters from a stochastic model which is tuned to the characteristics of the airspace of interest.

These artificial encounters are then used in computer simulations of the performance of ACAS together with models of pilot response to any RAs that are generated. The separations in the original encounters and in the encounters with ACAS simulated (and pilot response modelled) are then compared, taking full account of altimetry error, to determine the risk reduction that can be achieved by the ACAS algorithms (the so called ‘logic’ risk ratio – this term is explained below in Section 2.4) over the whole set of simulated encounters.

2.1.3 Contingency tree and Full System risk ratio

The logic risk assesses the performance of the ACAS algorithms in isolation. However, other factors, from environmental and human factors considerations, come into play in determining the safety of the ‘full system’. These other considerations include events such as: whether the threat is transponder equipped and whether it is reporting altitude; whether the controller becomes involved and whether the pilot responds to the ACAS RA or a controller instruction; whether the pilot visually acquires the threat; *etc*.

A tool known as a contingency tree (a type of fault tree, except the events represented are not necessarily faults) combines the logic risks with the environmental and human factors, taking account of the probabilities of the various events and their interdependencies. Using the contingency tree (and a set of probabilities for the events) a measure of the safety of ACAS, known as the full-system risk ratio (risk ratio is explained below in Section 2.4), can be evaluated.

The logic risk ratio represents an upper bound on the safety benefit that can be delivered by a specific set of collision avoidance algorithms; the full-system risk ratio represents the safety benefit likely to be realised in practice when factors beyond the operation of the collision avoidance algorithms are also taken into consideration.

2.1.4 Application to UAS collision avoidance

The tools used in the previous EUROCONTROL studies have been used here to give an indication of possible safety benefits to be achieved from equipage of UAS with an ACAS-like collision avoidance system in non-segregated airspace.

Precise details of the future environment in which UAS will operate, the level of UAS traffic, the characteristics of the trajectories they will fly, and (most significantly) the specification of any UAS collision avoidance system, are not known. Consequently any assessment of the benefits of UCAF deployment can only be tentative. However, by making some broad assumptions (described in Sections 2.2 to 2.3) certain indicative results are presented in Section 2.5.

2.2 Future airspace environment assumptions

2.2.1 Non-segregated airspace

2.2.1.1 Underlying risk of collision

The underlying risk of collision is the rate at which collisions would occur (expressed in terms of the expected number collisions per aircraft flight-hour) in the absence of any collision avoidance capability more effective than See & Avoid. The value of the underlying risk of collision is important because it influences the effectiveness of ACAS (or any other collision avoidance system): in a very safe airspace the few risk bearing encounters that do occur tend to be of a kind which are inherently difficult to resolve, consequently the performance of ACAS (in terms of risk ratio) is less dramatic.

Manned aircraft operations are very safe and mid-air collisions are correspondingly infrequent events. The paucity of operational incidents has always made it difficult to give precise estimates of the risk of collision in a given airspace. The widespread equipage with ACAS means that even the underlying risk of collision can now no longer be directly observed.

Nevertheless, estimates of the underlying risk of collision have been used in the EUROCONTROL studies, based on the best available data. In the ACASA, ASARP, and AVAL studies (which span a period of 10 years) the same rate of 3 NMACs[5] per 10 million flight-hours of IFR traffic has been used. The corresponding collision rate is about 3×10^{-8} per flight-hour.

By assuming that this underlying risk remains static into the 2020–2050 timeframe, and by assuming that the risk is not significantly effected by the advent of UAS operations, the results of the former studies can be adapted to perform a broad assessment of the likely risk when UCAF equipped UAS operate in non-segregated airspace. Note that while it is assumed that the underlying risk remains static this corresponds to an increase in the safety of ATM service provision because in the same time the level of traffic has increased with a corresponding increase in the number of encounters (in each of which there is potentially a small but finite risk of collision) per flight-hour.

2.2.1.2 Controlled and uncontrolled airspace

A broad high-level distinction in the type of airspace in which collision avoidance systems operate can be made on the basis of the distinction between controlled airspace (airspace classes A, B, C, D, and E) and uncontrolled airspace (airspace classes F and G) set out in [13].

It is assumed, for the analysis here, that the principal difference (from the point of view of the operation of collision avoidance systems) is the proportion of the traffic that is equipped with ACAS.[6] Recent airprox data[7] was assembled for the AVAL study and analysing this data the proportions of ACAS equipped traffic involved in reported airproxes were found to be:

- Controlled airspace – proportion of manned aircraft equipped with ACAS in reported airproxes is 81.3%;
- Uncontrolled airspace – proportion of manned aircraft equipped with ACAS in reported airproxes is 42.5%.

Note that the proportion of ACAS equipped traffic in each type of airspace as a whole may be markedly different from the proportion that are involved in potential collisions (due to such factors as the altitudes at which aircraft operate, traffic patterns, and the greater probability of sighting slow moving traffic): it is the latter proportion that is needed in the analysis here.

[5] NMAC = Near Mid-Air Collision: an encounter in which the aircraft are simultaneously within 500ft of each other horizontally and 100ft of each other vertically. There is about a 1 in 10 chance that an NMAC will in fact be an actual collision, and so the collision rate is approximately one tenth of the NMAC rate.

[6] In practice it can be expected that encounter geometries and level of ATC intervention will be different in controlled and uncontrolled airspace, leading in turn to different underlying risks of collision. However, it is not possible to estimate the impact of these effects in this simple analysis.

[7] UK airprox reports from 2001–2002 and 2005–2008. The data covers a period of 1,516 days, involve 882 IFR aircraft, and correspond to 2.23×10^{7} flight-hours by IFR traffic in UK airspace.

2.2.2 ACAS performance

It is a notable result of the EUROCONTROL ACAS safety studies (mentioned in Section 2.1.1) that the theoretically achievable performance (as measured by the logic risks) is in practice diluted by human factors considerations. The two most significant effects are:

- ATC intervention – a controller may attempt to provide collision avoidance instructions to one or both of the aircraft that are on a collision course. As a consequence of receiving a controller instruction a pilot might not respond correctly to any ACAS RA.
- Pilot response – even in the absence of a controller instruction a pilot might ignore an ACAS RA, execute an inaccurate response, or even manoeuvre the aircraft in the opposite sense to the RA.

For a number of reasons we can expect these effects to be less significant in the future:

- Improved training for controllers, and the ability to downlink ACAS alerts from aircraft and display these in near real-time at controller's working positions, should reduce the incidence of pilots being presented with controller instructions that conflict with an ACAS resolution advisory.
- Pilots' increasing familiarity with ACAS, improved training, and the use of 'auto-flight' systems,[8] can be expected to reduce the frequency of incorrect response to RAs both generally and when presented with conflicting instructions from ATC.

In the analysis below it has therefore been assumed that there is no controller intervention, that pilots always respond to ACAS RAs, and that they respond accurately (with the standard response).

2.2.3 UAS traffic

Currently IFR traffic accounts for about 14.3 million flight-hours per year in Europe [14].

The EUROCONTROL Market Outlook [15] suggests that by 2020 there could be 200 MALE (Medium Altitude Long Endurance) UAS and 10 HALE (High Altitude Long Endurance) UAS operating in Europe.

Assuming a high utilisation (*i.e.* flying for 12 hours out of every 24 hours) these UAS could accumulate 920,000 flight-hours each year. This is approximately 6% of the current IFR flight hours per year.

Current manned traffic levels can be expected to increase in the future, but the number of UAS operations in non-segregated airspace might also be higher than forecast. To cover a range of possible projections the calculations that follow consider scenarios in which UAS account for 5% and for 10% of the total IFR traffic.

[8] Systems in which the ACAS RA is flown automatically by the autopilot, or is indicated on the flight director to be followed by the pilot.

In practice some UAS traffic will operate in addition to manned traffic while other UAS traffic will effectively replace some manned traffic. All other things being equal, additional traffic can be expected to increase the incidence of mid-air collisions (as explained above). So that this effect (*i.e*. an increase in the underlying frequency of mid-air collisions due to the introduction of additional traffic) does not obscure any other trends, the analysis below assumes that UAS traffic will replace a proportion of manned traffic (both those covered by the ACAS mandate and those not ACAS equipped).

2.3 UAS Collision avoidance assumptions

2.3.1 Sense & Avoid

It is assumed that, to be permitted to fly in non-segregated airspace UAS will require an approved Sense & Avoid system. This will provide, *inter alia*, some capability to avoid hazards (*e.g.* terrain, significant weather, airborne objects, and other traffic) under all flight-rules.

By the strictest interpretation of the principle of equivalence this Sense & Avoid function would need only to be as effective as See & Avoid executed by the flight-crew of manned aircraft.

In this circumstance the collision avoidance capability of UAS would only be as effective as that of current manned aircraft without ACAS.

2.3.2 ACAS-like system

Experience shows that See and Avoid is often unreliable, and in practice, it is anticipated that UAS will generally have a collision avoidance capability that is more effective than See & Avoid, so that UAS collision avoidance capability may approach or surpass that of manned aircraft equipped with ACAS II.

2.3.2.1 Performance relative to ACAS

The performance of collision avoidance systems on UAS cannot be directly evaluated at this stage since the specification of such systems does not yet exist.

However, some pointers to the likely performance can be gained by considering the performance of the well characterised ACAS system that is mandated on manned aircraft.

For the analysis presented here it is assumed that UCAF performance in an encounter (with a specific equipage combination) can be related to ACAS performance by a function that represents UCAF performance as being *n* times as effective as ACAS performance in the same circumstance.[9]

[9] For example, consider a case in which ACAS is effective and reduces the risk to a small percentage of its original value (produces a risk ratio of, say, 2% - *i.e.* reduces the risk to 2% of the value in the absence of ACAS): if UCAF is twice as effective as ACAS then it will reduce the risk to half this value (*i.e.* 1% of its original value); if UCAF is only half as effective as ACAS then UCAF will reduce the risk to twice the value that ACAS can achieve (*i.e.* 4% of its original value in our example).

To allow for a wide range of potential UCAF designs, the analysis here considers systems that are half as effective as ACAS (n = ½)[10]; equally as effective as ACAS (n = 1); and twice as effective as ACAS (n = 2)[11].

The analysis also considers the case that UCAF is no more effective than See & Avoid by flight-crew of a manned aircraft: effectively n = 0.

2.3.2.2 Coordination

The performance of ACAS differs markedly between encounters where both aircraft are equipped (where the sense of avoidance manoeuvres is coordinated) and encounters in which one of the aircraft is unequipped (where adverse manoeuvres by the unequipped aircraft are not inhibited).

When RAs are followed accurately the risk reduction is considerably enhanced in encounters where both aircraft are ACAS equipped and the avoidance manoeuvres are coordinated, compared to encounters in which only one of the aircraft is ACAS equipped.

The behaviour of any UAS Collision Avoidance Function can similarly be expected to depend on whether the systems delivering the function act independently of collision avoidance on other aircraft,[12] or whether they act cooperatively to coordinate avoidance manoeuvres (with ACAS on manned aircraft, with UCAF on other UAS).

2.4 Risk ratio

Risk ratio is the principal means of assessing the performance of safety nets. It is a relative measure of the safety benefit (or disbenefit) brought about in a given environment by some change in procedures or equipment.

Conversely, consider a case where ACAS is less effective and only slightly reduces the risk compared to its original value (produces a risk ratio of, say, 98%): if UCAF is twice as effective as ACAS then it will reduce the risk by twice as much (*i.e.* to 96% of its original value); if UCAF is only half as effective as ACAS then UCAF will reduce the risk by only half the reduction that ACAS can achieve (*i.e.* to 99% of its original value in our example).

[10] UAS collision avoidance could be less effective than ACAS for a number of reasons: *e.g.* if surveillance and tracking were less reliable than that employed by ACAS; shorter nominal warning times were employed; or if the UA were not able to match the accelerations and vertical rates employed in ACAS RAs.

[11] UAS collision avoidance could be more effective than ACAS for a number of reasons: *e.g.* if surveillance and tracking were more reliable than that employed by ACAS; longer nominal warning times were employed; if the UA were able to perform more aggressive avoidance manoeuvres than those required by ACAS RAs; or if horizontal manoeuvres were employed as well as vertical manoeuvres.

[12] For the purpose of this analysis, it is assumed that when a UA encounters another aircraft with a comparable collision avoidance capability (UCAF on a UAS, or ACAS on a manned aircraft) and yet devises a collision avoidance manoeuvre independently of the other system (*i.e.* does not coordinate the sense of the manoeuvre) then the reduction in collision risk is likely to be the same as if the UA had encountered an unequipped manned aircraft (which might initiate an uncoordinated manoeuvre on the basis of visual acquisition).

For collision avoidance systems safety is measured in terms of the risk of mid-air collision:[13] the risk ratio compares the safety level when aircraft have a particular collision avoidance capability to the corresponding safety level when aircraft do not have this capability.

$$\text{risk ratio} = \frac{\text{risk of collision with safety net}}{\text{risk of collision without safety net}}$$

- A value of risk ratio that is less than unity indicates that the deployment of the safety net reduces the risk of collision and thus provides a safety benefit.
- A risk ratio of precisely unity indicates that the safety net is ineffectual and makes no difference to the risk of collision.
- A risk ratio greater than unity would indicate that the safety net causes positive harm and increases the risk of collision.

It is important to note that risk ratio is a relative measure and does not directly determine an absolute level of safety. In particular the risk ratio will depend on the underlying risk of collision (described previously in Section 2.2.1.1): this will generally be different in different airspaces and so one must expect different risk ratios when the same system is deployed under different circumstances.

When airborne collision avoidance is provided by a population of systems deployed on individual aircraft, the risk ratio can be evaluated from different perspectives as explained below.

2.4.1 Airspace perspective

In the airspace perspective the risks of mid-air collision in the airspace as a whole are compared. The risk of mid-air collision when airborne collision avoidance safety nets are deployed is compared with the underlying risk that would exist were See & Avoid (or an equivalent Sense & Avoid capability) the only means of collision avoidance when ATC failed to prevent a collision.

This is the perspective of interest to a regulator or ANSP who wants to assess the benefit that will accrue from requiring widespread equipage with airborne collision avoidance safety nets in their airspace.

2.4.2 Aircraft perspective

In the aircraft perspective the risks of mid-air collision to an individual aircraft are compared. The risk of mid-air collision to an individual aircraft when that aircraft operates an airborne collision avoidance safety net is compared to risk that exists were that aircraft to rely solely on See & Avoid (or an equivalent Sense & Avoid capability). The equipage of other aircraft remains the same in the two scenarios and so a degree of protection exists in both cases from the potential equipage of the collision threat.

[13] All mid-air collisions are considered to be of equal severity – no account is taken of: survivability; the number of fatalities; or the financial consequences.

This is the perspective of interest to an operator who wants to assess the benefit that will accrue from equipping individual aircraft with an airborne collision avoidance safety net, or a pilot who wants to assess the benefit that will accrue from activating such a safety net (or the disbenefit that will result from deactivating such a safety net) on his aircraft.

When considering the potential equipage of a population of the aircraft within an airspace the aircraft risk ratio can address two boundary conditions:

- **Initial aircraft risk ratio.** The risk ratio associated with the first aircraft of the population to equip – other aircraft of the subset are not equipped. This risk ratio expresses the benefit to be obtained from voluntarily equipping in the absence of a mandate.
- **Final aircraft risk ratio.** The risk ratio associated with the last aircraft of the population to equip – other aircraft of the population are already equipped. This risk ratio expresses the benefit to be obtained from fixing a faulty system rather than flying with the system inoperative.

2.5 Analysis

2.5.1 Controlled airspace

2.5.1.1 Airspace risk ratio in controlled airspace

In the future, in controlled airspace, it is anticipated that the ACAS mandate for manned aircraft could achieve an airspace risk ratio of 5.5% – *i.e.* a rate of collisions of 3×10^{-8} per flight-hour that would exist if no aircraft were ACAS equipped is reduced to 5.5% of this value by ACAS equipage, *viz.* 0.17×10^{-8} per flight-hour. Note that this value implies better performance of ACAS than is estimated in the EUROCONTROL studies mentioned above (see Section 2.1.1) because it is assumed that there is no controller intervention and that all pilots follow their RAs and follow them accurately.

The airspace risk ratios when a proportion of manned aircraft in controlled airspace are replaced by UAS are shown in Table 1 for various levels of UAS collision avoidance capability.

If the UAS have a collision avoidance capability no better than See & Avoid in manned aircraft then the risk ratio rises to between 8.3% and 11.2% (depending on the level of UAS traffic). This is still a reduction compared to the underlying risk of collision (the risk if all aircraft relied solely on See & Avoid) but is between one-and-a-half and two times the risk level achievable by the ACAS mandate. The benefit arises principally from the ACAS equipage of other aircraft rather than the See & Avoid capability of UAS.

	effectiveness of UAS collision avoidance			
	equivalent to See & Avoid	half as effective as ACAS	equally effective as ACAS	twice as effective as ACAS
independent	8.3% (11.2%)	7.7% (9.6%)	6.5% (7.4%)	5.8% (6.1%)
coordinating	–	5.7% (5.7%)	5.4% (5.4%)[14]	5.2% (4.8%)

Table 1: Airspace risk ratio for UCAF in controlled airspace with UAS replacing 5% of manned traffic (values for 10% in brackets).

When UAS are equipped with a collision avoidance system whose performance is comparable with that of ACAS, risk ratios approaching that which is achievable in the absence of UAS are achieved. For a system that is at least as effective as ACAS, and which coordinates resolution manoeuvres with other collision avoidance systems, there is an improvement in the overall risk reduction compared to the situation in the absence of UAS.

The benefit of coordinating manoeuvres is emphasised by the fact that a UAS Collision Avoidance Function that is only half as effective as ACAS and yet coordinates manoeuvres allows a greater reduction in risk than a system that is twice as effective as ACAS and yet acts independently of other collision avoidance systems.

2.5.1.2 Aircraft risk ratio in controlled airspace

The aircraft risk ratios for a UAS entering controlled airspace which already includes a proportion of UAS are shown in Table 2 and Table 3. Table 2 shows the initial aircraft risk ratio (effectively the benefit to the first UAS that equips with a collision avoidance system better than See & Avoid alone), while Table 3 shows the final aircraft risk ratio (effectively the benefit to the last UAS that equips with a collision avoidance system better than See & Avoid alone).

It is notable that the corresponding risks ratios in the two tables are broadly similar indicating that the benefit to a UAS that equips with a collision avoidance system (better than See & Avoid alone) is about the same regardless of the equipage of the rest of the UAS population.

	effectiveness of UAS collision avoidance		
	half as effective as ACAS	equally effective as ACAS	twice as effective as ACAS
independent	76.7% (69.7%)	44.2% (40.2%)	23.9% (21.7%)
coordinating	22.3% (22.9%)	12.5% (12.9%)	6.7% (6.9%)

Table 2: Initial aircraft risk ratio for UCAF in controlled airspace with UAS replacing 5% of manned traffic (values for 10% in brackets).

[14] These values are less than the risk ratio when UAS are absent because a proportion of manned aircraft not equipped with ACAS have been replaced by UAS with a collision avoidance capability as effective as ACAS.

	effectiveness of UAS collision avoidance		
	half as effective as ACAS	equally effective as ACAS	twice as effective as ACAS
independent	85.8% (86.5%)	50.4% (51.7%)	27.6% (28.7%)
coordinating	21.0% (20.5%)	11.9% (11.8%)	6.4% (6.4%)

Table 3: Final aircraft risk ratio for UCAF in controlled airspace with UAS replacing 5% of manned traffic (values for 10% in brackets).

The benefit of coordinating manoeuvres is even more apparent than with the airspace risk ratios. For the case of a UAS Collision Avoidance Function that is twice as effective as ACAS, coordinated manoeuvres reduce the risk to better than one third of the risk that remains with independent manoeuvres.

2.5.2 Uncontrolled airspace

2.5.2.1 Airspace risk ratio in uncontrolled airspace

In the future, in uncontrolled airspace, it is anticipated that the ACAS mandate for manned aircraft could achieve an airspace risk ratio of 11.4%. The reduction in risk is not as great as that achievable in controlled airspace because we have assumed a smaller proportion of ACAS equipped aircraft (42.5% *vice* 81.3%).

The airspace risk ratios when a proportion of manned aircraft in uncontrolled airspace are replaced by UAS are shown in Table 4.

If the UAS have a collision avoidance capability no better than See & Avoid in manned aircraft then the risk ratio rises to between 18.8% and 25.5% (depending on the level of UAS traffic). Again, as in controlled airspace, this reduction in the underlying risk of collision is between only one-and-a-half and two times the risk level achievable by the ACAS mandate. The benefit arises principally from the ACAS equipage of other aircraft rather than the See & Avoid capability of UAS. The risk ratio is higher than in controlled airspace due to the greater proportion of manned traffic not equipped with ACAS.

	effectiveness of UAS collision avoidance			
	equivalent to See & Avoid	half as effective as ACAS	equally effective as ACAS	twice as effective as ACAS
independent	18.8% (25.5%)	13.5% (15.3%)	12.0% (12.4%)	11.0% (10.6%)
coordinating	–	12.0% (12.5%)	11.1% (10.7%)	10.5% (9.7%)

Table 4: Airspace risk ratio for UCAF in uncontrolled airspace with UAS replacing 5% of manned traffic (values for 10% in brackets).

When UAS are equipped with a collision avoidance system whose performance is comparable with that of ACAS, risk ratios approaching that that is achievable in the absence of UAS are achieved.

As with controlled airspace there is better performance when the UAS coordinate manoeuvres with other collision avoidance systems, but the effect is less marked because there is a greater proportion of manned aircraft not equipped with ACAS (with which manoeuvres cannot be coordinated).

2.5.2.2 *Aircraft risk ratio in uncontrolled airspace*

The aircraft risk ratios for a UAS entering uncontrolled airspace which already includes a proportion of UAS are shown in Table 5 and Table 6. Table 5 shows the initial aircraft risk ratio (effectively the benefit to the first UAS that equips with a collision avoidance system better than See & Avoid alone), while Table 6 shows the final aircraft risk ratio (effectively the benefit to the last UAS that equips with a collision avoidance system better than See & Avoid alone).

Again, as in controlled airspace, it is notable that the corresponding risk ratios in the two tables are broadly similar indicating that the benefit to a UAS that equips with a collision avoidance system (better than See & Avoid alone) is about the same regardless of the equipage of the rest of the UAS population.

	effectiveness of UAS collision avoidance		
	half as effective as ACAS	equally effective as ACAS	twice as effective as ACAS
independent	40.2% (39.2%)	23.2% (22.6%)	12.5% (12.2%)
coordinating	25.3% (25.4%)	14.5% (14.6%)	7.8% (7.9%)

Table 5: Initial aircraft risk ratio for UCAF in uncontrolled airspace with UAS replacing 5% of manned traffic (values for 10% in brackets).

	effectiveness of UAS collision avoidance		
	half as effective as ACAS	equally effective as ACAS	twice as effective as ACAS
independent	42.6% (43.9%)	24.8% (25.8%)	13.5% (14.1%)
coordinating	24.9% (24.5%)	14.3% (14.2%)	7.8% (7.8%)

Table 6: Final aircraft risk ratio for UCAF in uncontrolled airspace with UAS replacing 5% of manned traffic (values for 10% in brackets).

The benefit of coordinating manoeuvres is still apparent even though there are fewer other aircraft equipped with collision avoidance systems (compared to controlled airspace) with which to coordinate manoeuvres. For the case of a UAS Collision Avoidance Function that is twice as effective as ACAS, coordinated manoeuvres reduce the risk to almost half of the risk that remains with independent manoeuvres.

2.5.3 Significance for UAS ATM collision avoidance requirements

EUROCONTROL studies have demonstrated the benefit, in terms of the reduction in the risk of mid-air collision, which is enjoyed as a result of the widespread equipage of manned aircraft with ACAS. This benefit is expected to continue in future airspace environments, and even to improve as a result of improved training and new technologies (such as the down-linking of ACAS alerts to controller working positions and the automatic flying of ACAS manoeuvres by autopilots).

The replacement of a proportion of manned aircraft by UAS will have an effect on this safety benefit. If the UAS collision avoidance capability is no better than See & Avoid by the flight-crew of manned aircraft then, although an overall reduction in the underlying risk of collision will still exist, the safety benefit will be worse than that in the absence of UAS.

When UAS have a collision avoidance capability that is comparable to the combined effect of ACAS and See and Avoid (on manned aircraft) then the safety benefit can approach or even surpass that achieved in the absence of UAS.

The benefit to an individual UAS from having a collision avoidance capability that is comparable to that of ACAS and See and Avoid remains broadly the same regardless of the proportion of other UAS with a similar capability.

The ability to coordinate collision avoidance manoeuvres with other collision avoidance systems can dramatically improve the safety benefit. This is particularly the case in controlled airspace where a large proportion of other aircraft can be expected to be equipped with a similar system.

2.5.3.1 Summary

Ensuring that UAS have a collision avoidance capability that approaches or exceeds that of ACAS equipped manned aircraft is both:

- **Worthwhile** – from the perspective of individual UAS. The UAS receives a safety benefit in terms of a reduced risk of collision (regardless of equipage levels and the corresponding degree of protection that the UAS receives from the equipage of other traffic); **and**
- **Necessary** – from the perspective of the airspace as a whole. The safety benefit delivered by ACAS equipage of manned aircraft can be significantly eroded by the introduction of only a small proportion of UAS whose collision avoidance capability is no better than See & Avoid of manned aircraft.

The ability to coordinate collision avoidance manoeuvres with other collision avoidance systems can dramatically improve the safety benefit.

3. COLLISION AVOIDANCE FUNDAMENTALS

3.1 Purpose

The evolution of aerospace technologies in the field of unmanned aircraft systems (UAS), including autonomous operations, will impact European ATM as regards new military and civil applications. UAS will present new challenges as well as new opportunities for the design of future ATM systems in the context of both SESAR and beyond (into the 2050 timeframe).

EUROCONTROL, in executing its responsibilities associated with the management of the pan-European ATM network, must ensure that UAS operations do not negatively impact overall levels of ATM security, safety, capacity and efficiencies.

One of the basic tenets for deployment of UAS in non-segregated airspace is that UAS operations should possess the dual properties both of equivalence and transparency: in short, the UAS must behave like a manned aircraft. More specifically, a UAS shall adhere to all the ICAO SARPS and Procedures related to aircraft operations, even though these were originally conceived for an aviation system in which a pilot is physically central to the aircraft and its local environment.

The dislocation of the pilot in a UAS, and the inevitable adjustments to their interaction with the aircraft, its systems, and its environment, can therefore present a challenge when trying to relate long-established concepts (and their associated terminologies) to the problem of safe UAS operations.

The scope of the CAUSE Project is limited to mid-air collision avoidance.[15] Therefore, as a basis for reasoning concerning the need for, and required behaviour of, a UCAF the fundamental concepts behind collision avoidance should first be established. The ICAO SARPS and Procedures by themselves do not necessarily capture these 'Fundamentals' because each one focuses on the rules to be applied by a different actor in the aviation system. As such, they essentially represent a decomposition and elaboration of the basic concepts.

The purpose of the work in this section was therefore to present these Fundamentals in order to:

- provide a basis for agreement with EUROCONTROL about the precise scope of CAUSE and the appropriate terminology to be used; and
- identify the parameters of the UAS collision avoidance problem so that the relevance of, and interrelationships between, the CAUSE Work Packages became evident.

[15] Therefore, unless otherwise stated, the term 'collision' used herein refers only to mid-air collision.

3.2 Methodology

The methodology used here to derive UAS collision avoidance Fundamentals is as follows:

- Identify ICAO documents that might be relevant to UCAF. These documents are identified in Section 3.3.
- List and analyse, in the UAS context, the specific ICAO provisions relevant to UCAF. This is shown in Appendix B.
- Since the ICAO Global ATM Operational Concept [1] does not comprise a set of specific provisions (rules) as such, the meaning of collision avoidance within the Operational Concept is instead summarised in Section 3.4. Its adaptation to the UAS context is then shown in Section 4.
- Consolidate the analysis of the relevant ICAO provisions into a set of Fundamentals, as recorded in Section 4.

3.3 ICAO Material

The various levels of definition for manned aircraft collision avoidance within the ICAO document set, and their linkage to the current document, are shown in Figure 1. Interactions between collision avoidance and ATS are considered to be outside the current scope of the CAUSE project. Therefore, ICAO Annex 11 (*Air Traffic Services*) [13] and ICAO Doc 4444 (*PANS-ATM*) [16] are not shown.

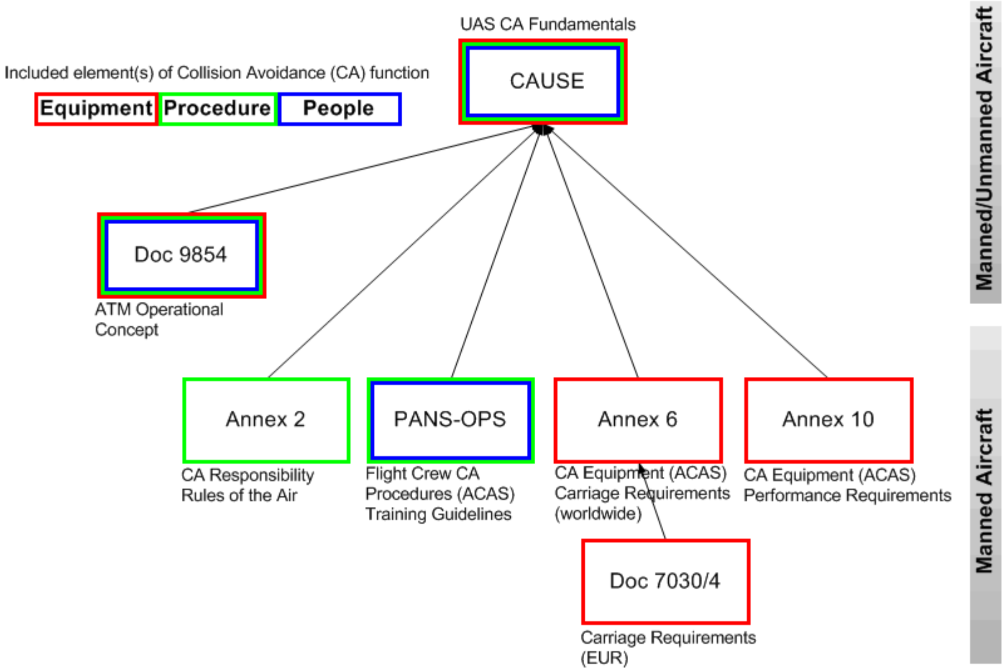

Figure 1: Collision Avoidance – Levels of Definition.

The nature of the collision avoidance related content of these documents is as follows:

- A suitable starting point for explaining how collision avoidance contributes to aviation safety is ICAO Doc 9854 [1]. This presents the

ICAO vision of an integrated, harmonized and globally interoperable ATM system for the period up to 2025 and beyond (accommodating, *inter alia*, UAS). It includes a description of Conflict Management, a key component of the 'emerging and future' ATM Operational Concept.

- The pilot's ultimate responsibility for collision avoidance, and the means of achieving it with or without ACAS and right-of-way rules, are addressed in ICAO Annex 2 [5].
- Actions by flight-crew in response to ACAS indications are defined in ICAO Doc 8168 [17].
- ACAS (and transponder) performance requirements are defined in ICAO Annex 10 [7].
- Requirements for carriage of ACAS II in the EUR region are defined in ICAO Doc 7030 [18]. In addition, ICAO Annex 6 [19] includes requirements for carriage and operation of altitude-reporting transponders compatible with ACAS.
- ACAS is not a replacement for the Collision Avoidance Function. Flight-crew of aircraft equipped with ACAS are responsible for collision avoidance regardless of the provision of ACAS alerts.
- Since ACAS is equipment specifically not designed for unmanned aircraft,[16] the provisions in ICAO Doc 8168 [17], ICAO Annex 10 [7], ICAO Doc 7030 [18], and ICAO Annex 6 [19] are deemed to be not relevant to deriving the fundamentals of UAS collision avoidance and are not analysed further.[17]

3.4 Conflict Management

In accordance with the ICAO Concept [1], Conflict Management is applied in three layers: Strategic Conflict Management, Separation Provision, and Collision Avoidance. How this service-level concept works in practice, and relates to the underlying ATM system (ground and airborne components), is depicted in Figure 2. The input to this simple model is the air traffic, the existence of which represents hazards to, *inter alia*, other aircraft within it.

[16] See paragraph 1.5.3 of ICAO Doc 9863 [20].

[17] This is in line with the guidance given in Section 7.3 of ICAO Doc 9863 (ACAS Manual) [17]: "There is no basis for interpreting the ICAO requirements to fit ACAS as a requirement for UAVs; Further safety studies and analyses are necessary to assess the safety impact of ACAS-on-UAV operation before its operation is permitted."

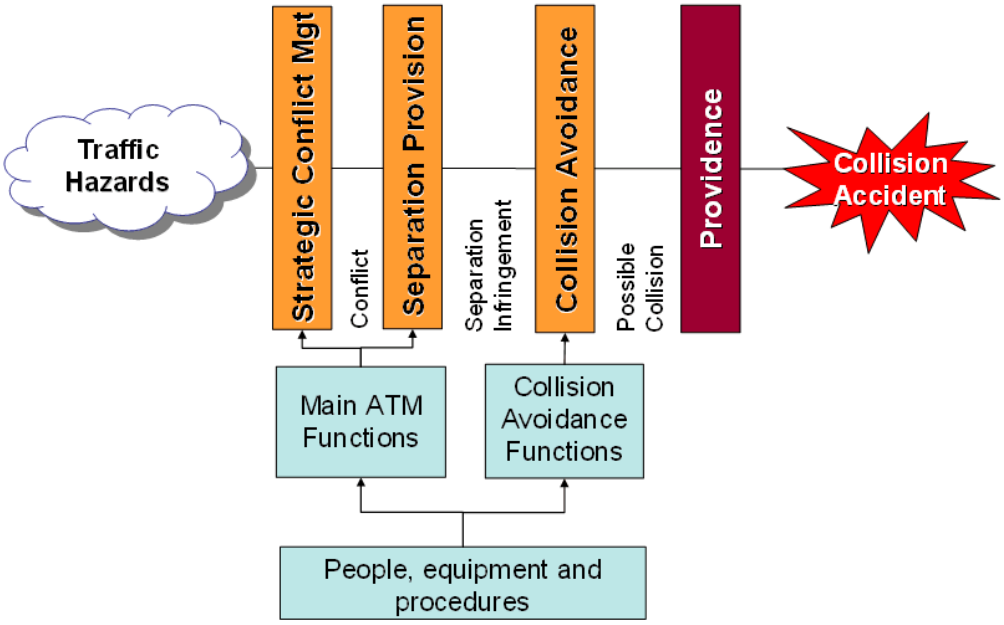

Figure 2: Conflict Management Model.

The three layers of Conflict Management identified in Figure 2 can be thought of as barriers which prevent those hazards leading to an accident, and each one has a specific purpose, as follows:

- The **Strategic Conflict Management** barrier is provided by the following main ATM functions:
  - Airspace design which provides structuring of the airspace so as to keep aircraft apart spatially, in the lateral and/or vertical dimensions.
  - Flow and Capacity Management which mainly prevents overload of the Separation Provision barrier.
  - Traffic Synchronisation which involves the planning of the routing and timing of individual flights so that the aircraft, if they followed their planned trajectories, would pass each other without infringing the prescribed minimum separation.
- The **Separation Provision** barrier is the second layer of Conflict Management and is the process of keeping aircraft away from each other, and from fixed obstacles, by at least the appropriate separation minima, by means of tactical intervention [1]. Separation Provision is necessary due to the inherent limitations of Strategic Conflict Management in eliminating all conflicts and may be the responsibility of an ANSP, the airspace user, or a combination of the two. Application by flight-crews of the Annex 2 right of way rules, constitute the means of separation provision by flight-crew.[18]
- **Collision Avoidance** is intended to recover the situation only when the previous two barriers have failed to remove conflicts to the point that flight-crew or on-board systems perceive that there is a risk of

[18] In the future, separation provision by flight-crew may also be aided by on-board separation assistance systems.

collision. In the context of manned aircraft operations, it is initiated on-board in response to:

- o instructions provided to flight-crew by controllers (often supported by ground-based safety nets such as STCA);
- o alerts and advice provided by airborne safety nets such as ACAS (these advise the flight-crew or initiate automatic response by the aircraft); or
- o visual acquisition of a threat, resulting from routine visual scanning by flight-crew, or prompted by verbal traffic information from ATC or a cockpit display of traffic information.

The positioning of these collision-avoidance elements with respect to the Conflict Management model is shown in Figure 3.[19]

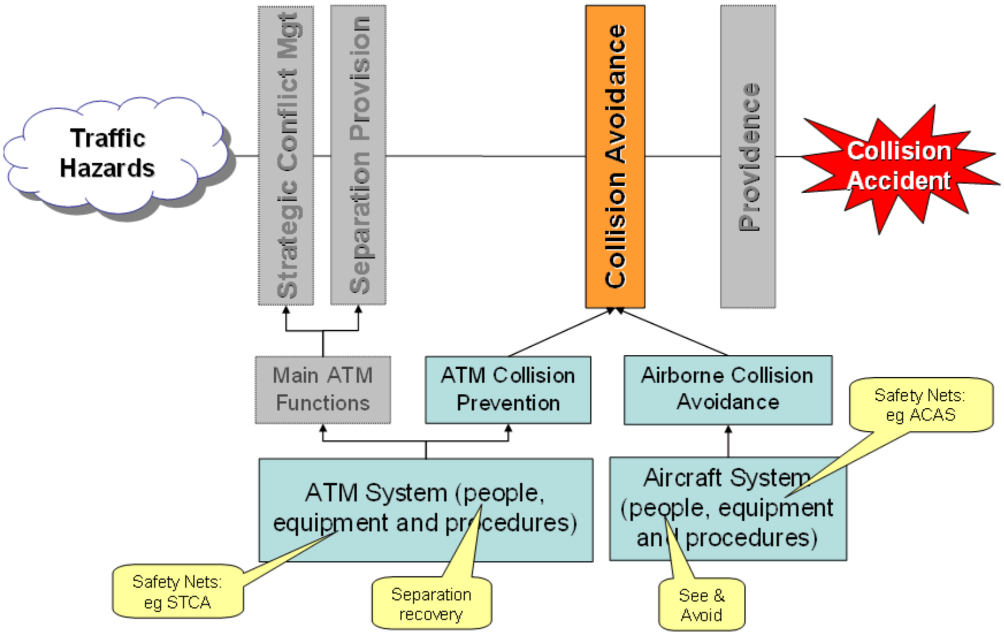

Figure 3: Manned Aircraft Collision Avoidance Elements.

Providence is the final barrier and simply represents the probability that aircraft involved in a given encounter, albeit in close proximity with another aircraft or obstacle, would not actually collide. Although a matter of chance, Providence can be affected by such things as procedures (*e.g.* applying lateral offsets when flying specific routes, flying at levels governed by semi-circular/quadrantal rules, and application of the rules of the air) and airspace/runway design traffic distribution which, if designed appropriately, can slant the odds in aircraft's favour.

[19] The diagram shows the 'barrier model' of collision avoidance implied by the layers of conflict management laid out in the ICAO ATM Concept of Operations. This model has limitations and the interactions between the layers may be more complicated in certain circumstances. Furthermore the ICAO conops overlooks an additional potential barrier that sits between 'separation provision' and 'collision avoidance' which can be termed 'separation restoration' – *e.g.* STCA can alert a controller to a loss of separation and he can take appropriate action far in advance of the need for last-ditch collision avoidance.

3.5 Collision Avoidance Functionality

At an abstract level, mid-air collision avoidance functionality can be represented as shown in Figure 4. This depicts collision avoidance as being the result of aircraft movement arising from three basic functions on each of the involved aircraft.

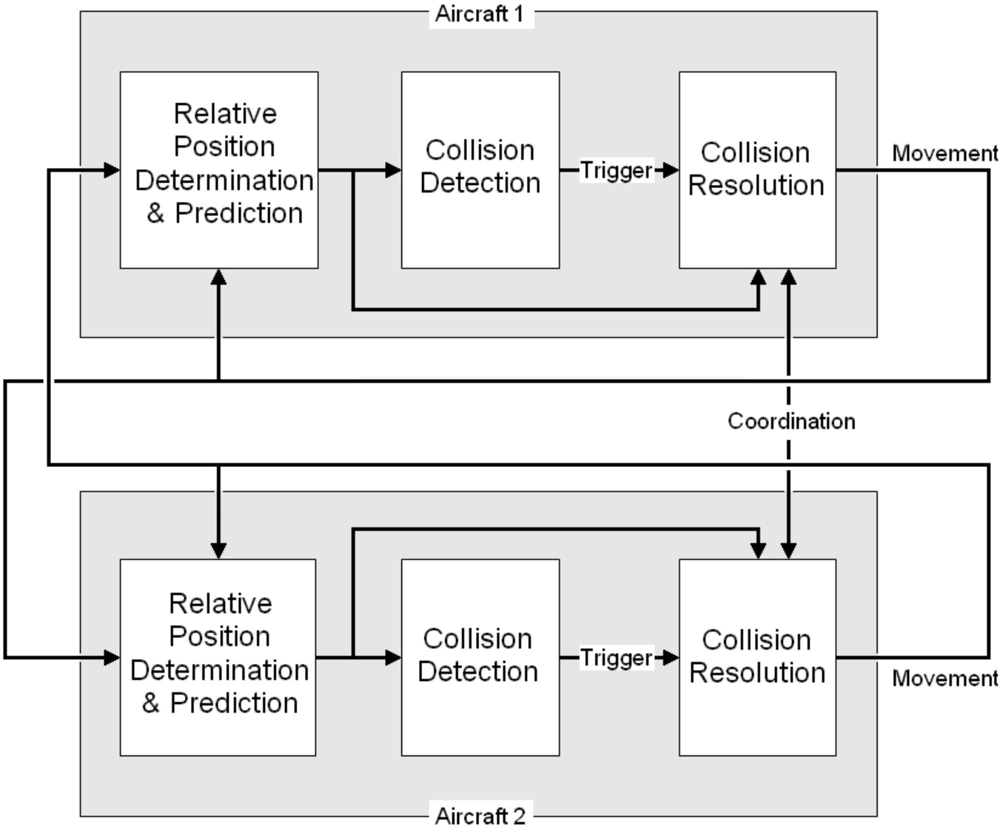

Figure 4: Collision Avoidance Functional Model (for a single pair of aircraft).

Collision resolution is triggered by the collision detection function. Both require knowledge of the relative position of the potential collision threat.

Collision avoidance can be enhanced by coordinating the collision resolution action between the two involved aircraft.[20] Therefore, the functionality involves interdependency between aircraft if such enhancement is necessary.

[20] With onboard collision avoidance avionics systems, coordination can be achieved by an exchange of information between the systems on the two aircraft. With See & Avoid 'coordination' can be achieved by observing the movements of the other aircraft and applying the right of way rules.

4. UAS COLLISION AVOIDANCE

4.1 Application of Collision Avoidance Fundamentals to UAS

In the context of UAS operations, the (mid-air) collision avoidance layer within the Conflict Management model, and its supporting system elements, can be depicted as shown in Figure 5.

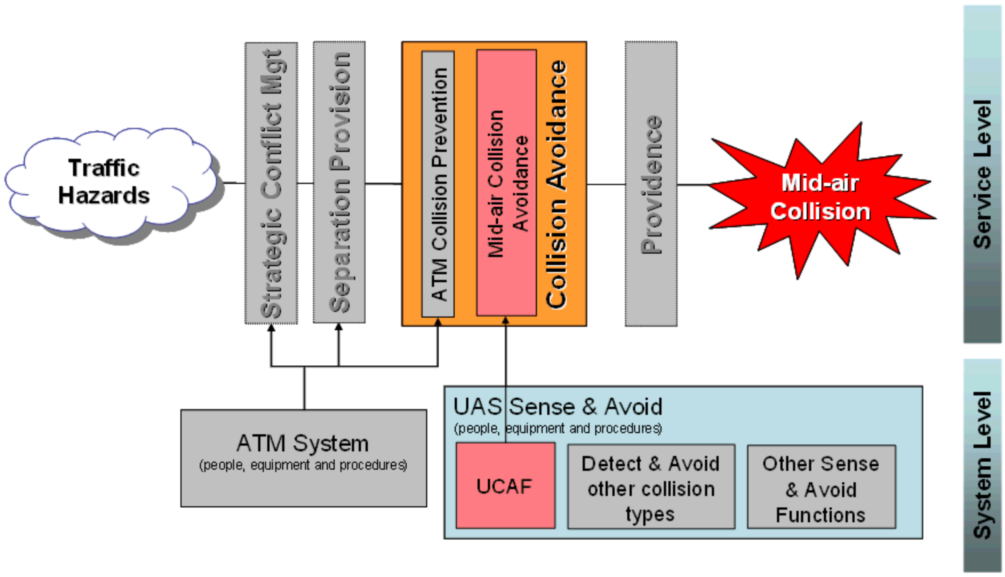

Figure 5: UAS Collision Avoidance Elements.

4.1.1 Sense & Avoid

UAS mid-air collision avoidance constitutes one of the sub-functions of a UAS Sense & Avoid system.

The remaining sub-functions of Sense & Avoid comprise:

- maintenance of separation from other traffic when flying VFR;
- detection and avoidance of collision with terrain or obstacles on the ground;
- detection and avoidance of collision with aircraft and obstacles during operations on or in the vicinity of the aerodrome;
- detection and avoidance of adverse weather;
- detection of IMC and VMC (flying under VFR is not permitted in IMC);
- detection and avoidance of nearby aircraft in uncontrolled airspace or when flying VFR, in order to maintain visual separation.

UAS collision avoidance may utilise the same physical elements (sensing, processing, communication, actuation, human) as the other Sense & Avoid sub-functions.

4.1.2 Separation Provision

In being confined to the UAS, UCAF is deemed to provide collision avoidance only, according to ICAO definitions.

UCAF does not provide Separation Provision, regardless of the means of detecting nearby aircraft.[21]

4.2 Assumptions and Principles

4.2.1 Objectives

The timing and nature of the UAS collision avoidance action is dictated by a compromise between the following objectives:

- Safety objectives;
  - to reduce the risk of collision;
  - to allow time for accurate detection of a potential collision, formulation, and execution of resolution action;
  - compatibility with the minimum airframe capabilities of the UAS in the environment of use;
  - compatibility with the minimum pilot capabilities, if the UCAF is not fully autonomous;
  - to minimise the required deviations in aircraft attitude, body rates and acceleration to avoid stress on the airframe;
  - the need to accommodate unpredictable movement of the other involved aircraft;
- Operational acceptability objectives (provided these can be achieved while meeting the safety objectives);
  - to minimise the displacement from flight path to avoid consequential loss of separation with third-party aircraft, and disruption to ATC; and
  - to minimise the incidence of nuisance alerts.

[21] Notwithstanding the disjoint nature of separation provision and collision avoidance invoked here, a recent series of FAA Sense & Avoid workshops [30] envisages an additional ‘self-separation’ function of Sense & Avoid. Self-separation would sit between compliance with separation provision and collision avoidance and would aim to allow the UAS to comply with the regulatory requirement to remain ‘well clear’ of other traffic. Specifically it is defined as the issuance of an early manoeuvre (limited to operation after standard separation has been infringed) that avoids the need for a later collision avoidance manoeuvre. As such, self-separation would correspond to the additional barrier identified in the footnote to Section 3.4. Although half-way between separation provision and collision avoidance the self-separation function is best thought of as a second layer of separation provision and as such should remain, as far as possible, independent of UCAF (or at least the probability of occurrence of common failure modes should be sufficiently remote) although it is acknowledged that these functions might share common components.

Although not an objective in its own right, it may be found desirable to include with the objectives listed above:

- coordination of resolution manoeuvres with any collision avoidance system on the threat aircraft.

To satisfy these objectives, the collision avoidance action obeys the following principles:

- collision avoidance is initiated using relatively benign control action, and at the latest time commensurate with collision avoidance efficacy and a tolerable level of unnecessary manoeuvres;
- collision avoidance control action shall allow for variability in pilot response, if the UCAF is not fully autonomous;
- the nature of the avoidance action can change during the course of collision avoidance.

4.2.2 Principles

4.2.2.1 Independence

Since a potential mid-air collision can generally be attributed to a failure of separation provision, UCAF must operate autonomously and independently of the ATM system (which provides, *inter alia*, the ATC service) or any other means of UAS separation provision.

So that it will continue to function when separation provision has failed, the design of UCAF must ensure that:

- it is unaffected by the behaviour of the Air Traffic Services leading up to the potential collision;
- it does not rely on any part of the ATM system in order to provide its collision avoidance function;[22] and
- it is unaffected by interference from separation provision (either by Air Traffic Services or other means of UAS separation provision) while resolving the collision.

The need for timely detection and resolution of potential collisions by UCAF, and independence from the ground-based ATM system, leads to a solution which is self-contained to the UAS ground and airborne components.

4.2.2.2 Sense & Avoid used for other functions

Closely related to the issue of independence from the ground-based ATM system are the issues that arise when the UAS Sense & Avoid capability is used for functions other than collision avoidance:

- Sense & Avoid is intended to detect any hazard (not just mid-air collision) *e.g.* terrain and obstacles on the ground, wake turbulence, significant weather. The other demands on Sense & Avoid could compromise the collision avoidance capability: either by degrading

[22] Interpretations of the requirement for independence are being developed by the FAA and EUROCAE WG-75.

the collision avoidance functionality; or causing it to generate advice incompatible with collision avoidance.

- Sense & Avoid could be used as the means of providing separation provision (especially in VFR flight). This potentially compromises the independence of the collision avoidance capability (and thus its ability to act as an effective safety net) in circumstances where separation provision has failed.

Independence of UCAF and the other functions of Sense & Avoid can be provided either: through duplication of systems (which would, however, still be susceptible to incorrect input data); or the use of dual systems using alternative techniques to derive the same information about potential hazards.

However, it should be noted that independence of the collision avoidance capability and the other functions of Sense & Avoid is not an aim in itself. Rather, an appropriate level of safety needs to be delivered by the combined systems. Systems that are not independent are susceptible to common failure modes, but an appropriate level of safety can still be delivered if it is ensured that the integrity of the common data and reliability of the common components is sufficiently high.

4.2.2.3 Prioritisation

UAS collision avoidance needs to be prioritised with respect to certain other functions on the UAS. Even though it provides protection against a potential mid-air collision, UCAF does not take priority over, and should not interfere with, the need to rectify situations which present an even higher risk of accident to the UAS or harm to its environment.

Similarly, rectifying those situations which have less likelihood than potential mid-air collision to lead to an accident must not take priority over, or interfere with, UCAF.

4.2.2.4 Environment

UCAF operates during those phases of flight in which it is capable of reliably detecting the risk of a mid-air collision and safely resolving that risk. Hence, it does not operate when the UAS is close to, or on, the ground.

UCAF operates in all those classes of airspace in which the UAS flies.

UCAF must provide collision avoidance against all classes of aircraft permitted in the environment in which the UAS is operating, and all permitted Transponder equipages and capabilities on those aircraft.

UCAF operation when the UAS is being subjected to interception by military aircraft needs to be defined (and will naturally depend on the UAS’s ability to detect that it is the subject of a military intercept).

UCAF needs to detect nearby aircraft type, towing configuration, phase of flight, and emergency status if it is to apply all provisions of the right-of-way rules.

UCAF needs to be effective against varying levels of collision avoidance functionality in manned intruder aircraft. Therefore, it needs to be effective in providing collision avoidance in the presence of varying levels of:

- visibility;[23]
- ACAS equipage on intruder aircraft; and
- manoeuvring capability of intruder aircraft.

UCAF needs to be effective against intruder UAS for reasons of:

- avoiding consequential harm to people and property both on the surface and in the air; and
- satisfying mission objectives.

4.2.2.5 Universality

Mid-air collision avoidance depends upon a UAS having the capability to determine, to some extent, the relative position and motion of an intruder aircraft.[24] Its ability to effect collision avoidance also depends upon how well it uses this information to produce an avoidance action. The determination of a suitable collision avoidance manoeuvre arises from a processing mechanism (either algorithmic or cognitive) which can accommodate the range of possible movements of the UAS and the intruder aircraft.

Due to the fact that UAS collision avoidance relies upon compatibility between the UCAF and the collision avoidance function on the intruder aircraft (which might be a UAS, or a manned aircraft), the UCAF must be based upon system specifications which are applicable worldwide since the involved aircraft might originate anywhere.

4.2.2.6 Compatibility

UCAF shall not adversely affect the efficacy of collision avoidance by a manned intruder aircraft when the manned aircraft encounters a UAS.

This implies that UCAF shall be compatible with ACAS-produced collision avoidance actions only.[25] In contrast See & Avoid by manned aircraft is an unpredictable action without direct compatibility or coordination with the intruder aircraft.[26]

Since visual acquisition of certain types of UAS by a manned aircraft is unlikely, this implies that carriage of compatible transponders by UAS is

[23] Which affects visual acquisition by a manned intruder aircraft.

[24] This may be limited (as with ACAS) to the range and altitude of the intruder, and the rate at which these quantities are changing.

[25] This does not mean that ACAS must perform in exactly the same way for a UAS encounter as for an ACAS encounter, provided there is sufficient risk reduction; *e.g.* it could involve the UCAF suspending any avoidance manoeuvre upon an encounter with an ACAS equipped intruder.

[26] Some indirect compatibility and coordination are provided by compliance with the Rules of the Air but this cannot be relied upon in extreme circumstances such as an impending mid-air collision.

necessary in order not to compromise ACAS as being an effective collision avoidance mechanism on the manned aircraft.[27]

4.2.2.7 *Deployment*

Since UCAF is the means by which UAS will conform to the collision avoidance requirements in Annex 2, UAS will not be operated in non-segregated airspace without UCAF,[28] regardless of UAS airframe type (*i.e.* it is assumed that UAS will not be permitted to operate outside segregated airspace without UCAF).

4.3 Warning times

Collision avoidance systems must generate alerts in a timely manner so that there is sufficient time to initiate any required manoeuvre and achieve the desired miss distance from the threat.

4.3.1 Warning times on manned aircraft

In the design of collision avoidance systems for manned aircraft (*i.e.* ACAS) the warning times (*i.e.* the time between the generation of the alert and the potential collision) incorporate two factors:

- pilot delay – a period during which the pilot must notice the alert, determine what response is required, and initiate this response; and
- manoeuvre delay – the time that it takes to achieve the desired miss distance assuming a standard acceleration to a standard speed.

4.3.2 Warning times on UAS

The two factors mentioned above (*viz*. pilot delay, and manoeuvre delay) must also be considered when determining warning times in the design of collision avoidance for UAS.

The allowance for pilot delay offers two distinct approaches to the design of collision avoidance for UAS, which are discussed below.

4.3.2.1 *Response by a remote pilot*

The response to collision avoidance alerts could be initiated by the remote pilot of a UAS. Under these circumstances the pilot delay will include the response time of the remote pilot (taking account of the specific control interface used) and the round trip latency associated with communicating the alert to the remote pilot[29] and communicating his response back to the UA.

[27] UAS will also need to be transponder equipped for ATC purposes when in controlled airspace.

[28] Deployment of UCAF therefore differs from the progressive introduction of ACAS in manned aircraft, because non-ACAS equipped manned aircraft already have a means to satisfy Annex 2 using See & Avoid.

[29] Assuming that sensor outputs are processed on-board the UA to generate alerts. The same delay will apply if the sensor outputs are communicated to the ground with collision avoidance processing taking place remotely from the UA.

It is likely then, that the warning times for a system with response initiated by the remote pilot will be longer than the warning times employed in manned aircraft's collision avoidance systems.

Generally, increased warning times lead to an increased number of nuisance alerts, particularly with a 'time to collision' based system (such as ACAS) which relies on range information alone in the horizontal dimension.

4.3.2.2 Automated response

Alternatively response to collision avoidance alerts could be initiated automatically on board the UA.

An automated response to alerts generated by UCAF would mean that the response times would be close to zero. Consequently an automated response could use reduced warning times,[30] compared to a response initiated by a remote pilot, and yet a comparable level of protection. The advantage of having shorter warning times is that it can reduce the number of nuisance alerts.

Even with an automated response to alerts the pilot must still be alerted and have the ability to re-take active control of the UAS if necessary (*e.g.* in case of an inappropriate UCAF manoeuvre).

[30] Presupposing that UCAF alerts were based on the proven 'time to go to collision' principle used by ACAS and first described by Dr. Morrel in 1958 [21].

5. REQUIREMENTS FOR UAS COLLISION AVOIDANCE

5.1 Aim and Purpose

This section identifies the functional requirements that need to be achieved by a UAS Collision Avoidance Function (*i.e.* the type of airborne objects that need to be detected, tracked, and avoided) in order for it to have an equivalent or better level of performance than manned aircraft.

The functional requirements identified in this section, along with other issues related to the operation of UAS and performance limitations of ACAS, are used to derive capability requirements for a UAS Collision Avoidance Function.

5.2 Background

5.2.1 Scope

The evolution of aerospace technologies in the field of unmanned aircraft systems (UAS), including autonomous operations, will impact European ATM as regards new military and civil applications. UAS will present new challenges as well as new opportunities for the design of future ATM systems in the context of both SESAR and beyond (into the 2050 timeframe).

EUROCONTROL, in executing its responsibilities associated with the management of the pan-European ATM network, must ensure that UAS operations do not negatively impact overall levels of ATM security, safety, capacity and efficiencies.

One of the basic tenets for deployment of UAS in non-segregated airspace is that UAS operations should possess the dual properties both of equivalence and transparency: in short, the UAS must behave like a manned aircraft. In more concrete terms, a UAS shall adhere to all the ICAO SARPS and Procedures related to aircraft operations, even though these were originally conceived for an aviation system in which a pilot is physically central to the aircraft and its local environment.

The dislocation of the pilot in a UAS, and the inevitable adjustments to their interaction with the aircraft, its systems, and its environment, can therefore present a challenge when trying to relate long-established concepts (and their associated terminologies) to the problem of safe UAS operations.

The scope of the CAUSE Project is limited to mid-air collision avoidance. Therefore, as a basis for reasoning concerning the need for, and required behaviour of, UCAF the fundamental concepts behind collision avoidance should first be established. The ICAO SARPS and Procedures by themselves do not necessarily capture these ‘Fundamentals’ because each one focuses on the rules to be applied by a different actor in the aviation system. As such, they essentially represent a decomposition and elaboration of the basic concepts.

5.3 Application of Collision Avoidance

5.3.1 Basic definitions

It is helpful at this stage to remind ourselves of some basic definitions:

- **Separation Provision** is the process of maintaining sufficient physical separation between aircraft, terrain and other objects so that there is no discernable risk of collision.
- **Collision Avoidance** is the process of avoiding a collision (with another aircraft, vehicle, structure or terrain). In general terms, collision avoidance is intended to operate when separation assurance cannot be maintained.
- **See & Avoid** is the process performed by flight-crew with the ability to visually detect other aircraft, terrain or objects in order to perform separation assurance or collision avoidance.
- **Sense & Avoid** is the term used to collectively describe the combined functions of separation assurance and collision avoidance. It is the corresponding function of the analogous See & Avoid function performed by the flight-crew of manned aircraft.

Figure 6 shows the various systems and processes that are used in conventional (manned) aviation to provide Sense & Avoid. Some of these systems and processes are used exclusively for separation assurance, and some for collision avoidance. However, of key importance is the fact that See & Avoid is common to both, and in many cases this is the only means of detection of aircraft that are unknown to ATC, or other airborne objects (*e.g.* birds).

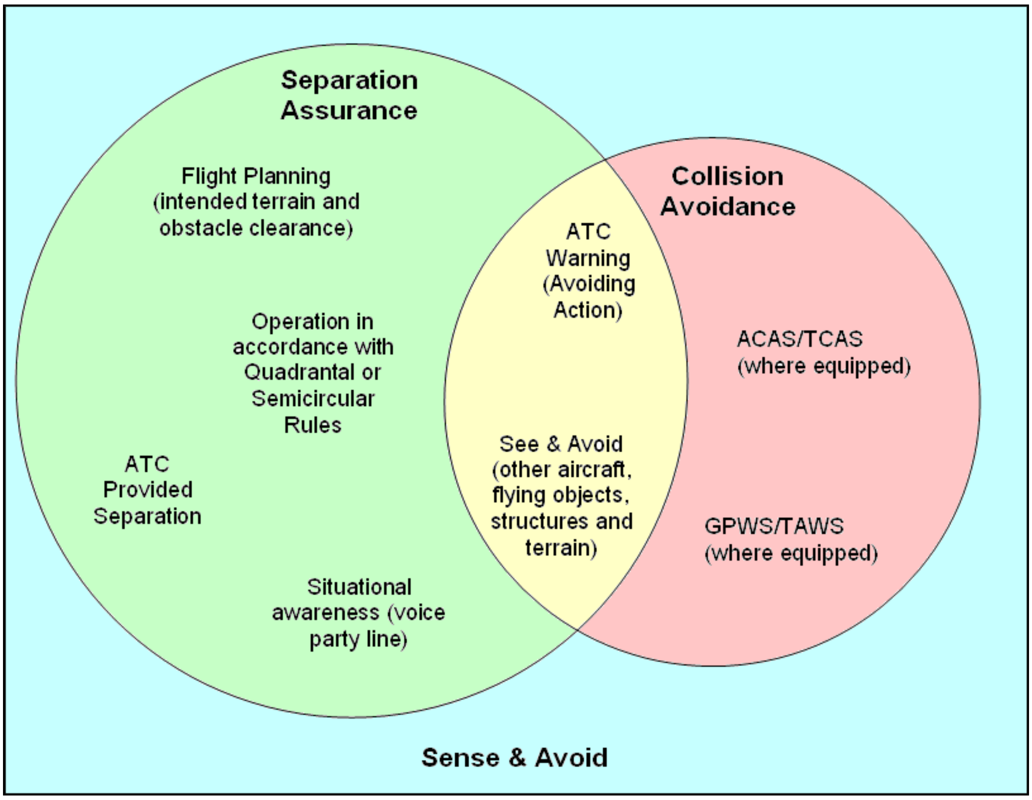

Figure 6: Venn Diagram for Conventional Sense & Avoid performed by Conventional (Manned) Aircraft.

5.3.2 Application to Manned Aircraft

For conventional (manned) aircraft, collision avoidance relies heavily on the ability for the pilot(s) to see and avoid other traffic. For aircraft that are fitted with ACAS, warnings are generated to highlight the risk of collision with SSR equipped aircraft, and aural advisory messages are generated. However, ACAS is not an autonomous system, and it was designed to be used in conjunction with an onboard pilot who is able to assess all available information, and then decide whether or not to take collision avoidance action.

Depending on the classification of airspace and flight rules being applied, separation can be provided by the aircraft's pilot(s), Air Traffic Control (ATC) or both.

Whilst the pilot has a responsibility to ensure separation from terrain and physical structures when planning a flight, the responsibility for providing separation from other aircraft can be transferred to ATC in certain circumstances.

For aircraft that are operated under Instrument Flight Rules (IFR), the standard separation is 5 NM laterally and 1,000 ft vertically. There is no standard definition of minimum separation for Visual Flight Rules (VFR) traffic, but it is generally accepted that 500 ft, either vertical or horizontal is the minimum acceptable separation for aircraft that can see and avoid each other in Visual Metrological Conditions (VMC) (see *e.g.* the discussion section 3.7.2 of [24]). A horizontal separation of 0.5 NM, in line with 'Specification UAV11' of [24], is probably more practical.

5.3.3 Application to Unmanned Aircraft

It is widely accepted that for an Unmanned Aircraft to be permitted to operate outside segregated airspace amongst other aircraft, it must demonstrate equivalence and transparency in all areas of operation, and this is particularly so for any aspect of operation with the potential to impact on safety and interoperability.

By definition, these principles apply equally to the capability performance of Sense & Avoid, and its integral processes of separation assurance and collision avoidance.

However, a fundamental difference is the lack of onboard flight-crew (who can perform 'See & Avoid' using human vision). Therefore, as part of defining specific performance requirements for UCAF, it will be necessary to characterise the performance of the See & Avoid process that is achieved by today's manned aircraft. Such an exercise is beyond the scope of the current study but some observations about the functional requirements (gained from experience in the AVAL study with the implementation of a visual acquisition model [22] and the modelling of horizontal manoeuvres [23]) are presented in Appendix E.

5.3.4 Extended principle of equivalence

As previously stated in Section 5.2.1, one of the basic tenets for deployment of UAS in non-segregated airspace is that UAS operations should possess the dual properties both of equivalence and transparency: in short, the UAS must behave like a manned aircraft.

For example the UK CAA Directorate of Airspace Policy (DAP) publication '*Unmanned Aircraft System Operations in UK Airspace – Guidance'* [28] states:

> "The fundamental principles of equivalence and transparency have been established to ensure that operation of UAS does not constitute a greater risk to flight safety, the safety of other airspace users, and the safety of third parties than current manned aircraft operations."

This position is expressed more succinctly in [29]:

> "… the CAA's starting point for the consideration of the regulation of UAVs is that they should pose no greater risk to persons or property in the air or on the ground than that presented by equivalent manned aircraft."

In the context of collision avoidance this position demands that:

- all UAS should have Sense & Avoid performance that is equivalent to (or exceeds) the See & Avoid performance of manned aircraft;
- in addition, certain UAS should also have collision avoidance performance that is equivalent to (or exceeds) the collision avoidance performance of ACAS equipped manned aircraft (where the "equivalent manned aircraft" would be subject to the ACAS mandate – see Section 1.1.3).

It is beyond the scope of this study to determine precise criteria by which certain UAS should be required to have a collision avoidance performance that matches that of ACAS equipped manned aircraft. However, such criteria should be based on potential risk to other airspace users and third parties on the ground. In practice this will probably mean that equipage requirements are broadly based on the "size" of the UA so that, as with the ACAS mandate, heavier aircraft are required to have the requisite performance. A threshold based on MTOM need not be set at the same level as the ACAS mandate (*viz.* 5,700 kg) and should certainly not be higher.[31] Any criteria might also be airspace dependent (*e.g.* being more stringent above FL100, or less stringent in uncontrolled airspace).

5.3.5 UAS equipage with ACAS

The development and eventual mandating of ACAS was pursued in response to a perceived requirement that Commercial Air Traffic needed a collision avoidance capability (in the event that separation provision failed) superior to that offered by routine See & Avoid carried out by flight-crew by ACAS suitable for manned aircraft.

Since ACAS II is deemed to meet this requirement then the question naturally arises as to whether the same system can fulfil any similar requirement for UAS.

For various reasons the safety benefit resulting from the mandated equipage of manned aircraft is not necessarily immediately realisable when UAS are equipped with ACAS:

- ACAS provides collision avoidance advice which is presented to the pilot who is required to implement the advised manoeuvre.[32] On a UAS some means of presenting this advice to a remote pilot and/or having manoeuvres flown automatically by the UAS would be required;
- ACAS surveillance can be affected by the siting of the ACAS antennae. The shape of the UAS airframe and the potential proximity of various furniture could interfere with the optimal performance of ACAS surveillance;
- Aspects of the ACAS design assume deployment on civil fixed-wing aircraft. The performance of ACAS algorithms might be impaired by the routine flight dynamics of some UAS;
- ACAS collision avoidance manoeuvres require specific response times, vertical accelerations, and vertical rates. If these cannot be achieved by the UAS then the appropriateness of the ACAS advice is not guaranteed.

These issues are discussed in more detail in Appendix D.

[31] Suitable criteria might be the CAA's thresholds for qualification as a "light UAV": *viz*. MTOM below 150 kg; and maximum kinetic energy on impact not exceeding 95 kJ; and maximum sustained speed in level flight not exceeding 70 kt. [28]

[32] Although an 'auto-pilot/flight director' ACAS mode has recently been certified on the Airbus A380, and similar implementations can be expected on other aircraft types.

5.4 Airborne objects and their attributes

5.4.1 Introduction

In order to take a holistic view of collision avoidance, it is first necessary to identify every type of aerial object that a UAS might reasonably encounter. For each object, key attributes can be recorded such as size, mass, velocity and altitude range. It is also important to categorise objects in terms of their ability to maintain separation assurance and perform collision avoidance.

The types of aircraft and objects for which a risk of collision might exist are listed in Section 5.4.2.

A range of attributes are defined in Sections 5.4.3 to 5.4.7. These enable the risk to be captured as a set of functional requirements, depending upon the type of airspace, meteorological conditions, and altitude range in which the UAS operates.

Table 7 records the types of object in groups and their attributes.

5.4.2 Grouping of airborne objects

For the purpose of this study objects have been organised into seventeen groups (and assigned a code letter):

- **F** – Fauna. Birds[33] the size of a goose or larger. Birds do not generally fly in IMC nor above 1,000 ft AGL;[34]
- **K** – Kites and tethered balloons. Both the object itself and the cable connecting it to the ground. Operation above 400 ft should be notified by NOTAM (*i.e.* known to ATC).
- **R** – Radio controlled model aircraft operated by hobbyists. Generally operated in VMC below 400 ft AGL and within line of sight of the operator (typically 500 m). Operation above 400 ft should be notified by NOTAM (*i.e.* known to ATC).
- **B** – Hot air balloons. Do not operate in IMC.
- **D** – Dirigible airships.
- **G** – Gliders. Do not operate in IMC.
- **P** – Parachutists. Do not operate in IMC. Activity should be notified by NOTAM (*i.e.* known to ATC).
- **S** – Powered air sports: very light aircraft, ultralights, motor gliders, motor paragliders, *etc.* Do not operate in IMC.
- **A** – Unpowered air sports: hang gliders, paragliders, *etc.* Do not operate in IMC.

[33] And, conceivably, bats.

[34] However, migrating birds can be encountered higher than this, typically in the range 5,000 ft to 7,000 ft AGL, often at specific times of year and in specific locations. Generally, the greater the height above the ground the less likely it is that birds will be encountered. The threshold of 1,000 ft has been adopted here as a reasonable cut-off.

- **H** – Helicopters (both civil and military).
- **L** – Light aircraft (*i.e.* non-pressurised general aviation).
- **Q** – Pressurised general aviation with MTOM less than 5,700 kg.
- **M** – Military fighters and high performance jets. May be fitted with a collision warning system (CWS) to aid pilot's visual acquisition of collision threats.
- **N** – Pressurised passenger aircraft not required to carry ACAS (*i.e.* less than 20 seats and MTOM less than 5,700 kg).
- **T** – Pressurised passenger aircraft required to carry ACAS (*i.e.* more than 19 seats or MTOM over 5,700 kg).
- **C** – Cargo aircraft or military air transport. Generally MTOM over 5,700 kg and thus expected to be ACAS equipped.
- **U** – Unmanned Aircraft. A wide ranging group covering a variety of sizes, airframe designs, and capabilities.

5.4.3 Physical properties

Visible size – Column 4 of Table 7 gives the approximate physical size of the object (in metres), as seen from another aircraft on a collision course (*i.e.* wing span in the case of aircraft). The physical size of the threat and the UA will determine the likelihood that providence will prevent a collision, in a close encounter in which any separation is fortuitous. The size of the threat also determines the angular resolution required for detection of the threat by optical techniques.

Mass and **speed** – Columns 5 and 6 of Table 7 give the typical mass (in kilograms) and typical speed (in knots) of the object. Jointly these attributes, along with the mass and speed of the UA, determine the **kinetic energy** associated with any collision – the typical energy (in kilojoules) is shown in column 7. The effect on the victim aircraft (UA in this case) will depend upon whether it is designed to withstand a collision delivering such energy. For example, a large passenger aircraft is typically designed to survive a collision with a large bird (*e.g.* goose) at a closing speed of 480 kt[35] which would impart about 250 kJ of energy – about the same as a head-on collision between two saloon cars travelling at 55 kph.

For a given angular resolution the physical size of the threat, together with the closing speed, will determine the time at which the threat is likely to be detected by optical techniques.

Radar cross-section – Column 8 of Table 7 gives the typical radar cross-section of the object on a grade scale of 'negligible', 'poor', 'medium' and 'large'. The radar cross-section determines the ease with which an object can be detected by primary radar. All other things being equal, larger objects will have a larger radar cross-section. However, the material composition of the object has a more significant effect with predominantly metal objects being easier to detect than similarly sized objects composed of other materials.

[35] FAA Regulation 25.631 requires that the empennage can withstand an impact by an 8 lb (3.64 kg) bird at a closing speed of the design cruising speed at 8,000ft. For a B737-400 this is 476 kt.

5.4.4 Obligations and abilities

Right of Way – Under ICAO rules of the air, certain types of aircraft have right of way over others:

- balloons have right of way over gliders, airships and powered aircraft;
- gliders have right of way over airships and powered aircraft;
- airships have right of way over powered aircraft.

Adherence to these rules is most relevant to separation assurance, but failure by one party to comply could invoke the need for collision avoidance.

Column 9 of Table 7 indicates whether the object has right of way over a UA (which is, by definition (cf. Section 1.2.1), a powered vehicle). The table reflects the current rules which do not directly take account of the presence of UAS. It is possible that future right of way rules might be reframed to take account of UAS whose responsiveness can be affected by latency of communication between the UA and the remote pilot (see, *e.g.* [23]).

Capable of taking avoiding action – Column 10 of Table 7 indicates whether the object is capable of taking effective avoiding action if an imminent collision risk is detected. Not all aircraft or objects will be capable of taking avoiding action. For example, hot air balloons and parachutists cannot be relied upon to take effective avoiding action (often because such action is impossible even if the threat is detected). The same is true for birds. Where the third party is unable to take avoiding action, the residual risk of collision will be significantly greater.

5.4.5 Airspace

The airspace in which the UAS is operating is key to the level of collision avoidance capability required as it dictates the type of airborne objects that the UAS is likely to encounter.

In very general terms, airspace can be classified as comprising either a 'Known Traffic Environment' or an 'Unknown Traffic Environment'. These are defined as:

- **Known traffic environment** – an airspace environment within which the position of all traffic is known to ATC. Below FL100 a known traffic environment is provided by the application of Airspace Classifications A to D (as defined in paragraph 2.6.1 of ICAO Annex 11 [13]). The airspace at and above FL100 is a Known Traffic Environment due to the requirement for transponder carriage (see Section 5.4.7).[36]
- **Unknown traffic environment** – an airspace environment within which the position of not all traffic is known to ATC. An unknown traffic environment is provided by the application of Airspace

[36] *N.B.* This definition encompasses 'known traffic' in the collision avoidance context (*i.e.* transponder equipped), for the purpose of this study. In the ATC context traffic would only be considered 'known' if, as well as its position, its intentions were also known – *e.g.* transponder equipped aircraft in class E, F, or G airspace would be considered unknown in the ATC context but is considered known here.

Classifications E to G (as defined in paragraph 2.6.1 of ICAO Annex 11 [13]) below FL100.

The equipment carriage requirements that enable aircraft to operate in a known traffic environment mean that it is also possible for a collision avoidance system to reliably detect and track aircraft beyond visual range. This greatly improves the efficacy of a collision avoidance system.

Column 11 of Table 7 indicates which objects are likely to be encountered in a known traffic environment.

Column 12 of Table 7 indicates the typical **Maximum Operating Altitude** of the various groups of objects. Above this altitude the objects are unlikely to be encountered.

5.4.6 Meteorological conditions

Meteorological conditions are classified as either 'Visual' or 'Instrument'.

- **Visual Meteorological Conditions** (VMC) are said to exist when there is the required forward in-flight visibility, and, in some airspace classes, the Earth's surface remains in sight.
- **Instrument Meteorological Conditions** (IMC) are deemed to exist if VMC cannot be maintained at any stage during the flight.

Many small aircraft are only permitted to fly in VMC under Visual Flight Rules (VFR), and this effectively limits their access to certain airspace. For example, VFR operation is not permitted in Class A airspace.

The detection of collision threats by optical techniques (see Section 5.5.1.2) cannot be relied upon in IMC which can include zero visibility when in cloud. However, it should be noted that while IMC does not provide sufficient visibility for VFR flight at the upper limit of visibility this might be sufficient for the timely detection of certain slow moving collision threats.

Column 13 of Table 7 indicates whether the object is likely to be encountered in IMC.

5.4.7 Equipment carriage

This section indicates the equipment that an aircraft is expected to carry. This may be due to mandatory requirements, or voluntary equipage.

- **Radio** – Column 14 of Table 7 indicates whether radio equipage is required. Whilst this is not mandatory for non-public transport aircraft operating outside controlled airspace, many recreational aircraft (including balloons and gliders) will carry radios.
- **Transponders** – Column 15 of Table 7 indicates whether equipage with an altitude reporting SSR transponder is required. Transponder carriage is required for flight above FL100 and to access notified airspace. In addition, public transport flights require carriage of a transponder regardless of the airspace they are operated in.

- **ACAS II** (effectively **TCAS II**) – Column 16 of Table 7 indicates whether equipage with ACAS II is required. ACAS II is mandated for civil fixed-wing turbine-engined aircraft with MTOM more than 5,700 kg, or with 19 seats or more. However, it should be noted that it is permissible to fly with an inoperative ACAS under MEL exemptions[37] provided the transponder is still serviceable.
    - Some aircraft not covered by the ACAS mandate may voluntarily equip with TCAS I. TCAS I is mandated for certain smaller aircraft in the USA but there is no equipage requirement in any European state. It should be noted that TCAS I provides TAs only and as an aid to visual acquisition.
    - Some military fighter aircraft will be equipped with their own collision warning systems (CWS).
    - Other UAS can be expected to have a UCAF which might provide a similar level of capability as ACAS II.

[37] Generally applicable for 10 days but in some states for only 3 days.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
			physical properties					abilities		airspace			equipage		
cat.	group	description	size (m)	mass (kg)	speed (kt)	collision energy (kJ)	RCS	RoW over UA	can avoid	in known environ-ment?	typical max. altitude	in IMC	radio	trans-ponder	ACAS II
1	F	Large bird	1	10	20	100	neg.	✓	x	x	3000ft	x	x	x	x
	K	Kite or tethered balloon	2	20	0	100	neg.	✓	x	✓	500ft	✓	x	x	x
	B	Hot air balloon	10	200	10	500	poor	✓	x	x	FL100	x	x	x	x
	P	Parachutist	5	100	1	500	neg.	✓	x	x	FL100	x	x	x	x
	A	Unpowered air sports	5	150	20	500	poor	✓	x	x	FL100	x	x	x	x
2	R	Radio control model a/c	2	10	20	100	poor	✓	x	x	400ft	x	x	x	x
	G	Glider	10	500	50	2000	med.	✓	x	x	FL100	x	x	x	x
	S	Powered air sports	5	200	20	1000	med.	✓	x	x	FL100	x	x	x	x
3	D	Airship	20	500	50	2000	med.	x/✓[38]	x	✓	FL100	✓	✓	✓	x
4	H	Helicopter	10	2000	150	5000	large	x	✓	✓	FL100	✓	✓	✓	x
	L	Non-pressurised GA	10	1500	200	5000	large	x	✓	✓	FL100	✓	✓	✓	x
	Q	Pressurised GA	15	1500	200	5000	large	x	✓	✓	FL200	✓	✓	✓	x
	N	Pressurised passenger aircraft (not ACAS)	20	5000	250	10000	large	x	✓	✓	FL200	✓	✓	✓	x
4, 5	T	Pressurised passenger aircraft (ACAS)	50	50000	500	20000	large	x	✓	✓	FL400	✓	✓	✓	✓
	C	Cargo aircraft	50	100000	500	20000	large	x	✓	✓	FL400	✓	✓	✓	✓
	M	Military Fighter	15	1500	1500	100000	large	x	✓	✓	FL600	✓	✓	✓	x
	U	Unmanned aircraft[39]	5	200	150	2000	med.	x	✓	✓	FL600	✓	✓[40]	✓	x

Table 7: Attributes of aerial objects by group.

[38] If the UA is an airship then other airships will not automatically have right-of-way.

[39] A wide ranging group. Typical values are given but individual UA may have significantly different attributes.

[40] UAS in non-segregated airspace will effectively be ‘radio equipped’ in as much as ATC will be in voice communication with the remote pilot.

5.5 Functional Requirements for Collision Avoidance

5.5.1 Criteria for categorisation of objects

The object types listed in Section 5.4.2 can be categorised on the basis of three criteria that directly affect the functional requirements of a collision avoidance system on a UAS that might encounter them. These criteria are considered below and the objects that fall into each category (on the basis of the attributes listed in Table 7) are indicated.

5.5.1.1 Cooperation with ATC

Objects may or may not be able to cooperate with ATC by taking necessary avoiding action when so instructed:[41]

- **ATC-cooperative objects**: essentially aircraft – airships (**D**), helicopters (**H**), general aviation (**L**, **Q**), commercial air transport and military transport (**N**, **T**, **C**), military fighters (**M**), unmanned aircraft (**U**);
- **non-ATC-cooperative objects**: birds (**F**), kites and tethered balloons (**K**), hot air balloons (**B**), parachutists (**P**), air sports vehicles (**S**, **A**), model aircraft (**R**), gliders (**G**).

5.5.1.2 Detectability

Objects may be detectable only by optical techniques[42] or also detectable by non-optical techniques.

Optical techniques are based on visible and near-visible (ultraviolet and infrared) electromagnetic radiation. Examples include video, LIDAR, and thermal imaging. Optical techniques are generally ineffective in IMC.

Non-optical techniques are based mainly on radio-frequency electro-magnetic (including microwave) radiation.[43] Examples include primary radar, SSR, ADS-B, and multilateration. Non-optical techniques are generally not dependent on meteorological conditions.

The groups of objects are categorised as follows:

- detectable by **optical techniques** only – birds (**F**), kites and tethered balloons (**K**), hot air balloons (**B**), parachutists (**P**), air sports vehicles (**S**, **A**), model aircraft (**R**), gliders (**G**);
- detectable by **non-optical techniques** – airships (**D**), helicopters (**H**), general aviation (**L**, **Q**), military fighters (**M**), commercial air transport and military transport (**N**, **T**, **C**), unmanned aircraft (**U**).

It so happens that the group of object types only detectable by optical techniques corresponds to non-ATC-cooperative objects, and that the group of

[41] The terms 'ATC-cooperative' and 'non-ATC-cooperative' are used to avoid confusion with the usage whereby a cooperative target is merely one equipped with a transponder or broadcasting its position.

[42] *I.e.* techniques using electromagnetic radiation whose behaviour is covered by the science of optics.

[43] But not excluding other techniques, *e.g.* sonic techniques.

object types detectable by non-optical techniques corresponds to ATC-cooperative objects.

5.5.1.3 Ability to take effective avoiding action

Objects may or may not be able to take effective avoiding action when a risk of collision is detected depending on how manoeuvrable they are:

- **able to take effective avoiding action**: model aircraft (**R**), gliders (**G**), powered sports vehicles (**S**), helicopters (**H**), general aviation (**L**, **Q**), commercial air transport and military transport (**N**, **T**, **C**), military fighters (**M**), unmanned aircraft (**U**).
- **unable to take effective avoiding action**: birds (**F**), kites and tethered balloons (**K**), hot air balloons (**B**), parachutists (**P**), unpowered air sports vehicles (**A**), airships (**D**).

5.5.2 Categories of airborne objects

The criteria described above (see Section 5.5.1) allow the groups of objects defined in Section 5.4.2 to be grouped into five categories detailed below. Column 1 of Table 7 indicates to which category each group belongs.

5.5.2.1 Category 1

Non-ATC-cooperative objects that can only be detected by optical techniques, and are unable to take effective avoiding action.

This category consists:

- Birds (**F**), kites and tethered balloons (**K**), hot air balloons (**B**), parachutists (**P**), and unpowered air sports vehicles (**A**).

These objects are slow moving and so, in a collision geometry, will not overtake the UAS (*i.e.* are not expected to approach from behind).

The need to have a collision avoidance capability against this category of object gives rise to the following functional requirements, using optical techniques:

- acuity (*i.e.* angular resolution and contrast discrimination – see Appendix E.2.2) comparable to that of the human eye;
- horizontal coverage within the forward sector;
- vertical coverage comparable to that needed by the pilot of a manned aircraft (see Appendix E.2.1.2);
- perception of slow moving objects (*i.e.* ability to determine range and relative motion) comparable to that of human vision; and
- level of reliability (*i.e.* probability of timely detection of the threat) that is equal to, or exceeds, that achieved by flight-crew of manned aircraft in encounters with slow moving objects.[44]

[44] Which, potentially, can be assured by specifying the required 'search intensity' of the Sense & Avoid process (see Appendix E.2.3).

The capability requirement is:

- a reduction in collision risk with slow moving objects equal to, or exceeding, that achieved by flight-crew of manned aircraft using See & Avoid.

5.5.2.2 *Category 2*

Non-ATC-cooperative objects that can only be detected by optical techniques, but are able to initiate effective avoiding action.

This category consists of:

- Radio controlled model aircraft (**R**), gliders (**G**), and powered air sports vehicles (**S**).

These objects are faster than the slow moving objects of Category 1 and so, in a collision geometry, could overtake the UAS (*i.e.* could approach from behind) depending on the minimum speed of the UAS compared to the maximum speed of the objects.

The need to have a collision avoidance capability against this category of object gives rise to the following functional requirements, using optical techniques:

- acuity comparable to that of the human eye;
- horizontal coverage within a sector adequate for the minimum speed of the UA (*i.e.* potentially greater than the forward sector up to 110 deg either side of straight-ahead – see Appendix E.2.1.1);
- vertical coverage comparable to that needed by the pilot of a manned aircraft;
- perception of fast moving objects comparable to that of human vision within the same sector; and
- level of reliability that is equal to, or exceeds, that achieved by flight-crew of manned aircraft in encounters with manned aviation.

The capability requirement is:

- a reduction in collision risk with fast moving objects equal to, or exceeding, that achieved by flight-crew of manned aircraft using See & Avoid.

5.5.2.3 *Category 3*

Co-operative objects (aircraft) that can be detected by non-optical techniques, but are unable to take effective avoiding action.

This category consists of:

- Airships (**D**).

The need to have a collision avoidance capability against this category of object gives rise to the following functional requirements, using non-optical techniques:

- surveillance and tracking of transponder replies (using active interrogation where necessary);
- detection range commensurate with the maximum likely closing speed, and the ability to calculate and execute an effective avoidance manoeuvre given this speed; and
- level of reliability (*i.e.* probability of timely tracking of the threat) that is equal to, or exceeds, that achieved by ACAS in a known traffic environment.

The capability requirement is:

- *for UAS required to have a collision avoidance capability matching that of ACAS equipped manned aircraft* – a reduction in collision risk equal to, or exceeding, that achievable by the correct response to ACAS RAs;
- *for other UAS* – a reduction in collision risk with fast moving objects equal to, or exceeding, that achieved by flight-crew of manned aircraft using See & Avoid.

5.5.2.4 Categories 4 and 5

Co-operative objects (aircraft) that can be detected by non-optical techniques, and are able to initiate effective avoiding action.

A further distinction can be made on the basis of whether the aircraft are unable to initiate avoiding action in IMC without intervention from ATC.

5.5.2.4.1 Category 4

Co-operative objects (aircraft) that can be detected by non-optical techniques, and are able to initiate avoiding action in VMC, and in IMC with ATC intervention.

This category consists of:

- Helicopters (**H**), general aviation (**L**, **Q**), military fighter (**M**), commercial air transport (**N**, **T**, **C**), and unmanned aircraft (**U**).

The need to have a collision avoidance capability against this category of object gives rise to the following functional requirements, using non-optical techniques:

- surveillance and tracking of transponder replies (using active interrogation where necessary);
- detection range commensurate with the maximum likely closing speed, and the ability to calculate and execute an effective avoidance manoeuvre given this speed; and
- level of reliability that is equal to, or exceeds, that achieved by ACAS in a known traffic environment.

The capability requirement is:

- *for UAS required to have a collision avoidance capability matching that of ACAS equipped manned aircraft* – a reduction in collision risk with transponder equipped aircraft equal to, or exceeding, that achievable by the correct response to ACAS RAs;
- *for other UAS* – a reduction in collision risk with fast moving objects equal to, or exceeding, that achieved by flight-crew of manned aircraft using See & Avoid.

5.5.2.4.2 Category 5

Co-operative objects (aircraft) that can be detected by non-optical techniques, and are able to initiate avoiding action in VMC, and in IMC with or without ATC intervention.

This category consists of:

- ACAS mandated aircraft (**T**, **C**), and suitably equipped military fighters (**M**) and unmanned aircraft (**U**).

The need to have a collision avoidance capability against this category of object gives rise to the following functional requirements, using non-optical techniques:

- surveillance and tracking of transponder replies (using active interrogation where necessary);
- detection range commensurate with the maximum likely closing speed, and the ability to calculate and execute an effective avoidance manoeuvre given this speed;
- compatibility with ACAS and UCAF (especially ability to coordinate avoidance manoeuvres); and
- level of reliability that is equal to, or exceeds, that achieved by ACAS in a known traffic environment.

The capability requirement is:

- *for UAS required to have a collision avoidance capability matching that of ACAS equipped manned aircraft* – a reduction in collision risk with collision avoidance system equipped aircraft equal to, or exceeding, that achievable by the correct response to coordinated ACAS RAs;
- *for other UAS* – a reduction in collision risk with fast moving objects equal to, or exceeding, that achieved by flight-crew of manned aircraft using See & Avoid.

5.6 Baseline Performance Requirements

5.6.1 Introduction

In this section the five categories of object defined in Section 5.5.2 are considered in each of four airspace regimes (derived in Section 5.6.2), together with the altitudes at which the objects are expected to be encountered.

From these, and the attributes of the objects, baseline UAS Collision Avoidance capability requirements are derived for those UAS required to have a collision avoidance capability matching that of ACAS equipped manned aircraft (see Section 5.3.4).

For other UAS the capability requirement is the same in all airspace regimes: simply that they achieve a reduction in collision risk with fast moving objects equal to, or exceeding, that achieved by flight-crew of manned aircraft using See & Avoid.

5.6.2 Airspace regimes

There are four airspace regimes of interest from the combination of two traffic environments (known *vs.* unknown – see Section 5.4.5) and two sets of meteorological conditions (IMC *vs.* VMC – see Section 5.4.6).

For each of these regimes the set of object types (listed in Section 5.4.2) is considered and the altitude bands in which they might reasonably be encountered by a UAS is indicated in the corresponding table. To indicate a likely encounter a '✓' in a red cell is used; to indicate a possible encounter a '**?**' in a yellow cell is used; to indicate an unlikely encounter an '**x**' in a green cell is used.

5.6.3 Known Traffic Environment – VMC

The altitude bands in which objects might reasonably be encountered in visual meteorological conditions in an environment where all traffic is 'known' are shown in Table 8.

cat.	code	description	upper operating altitude of UAS				
			500 ft AGL	3,000 ft AGL	up to FL100	up to FL195	above FL195
1	F	Large bird	✓	✓	?	x	x
	K	Kite or tethered balloon	✓	x	x	x	x
	B	Hot air balloon	x	x	x	x	x
	P	Parachutist	x	x	x	x	x
	A	Unpowered air sports	x	x	x	x	x
2	R	Radio control model a/c	x	x	x	x	x
	G	Glider	x	x	x	x	x
	S	Powered air sports	x	x	x	x	x
3	D	Airship	✓	✓	✓	x	x
4	H	Helicopter	✓	✓	✓	x	x
	L	Non-pressurised GA	✓	✓	✓	x	x
	Q	Pressurised GA	✓	✓	✓	✓	x
	N	Pressurised passenger aircraft (not ACAS)	✓	✓	✓	✓	✓
4, 5	T	Pressurised passenger aircraft (ACAS)	✓	✓	✓	✓	✓
	C	Cargo aircraft	✓	✓	✓	✓	✓
	M	Military Fighter	✓	✓	✓	✓	✓
	U	Unmanned aircraft	✓	✓	✓	✓	✓

Table 8: Airborne objects that might be encountered by UAS operating in VMC in a Known traffic environment.

5.6.3.1 Below FL100

Detection of the following objects is required:

- Category 1 objects up to 3,000 ft AGL;[45]
- Category 3 objects up to FL100;
- Category 4 objects up to FL100;
- Category 5 objects up to FL100.

[45] For a UAS that does not have a requirement to routinely operate at or below 3,000 ft, the risk of collision with Category 1 objects could be mitigated by performing climb and descent only in specified areas: in specific locations observers could be used to detect any hazards; in segregated airspace the risk from tethered objects, hot air balloons, parachutists, and unpowered air sports vehicles (but not birds) would be removed.

This leads to the following, most demanding, functional requirements:

- optical techniques:
  - acuity comparable to that of the human eye;
  - horizontal coverage within the forward sector;
  - vertical coverage comparable to that needed by the pilot of a manned aircraft;
  - perception of slow moving objects comparable to that of human vision; and
  - level of reliability that is equal to, or exceeds, that achieved by flight-crew of manned aircraft in encounters with slow moving objects.
- non-optical techniques:
  - surveillance and tracking of transponder replies (using active interrogation where necessary);
  - detection range commensurate with, and the ability to calculate and execute an effective avoidance manoeuvre at, the maximum likely closing speed;
  - compatibility with ACAS and UCAF (especially ability to coordinate avoidance manoeuvres); and
  - level of reliability that is equal to, or exceeds, that achieved by ACAS in a known traffic environment.

The capability requirements are:

- a reduction in collision risk with fast moving objects equal to, or exceeding, that achieved by flight-crew of manned aircraft using See & Avoid; and
- a reduction in collision risk with transponder equipped aircraft equal to, or exceeding, that achievable by the correct response to ACAS RAs.

5.6.3.2 Above FL100

Detection of the following objects is required:

- Category 4 objects at all altitudes;
- Category 5 objects at all altitudes.

This leads to the following, most demanding, functional requirements:

- optical techniques:
  - optical techniques are not required as Category 4 and 5 objects are expected to be transponder equipped;[46]
- non-optical techniques:
  - surveillance and tracking of transponder replies (using active interrogation where necessary);

[46] However, optical techniques can assist in detection of transponder equipped threats and this functional requirement is not intended to proscribe their use in addition to other techniques.

   - detection range commensurate with, and the ability to calculate and execute an effective avoidance manoeuvre at, the maximum likely closing speed;
   - compatibility with ACAS and UCAF (especially ability to coordinate avoidance manoeuvres); and
   - level of reliability that is equal to, or exceeds, that achieved by ACAS in a known traffic environment.

The capability requirement is:

- a reduction in collision risk with transponder equipped aircraft equal to, or exceeding, that achievable by the correct response to ACAS RAs.

5.6.4 Known Traffic Environment – IMC

The altitude bands in which objects might reasonably be encountered in instrument meteorological conditions in an environment where all traffic is ‘known’ are shown in Table 9.

cat.	code	description	upper operating altitude of UAS				
			500 ft AGL	3,000 ft AGL	up to FL100	up to FL195	above FL195
1	F	Large bird	x	x	x	x	x
	K	Kite or tethered balloon	✓	x	x	x	x
	B	Hot air balloon	x	x	x	x	x
	P	Parachutist	x	x	x	x	x
	A	Unpowered air sports	x	x	x	x	x
2	R	Radio control model a/c	x	x	x	x	x
	G	Glider	x	x	x	x	x
	S	Powered air sports	x	x	x	x	x
3	D	Airship	✓	✓	✓	x	x
4	H	Helicopter	✓	✓	✓	x	x
	L	Non-pressurised GA	✓	✓	✓	x	x
	Q	Pressurised GA	✓	✓	✓	✓	x
	N	Pressurised passenger aircraft (not ACAS)	✓	✓	✓	✓	✓
4, 5	T	Pressurised passenger aircraft (ACAS)	✓	✓	✓	✓	✓
	C	Cargo aircraft	✓	✓	✓	✓	✓
	M	Military Fighter	✓	✓	✓	✓	✓
	U	Unmanned aircraft	✓	✓	✓	✓	✓

Table 9: Airborne objects that might be encountered by UAS operating in IMC in a Known traffic environment.

5.6.4.1 Below FL100

Detection of the following objects is required:

- Category 1 objects up to 500 ft AGL;
- Category 3 objects up to FL100;
- Category 4 objects up to FL100;
- Category 5 objects up to FL100.

This leads to the following, most demanding, functional requirements:

- optical techniques:
  - o optical techniques are not required as they cannot be relied upon in IMC;[47]

[47] However, optical techniques can assist in detection of threats in some IMC and this functional requirement is not intended to proscribe their use in addition to other techniques.

- non-optical techniques:
    - surveillance and tracking of transponder replies (using active interrogation where necessary);
    - detection range commensurate with, and the ability to calculate and execute an effective avoidance manoeuvre at, the maximum likely closing speed;
    - compatibility with ACAS and UCAF (especially ability to coordinate avoidance manoeuvres); and
    - level of reliability that is equal to, or exceeds, that achieved by ACAS in a known traffic environment.

The capability requirement is:

- a reduction in collision risk with transponder equipped aircraft equal to, or exceeding, that achievable by the correct response to ACAS RAs.

5.6.4.2 Above FL100

Detection of the following objects is required:

- Category 4 objects at all altitudes;
- Category 5 objects at all altitudes.

This leads to the following, most demanding, functional requirements:

- optical techniques:
    - optical techniques are not required as they are unreliable in IMC, and Category 4 and 5 objects are expected to be transponder equipped;
- non-optical techniques:
    - surveillance and tracking of transponder replies (using active interrogation where necessary);
    - detection range commensurate with, and the ability to calculate and execute an effective avoidance manoeuvre at, the maximum likely closing speed;
    - compatibility with ACAS and UCAF (especially ability to coordinate avoidance manoeuvres); and
    - level of reliability that is equal to, or exceeds, that achieved by ACAS in a known traffic environment.

The capability requirement is:

- a reduction in collision risk with transponder equipped aircraft equal to, or exceeding, that achievable by the correct response to ACAS RAs.

5.6.5 Unknown Traffic Environment – VMC

The altitude bands in which objects might reasonably be encountered in visual meteorological conditions in an environment where some traffic is ‘unknown’ are shown in Table 10.

cat.	code	description	upper operating altitude of UAS				
			500 ft AGL	3,000 ft AGL	up to FL100	up to FL195	above FL195
1	F	Large bird	✓	✓	?	–	–
	K	Kite or tethered balloon	✓	x	x	–	–
	B	Hot air balloon	✓	✓	?	–	–
	P	Parachutist	✓	✓	?	–	–
	A	Unpowered air sports	✓	✓	?	–	–
2	R	Radio control model a/c	✓	x	x	–	–
	G	Glider	✓	✓	✓	–	–
	S	Powered air sports	✓	✓	✓	–	–
3	D	Airship	✓	✓	✓	–	–
4	H	Helicopter	✓	✓	✓	–	–
	L	Non-pressurised GA	✓	✓	✓	–	–
	Q	Pressurised GA	✓	✓	✓	–	–
	N	Pressurised passenger aircraft (not ACAS)	✓	✓	✓	–	–
4, 5	T	Pressurised passenger aircraft (ACAS)	✓	✓	✓	–	–
	C	Cargo aircraft	✓	✓	✓	–	–
	M	Military Fighter	✓	✓	✓	–	–
	U	Unmanned aircraft	✓	✓	✓	–	–

Table 10: Airborne objects that might be encountered by UAS operating in VMC in an Unknown traffic environment.[48]

Detection of the following objects is required:

- Category 1 objects up to 3,000 ft AGL;
- Category 2 objects up to FL100;
- Category 3 objects up to FL100;
- Category 4 objects up to FL100;
- Category 5 objects up to FL100.

This leads to the following, most demanding, functional requirements:

- optical techniques:
  - o acuity comparable to that of the human eye;
  - o horizontal coverage within a sector extending 110 deg either side of straight-ahead;

[48] There is no unknown traffic (in the collision avoidance context – see Section 5.4.5) above FL100 due to the requirement for transponder carriage.

    - vertical coverage comparable to that needed by the pilot of a manned aircraft;
    - perception of fast moving objects comparable to that of human vision within the same sector; and
    - level of reliability that is equal to, or exceeds, that achieved by flight-crew of manned aircraft in encounters with manned aviation.
- non-optical techniques:
    - surveillance and tracking of transponder replies (using active interrogation where necessary);
    - detection range commensurate with, and the ability to calculate and execute an effective avoidance manoeuvre at, the maximum likely closing speed;
    - compatibility with ACAS and UCAF (especially ability to coordinate avoidance manoeuvres); and
    - level of reliability that is equal to, or exceeds, that achieved by ACAS in a known traffic environment.

The capability requirements are:

- a reduction in collision risk with fast moving objects equal to, or exceeding, that achieved by flight-crew of manned aircraft using See & Avoid; and
- a reduction in collision risk with transponder equipped aircraft equal to, or exceeding, that achievable by the correct response to ACAS RAs.

5.6.6 Unknown Traffic Environment – IMC

The altitude bands in which objects might reasonably be encountered in instrument meteorological conditions in an environment where some traffic is 'unknown' are shown in Table 11.

cat.	code	description	upper operating altitude of UAS 500 ft AGL	3,000 ft AGL	up to FL100	up to FL195	above FL195
1	F	Large bird	x	x	x	–	–
	K	Kite or tethered balloon	✓	x	x	–	–
	B	Hot air balloon	x	x	x	–	–
	P	Parachutist	x	x	x	–	–
	A	Unpowered air sports	x	x	x	–	–
2	R	Radio control model a/c	x	x	x	–	–
	G	Glider	x	x	x	–	–
	S	Powered air sports	x	x	x	–	–
3	D	Airship	✓	✓	✓	–	–
4	H	Helicopter	✓	✓	✓	–	–
	L	Non-pressurised GA	✓	✓	✓	–	–
	Q	Pressurised GA	✓	✓	✓	–	–
	N	Pressurised passenger aircraft (not ACAS)	✓	✓	✓	–	–
4, 5	T	Pressurised passenger aircraft (ACAS)	✓	✓	✓	–	–
	C	Cargo aircraft	✓	✓	✓	–	–
	M	Military Fighter	✓	✓	✓	–	–
	U	Unmanned aircraft	✓	✓	✓	–	–

Table 11: Airborne objects that might be encountered by UAS operating in IMC in an Unknown traffic environment.[49]

Detection of the following objects is required:

- Category 1 objects up to 500 ft AGL;
- Category 3 objects up to FL100;
- Category 4 objects up to FL100;
- Category 5 objects up to FL100.

This leads to the following, most demanding, functional requirements:

- optical techniques:
  - o optical techniques are not required as they are unreliable in IMC;

[49] There is no unknown traffic (in the collision avoidance context – see Section 5.4.5) above FL100 due to the requirement for transponder carriage.

- non-optical techniques:
    - o surveillance and tracking of transponder replies (using active interrogation where necessary);
    - o detection range commensurate with, and the ability to calculate and execute an effective avoidance manoeuvre at, the maximum likely closing speed;
    - o compatibility with ACAS and UCAF (especially ability to coordinate avoidance manoeuvres); and
    - o level of reliability that is equal to, or exceeds, that achieved by ACAS in a known traffic environment.

The capability requirement is:

- a reduction in collision risk with transponder equipped aircraft equal to, or exceeding, that achievable by the correct response to ACAS RAs.

5.6.7 Summary of Baseline Performance Requirements

The categories of airborne objects that might be encountered (and against which UAS therefore needs a collision avoidance capability) are summarised in Table 12. An '**x**' in a green cell indicates categories of object that are unlikely to be encountered; a '✓' in a red cell indicates categories of object that could be encountered; the '✓*' symbol against category 1 objects in IMC below FL100 serves to indicate that tethered objects below 500 ft AGL are the only group of objects in this category that might be encountered.

		unknown		known traffic environment			
		below FL100				above FL100	
category		VMC	IMC	VMC	IMC	VMC	IMC
non-ATC-cooperative objects	1	✓	✓*	✓	✓*	x	x
	2	✓	x	x	x	x	x
ATC-cooperative objects	3	✓	✓	✓	✓	x	x
	4	✓	✓	✓	✓	✓	✓
	5	✓	✓	✓	✓	✓	✓

Table 12: Categories of airborne objects that might be encountered in the various airspace regimes.

The performance requirements can be further summarised into three main collision avoidance performance capabilities, by considering objects that can cooperate with ATC (and which are transponder equipped) and non-ATC-cooperative objects (which can not be assumed to be transponder equipped):

- ability to avoid non-ATC-cooperative and ATC-cooperative objects – the most demanding capability;
    - o required in VMC below FL100;

- ability to avoid ATC-cooperative objects and tethered objects near the ground;
    - required in IMC below FL100;
- ability to avoid ATC-cooperative objects – the least demanding capability;
    - required above FL100.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

UAS operations are currently confined to specifically reserved areas of segregated airspace. It is likely that an increasing use of UAS for civil applications will create demand for UAS to be allowed to operate in non-segregated airspace alongside manned aircraft. Any such use of non-segregated airspace will be on the basis of equivalence and transparency: UAS must work within the existing regulatory framework and pose no greater risk to persons or property in the air or on the ground than that presented by equivalent manned aircraft [28]; and UAS will be treated by ATC as any other aircraft.

It is possible that by 2020 UAS operations could account for as much as 6% of the IFR flight-hours in European airspace.

6.1.1 Safety benefits and disbenefits

Operational experience and EUROCONTROL studies have demonstrated the continuing safety benefit (in terms of a reduction in the risk of mid-air collision) delivered by the mandate for carriage of the ACAS II collision avoidance system.

Even a relatively small proportion of UAS operations could significantly degrade this safety benefit if the UAS collision avoidance capability performs no better than that delivered by See & Avoid on manned aircraft. This is particularly so in an airspace where there is a high proportion of manned aircraft carrying ACAS II.

Conversely, if UAS are equipped with a collision avoidance capability whose performance approaches that of ACAS II on manned aircraft then much of the safety benefit is restored, or even exceeded.

It is notable that, for a system that generates collision avoidance manoeuvres that are not coordinated with the manoeuvres generated by other collision avoidance systems (on manned and on unmanned aircraft), a greater safety benefit may be achieved by ensuring that the UAS collision avoidance manoeuvres are coordinated, than by improving the efficacy of its uncoordinated manoeuvres.

UAS will receive some protection from mid-air collision due to the equipage of a proportion of manned aircraft with ACAS II. However, the further safety benefit to an individual UAS that operates a collision avoidance system with performance comparable to the performance of ACAS II (rather than having a collision avoidance capability no better than See & Avoid on manned aircraft) is considerable no matter what the level of equipage of manned aircraft. The safety benefit to the individual UAS is available no matter what proportion of other UAS are so equipped.

6.1.2 UAS equipage with ACAS II

Equipage with ACAS II has been demonstrated to deliver a safety benefit to manned aircraft that operate the system and comply with the RAs that it generates.

However, the safety benefit is not automatically guaranteed to UAS that choose to equip and operate the system:

- Limitations of ACAS performance – ACAS is implicitly designed for operation on commercial civil fixed-wing aircraft. Limitations in ACAS hardware (particularly antennae and their siting) may become apparent when ACAS is deployed on a UAS airframe, and limitations in the ACAS software (particularly tracking algorithms) may become apparent if the UAS aerodynamic performance exceeds that expected from a commercial civil fixed-wing aircraft. These limitations will manifest themselves as degraded surveillance performance and lower reliability and quality of the tracking of targets.
- Limitations of UAS performance – the proven safety benefit of ACAS II deployed on manned aircraft is dependent on prompt and accurate compliance with the RAs that it generates. These RAs require a response within a specified time, at an acceleration of a specified strength, to achieve a specified vertical rate. If for any reason the UAS cannot achieve this standard response the efficacy of the RA can be compromised.

6.1.3 UCAF interoperability with ACAS II

No matter what form a UAS collision avoidance function takes it is essential that it is interoperable with ACAS II and does not significantly degrade the safety benefit that ACAS II equipage delivers.

It is most likely that, for operational reasons, UAS will be required to equip with altitude reporting SSR transponders. Such equipage is essential if UAS are to be detected and tracked by ACAS.

In part the effectiveness of ACAS II is derived from the fact that when two ACAS II equipped aircraft encounter one another the sense of any avoidance manoeuvres is coordinated so that the two aircraft select compatible manoeuvres. To ensure this continued effectiveness UAS that encounter an ACAS II equipped aircraft need to, at least, respect the sense of any ACAS II RA that is generated, and ideally participate in the coordination process by communicating the sense of their own avoidance manoeuvre to the ACAS on the other aircraft.

The primary purpose of SSR transponder equipage is to provide visibility of aircraft to ATC. Collision avoidance systems (such as ACAS) that detect other aircraft by active interrogations of their SSR transponders must limit the overall level of these interrogations so as not to unduly degrade the surveillance performed by ground-based SSR. ACAS achieves this by implementing specific interference limiting algorithms. It will be necessary for an UAS collision avoidance function that similarly interrogates SSR transponders to also ensure that no undue degradation of SSR surveillance occurs (*e.g.* by implementing its own interference limiting that achieves the same high-level performance targets of the ACAS interference limiting algorithms).

6.1.4 UAS Collision Avoidance Requirements

UAS Collision Avoidance Capability should equal or exceed that of manned aircraft in the same environment (known ATC environment or unknown ATC environment) and conditions (IMC or VMC[50]).

The performance of a UAS Collision Avoidance Function that does not coordinate the sense of avoidance manoeuvres with other aircraft (even when they are equipped with ACAS II or another UAS Collision Avoidance Function) should nevertheless equal or exceed the performance of ACAS II (which does coordinated the sense of avoidance manoeuvres where possible) in the same circumstance.

6.2 Recommendations

6.2.1 UAS Collision Avoidance Performance

1. All UAS should be equipped with a collision avoidance function that performs at least as well as the collision avoidance capability of See & Avoid exercised by the flight-crew of manned aircraft.[51] This is proposed as a minimum requirement and should not discourage the development of systems whose performance exceeds See & Avoid, particularly in the detection of non-transponder equipped objects.

2. UAS whose size is above appropriate thresholds should be equipped with a collision avoidance function that generates avoidance manoeuvres that are at least as effective as those generated by ACAS II on manned aircraft.
   - The thresholds could be airspace dependent.
   - A UAS collision avoidance function should take account of the fact that ACAS II equipped aircraft will coordinate avoidance manoeuvres with suitably equipped threats.

3. Certification of any UAS equipage with ACAS II should be conducted on a case-by-case basis for each airframe/equipment configuration.
   - It would need to be established that ACAS II surveillance was adequate for the purposes of collision avoidance, <u>and</u> that the UAS was able to comply with ACAS II RAs promptly and accurately.

[50] In VMC the capability of manned aircraft is achieved through the exercise of See & Avoid and the carriage of ACAS II.

[51] This equivalent (or better) performance need not be demonstrated directly: target levels of safety can be defined which, if met, guarantee performance better than that achieved by manned aircraft – the UCAF would then need only to demonstrate that it achieved the target level of safety. This is the approach advocated in [30].

6.2.2 Further work

4. Appropriate criteria should be determined for the requirement that certain UAS have a collision avoidance performance that matches that of ACAS II on manned aircraft.
    - These criteria could be a set of thresholds based on various factors (*e.g.* maximum take-off mass, kinetic energy of impact, and maximum cruising speed).
    - The thresholds could vary according to circumstances (*e.g.* being dependent on classification of airspace, and/or operating altitude).

5. The ICAO Annexes need to be reviewed in detail and appropriate changes proposed to take account of UAS operations.
    - The ICAO Annexes have been written without unmanned aircraft in mind. In many cases it is inappropriate to apply the provisions of the Annexes to unmanned aircraft.[52]
    - The ICAO ACAS Manual [20] makes it clear that the provisions of the ACAS SARPs [7] should not be interpreted as applying to UAS. Consequently, if UAS are to be required to carry a collision avoidance system with a capability that goes beyond mere Sense & Avoid then appropriate performance based SARPs for such a system should be developed and included in the appropriate Annex.

6. The performance of UAS collision avoidance should be quantitatively compared with the collision avoidance of manned aircraft (both comparing Sense & Avoid with See & Avoid, and comparing the performance of UCAF with ACAS II).
    - This will necessitate the development of performance metrics of both safety benefit and operational acceptability for UAS collision avoidance functions, by which the adequacy of their performance can be judged.

[52] Particular examples being some of the responsibilities of the pilot in charge who is implicitly assumed to be co-located with the aircraft, and the ACAS equipage requirements (in the latter case the situation is clarified in ICAO guidance material but this needs to be reflected in the appropriate Annex and the ACAS equipage requirements).

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A. ACRONYMS AND ABBREVIATIONS

ACAS	Airborne Collision Avoidance System
ACASA	ACAS Analysis project
ADS-B	Automatic Dependent Surveillance – Broadcast
AGL	Above Ground Level
Airprox	Air Proximity Hazard
ANSP	Air Navigation Service Provider
A-SMGCS	Advance Surface Movement Guidance & Control System
ASARP	ACAS Safety Analysis Post-RVSM Project
ATC	Air Traffic Control
ATM	Air Traffic Management
ATS	Air Traffic Services
AVAL	ACAS on VLJs and LJs – Assessment of Safety Level project
CAT	Commercial Air Transport
CAUSE	Collision Avoidance Requirements for Unmanned Aircraft Systems study
CNS	Communication, Navigation, and Surveillance
CWP	Controller's Working Position
CWS	Collision Warning System
DAP	Directorate of Airspace Policy
EASA	European Aviation Safety Agency
ECAC	European Civil Aviation Conference
EUR	ICAO European region
FARADS	Feasibility of ACAS RA Downlink Study
FL	Flight Level
FoR	Field of Regard
fpm	feet per minute
ft	feet
HALE	High Altitude Long Endurance (UAS)
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
kg	kilograms
kJ	kilojoules
kph	kilometres per hour
kt	knots

LIDAR	Light Detection and Ranging
LJ	Light Jet
MALE	High Altitude Long Endurance (UAS)
MEL	Minimum Equipment List
MOPS	Minimum Operational Performance Standards
MTOM	Maximum Take-Off Mass
MUAS	Mini/Micro UAS
NM	international nautical mile
NMAC	Near Mid-Air Collision
NOTAM	Notice to Airmen
NTA	Number of TCAS Aircraft
RA	Resolution Advisory
RAC	Resolution Advisory Complement
RCS	Radar Cross-Section
ROA	Remotely Operated Aircraft
RoW	Right of Way
SARPs	Standards and Recommended Practices
SESAR	Single European Sky ATM Research
SSR	Secondary Surveillance Radar
RF	Radio Frequency
TA	Traffic Advisory
TCAS	Traffic Alert and Collision Avoidance System
UA	Unmanned Aircraft
UAV	Unmanned Aerial Vehicle (the term UA is preferred)
UAS	Unmanned Aircraft System
UCAF	UAS Collision Avoidance Function
UK	United Kingdom of Great Britain and Northern Ireland
USA	United States of America
VFR	Visual Flight Rules
VLA	Very Light Aircraft
VLJ	Very Light Jet
VMC	Visual Meteorological Conditions
WP	Work Package

B. RELEVANT ICAO ANNEX 2 PROVISIONS

B.1 CHAPTER 2 – APPLICABILITY OF THE RULES OF THE AIR

B.1.1 2.2 Compliance with the rules of the air

ICAO Provision	UAS context
The operation of an aircraft either in flight or on the movement area of an aerodrome shall be in compliance with the general rules and, in addition, when in flight, either with:	Applicable to UAS. The scope of CAUSE is limited to mid-air collision avoidance, even though Annex 2 covers collisions in general.
a) the visual flight rules; or	Applicable to Sense & Avoid. N/A to CAUSE
b) the instrument flight rules.	Applicable to Sense & Avoid. N/A to CAUSE
Note 1.— Information relevant to the services provided to aircraft operating in accordance with both visual flight rules and instrument flight rules in the seven ATS airspace classes.	N/A to CAUSE
Note 2.— A pilot may elect to fly in accordance with instrument flight rules in visual meteorological conditions or may be required to do so by the appropriate ATS authority	Applicable to Sense & Avoid. N/A to CAUSE

B.1.2 2.3 Responsibility for compliance with the rules of the air

B.1.2.1 2.3.1 Responsibility of pilot-in-command

ICAO Provision	UAS context
The pilot-in-command of an aircraft shall, whether manipulating the controls or not, be responsible for the operation of the aircraft in accordance with the rules of the air, except that the pilot-in-command may depart from these rules in circumstances that render such departure absolutely necessary in the interests of safety.	Applicable to UAS pilot. Cannot be applied (as worded) to un-piloted aircraft such as fully autonomous UAS. Under these circumstances, these responsibilities should pass up to the person-in-charge of the UAS mission. (Similarly for the next two paragraphs.)

B.1.2.2 2.3.2 Pre-flight action

ICAO Provision	UAS context
Before beginning a flight, the pilot-in-command of an aircraft shall become familiar with all available information appropriate to the intended operation. Pre-flight action for flights away from the vicinity of an aerodrome, and for all IFR flights, shall include a careful study of available current weather reports and forecasts, taking into consideration fuel requirements and an alternative course of action if the flight cannot be completed as planned.	N/A to CAUSE. Cannot be applied (as worded) to un-piloted aircraft such as fully autonomous UAS. Under these circumstances, these responsibilities should pass up to the person-in-charge of the UAS mission.

B.1.3 2.4 Authority of pilot-in-command of an aircraft

ICAO Provision	UAS context
The pilot-in-command of an aircraft shall have final authority as to the disposition of the aircraft while in command.	Applicable to UAS pilot. Applicable to UAS pilot. Cannot be applied (as worded) to un-piloted aircraft such as fully autonomous UAS. Under these circumstances, these responsibilities should pass to the person-in-charge of the UAS mission.

B.2 CHAPTER 3 – GENERAL RULES

B.2.1 3.2 Avoidance of collisions

ICAO Provision	UAS context
Nothing in these rules shall relieve the pilot-in-command of an aircraft from the responsibility of taking such action, including collision avoidance manoeuvres based on resolution advisories provided by ACAS equipment, as will best avert collision.	This is the collision avoidance 'subset' of 2.3.1. Applicable to UAS pilot. UAS pilot can suspend right-of-way rules if pilot is part of UCAF. Cannot be applied to un-piloted aircraft such as fully autonomous UAS. The principle behind Annex 2 is that the pilot has ultimate responsibility for the safety of the aircraft and must use all means at his disposal to discharge this responsibility. Safety in the context of CAUSE means the avoidance of collision only (not adverse weather, air rage, nor other phenomena). This principle means that the pilot is empowered to ignore or override alerts from any automatic collision avoidance system (ACAS, GPWS, *etc.*) if he feels there are sufficient grounds for doing so; *e.g.* an inappropriate alert, or a more serious threat exists or would ensue. If this is adopted by UAS, it is clear that the pilot on the ground remains responsible for the safety of the UAV (only) regardless of the provision of on-board or ground-based systems. One might say that if the UAV pilot had no other means of detecting and avoiding collision (*e.g.* visual acquisition), then he would still be discharging his responsibility by relying solely on a fully automated collision avoidance system because that was the sole means at his disposal. *N.B.* The notion of responsibility cannot, in this context, be applied to a system. Ultimately some person needs to have responsibility for the aircraft (even if the aircraft is a fully autonomous UAS with an automated response to a collision avoidance system). UCAF must provide a means for the UAS pilot to subsequently override any autonomously produced collision avoidance actions.

Note 1. – It is important that vigilance for the purpose of detecting potential collisions be exercised on board an aircraft, regardless of the type of flight or the class of airspace in which the aircraft is operating, and while operating on the movement area of an aerodrome.	Applicable to UCAF since on-board sensors provide vigilance. Potential collision detection while operating on movement area of aerodrome is outside scope of CAUSE.
Note 2. – Operating procedures for use of ACAS detailing the responsibilities of the pilot-in-command are contained in PANS-OPS (Doc 8168), Volume I, Part VIII, Chapter 3.	Applicable only if ACAS is part of UCAF.
Note 3. – Carriage requirements for ACAS equipment are addressed in Annex 6, Part I, Chapter 6 and Part II, Chapter 6.	N/A to UAS operations (see Section 7.3 of ICAO Doc 9863 [20]).

B.2.1.1 3.2.1 Proximity

ICAO Provision	UAS context
An aircraft shall not be operated in such proximity to other aircraft as to create a collision hazard.	An interpretation is that UAS must not be intentionally operated in such a way that a collision becomes possible. Collision avoidance provisions, including adherence to right-of-way rules, are intended to cover unexpected situations only. Annex 2 does not refer to *separation* other than in the context of formation flights and ATS. Annex 2 only refers to collision avoidance. Separation Provision (SP) [1] can only be provided by having full knowledge of the environment in the airspace in which SP is being provided; *e.g.* FLs of nearby aircraft. ATC has access to this information, however, an individual pilot does not. So whereas a VFR pilot can use See & Avoid to provide a sort of 'SP', *i.e.* a medium term collision avoidance to avoid a later urgent collision avoidance action, this is not assuring separation in the same way as ATC. Moreover, he is not required, or able, to maintain separation in accordance with any particular minima because they are only defined with respect to ATC-provided separation. Applicable to Sense & Avoid, not applicable to UCAF.

B.2.1.2 3.2.2 Right-of-way

ICAO Provision	UAS context
The aircraft that has the right-of-way shall maintain its heading and speed.	UCAF cannot depend upon the intruder aircraft performing collision avoidance during an encounter in which a right-of-way exists. Provision 3.2 allows pilots of unpowered aircraft and powered lighter-than-air aircraft to execute See & Avoid in an encounter with a UAS (or any other aircraft) if they 'mistrust' the aircraft.
3.2.2.1 An aircraft that is obliged by the following rules to keep out of the way of another shall avoid passing over, under or in front of the other, unless it passes well clear and takes into account the effect of aircraft wake turbulence.	Applicable to UCAF. Beyond scope of CAUSE
3.2.2.2 *Approaching head-on.* When two aircraft are approaching head-on or approximately so and there is danger of collision, each shall alter its heading to the right.	Applicable to UCAF. Beyond scope of CAUSE
3.2.2.3 *Converging.* When two aircraft are converging at approximately the same level, the aircraft that has the other on its right shall give way, except as follows:	Within scope of Sense & Avoid, outside scope of UCAF? ACAS supports pilot in performing collision avoidance regardless of right-of-way rules? The same would apply to UCAF? Are right-of way rules applicable to UCAF?
a) power-driven heavier-than-air aircraft shall give way to airships, gliders and balloons;	Applicable to power-driven heavier-than-air UAS. *N.B.* There is no right-of-way prioritisation between UAS and manned power-driven heavier-than-air aircraft.
b) airships shall give way to gliders and balloons;	Only applicable if UAS platform is an airship.
c) gliders shall give way to balloons;	Not applicable to UAS.
d) power-driven aircraft shall give way to aircraft which are seen to be towing other aircraft or objects.	Within scope of Sense & Avoid, outside scope of UCAF

3.2.2.4 *Overtaking.* An overtaking aircraft is an aircraft that approaches another from the rear on a line forming an angle of less than 70 deg with the plane of symmetry of the latter, *i.e.* is in such a position with reference to the other aircraft that at night it should be unable to see either of the aircraft's left (port) or right (starboard) navigation lights. An aircraft that is being overtaken has the right-of-way and the overtaking aircraft, whether climbing, descending or in horizontal flight, shall keep out of the way of the other aircraft by altering its heading to the right, and no subsequent change in the relative positions of the two aircraft shall absolve the overtaking aircraft from this obligation until it is entirely past and clear.	Applicable to UCAF. Beyond scope of CAUSE
3.2.2.5 Landing	
3.2.2.5.1 An aircraft in flight, or operating on the ground or water, shall give way to aircraft landing or in the final stages of an approach to land.	Within scope of Sense & Avoid, outside scope of UCAF
3.2.2.5.2 When two or more heavier-than-air aircraft are approaching an aerodrome for the purpose of landing, aircraft at the higher level shall give way to aircraft at the lower level, but the latter shall not take advantage of this rule to cut in front of another which is in the final stages of an approach to land, or to overtake that aircraft. Nevertheless, power-driven heavier-than-air aircraft shall give way to gliders.	Within scope of Sense & Avoid, outside scope of UCAF
3.2.2.5.3 *Emergency landing.* An aircraft that is aware that another is compelled to land shall give way to that aircraft.	Within scope of Sense & Avoid, outside scope of UCAF
3.2.2.6 *Taking off.* An aircraft taxiing on the manoeuvring area of an aerodrome shall give way to aircraft taking off or about to take off.	Within scope of Sense & Avoid, outside scope of UCAF

C. INTEROPERABILITY OF UAS COLLISION AVOIDANCE WITH ACAS

C.1 Introduction

Currently, non-segregated airspace in Europe is used by a variety of manned aircraft and the carriage of ACAS II is mandated for all civil fixed-wing turbine-engined aircraft with a maximum take-off mass over 5,700 kg, or capable of carrying more than 19 passengers.

At some point in the future it is envisaged that a variety of UAS will also operate in non-segregated airspace and will be appropriately equipped with Sense & Avoid (the function corresponding to See & Avoid in manned aircraft) including collision avoidance capabilities.

It will be a prerequisite that the introduction of UAS operations does not compromise the safety of manned aircraft operations. With regard to the safety benefit currently delivered by the carriage of ACAS, the collision avoidance capability of a UAS must be interoperable with ACAS on manned aircraft – specifically, in this context, 'interoperable' means that the risk of collision to which ACAS equipped manned aircraft are exposed must be no worse when UAS operate in the airspace than if an equivalent population of manned aircraft (*i.e.* with similar sizes and weights, and equipped with ACAS as required by the mandate) were substituted.

The potential effect of individual UAS on the operation of ACAS onboard manned aircraft can be both direct and indirect:

- direct – affecting the performance of ACAS on an aircraft which is on a collision course with the UAS;
- indirect – affecting the performance of ACAS on aircraft in the vicinity of the UAS (with which there is not an immediate risk of collision);

The UAS collision avoidance capability must not compromise the safety of ACAS equipped aircraft in both these circumstances.

C.1.1 Areas of interaction

The areas of interaction between ACAS equipped manned aircraft and UAS which affect the safety benefit delivered by ACAS fall into three areas. Two areas concern the direct interaction between ACAS equipped aircraft and UAS:

- the ability of ACAS to detect (and thus track) UAS which constitute a collision threat, in order to generate resolution advisories (RAs) – this area is explored further in Section C.2;
- the ability of UCAF to produce an avoidance manoeuvre that is not incompatible with RAs generated by ACAS – this area is explored further in Section C.3.

The third area concerns an indirect effect of UAS on the performance of ACAS:

- the ability of aircraft transponders to reply to ground-based and ACAS interrogations – this area is explored further in Section C.4.

C.2 Detection and tracking

C.2.1 ACAS surveillance

ACAS II is an airborne avionics system designed to reduce the risk of mid-air collision by alerting flight-crew when nearby transponder equipped aircraft (‘intruders’) are diagnosed as constituting a potential threat to own aircraft.

ACAS works by interrogating the transponders of nearby Mode C and Mode S equipped aircraft. From the replies, ACAS estimates and tracks the relative position (range and altitude) of intruders. Alerts are issued when a sequence of tracked positions indicate that there is a risk of imminent collision.

ACAS surveillance of Mode C and Mode S equipped intruders is conducted separately:

- Once per cycle (of nominal duration 1 s), ACAS sends a sequence of whisper-shout ‘Mode C all-call’ interrogations. The highest power interrogations in a particular sequence determine the range within which aircraft will hear and reply to interrogations, and thus the number of aircraft that reply. All aircraft within range equipped with Mode C (but not equipped with Mode S) will reply – typically to no more than two of the interrogations in the sequence;
- Once per cycle ACAS sends addressed interrogations to each of the Mode S equipped aircraft (which can include other ACAS equipped aircraft) that it is tracking. With each interrogation only the addressed aircraft replies. The power of these interrogations determines the range within which Mode S equipped aircraft will reply.

Note that ACAS employs the same transponders and frequency spectrum as ground-based SSR used by ATC (and A-SMGCS used by aerodrome control). Consequently some small degradation of SSR coverage, due to the operation of ACAS, is inevitable but can be justified since an overall safety benefit (in terms of the reduced risk of mid-air collision) is achieved. This subject is discussed further in Section C.4.1.

Transponder equipped intruders can be the subject of ACAS traffic advisories (TAs); in addition intruders that report altitude through their transponders can be the subject of ACAS resolution advisories (RAs). It is through RAs that ACAS achieves a reduction in the risk of collision.

C.2.2 UAS equipage

In principle there are two radically different approaches to UAS equipage that could be adopted while still providing as much protection against mid-air collision for ACAS equipped aircraft as when they encounter manned aircraft:

a. UAS collision avoidance could operate completely independently of ACAS with UAS being equipped with neither Mode C nor Mode S transponders. The population of UAS would be invisible to ACAS and it would be the responsibility of UAS to resolve any collision risk in encounters with ACAS equipped manned aircraft. To ensure no degradation in protection against collision it would be necessary to demonstrate that the UAS's collision avoidance capability was at least equal to the protection ACAS could provide should the UAS have been transponder equipped;

b. Alternatively UAS could be equipped with a Mode C or Mode S transponder reporting altitude. The UAS would then (potentially[53]) be detected and tracked by ACAS equipped aircraft as any other manned aircraft, and RAs would be generated onboard the ACAS aircraft as required.

In practice approach (a) would probably prove unacceptable because of other operational considerations: if UAS were invisible to ACAS then they would also be invisible to ATC (and potentially to future ASAS (Airborne Separation Assistance Systems)) that rely on replies from transponders. Consequently approach (a) could not be adopted in controlled airspace in which a radar based ATC service was provided.

Assuming that approach (b) is adopted (*viz.* the requirement for UAS to be equipped with SSR transponders) then the performance of ACAS (and ground-based radar tracking systems) is best served by requiring the carriage of Mode S transponders <u>reporting altitude</u>, preferably with <u>25-ft quantisation</u>.[54]

C.3 Coordination

C.3.1 ACAS coordination

In an encounter between an ACAS equipped aircraft and an unequipped aircraft, ACAS is free to choose the most effective RA, in either the upward sense (*i.e.* pass above the intruder) or downward sense (*i.e.* pass below the intruder).

In an encounter between two ACAS equipped aircraft the sense of the RAs in each aircraft need to be coordinated to ensure that compatible manoeuvres are executed. This is achieved by each ACAS sending an RA complement

[53] An issue of relevance to both tracking by ACAS and tracking by ATC radar is whether the siting of the transponder on the UAS airframe and the flight dynamics of the UAS (which may adopt more extreme attitudes than manned aircraft) will allow reliable detection of the transponder (*e.g.* whether, and to what extent, the transponder might be masked by the airframe during normal operations).

[54] Simulations of ACAS performance consistently show that ACAS performs best (in terms of both safety benefit and operational acceptability) when altitude intruders report altitude in 25-ft rather than 100-ft quantisation.

(RAC) message which indicates the sense of the RA selected by that aircraft against that threat.

After declaring an equipped intruder to be a threat, ACAS first checks to see if it has received an RAC message from that threat. If so, ACAS selects an RA that is compatible with the vertical sense selected by the threat. If not, ACAS selects an RA based on the geometry of the encounter. In either case, ACAS begins to transmit vertical sense information to the threat (once per cycle) in the form of an RAC in a resolution message. The RAC is “don’t pass above” when the ACAS aircraft intends to pass above the threat and “don’t pass below” when the ACAS aircraft intends to pass below the threat.

This process is mirrored on the threat. If for any reason the two aircraft select the same (incompatible) sense, the aircraft with the higher Mode S address[55] reverses its sense (the so called ‘tie-break’). This could happen if the two aircraft detect each other as threats simultaneously, or if there were a temporary link failure preventing successful communication.

An RAC is directed to the specific aircraft which is the intruder. This is necessary since in multiple encounters (*i.e.* situations in which an ACAS aircraft has simultaneous RAs against two or more intruders) ACAS may select different sense RAs against different intruders.

C.3.2 Safety considerations

Safety studies show that in encounters in which both aircraft are ACAS equipped and coordinate their manoeuvres, the risk reduction is greater than in encounters in which only one of the aircraft is ACAS equipped.[56]

However, it is essential that aircraft manoeuvres respect the vertical sense of RACs so that the full safety benefit of ACAS RAs (in terms of reducing the risk of mid-air collision) can be realised. This is because the coordination of vertical senses restricts the freedom of choice of RA in at least one of the aircraft. The RA chosen in a coordinated encounter may differ from the RA that would be chosen against an unequipped threat – the coordinated RA will only be more effective if the other aircraft executes a compatible manoeuvre.

In an encounter the threat might manoeuvre adversely in such a way that thwarts the RA chosen by an ACAS aircraft. In these circumstances, if only one of the aircraft is ACAS equipped it has the option to reverse the sense of RA. In encounters between two ACAS aircraft this option may be restricted depending on the Mode S addresses of the two aircraft.[57]

The restriction of freedom means that in certain coordinated encounter geometries, the consequences of an aircraft being ACAS equipped (and in full TA/RA mode) but manoeuvring in a sense contrary to the RA, can be worse than if the aircraft were not ACAS equipped (or in TA-only mode) and allowed the other aircraft to choose the most effective RA.

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[55] *I.e.* the ICAO 24-bit aircraft address.

[56] Furthermore, the vertical deviations required are generally smaller, resulting in less disruption to ATC operations.

[57] The aircraft with the lower Mode S address may reverse the sense of its RA on the basis of the encounter geometry. The aircraft with the higher Mode S address may not.

Consequently, it is essential that UAS respect ACAS RACs if they choose to receive them (*i.e.* indicate to ACAS equipped aircraft that they themselves are ACAS equipped). This point is expanded further in Section C.3.3.

These comments apply even if the UAS were able to accurately judge that there was in fact no risk of collision, since the ACAS aircraft may be involved in a multiple RA in which further coordination (of which the UAS was unaware) with a third party could be occurring.

C.3.3 Potential UAS behaviours

In Section C.3.2 it was explained that it is essential that if UAS choose to receive RA complements from ACAS equipped aircraft that these RACs be respected when the UAS executes any collision avoidance manoeuvre.

There are three basic behaviours that could potentially be adopted by UAS collision avoidance, so as not to compromise the RAs selected on the other aircraft in encounters with ACAS equipped aircraft. These range from complete independence to full coordination and are indicated below:

c. **Complete independence** – UAS collision avoidance would act independently of ACAS on manned aircraft. The UAS could be transponder equipped and detectable by ACAS surveillance but the UAS would not indicate that it was ACAS equipped and would not coordinate collision avoidance manoeuvres with ACAS equipped aircraft. This behaviour is discussed in more detail in Section C.3.3.1.

d. **Partial Coordination** – UAS collision avoidance could partially coordinate with ACAS behaving as a quasi-ACAS in TA-only mode. The UAS should indicate in replies to Mode S interrogations from other ACAS aircraft that it was “ACAS with resolution capability inhibited”. This behaviour is discussed in more detail in Section C.3.3.2.

e. **Full coordination** – UAS collision avoidance could coordinate fully with ACAS behaving as a quasi-ACAS in full TA/RA mode. The UAS should indicate in replies to Mode S interrogations from other ACAS aircraft that it was “ACAS with vertical-only resolution capability” or “ACAS with vertical and horizontal resolution capability” as appropriate. This behaviour is discussed in more detail in Section C.3.3.3.

C.3.3.1 Complete independence

UAS collision avoidance would act independently of ACAS on manned aircraft. The UAS could be transponder equipped and detectable by ACAS surveillance but the UAS would not indicate that it was ACAS equipped. Consequently there would be no coordination of any vertical manoeuvre selected by the UAS and any RA selected by the ACAS equipped aircraft.

The ACAS equipped aircraft would be free to select the most effective RA based on the geometry of the encounter. No RAC would be sent to the UAS which would therefore also be free to select any avoidance manoeuvre it diagnosed as appropriate.

If both the ACAS equipped aircraft and the collision avoidance equipped UAS diagnosed each other as a threat then, due to the lack of coordination, there would be a risk that the manoeuvres selected by the two aircraft would be incompatible. Such a situation is similar, in principle, to the case of ACAS avoiding an unequipped manned aircraft whose pilot might visually acquire the ACAS aircraft and initiate an uncoordinated avoidance manoeuvre based on See & Avoid: in this circumstance ACAS is free to reverse the vertical sense of the RA based on the geometry. However, when the non-ACAS aircraft has a capability better than See & Avoid the possibility of an adverse manoeuvre is likely to be greater.

The UAS would be free to coordinate manoeuvres with any other UAS equipped with a collision avoidance system.

C.3.3.2 Partial coordination

UAS collision avoidance could partially coordinate with ACAS behaving as a quasi-ACAS in TA-only mode. ACAS equipped aircraft would attempt to coordinate with the UAS collision avoidance system[58] by sending RACs but the UAS would not send RACs in return – consequently the ACAS aircraft would be free to choose what it diagnosed to be the most effective RA sense.

The UAS should indicate in replies to Mode S interrogations from other ACAS aircraft that it was “ACAS with resolution capability inhibited” (see paragraph 4.3.8.4.1.2 of [7], ‘RI (air-air reply information)’).

UCAF would not need to make Mode S interrogations of intruders to determine their ACAS equipage and status of intruders because it would not be coordinating manoeuvres with these aircraft if they were ACAS equipped.

As explained in Section C.3.2 it is essential that RACs received by the UAS from ACAS equipped aircraft are respected in any avoidance manoeuvre selected by the UAS – without this the effectiveness of ACAS on the other aircraft will be compromised.[59]

This requirement means that situations could occur where the UCAF has already selected (and potentially started to implement) a vertical manoeuvre against an ACAS equipped threat and yet has to reverse the sense of the manoeuvre due to the RA selected by the ACAS aircraft. In these circumstances it can be expected that the benefit provided by the collision avoidance manoeuvres of both aircraft would not be as great as the benefit provided by coordinated manoeuvres.

C.3.3.3 Full coordination

UAS collision avoidance could fully coordinate with ACAS behaving as a quasi-ACAS in full TA-RA mode. ACAS equipped aircraft would coordinate with UCAF by sending RACs and the UAS would send RACs in return.

[58] RACs are sent to other ACAS even if they are in TA-only mode to allow for the possibility that the intruder’s ACAS might switch to full TA/RA mode (either because the aircraft climbs out of sensitivity level 2 or the pilot switches the mode of operation), in which case the intruder’s ACAS needs to know the sense of the RA already selected on the first aircraft.

[59] The ACAS aircraft’s ability to reverse sense depends on whether the threat is diagnosed to be ACAS equipped, not on whether an RAC has been received from the threat.

Currently mandated ACAS is 'ACAS II': this provides collision avoidance advice in the form of RAs in the vertical sense only. ACAS with an additional capability of providing RAs in the horizontal direction (*i.e.* "turn left", or "turn right") – as well as RAs in the vertical direction – has been envisaged and is known as 'ACAS III'. A detailed specification of ACAS III does not exist (nor have implementations of the concept been produced[60]) but provisions in the current ACAS SARPs provide the necessary formats for aircraft to indicate that they are ACAS III equipped, and to send RACs indicating that a horizontal RA has been selected.

Although ACAS III systems are not currently operational, it is conceivable that UCAF will have the capability to generate avoidance manoeuvres in the vertical and/or horizontal directions as appropriate. Such systems should 'future-proof' themselves against the introduction of ACAS III by each behaving as a quasi-ACAS III in terms of the indication of ACAS capability and RACs that are sent.

The UAS would indicate in replies to Mode S interrogations from other ACAS aircraft that it was "ACAS with vertical-only resolution capability" or "ACAS with vertical and horizontal resolution capability" (see paragraph 4.3.8.4.1.2 of [7], "RI (air-air reply information)") as appropriate.

The UAS would need to make its own Mode S interrogations of Mode S equipped intruders (as do ACAS units) in order to determine their ACAS equipage and status so as to coordinate any collision avoidance manoeuvres (by sending appropriate RACs).

The RACs sent by UCAF (see paragraph 4.3.8.4.2.2.1.2 of [7]) should indicate the sense both of vertical sense avoidance manoeuvres and of horizontal avoidance manoeuvres as appropriate.

C.4 Use of the SSR spectrum

C.4.1 ACAS interference limiting

Note that ACAS employs the same transponders and frequency spectrum as ground-based SSR used by ATC (and systems like A-SMGCS used by aerodrome control). Consequently some small degradation of SSR coverage is inevitable but is justified since an overall safety benefit (in terms of the reduced risk of mid-air collision) is achieved.

The combined effect of interrogations from many ACAS units operating in a comparatively small area could degrade SSR coverage to an unacceptable degree through mutual interference that limits the availability of transponders and by causing an unacceptably high fruit rate in ATC SSR systems.

[60] TCAS III and TCAS IV are proposed implementations of the ACAS III concept (achieving the required functionality by different means). Neither has gone in to production and it is unlikely (but not inconceivable) that any implementation of the ACAS III concept will be available for manned civil aircraft in the foreseeable future.

The operation of ACAS interferes with the operation of other transponder interrogators (SSR, Mode S, other ACAS units, and potentially UAS collision avoidance) in two ways:

- firstly, replies to the ACAS interrogations, referred to as ‘fruit’, interfere directly with replies to other interrogators;
- secondly, ACAS interrogations occupy the transponders on all aircraft, whether or not they reply, preventing them from processing any further interrogations for the duration of the occupation.

To limit these effects the ACAS specification contains ‘interference limiting’ algorithms which are implemented by ACAS aircraft at or below FL180 (see section 2.2.3.6 of the TCAS MOPS [8], or section 3.2.3 of the ACAS SARPs [7]). When many ACAS units are operating in a comparatively small area the number and power of interrogations by each ACAS unit is reduced to limit the overall reduction in the availability of all transponders.

This interference limiting is achieved by procedures implemented independently in each ACAS unit. These procedures take the form of a reduction in the rate and power of interrogations (both Mode C and Mode S) until three separate inequalities in the ACAS algorithms are simultaneously satisfied. The three inequalities are associated with the following physical mechanisms:

i. This inequality limits the total power of all interrogations (Mode C and Mode S) by a single ACAS unit, with the aim of limiting the unavailability of other transponders to SSR surveillance. The inequality aims to ensure that a ‘victim’ transponder never receives more than 280 ACAS interrogations during a 1 s period.

ii. This inequality limits the number of interrogations by a single ACAS unit so that the unavailability of the aircraft’s own transponder (due to mutual suppression during interrogations to prevent the aircraft from replying to its own interrogations) is limited. The inequality ensures that the aircraft’s own transponder is not unavailable, due to mutual suppression, for more than 1% of the time.

iii. This inequality limits the total power of Mode C all-call interrogations by a single ACAS unit, with the aim of limiting Mode C fruit to acceptable levels. The inequality aims to ensure that a victim Mode C transponder will not generate more than 40 replies, due to ACAS interrogations, during a 1 s period.[61]

As detailed in the ACAS SARPs (and implemented in the TCAS MOPS), inequalities (i) and (iii) both use a count of the total number of operating ACAS units (*i.e.* ACAS units in TA-only mode or in full TA/RA mode) that an individual ACAS unit has detected. An individual ACAS unit determines this ‘number of TCAS aircraft’ (NTA) by passively monitoring the ACAS broadcast messages of other aircraft.

[61] A rate of 40 replies per second is typically 20% of the reply rate due to SSR in an area of multiple coverage.

C.4.2 UAS surveillance

A UAS will need to perform surveillance of nearby traffic for the purpose of collision avoidance.

Conceivably this surveillance could be performed using techniques that did not use frequencies within the SSR spectrum. In that case there would be no issue with ACAS interoperability.

However, in practice it is likely that UAS collision avoidance will exploit the fact that a large proportion of traffic will be equipped with SSR transponders (Mode C or Mode S) and base its surveillance, at least partially, on this equipage.

If using the SSR spectrum each UCAF will need to ensure that their surveillance process does not unacceptably impinge on the availability of transponders to ground-based ATC radar and ACAS. This can be achieved by ensuring that the surveillance complies with the high level requirements of the ACAS interference limiting algorithms (as listed in Section C.4.1).

One obvious way of complying with the high level requirements of the ACAS interference limiting procedures would be to adopt the ACAS surveillance regime and implement the interference limiting algorithms as detailed in the ACAS SARPs (and TCAS MOPS). Research would be required into whether or not UAS would also need to announce itself as an ACAS interrogator by making the ACAS broadcast (a long Mode S air-air surveillance interrogation (UF = 16) with the broadcast address) every 8 s to 10 s so that it can be included in the NTA count of other ACAS units (see paragraph 4.3.7.1.2.4 of [7]).[62]

C.5 Communication with ground stations

Two aspects of UCAF functionality could, while not directly impinging on interoperability with ACAS, affect the seamless integration of UCAF into an airspace where ACAS is widely deployed. These are described below.

Neither of these issues is strictly related to the collision avoidance capability of UCAF but, since they might affect the operational acceptability of UCAF systems in specific airspace, could be the subject of additional functional requirements imposed on UAS wishing to enter non-segregated airspace.

C.5.1 Uplinking of Sensitivity Level

The sensitivity level in which individual ACAS units are operated can be set by addressed uplink messages from Mode S ground stations. This allows the ACAS threat detection parameters to be set to less sensitive values (than would be set on the basis of aircraft altitude alone), and even for the ACAS unit to be placed in TA-only mode.

Although this option has not been implemented by any ANSP it may be desirable to allow a similar functionality in UCAF. Even if a particular UCAF does not detect conflicts in the same manner as ACAS (making the setting of

[62] This would ultimately depend on the SSR spectrum budget allocated to UAS.

the sensitivity of threat detection parameters not meaningful) it may still be desirable to be able to disable the generation of avoidance manoeuvres from the ground (*i.e.* the equivalent of setting ACAS to TA-only mode).

C.5.2 Downlinking of RA information

The downlinking of ACAS resolution advisories to controller working positions has been demonstrated to be feasible through a number of techniques (the two favoured techniques being through aircraft's RA broadcast messages and Mode S RA reports).

If ANSPs wish to routinely downlink all collision avoidance advisories (from both ACAS and UCAF) then UCAF will need to broadcast the advisory information, or broadcast the fact that advisory information is available to be downloaded, in the appropriate format.

No single standardised means of downlinking RA information has yet been established. Indeed, four viable candidate techniques have been identified[63] [25] and each of the two most favoured have been implemented in different geographical areas.

[63] *Viz.* Mode S RA report, RA broadcast, ACAS coordination message, and 1090 MHz extended squitter.

D. ISSUES WITH ACAS II EQUIPAGE OF UAS

D.1 ACAS

UAS may equip with ACAS either as a solution to the need for a collision avoidance either as a stand-alone system or in tandem with other collision avoidance systems.

D.1.1 ACAS implicitly designed for civil fixed-wing aircraft

ACAS is designed to reduce the risk of collision for civil manned aeroplanes by recommending avoidance manoeuvres (RAs) with a particular vertical sense and strength (*i.e.* requiring a specific vertical rate to be achieved).

At first sight it would seem that some aspects of the problem of providing a collision avoidance capability for UAS might be solved simply by deploying the proven ACAS II system (which is mandatory carriage on certain manned aircraft).

For certain UAS this may be the case but aspects of the ACAS design mean that the appropriateness of fitting ACAS to any specific UAS is not a foregone conclusion.

Some aspects of the ACAS design contain implicit assumptions that the system is carried by a typical fixed-wing commercial air-transport aircraft. These assumptions may not be valid for specific UAS and consequently ACAS may not perform as might be anticipated if deployed on these UAS.[64]

D.1.2 Standard response

The collision avoidance algorithms used by ACAS (which determine the vertical sense and strength of RA required to reduce the risk of collision) assume a standard response by the pilot:

- the pilot will manoeuvre the aircraft (if required) to achieve the indicated vertical rate;
- the pilot will perform any manoeuvre with an acceleration of 0.25 *g* for an initial RA and with an acceleration of 0.35 *g* if the RA should subsequently strengthen to an increase-rate RA, or if there is a reversal in the vertical sense of the RA; and
- the pilot will initiate any manoeuvre required by the initial RA within 5 s of it being generated and that the pilot will respond within 2.5 s to any subsequent modification of the RA.

The effectiveness of ACAS is dependent on a prompt and accurate response (*i.e.* at least as good as the standard response assumed by the ACAS

[64] However, ACAS II has been successfully trialled and subsequently certificated on certain helicopters, and so the efficacy of equipage of UAS with ACAS would need to be considered on a case-by-case basis.

algorithms) to the RAs that ACAS generates. A response that is not counter to the vertical sense of the RA is particularly important in encounters between two ACAS equipped aircraft where the vertical sense of the RAs in the two aircraft are coordinated, and the effectiveness of the RA on one aircraft (even if flown accurately) can be dependent on a correct response in the other aircraft as well.

D.2 Limitations of ACAS Performance

The rest of this section describes these limitations in three sub-sections:

- hardware (see sub-section D.2.1);
- ACAS surveillance tracking (see sub-section D.2.2); and
- UAS performance (see sub-section D.3).

D.2.1 Hardware

D.2.1.1 Components

An ACAS II installation requires several components which occupy physical space within the aircraft and contribute to the overall mass – both of these resources may be at a premium on a UAS.

An ACAS installation on a UAS would require certain dedicated components:

- TCAS processor;
- upper TCAS antenna (direction-finding); and
- lower TCAS antenna (direction-finding or omni-directional).

Other required components may already be present as part of other systems:

- Mode S transponder;
- Mode S antennae; and
- radio altimeter and antenna.

Certain ACAS components used by the pilot on manned aircraft would not be required on the airframe of a UAS ACAS installation:

- TCAS/SSR control panel;
- traffic display;
- RA displays; and
- speakers for aural annunciations.

The required components for Mode S equipage could weigh up to 10 kg with components for ACAS II equipage weighing a further 10 kg.

D.2.1.2 Antennae

An ACAS II installation requires a top mounted direction-finding antenna and a bottom mounted antenna which may be either a direction-finding antenna or an omni-directional antenna. Standard ACAS direction-finding antennae are a quadrapole housed in scab housing; a standard omni-directional antenna can be a simple blade.

The design of standard ACAS antennae are a compromise between surveillance performance, weight constraints, and aerodynamic considerations, and have been designed to be mounted on the fuselage of medium-sized or larger aircraft (the mandate is for aircraft capable of carrying 20 or more passengers or with MTOM greater than 5,700 kg). Antenna performance is susceptible to interference effects caused by other 'furniture' on the fuselage (aerials, lights, pitot tubes, sensors, *etc.*) and multi-path reflections from other parts of the airframe; ACAS antennae perform best when sited well away from other furniture, and on a flat part of the fuselage. Such sites may not be available on certain UAS which can be comparatively small and 'knobbly'.

Particular problems can arise when the ACAS antenna can 'see' parts of the airframe that can cause reflections that vary on each cycle (*e.g.* propeller blades, or prop-shaft and rotor blades of rotorcraft). These present a greater problem than the static reflections associated with fixed parts of the airframe.

The transmissions from ACAS antenna are vertically polarised. A physical consequence of this is that the power of transmissions is a maximum in the horizontal direction and decreases with increasing elevation angle until the transmitted power of interrogations is zero in the vertical direction. This is generally of little consequence for fixed-wing manned aircraft (since a threat rarely approaches from directly overhead/underneath) but can matter for some types of UAS that can manoeuvre directly in the vertical direction – this is discussed further in Section D.2.2.4.

D.2.1.3 Radar altimeter

As part of a standard installation ACAS II interfaces with the radar altimeter. Height above terrain (as provided by the radio altimeter) is used:

- to set the appropriate sensitivity level for ACAS below 2,500 ft AGL;
- to determine whether all RAs should be inhibited, whether descend RAs should be inhibited, or whether increase descent RAs are inhibited;
- to determine whether other targets should be declared as 'aircraft on the ground' (in which case they are assumed not to constitute a threat, and RAs against these aircraft are inhibited).

Not all UAS will necessary be equipped with a radar altimeter and this would degrade the performance of ACAS near the ground.

D.2.2 Surveillance and Tracking

ACAS surveillance interrogates the transponders of nearby aircraft. Replies to these interrogations are used to determine the range (by time-of-flight of the signal) and approximate bearing (by angle-of-arrival of the reply) of other aircraft. These data are then used to track the other aircraft.

Naturally, tracking can only be as good as the input data and this can be affected by the siting of ACAS antennae on a UAS airframe as described in Section D.2.1.2.

Standard ACAS antennae and ACAS tracking algorithms have been designed to meet, at least, the minimum requirements of the SARPs. In a number of areas this can mean that ACAS tracking may not meet the requirements associated with UAS performance.[65] These areas are described below.

D.2.2.1 Closing speed

ACAS is required to generate tracks (with at least a 90% probability that the track is established 30 s before closest approach) for intruders in the forward quadrant with a closing rate (*i.e.* combined velocity of the UAS and the intruder) of up to 1,200 kt. In the side quadrants the limiting closing speed is 750 kt, and in the back quadrant the limiting closing speed is 430 kt.

Intruders for whom the closing speed exceeds these limiting values might not be tracked.

This might cause the late establishment of a track for an intruder initially approaching from behind which is subsequently approaching from in front due to a rapid change of direction of the UAS.

D.2.2.2 Vertical rates

TCAS is required to generate tracks for intruders with relative altitude rates of less than 10,000 fpm.

ACAS will not track altitudes (including own aircraft tracking) where vertical rates exceed 12,000 fpm, or vertical accelerations exceed 1.5 *g* (implied by a sequence of altitude reports).

Some high performance UAS might routinely execute vertical manoeuvres which could cause own aircraft altitude tracking and/or the tracking of intruders to be interrupted:

- if individual intruders are not tracked then a partial loss of protection against mid-air collision would result;
- if own aircraft altitude is not tracked then a total loss of protection against mid-air collision would result.

D.2.2.3 Turn rate

ACAS is required only to be able to track intruders whose rate of change of azimuth as measured relative to own aircraft's axis is 3 deg/s or less.

Some UAS (especially rotor-craft) could routinely execute turns that would cause the relative azimuth of all intruders to exceed 3 deg/s. In this circumstance all intruder tracks could be dropped meaning that there was no protection against mid-air collision until tracks were re-established a few seconds later.

[65] Although available ACAS installations may have performance that goes beyond the minimum requirements, tests and trials would be required to confirm this for any specific installation on a UAS.

D.2.2.4 TCAS antenna performance

ACAS interrogations (and transponder replies) are vertically polarised. The antenna beam pattern consequently has nulls directly above and below (relative to the fuselage).

To allow for timely detection of intruders with slow closing speeds approaching from above or below ACAS is required to have sufficient antenna within a ±10 deg elevation angle of the aircraft axis and this is generally provided by the ACAS directional antenna which typically has a nominal 3 dB vertical beam-width of 30 deg.

However, some UAS (especially rotor-craft) could routinely manoeuvre into these nulls which could be occupied by threats that are not tracked.

D.3 Limitations of UAS Performance

The safety benefit resulting from ACAS equipage of manned aircraft has been demonstrated, and it has also been demonstrated that this benefit results from timely and accurate response by pilots to the RAs that ACAS generates (*e.g.* see [1] and [10]).

A timely and accurate response to ACAS RAs (both initial RAs and any subsequent strengthening and/or reversal of the RA) could be limited by UAS performance.

D.3.1 Response time

If response to RAs generated by ACAS on UAS is initiated by a remote pilot there are issues concerned with the reliability and latency of the air-ground-air datalink by which the alert is communicated from the aircraft to the pilot and the pilot's response is communicated from the ground to the aircraft. These are in addition to any issues connected with the man-machine interface by which the alert is displayed to the pilot and the pilot responds to the alert.[66]

Reliability and latency of the datalink are most likely to be an issue for beyond line of sight communications, whether these be via satellite or relayed through ground infrastructure. The most challenging situation will be when an increase or a reversal in the vertical rate is required, since these require the shorter response time of 2.5 s and occur in encounters where the original sense and/or strength of RA is diagnosed by ACAS as being not able to deliver sufficient separation.

D.3.2 Aerodynamic performance

D.3.2.1 Vertical acceleration

ACAS RAs require vertical accelerations of 0.25 *g* routinely, and of 0.35 *g in extremis*. Certain UAS might not be able to achieve these accelerations in all configurations.

[66] The alternative approach of an automatic response initiated on the aircraft is discussed in Section D.4.

D.3.2.2 *Vertical rate*

ACAS RAs require climbs or descents at 1,500 fpm routinely, and at 2,500 fpm *in extremis*. Certain UAS might not be able to achieve these rates (particularly the climb rates) in all configurations.

The ACAS specification allows climb RAs and increase climb RAs to be separately inhibited, in which case the algorithms choose the most appropriate RA subject to these constraints. Any installation of ACAS on a UAS should ensure that these inhibits are implemented as necessary.

D.4 Automated response to ACAS Alerts

D.4.1 Introduction

The ACAS alert thresholds (the nominal warning times) are set at values that allow for a delay in response by the pilot (*i.e.* the response time in the standard response).

D.4.2 Response by remote pilot

As described above a prompt response to ACAS RAs is essential. It is possible that the round-trip latency of communication between the UAS and a remote pilot (or the possibility of intermittent communication failure) will mean that a prompt response (*i.e.* within 5 s for initial RA, and 2.5 s for subsequent changes in RA) initiated by a remote pilot cannot be guaranteed.

D.4.3 Automated response

To circumvent delay problems resulting from latency of communications UAS equipped with ACAS could have RA information directly coupled to the onboard navigation system. It would then be possible for the UAS to promptly initiate any required manoeuvre in response to an ACAS RA.[67]

An initial automated response to ACAS RAs need not prevent a remote pilot from subsequently electing not to continue to follow the RA for whatever reason (although this should only be done in full knowledge of the potential effect on other ACAS aircraft in coordinated encounters).

It should be noted that choosing not to follow an ACAS RA can be dangerous for two reasons:

- An RA might be ignored because the pilot believes that he has better information than ACAS and knows that the intruder does not constitute a collision threat. However this presupposes that the pilot has correctly identified the threat. An ACAS RA might be generated by a third party whose presence is not known to the pilot.

[67] It is likely that automated responses could be initiated with a shorter delay than those assumed in the standard response (*i.e.* up to 5s). Any RA manoeuvre should be initiated as soon as possible as a quicker response does not invalidate the effectiveness of the RA and can lead to an early weakening of the RA strength which potentially reduces the required deviation from the original flight-path thus minimising disruption.

- In encounters between two ACAS aircraft the RAs are coordinated. Choosing not to follow an RA in a coordinated encounter restricts the choices available to the other aircraft. Although there may be no risk of collision with the UAS, the other aircraft might be involved in a multiple encounter where it is at risk of collision with a third party.

D.4.4 Undesirable RAs

An automated response would initiate a manoeuvre in response to an RA (if required) even in circumstances where the pilot believes: it would jeopardise the safety of the aircraft; in which he knew that the UAS would not be able to respond; or where the remote pilot believed that avoiding action was not required.

Situations where this might be the case include:

- **nuisance RAs** – ACAS can issue RAs in encounters where there is in fact a significant horizontal miss distance (in collision avoidance terms) and the RA is not necessary for collision avoidance. The remote pilot of a UAS might have other information (*e.g.* from a UCAF operating separately from ACAS) that indicates that an ACAS RA is not necessary for collision avoidance.
- **conflicting advice** – a UAS carrying ACAS and a UCAF operating separately from ACAS might receive conflicting advice from the two systems on how to resolve a collision threat.
- **planned intercepts** – a UAS might deliberately intercept another aircraft or be the subject of such an interception itself. The planned proximity of the two aircraft could generate an ACAS RA that is not necessary for collision avoidance.
- **formation flying** – unlike commercial air transport, UAS might deliberately fly close to one another in formation resulting in ACAS RAs.
- **closely spaced parallel approaches** – approaches to closely spaced parallel runways are used at some airports. This can lead to nuisance RAs either between aircraft established on the glide slopes to separate runways, or between aircraft that are temporarily headed towards each other before they turn on to the final approaches to separate runways.
- **inability to respond** – there can be circumstances where a UAS will be unable to respond to every RA that could potentially be generated. For example a UAS might suffer an engine failure and be unable to climb at 1,500 fpm if required to do so by an RA.

E. PERFORMANCE OF SEE & AVOID

E.1 See & Avoid

See & Avoid is exercised by the flight-crew of manned aircraft. It is the process by which the flight-crew aim to visually detect and recognise ('visually acquire') hazards and subsequently mentally devise and physically execute any necessary avoidance manoeuvre. See & Avoid is a complex process involving both physiological and psychological factors.

When the hazard is a risk of mid-air collision with an airborne object then, as far as possible, the avoidance manoeuvre should be devised and executed with regard to the Right of Way rules laid out in ICAO Annex 2 (Rules of the Air) [5].

By the principle of equivalence UAS Sense & Avoid is required to be at least as good as manned aircraft See & Avoid. This then creates a need to quantify See & Avoid performance so that Sense & Avoid performance can be compared.

It is beyond the scope of the CAUSE study to definitively quantify See & Avoid performance but some observations about the functional requirements, gained from experience in the AVAL study with the implementation of a visual acquisition model [22] and the modelling of horizontal manoeuvres [23], are presented here.

E.2 Performance of 'See'

E.2.1 Field of regard

The field of regard (FoR) is the extent, in angle, of the directions from which signals arriving at a sensor can be detected. In See & Avoid the 'sensor' is the pilot's eyes and the FoR takes account of his ability to move his head, and may ultimately be limited by the extent of the windshield.

E.2.1.1 Horizontal

Collision threats that are moving slower than own aircraft cannot approach from behind. Consequently a FoR in the forward sector only (90 deg either side of straight-ahead) is sufficient to detect these threats.

Threats that are travelling faster than own aircraft can overtake and therefore approach from behind. When the angle of convergence is less than 70 deg the Rules of the Air dictate that the aircraft being overtaken has right of way (see paragraph 3.2.2.4 of ICAO Annex 2 [5]). Consequently, it is necessary (in principle) for the pilot to have a FoR that only extends to 110 deg either side of straight-ahead.

Advice to pilots might suggest that a FoR of 60 deg either side of straight-ahead is sufficient (*e.g.* see [26] and [27]): it is probably best to consider this as a core sector (within which the pilot's visual scan should be concentrated) of the full range.

E.2.1.2 Vertical

See & Avoid advice to pilots by the UK CAA [26] and US FAA [27] is that pilot's visual scan should extend, in the vertical, 10 deg above and below the axis of the aircraft.

E.2.2 Visual acuity

Even when an object is within the FoR the physiological limitations of human vision place constraints on whether the object can be detected.

E.2.2.1 Resolution

The optics of the human eye and the density of light detecting cells on the retina place a lower limit on the angular size of objects that can be reliably discerned.

Precise estimates of this limit, in the context of the visual acquisition of airborne objects, vary (see Appendix D of [22]) but generally are around 1 arc-minute.

E.2.2.2 Contrast

Even if an object subtends an angle greater than the limit of resolution of the eye it still needs to present sufficient contrast, compared to the background against which it is seen, to be detected.

Under normal daytime lighting conditions a luminance difference between object and background of at least 5% is generally considered necessary to detect the object.

E.2.3 Search intensity

Given that an object is within the FoR, while appearing sufficiently large with sufficient contrast, it can potentially be detected. When the object is on a collision course the likelihood of detection by a given time before collision (*e.g.* so that there is sufficient time remaining to devise and execute an effective avoidance manoeuvre) can be modelled as a stochastic process.

The likelihood at each instant is proportional to the apparent size and contrast of the object. The constant of proportionality is a parameter termed the 'search intensity' that reflects the time spent searching in the right direction and the assiduousness with which that search is conducted. The parameter can also be used to characterise Sense & Avoid using optical techniques.

The search intensity can be considerably enhanced when the pilot is alerted to the presence and position of a collision threat (*e.g.* by ATC traffic information, or an ACAS TA).

E.3 Performance of 'Avoid'

The human process of visual acquisition ('See') is relatively well understood; the human process of assessing the relative disposition and movement of a threat, and devising an avoidance manoeuvre ('Avoid') less so.

The paucity of real data means that an evaluation of the performance of the Avoid process requires either extensive trials with real pilots or the development of a mathematical model of the cognitive process.

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