Work Package 9: Final report on the safety of ACAS II in the European RVSM environment

ACAS Safety Analysis post-RVSM Project

ASARP Project

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RECORD OF CHANGES

Issue	Date	Detail of changes
0.1	24th February 2006	Document outline
0.2	4th April 2006	Material developed in all sections (apart from section 4.3 and the executive summary)
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1.1	11th May 2006	Editorials in all sections

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ACRONYMS

ACAS	Airborne Collision Avoidance System
ACASA	ACAS Analysis
AEM	Altimetry Error Model
ASARP	ACAS Safety Analysis post-RVSM
ASE	Altimetry System Error
ATC	Air Traffic Control
ATM	Air Traffic Management
CPA	Closest Point of Approach
CVSM	Conventional Vertical Separation Minima
DSNA	Direction des Services de la Navigation Aérienne
ECAC	European Civil Aviation Conference
FL	Flight Level
fpm	ft per minute
ft	Feet
HMD	Horizontal Miss Distance
HMU	Height Monitoring Unit
ICAO	International Civil Aviation Organization
IMC	Instrument Meteorological Conditions
MASPS	Minimum Aviation System Performance Specification
MTOM	Maximum Take-Off Mass
NMAC	Near Mid-Air Collision
OSCAR	Off-line Simulator for Collision Avoidance Resolution
QAR	Quick Access Recorder
RA	Resolution Advisory
RVSM	Reduced Vertical Separation Minima
SARPs	Standards and Recommended Practices
SSR	Secondary Surveillance Radar
TA	Traffic Advisory
TCAS	Traffic alert and Collision Avoidance System
TLS	Target level of Safety
VMC	Visual Meteorological Conditions
VMD	Vertical Miss Distance

GLOSSARY

ACAS	Airborne Collision Avoidance System – a system standardised in the ICAO SARPs that uses transponder replies from other aircraft to warn the pilot of a risk of impending collision Hereafter, ACAS always refers to ACAS II – a system that generates traffic advisories (TAs) and also generates resolution advisories (RAs) in the vertical plane.
ACASA project	ACAS Analysis – a study commissioned by EUROCONTROL in support of the mandate for the carriage of ACAS II in Europe, before implementation of RVSM. Work Package 1 of ACASA investigated the safety of ACAS and developed a European safety encounter model based on pre-RVSM radar data. Work Package 3 of ACASA investigated specifically the ACAS / RVSM interaction issue.
ASARP project	ACAS Safety Analysis post-RVSM Project – a study commissioned by EUROCONTROL to investigate the safety of ACAS following the introduction of RVSM in Europe.
AEM	Altimetry error model – a mathematical model which defines altimetry system errors of aircraft as a series of distributions that depend on altitude. The ASARP project determined an AEM applicable to the European RVSM airspace using HMU monitoring data.
Encounter	A traffic situation involving two (or more) aircraft. Distinction is hence made between a pair-wise encounter (involving two aircraft only) and a multiple aircraft encounter (with at least three aircraft). Furthermore, an encounter can either be: - an ‘actual’ encounter extracted from radar data recordings according to agreed capture criteria, or - a encounter generated from a safety encounter model.
NMAC	Near Mid Air Collision – a pair of aircraft for which, at some point, the horizontal separation is less than 500ft and simultaneously the vertical separation is less than 100ft.
Pilot response model	A set of parameters which characterise the pilot responses to ACAS RAs and which can be used to simulate pilot behaviour during ACAS simulations. The ASARP project determined a ‘typical pilot response’ model applicable to ACAS operations in Europe using recent onboard recorded data.

RA	Resolution Advisory – an ACAS alert providing advice to a pilot on how to modify or regulate his vertical speed to avoid a potential mid-air collision. For an individual aircraft in a multiple aircraft encounter, the RAs issued by the ACAS logic can either consist of: - sequential RAs against two distinct threats, or - a composite RA against two simultaneous threats.
Risk ratio	The ratio of the risk of mid-air collision when ACAS is deployed to the risk that would exist without ACAS. A risk ratio of 0% would indicate a perfect system that eliminated the risk of collision; a risk ratio of 100% would indicate an ineffective system that made no change to the risk of collision
RVSM	Reduced Vertical Separation Minima – the regime by which the standard vertical separation between FL285 and FL415 has been reduced from 2,000ft to 1,000ft.
Safety encounter model	A mathematical model which reproduces the distributions and interdependencies of the parameters characterising risk bearing encounters likely to occur in ATM operations. The encounters that matters are those in which (at least) two aircraft are on a close encounter course in which there exist a risk of mid-air collision or in which the response of pilots to RAs can result in a risk of mid-air collision. The ASARP project used post-RVSM radar data to update the ACASA safety encounter model and produced the post-RVSM European safety encounter model, viz. the ASARP safety encounter model. This model is for pair-wise close encounters. The project also developed a multiple aircraft safety encounter model (for three aircraft).
Standard pilot response	The pilot response model described in the ACAS SARPs and implicitly assumed in the ACAS collision avoidance algorithms, viz. an initial delay of 5s before the pilot responds with an acceleration of 0.25*g* to achieve the required vertical rate.
TA	Traffic Advisory – an ACAS alert warning the pilot of the presence of another aircraft that may become the subject of an RA
TCAS	Traffic alert and Collision Avoidance System – an aircraft equipment that is an implementation of an ACAS Hereafter, TCAS refers to TCAS II, version 7.0 – the equipment that complies with the ICAO SARPs, and whose carriage and operation is mandatory for many aircraft in Europe.

EXECUTIVE SUMMARY

E.1. Background

E.1.1. The Airborne Collision Avoidance System II is an essential component of the ATM system. It serves as a last resort safety net irrespective of any separation standards. The carriage and operation of the ACAS compliant equipment (i.e. TCAS II Version 7.0) is mandatory in Europe since 1st January 2005.

E.1.2. The Reduced Vertical Separation Minimum (of 1,000 ft) is operational in the European airspace, between FL 290 and FL 410 inclusive, since the 24th January 2002. In its area of applicability, it provides six additional cruising flight levels, resulting in substantial benefits.

E.1.3. ACAS safety studies formed in support to the mandates for the carriage of ACAS II in Europe were, perforce, based on prediction of the RVSM operational environment.

E.2. Scope and purpose

E.2.1. The **A**CAS **S**afety **A**nalysis post-**R**VSM **P**roject assessed whether the ACAS safety benefits anticipated prior to the introduction of RVSM operations are indeed achieved. To do so, the study replaced the operational assumptions made prior to RVSM introduction by actual RVSM operational data.

E.2.2. The focus was on the evaluation of the safety benefits (in terms of reduced risk of mid-air collision) afforded by ACAS in the European RVSM airspace, and the identification of the main factors that influence this risk reduction. The study not only dealt with situations involving two aircraft, but also addressed the issue of a third party aircraft flying in close proximity (‘multiple aircraft encounters’).

E.2.3. The project comes within the scope of the EUROCONTROL Mode S and ACAS Programme. It is of particular interest for Air Navigation Service Providers, national aviation authorities, the pilot and controller community, as well as other bodies involved in the safety management and monitoring of ATM in Europe.

E.3. European RVSM environment

E.3.1. To get a comprehensive understanding of both ACAS and RVSM operations, up-to-date operational data were collected, and analysed. These data included: *i)* European radar data including the busiest sectors of the RVSM airspace, *ii)* onboard data (from four European airlines for years 2001, 2002 and 2004) associated with actual ACAS events, and *iii)* RVSM monitoring data (from three Height Monitoring Units in the year 2004) related to altimetry performance of aircraft.

E.3.2. This enabled the building of a set of models, then used to determine the safety of ACAS in the European RVSM airspace. These models consist of a European safety encounter model that reflects the possible effect of RVSM operations, a model of typical pilot reaction in response to RAs and a model of altimetry errors applicable in the RVSM airspace.

E.3.3. The radar encounters observed at the RVSM altitudes (and whose properties are captured in the post-RVSM European safety encounter model) consisted of:

i) a great proportion (about two thirds) of 1,000 ft separation level-off encounters,

ii) a significant proportion (about one quarter) of encounters with a vertical crossing close to closest approach, *iii)* a noteworthy proportion of encounters involving two aircraft flying level at adjacent RVSM flight levels (but with poor altitude station keeping performance or flying with a vertical offset), and

iv) a small, but non-negligible, proportion of encounters with a vertical separation at closest approach lower than 100 ft. These encounters were of particular interest since they typically correspond to serious incidents.

E.3.4. Improved training and increased familiarity with ACAS were expected to have improved pilot behaviour during of ACAS events (compared to the early period of ACAS operations in Europe). This was indeed confirmed by the good pilot response rate (of about 90%) observed in the airborne recorded data. Furthermore, when responding to corrective RAs, their observed response was generally very close to the standard reaction expected from the ACAS logic, although the reactions adopted spanned a range of reaction times, vertical rates and vertical accelerations.

E.3.5. As avionics systems have improved, the standard altimetry error model defined in the ACAS SARPs has become progressively out-of-date. Using very many measurements of the Altimetry System Error made by Height Monitoring Units in Europe, the study established a post-RVSM altimetry error model. This model defines a typical ASE distribution applicable to all aircraft types operating at RVSM altitudes.

E.4. Evaluation of the safety benefits of ACAS in RVSM

E.4.1. To estimate the risk reduction delivered by ACAS in the European RVSM airspace, two operational scenarios were investigated which built upon each other and took into account increasing levels of details:

- a ‘reference scenario’ addressing typical ACAS operations in RVSM airspace (in terms of aircraft equipage and pilot responses to ACAS in ‘close’ encounters representative of the airspace). This scenario was also evaluated for the whole European airspace to allow for comparison between the RVSM altitudes and other altitude layers;
- a ‘full-system scenario’ addressing contingencies that can arise during typical operations of the ACAS system in RVSM airspace (including events related equipment limitations, late controller involvement and visual acquisition of the collision threat by the pilot).

E.4.2. Whatever the scenario, ACAS was demonstrated to reduce the risk of mid-air collision by a factor of about sixty (viz. an airspace-centred risk ratio of about 1.7%). The level of protection provided by ACAS has proven to be robust to the altimetry errors actually observed in RVSM airspace, as well as to other hazards that may affect ACAS operations.

E.4.3. This risk reduction was estimated to be ten times greater at the RVSM altitudes than in the airspace as a whole. This can be explained by *i)* the expectation that all commercial air transport aircraft flying in RVSM are ACAS equipped, and *ii)* the fact that encounters occurring in RVSM correspond to situations more easily solved by ACAS than other situations at lower altitudes (with fewer ACAS-equipped aircraft and more manoeuvring aircraft).

E.4.4. The key factor that influences the risk reduction delivered by ACAS in RVSM airspace was demonstrated to be the pilot response rate to the RAs. It was notably established that if all pilots would follow the RAs instead of sometimes giving preference to late controller instructions, the level of protection delivered by ACAS could be further increased by about a factor of two.

E.4.5. Taking into account the underlying risk in the absence of ACAS (estimated to be of about 1.7×10^{-8} mid-air collision per flight-hour), the risk ultimately achieved with ACAS in RVSM airspace was estimated to represent about three mid-air collisions every 10^{10} flight-hours. It was also established that about one third of the risk is an induced risk resulting from an inadequate use of the ACAS system, i.e. when one pilot manoeuvres contrary to the RA. It could be further reduced by modifying the ACAS collision avoidance logic as described in a change proposal (CP112E) currently being progressed.

E.5. Investigation of the multiple aircraft encounters

E.5.1. In those multiple aircraft encounters that might occur in RVSM airspace, ACAS has proven to issue stable and effective RAs, typically RAs that require own aircraft to level-off in-between the two simultaneous threats.

E.5.2. From an operational perspective, evidence was found that the pilot response to an initial RA (against a single threat) strongly influences the occurrence of an induced conflict with a third party aircraft at an adjacent RVSM flight level, and therefore, the occurrence of a multiple threat RA. A prompt and correct pilot response minimises this risk. However, if such a conflict occurs, the pilot response to the multiple threat RA then influences the occurrence of an ACAS domino-effect on the third party aircraft.

E.5.3. From a safety perspective, the risk of mid-air collision in the case of RVSM multiple aircraft encounters was estimated to be reduced by a factor of about fifteen thanks to ACAS (i.e. an airspace-centred risk ratio of 6%, on average). Some geometries were identified in which the ACAS multi-aircraft logic does not achieve its design purpose. However, this is considered tolerable since they constitute a small proportion of multiple aircraft ACAS/RVSM encounters, which are already rare events (estimated to occur about once every 500,000 flight-hours).

E.6. Conclusions and recommendations

E.6.1. ACAS, as actually observed to be operated, provides substantial safety benefits in the European RVSM airspace. As in any other portion of the airspace, prompt and correct pilot response to the RAs that ACAS generates is key to achieving maximum safety benefits. These benefits has also significant in the case of RVSM multiple aircraft encounters even though the risk reduction is four times less significant in such circumstances. Finally, it is evident that the induced ACAS risk is small in the context of the TLS for RVSM.

E.6.2. For the safety benefits of ACAS to be maximised, it is essential that all adhere to the standardised ACAS operational procedures, and that ACAS best practice is always applied. Further, to reduce the residual risk with ACAS in the European RVSM airspace, as in the whole airspace, it is essential to proceed with the implementation of change proposal CP112E to the ACAS collision avoidance logic.

E.6.3. In terms of future work, it is recommended to investigate further the shortcomings identified with the ACAS multi-aircraft logic and to propose solutions. Finally, future ACAS safety studies should exploit the enhanced tools developed in this project.

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1. Introduction

1.1. Objective and scope

1.1.1. The Airborne Collision Avoidance System II (ACAS) and the Reduced Vertical Separation Minimum (RVSM) have been operated jointly in Europe since January 2002. It is time to report whether the ACAS safety benefits anticipated prior to the introduction of RVSM operations in the European Civil Aviation Conference (ECAC) area are indeed achieved.

1.1.2. **ASARP** stands for **A**CAS **S**afety **A**nalysis post-**R**VSM **P**roject.

1.1.3. The focus was on the evaluation of the safety benefits (in terms of reduced risk of mid-air collision) afforded by ACAS in the European RVSM airspace. To achieve this, operational RVSM data were first collected, and analysed, to get a comprehensive understanding of the factors that may affect the performance of ACAS during RVSM operations. The project then evaluated the safety of ACAS in traffic situations representative of the RVSM environment and using operationally realistic assumptions with regard to ACAS operations. The study dealt not only with situations involving only two conflicting aircraft, but also addressed the issue of a third party aircraft flying in close proximity ('multiple aircraft encounters').

1.1.4. The ASARP project built on the methodology, and associated tools, that supported previous ACAS safety studies, i.e. the 'full-system safety study' completed in the 'ACAS Analysis' (ACASA) project [ACA1a], [ACA1b] and the 'ACAS safety study' [ACAe]. These studies, performed in support to the mandates for the carriage of ACAS II in Europe (i.e. prior to the introduction of RVSM operations), were, perforce, based on prediction of the RVSM operational environment. It was therefore essential to reassess the safety of ACAS in the new European airspace environment with operational RVSM data.

1.1.5. The project comes within the scope of the EUROCONTROL Mode S and ACAS Programme. It is of particular interest for Air Navigation Service Providers (ANSPs), national aviation authorities, the pilot and controller community, as well as other bodies involved in the safety management and monitoring of ATM in Europe. The project started in October 2004 for a one-year-and-a-half schedule. It was completed with an operational seminar in May 2006. The technical work was conducted by a consortium of three organisations (DSNA[1], QinetiQ[2] and Sofréavia[3]), the ATM division of Sofréavia being in charge of the project management.

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[1] The 'Air Navigation Services Department' (DSNA) is part of the French civil aviation administration and provides air navigation services in the French airspace as well as in the French overseas territories airspace.

[2] QinetiQ is a science and technology organisation involved in ATM research for bodies such as the UK Ministry of Defence, EUROCONTROL and national ANSPs.

[3] Sofréavia is an engineering and consulting company in the fields of airport, ATM and air transport industries. Its clients include EUROCONTROL, air navigation services providers, civil aviation administrations and industry.

1.2. Background and context

1.2.1. The role of ACAS in the ATM system

1.2.1.1. The Airborne Collision Avoidance System II has been introduced in order to reduce the risk of mid-air collisions. It serves as a last resort safety net irrespective of any separation standards. ACAS provides two levels of alert to the pilot, viz. Traffic Advisories (TAs) and vertical Resolution Advisories (RAs). The TAs aim at helping the pilot in the visual search for the 'intruder' aircraft, whereas as the RAs are indications to the pilot of manoeuvres intended to provide separation from all 'threats'; or manoeuvre restrictions intended to maintain existing separation.[4]

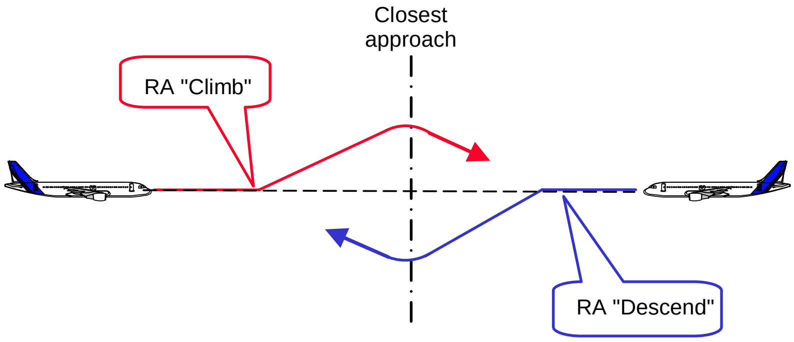

Figure 1: Illustration of a coordinated ACAS resolution

1.2.1.2. ICAO defines ACAS as "an aircraft system based on secondary surveillance radar (SSR) transponder signals which operates independently of ground-based equipment to provide advice to the pilot on potential conflicting aircraft that are equipped with SSR transponders" (cf. ICAO Annex 2 – Rules of the Air). It is recognised that "ACAS can have a significant effect on ATC (Air Traffic Control). Therefore, the performance of ACAS in the ATC environment should be monitored" (cf. ICAO PANS-ATM – Procedures in regard to aircraft equipped with airborne collision avoidance systems (ACAS)).

1.2.1.3. From 1st January 2005, the carriage and operation of ACAS compliant equipment (i.e. the Traffic alert and Collision Avoidance System (TCAS) II version 7.0) is mandatory in the ECAC area for all aeroplanes with a maximum takeoff mass exceeding 5,700 kg or authorised to carry more than 19 passengers. The ACAS mandate was implemented in two phases addressing distinct parts of the fleet. The Phase I implementation was completed by end of March 2001, whereas the transition period for Phase II implementation went until end of March 2006.

1.2.2. The European RVSM airspace

1.2.2.1. ICAO defines RVSM as the "Reduced Vertical Separation Minimum of 300m (1,000ft) between FL 290 and FL 410 inclusive" (cf. ICAO Manual on Implementation of [RVSM]).

[4] A guide to the use of ACAS and its functionality can be found in the EUROCONTROL ACAS brochure [ACA6].

1.2.2.2. On 24th January 2002, RVSM was introduced in 41 European and North African states. In its area of applicability, referred to as the EUR RVSM airspace (and shown in green in Figure 2), it provides six additional cruising flight levels, resulting in substantial reductions both in fuel costs and in-flight delays.

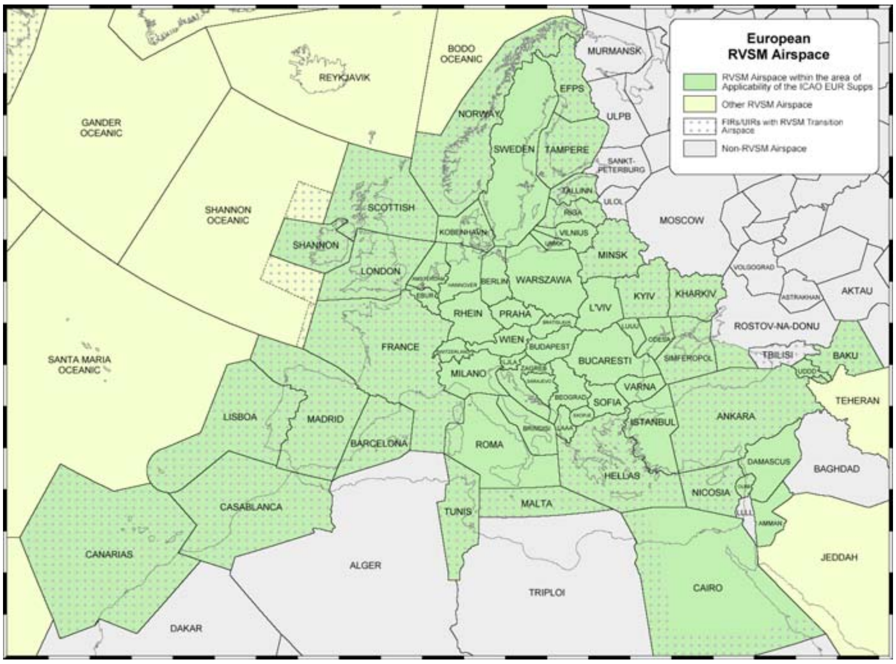

Figure 2: European RVSM airspace

1.2.2.3. In order to obtain RVSM airframe and operations approval an operator must satisfy their state regulatory authorities that the requirements listed in the JAA [TGL6] Revision 1 (or equivalent documents such as FAA Guidelines 91-RVSM, change 2) have been satisfied.

1.2.3. Previous ACAS / RVSM safety analyses

1.2.3.1. The ACASA project investigated a variety of issues relating to the safety of ACAS in support of the mandates for carriage in Europe. A dedicated work area specifically addressed the interaction between ACAS and RVSM, and ascertained whether there were any significant implications for ACAS performance due to European RVSM implementation; and whether the benefits expected from RVSM could be compromised due to the operation of ACAS [ACA3].

1.2.3.2. The ACASA study did not reveal any ACAS safety issues related to the introduction of RVSM in Europe and showed that going from a non-ACAS airspace to an ACAS airspace improves the level of safety whatever the applicable vertical separation minima. The study confirmed that ACAS continues to provide a significant safety benefit, as expected, when RVSM is introduced. It was also found that the introduction of RVSM could reduce the benefit in safety that is accrued solely due to the deployment of ACAS within the airspace.

1.2.3.3. The EUR RVSM Pre-Implementation Safety Case [PISC] was required, to allow for implementation of RVSM in the European airspace. It provided a Functional Hazard Assessment, Collision Risk Assessments and State National Safety Plans as main elements.

1.2.3.4. Among the safety critical hazards identified in the PISC were nuisance TAs and RAs and the pilots deviating from their clearances (viz. ‘level busts’). However, the deviations due to nuisance alerts were excluded from the Collision Risk Assessment. This was necessary to avoid the paradox whereby only the negative effect of ACAS nuisance alerts on risk would be taken into account. Further, due account was given to the results of ACASA showing that the nuisance alert rate in RVSM would be comparable with that already experienced below FL290 (where ACAS was assumed to be operationally acceptable).

1.2.3.5. The Post-implementation Safety Case [POSC] produced safety arguments demonstrating that RVSM was tolerably safe after implementation. Measures were also taken to ensure that the operation of RVSM in EUR airspace remains safe, including the continuous monitoring of technical height-keeping performance and of Altitude Deviation Reports sent by the participating states.

1.3. Document overview

1.3.1. Organisation of the document

1.3.1.1. The document is organised into five chapters, including this **Chapter 1** on the objectives and scope of the ASARP study.

1.3.1.2. **Chapter 2** presents the principles, methodological elements and tools that support the analysis of ACAS safety and that were used in the safety study presented here.

1.3.1.3. **Chapter 3** describes the operational RVSM data collected, and analysed, during the study. Also described is the manner in which these data have been used to update and enhance the tools mentioned above. These data included European radar data, onboard data associated with actual ACAS events and RVSM monitoring data related to altimetry performance of aircraft.

1.3.1.4. **Chapter 4** presents the results of the ACAS safety analysis conducted using the updated framework established during the study and which is tailored to the European RVSM environment. The focus is on the evaluation of the risk reduction achieved by ACAS in RVSM and the identification of the main factors that influence this risk reduction. The specific investigation of the performance of ACAS in the case of RVSM multiple aircraft encounters is also presented.

1.3.1.5. Finally, **Chapter 5** concludes the document with the main study findings and makes some recommendations in support of safe ACAS operations in Europe.

1.3.2. Note to the reader

1.3.2.1. The safety benefits (in terms of mid-air collision risk reduction) delivered by ACAS depend highly on the airspace in which it is operated. The present study was focused on the European RVSM airspace.

1.3.2.2. Therefore, the safety performance level of ACAS determined in this study does not necessarily apply to non-RVSM airspace, nor to RVSM operations in other airspace (e.g. the North Atlantic ICAO region).

2. Elements of ACAS safety analysis

2.1. Safety metrics

2.1.1. General

2.1.1.1. ACAS is not designed, nor intended, to achieve any specific 'Target level of Safety' (TLS). Rather ATM procedures and operations shall be designed to be "safe", i.e. to achieve some specific TLS[5], in the absence of ACAS.

2.1.1.2. It is then sufficient to demonstrate that the introduction of ACAS into the system reduces the risk of a mid-air collision, so that the full system including ACAS is safer still. This is done by comparing the risk of a mid-air collision occurring both with and without ACAS.

2.1.1.3. In the safety study presented here, and in the previous ACAS safety studies, what has been calculated is the risk of a 'Near Mid-Air Collision' (NMAC) rather than the risk of a mid-air collision. An NMAC is defined as an encounter during which at some time the horizontal separation of the two aircraft is less than 500 ft and simultaneously the vertical separation of the aircraft is less than 100 ft.

2.1.1.4. The thresholds defining an NMAC are sufficiently small that it is a reasonable assumption that any separation that does exist is fortuitous: if a collision does not occur, this is merely by chance. It is generally reckoned that there is a one in ten chance that an NMAC could be a collision.

2.1.2. Risk ratio, efficacy and induced risk

2.1.2.1. The safety benefit afforded by the deployment of ACAS is usually determined by comparing the risk of an NMAC both with and without ACAS in a 'risk ratio':

$$\text{risk ratio} = \frac{\text{NMAC rate with ACAS}}{\text{NMAC rate without ACAS}}$$

2.1.2.2. Any risk ratio less than unity indicates that the deployment of ACAS reduces the risk of collision and thus provides a safety benefit. It is important to note that risk ratio is a relative measure depending on the underlying risk without ACAS. This underlying risk will generally be different in different airspaces and which of two airspaces has the better level of safety when ACAS is deployed cannot be determined from the risk ratios alone.

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[5] ICAO requires subscribing states to implement a safety management programme, and to establish an acceptable target level of safety. A value of 5×10^{-9} fatal accidents per flight hour per dimension is recommended to be used for determining the acceptability of future en-route system implemented after the year 2000.

In the EUROCONTROL Safety Regulatory Requirement 4 (ESARR 4), a maximum tolerable probability of 1.55×10^{-8} accidents per flight hour is given for ATM directly contributing to an accident of a commercial air transport aircraft.

2.1.2.3. The risk reduction delivered by deploying ACAS can be evaluated either from the perspective of the aviation authorities in charge of the airspace as a whole (i.e. airspace-centred risk ratio) or from the perspective of an individual aircraft (i.e. aircraft-centred risk ratio). The airspace-centred risk ratio compares the risk when no aircraft are ACAS equipped to the risk when all mandated aircraft in the airspace are equipped. The aircraft-centred risk ratio compares the risk when own aircraft is not ACAS equipped (but all other mandated aircraft are equipped) to the risk when own aircraft, and all other mandated aircraft, are ACAS equipped.

2.1.2.4. As well as resolving mid-air collisions, ACAS can also induce mid-air collisions that would not have occurred had ACAS not been deployed. As long as the number of mid-air collisions that ACAS resolves outweighs the number of mid-air collisions that ACAS induces, there will still be an overall reduction in the risk achieved with ACAS.

2.1.2.5. The total risk with ACAS can, therefore, be partitioned into two components: an unresolved risk and an induced risk. Each of these separately compared to the risk of a mid-air collision without ACAS gives an unresolved risk ratio and an induced risk ratio respectively.

$$\text{risk ratio} = \frac{\text{unresolved NMACs}}{\text{NMACs without ACAS}} + \frac{\text{induced NMACs}}{\text{NMACs without ACAS}}$$

2.1.2.6. The efficacy of ACAS in resolving mid-air collisions is measured by the unresolved component of the risk ratio, whereas the induced component relates to the possibility of ACAS to induce a mid-air collision that would not otherwise occur.

2.1.3. Near Mid-Air Collision rate

2.1.3.1. The level of risk with ACAS can be expressed as a rate: the number of NMACs occurring per flight-hour. As the number of flight-hours occurring in a given airspace (i.e. the European RVSM airspace in the study presented here) over a given time interval can be known, the absolute rate at which NMACs occur with ACAS can be calculated. Induced risk rate measures how often induced NMAC events occur per unit of time in the airspace.

2.1.3.2. It is important to note that the underlying risk of NMACs (the one without ACAS) significantly affects the degree to which the unresolved and induced NMACs contribute to the risk ratio. Changing the underlying NMAC risk changes the risk ratio even though ACAS has not changed. For this reason, the underlying NMAC risk needs to be reported in parallel with the risk ratio and it is important to use encounter models that have been designed to provide realistic NMAC rates.

2.1.3.3. In the safety study presented here, operational data have been used to derive an absolute rate of NMAC events for the European RVSM airspace. The study has calculated the level of risk (the NMAC rate) in the absence of ACAS and found it to be 1.7×10^{-7} NMACs per flight-hour.

2.2. Factors influencing the safety benefits of ACAS

2.2.1. General

2.2.1.1. ACAS is a last resort safety net whose ability to prevent near mid-air collisions may be affected by several factors including the efficacy of the ACAS logic itself under specific circumstances, but also the possible interaction between ACAS and other lines of defence against the risk of mid-air collision.

2.2.1.2. In controlled airspace, these other lines notably include clearances and instructions issued by ATC to ensure aircraft separation and even late controller intervention with avoidance instructions (when separation provision has failed). "In the event of an RA, pilots shall […] follow the RA even if there is a conflict between the RA and an ATC instruction to manoeuvre" [PANS-OPS]. Finally, the principle of "see-and-avoid[6]" is very much a last line of defence against the risk of mid-air collision, and it is in no way a substitute for ATC or ACAS.

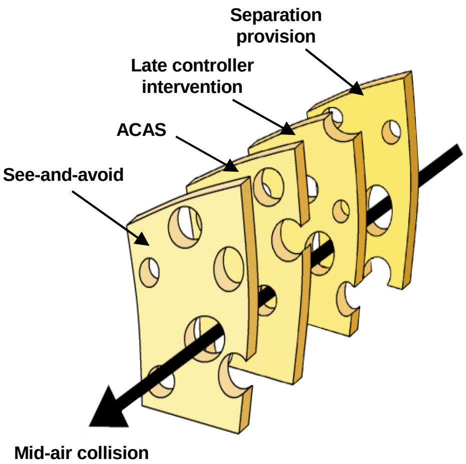

Figure 3: Lines of defence against mid-air collisions including ACAS

2.2.1.3. Figure 3 represents these lines of defence schematically. Any one line of defence can prevent a risk of collision which can only occur when all lines of defence fail (i.e. in the diagram, the holes line up).

2.2.2. Encounter characteristics in the considered airspace

2.2.2.1. Previous studies have shown that ACAS performance is very sensitive to the characteristics of the airspace. In other words, changes in 'encounter' types that may seem small can have a large effect on ACAS performance.

2.2.2.2. In the safety study presented here, the results are ultimately based on a large number of recent encounters extracted from en-route radar data recordings for the period ranging from end January 2002 to July 2004, which represents two and a half years of RVSM operations in Europe.

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[6] "See-and avoid" is the principle by which air-crew are expected to conduct a continuous routine visual scan of the surrounding airspace in order to visually acquire any other aircraft that may pose a collision threat to their own aircraft, and execute suitable avoidance manoeuvres.

2.2.2.3. As a consequence, it is again important to note that the safety results presented here can only be considered in the context of the European RVSM airspace, which is rather ‘ACAS-friendly’ with a high proportion of encounter geometries which are easily solved by ACAS (e.g. aircraft flying straight and level at constant speed).

2.2.3. Equipment characteristics and functioning

2.2.3.1. The level of ACAS equipage and the operating mode of ACAS are also factors that influence the safety benefits observed with the deployment of ACAS. If ACAS is unserviceable, is switched off, or is in standby-mode, then the aircraft is effectively unequipped. If ACAS is operated in TA-only mode, then it will indirectly provide some limited protection through the ability of TAs to prompt contact with the controller or aid visual acquisition. Maximum protection will be provided if ACAS is operated in full RA-mode.

2.2.3.2. The transponder equipage of aircraft is also of significance since this has an effect on ACAS surveillance and on the altitude reports that aircraft can provide (and on which the ACAS vertical tracking is based). Mode C equipped aircraft report altitude with a precision of 100-ft. Mode S equipped aircraft can report altitude with either 100-ft precision or with 25-ft precision. ACAS can use altitude in either reply format, but RAs issued on the basis of the more precise 25-ft altitude will generally be more effective.

2.2.3.3. The ACAS and transponder equipage level has been taken into account in the present safety study. It has been assumed that these systems always operate within their specifications.

2.2.4. Pilot behaviour in response to ACAS, controller and visual acquisition

2.2.4.1. The pilot behaviour is another key factor for the safety benefits delivered by ACAS and, in particular, the pilot response to the RAs issued by the ACAS logic. Previous studies have demonstrated that the RAs that are generated should be followed, and followed promptly, for best benefits.

2.2.4.2. In addition, the specific circumstance of a late controller intervention that would result in an instruction incompatible with the sense of a coordinated RA needs to be considered. In this case, the consequences of one pilot following the controller instruction while the other follows the RA matters significantly.

2.2.4.3. Finally, the possibility of the encounter being resolved by “see-and-avoid” needs to be considered. The probability of visual acquisition prompted by ACAS should be taken into account, along with the fact that visually acquiring a threat is no guarantee that a collision will be avoided.

2.2.4.4. All these environmental and human factors have been taken into account in the present safety study using best available evidence of their operational consequences and likelihood of occurrence.

2.2.5. Altimetry error

2.2.5.1. The vertical miss distance, i.e. the vertical separation at 'Closest Point of Approach' (CPA), diagnosed by ACAS is the perceived separation – simply the difference in the tracked altitudes of the two aircraft.

2.2.5.2. Altimetry error will inevitably be present in real aircraft systems. For any perceived vertical separation there is a finite probability that this separation will be negated by altimetry error and that a collision occurs. It is this probability that has to be calculated and summed to determine the overall risk in a set of encounters.

2.2.5.3. Altimetry errors, as observed in the European RVSM airspace, have been taken into account in the present safety study.

2.3. Tools to assess ACAS safety

2.3.1. General

2.3.1.1. As already mentioned, the present safety study built on the methodology and tools that supported previous ACAS studies in Europe. These tools include a set of models that allow the replication of the environment in which ACAS is being operated. These models consist essentially of a 'safety encounter model', a model of pilot reaction in response to RAs and a model of altimetry errors applicable in the considered airspace.

2.3.1.2. As shown in Figure 4, these models are then used to determine the risk that remains when ACAS is being operated (which results from the risk ratio achieved by ACAS and the underlying risk in the absence of ACAS). Distinction is made between the 'logic system risk' that consider the risk associated with the operation of the ACAS algorithms in the modelled airspace and the 'full-system risk' that also takes into account its interaction with other environmental and human.

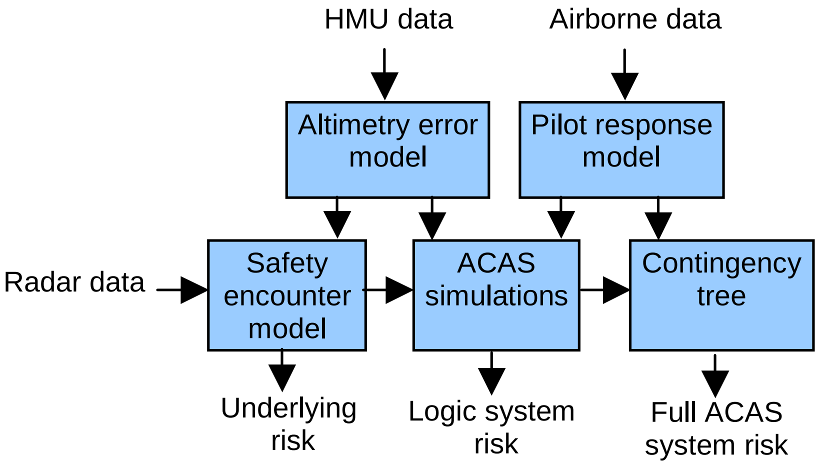

Figure 4: Tools to assess the safety of ACAS

2.3.1.3. The 'logic system risk' is usually determined through the performance of ACAS simulations that include the modelling of pilot response to RAs in a large set of modelled encounters, whereas the 'full-system risk' is usually determined using a 'contingency tree'[7] that combines pure ACAS logic risks and probabilities of other factors that may affect the safety of ACAS.

2.3.2. Safety encounter models

2.3.2.1. A 'safety encounter model' is a model of traffic situations (involving two aircraft only) that captures the properties of 'close' encounters[8] as a series of statistical distributions (defined as histograms and implemented as tables) describing the parameters of a typical encounter and their interdependencies. The encounter model approach is a powerful technique by which a large set of risk bearing encounters (which are rare events) can be stochastically generated to assess the safety benefits of ACAS or, indeed, any other ATM safety nets.

2.3.2.2. A specification of an encounter model by which the performance of differing ACAS logics can be compared is given in the ICAO Standards And Recommended Practices (SARPs) for [ACAS]. The ICAO encounter model is representative of no particular airspace. It was used as the starting point for the specification of a more sophisticated encounter model representative of European airspace in the ACASA project [ACA1b]. European radar data, that was then current, was used to populate the tables and produce an encounter model characteristic of the ECAC airspace at that time and over all altitudes.

2.3.2.3. The European safety encounter model developed ACASA reflected the ATM procedures that applied at the time, notably the use of 2,000-ft separation above FL285 (CVSM – Conventional Vertical Separation Minima). Since that time, RVSM has been introduced in the ECAC airspace and radar recordings of RVSM operations are available. In the safety study presented here, such data have been used to update the former European safety encounter model and produce a post-RVSM safety encounter model (i.e. the ASARP safety encounter model) that was used to assess the safety efficacy of ACAS in the European RVSM airspace.

2.3.3. Pilot response models

2.3.3.1. The 'standard' pilot response to a corrective RA is described in the ACAS SARPs. It notably requires the pilot to react to the RA within 5 seconds using an acceleration of 0.25*g* to achieve the required vertical velocity. The ACAS logic has been tuned for such a response.

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[7] The terms "fault-tree" and "event-tree" have been used in the ACASA project. The term "contingency tree" was finally preferred as the other terms have specific meanings in the field of safety analysis.

[8] The encounters that matters are those in which two aircraft are on a close encounter course (i.e. with a horizontal miss distance of less than the NMAC horizontal threshold) in which there exist a risk of mid-air collision or in which the response of pilots to RAs can result in a risk of mid-air collision.

2.3.3.2. A model of 'standard pilot response' to RAs is generally used in ACAS simulations to simulate the aircraft deviation that would result from pilot responses to RAs. This allows the assessment of the efficacy of ACAS using ideal assumptions with regard to the actual pilot behaviour in response to RAs.

2.3.3.3. During the ACASA project, data from on-board recorders were collected and examined to determine the actual response of pilots to operational RAs. The analysis indicated than the pilots reacted to corrective RAs in about only half of the cases. Further, when pilots did react, none of the pilot responses were close to the standard response. Actual pilot responses observed at that time fell into two distinct groups that were modelled as two distinct pilot response models, i.e. an 'aggressive response' model and a 'slow response' model.

2.3.3.4. Improved training and increased familiarity with ACAS were expected to have improved pilot behaviour and so the exercise was repeated. Recent onboard recording data provided by European airlines for years 2001, 2002 and 2004 have been collected, analysed and used to define an up-to-date model of actual pilot responses to RAs. In this model, pilot responses to corrective RAs form a multidimensional continuum ranging from non-responses or slow responses to aggressive responses. Established from actual pilot behaviours observed at all altitudes, this new pilot response model is considered valid for all Europe, including the RVSM airspace.

2.3.4. Altimetry error models

2.3.4.1. An 'altimetry error model' (AEM) is also an essential element in any determination of risk ratio. It is important that this model is as close as possible to actual avionics systems performance relevant to aircraft flying in a given airspace at a given time.

2.3.4.2. A standard altimetry error model is defined in the ACAS SARPs, which was developed in the early 1990s. As avionics systems have improved, it has become progressively out-of-date. In particular, an aircraft whose altimetry error was only as good as this 'traditional' AEM would not comply with the 'Minimum Aviation System Performance Specification' (MASPS) for flights in RVSM airspace.

2.3.4.3. In the safety study presented here, operational data collected by 'Height Monitoring Units' (HMU) were used to determine an altimetry error model applicable to the European RVSM airspace.

2.3.5. Off-line ACAS logic simulations and risk ratio computations

2.3.5.1. Risk ratios delivered by ACAS in a given airspace can be determined by performing ACAS simulations in a large set of close encounters representative of the airspace. These ACAS simulations allow the assessment, in a dynamic manner, of the safety performance of the ACAS logic given a probable scenario of aircraft equipage and pilot responses to RAs. Altimetry errors, that may affect the vertical separation actually achieved with ACAS, are also considered.

2.3.5.2. In the safety study presented here operational data were used to establish the most probable scenario of ACAS operations in the European RVSM airspace. Then, ACAS simulations were performed on the basis of the post-RVSM safety encounter model, the up-to-date models of pilot responses and altimetry errors defined within the study. Their execution and analysis were supported by the "Off-line Simulator for Collision Avoidance Resolution", i.e. the [OSCAR] test bench, version 5.0[9].

2.3.5.3. This simulator includes an implementation of the TCAS II logic Version 7.0 that conforms to the TCAS Minimum Operation Performance Standards [TCAS] incorporating the changes specified in the Technical Standard Order C119B [TSO-C119b]. It also incorporates the modification to the TSO recommended by RTCA SC-147 Requirement Working Group in 1999, i.e. the approved changes 1 to 92 and 98.

2.3.6. Contingency tree for calculation of ACAS safety

2.3.6.1. A complementary approach to the calculation of ACAS safety is the use of a contingency tree that combines pure ACAS logic risks (for basic scenarios of aircraft equipage and pilot response) and probabilities of other environmental and human factors (e.g. ACAS may fail to track an intruder, or pilot may elect not to follow an RA preferring instead controller advice or to exercise see-and-avoid).

2.3.6.2. Such a contingency tree (from which ACAS full-system risks can be determined) was first developed in the ACASA project. The need for a similar contingency tree arose in another EUROCONTROL project (which investigated the anticipated impact of a future operational concept on ACAS), and improvements were brought to the implementation of the tree at that occasion. The safety study presented here took advantage of the experience gained in these two former projects to develop a contingency tree that applies to the ACAS operations in the European RVSM airspace.

2.3.6.3. The contingency tree approach allows the assessment, in a static manner, of the influence of various factors (not only events relating to nominal operations, but also operational and technical hazards that may affect ACAS operations) on the mid-air collision risk ultimately achieved with ACAS.

[9] The OSCAR test-bench was developed by CENA, i.e. the former research and development entity of DSNA. Illustrations of ACAS simulation results (using the OSCAR display facilities) are included in this report with copyright permission.

3. European RVSM environment analysis and modelling

3.1. Safety-related encounters in RVSM airspace

3.1.1. European radar data gathering and analysis

3.1.1.1. Scope and approach

3.1.1.1.1. The radar data collected during the ASARP project covered a period spanning from the 24th January 2002 to the 31st July 2004. The data came from several en-route radars including the busiest sectors of the European RVSM airspace (which were not necessarily available at all times). About 1,310 days of radar recordings were finally made available, in which 1.72×10^6 flight-hours were observed in RVSM airspace.

3.1.1.1.2. The radar data recordings were processed, then analysed, using algorithms that incorporated a set of 'encounter capture criteria' tuned to identify those encounters at RVSM altitudes that could be used to update the tables of the post-RVSM safety encounter model (see section 3.1.2).

3.1.1.1.3. A preliminary radar data processing included a filtering of invalid or suspect altitude reports contained in the radar tracks. The objective was to avoid the capture of too many irrelevant encounters (resulting from invalid or garbled Mode C data), while enabling the capture of relevant encounters including those with limited radar data quality (e.g. occasional missing or erroneous Mode C data).

3.1.1.1.4. The encounter capture criteria then applied to the "clean" radar data included a 'closing time test' similar to the 'range test' and the 'altitude test' of the ACAS logic [ACAS], as well as a 'miss distance test' that prevented the capture of encounters in which aircraft passed relatively far from each other in the horizontal plane (at least from a collision avoidance perspective). The thresholds used for the various test parameters were similar to the corresponding TCAS II Version 7.0 thresholds for RAs with some additional margins.

3.1.1.1.5. Finally, an encounter filtering process was performed to discard undesired encounters, i.e. military/military encounters, military interceptions[10] of civil aircraft and spurious encounters resulting from radar tracking errors.

[10] According to the existing ICAO recommended practice for interception of civil aircraft [DOC9433], the military aircraft should temporally switch-off their Mode C reports, so as to avoid the issuance of any RA onboard the intercepted aircraft. Military interceptions are, therefore, out of the scope of the present safety study since ACAS would not normally be expected to intervene in such circumstances.

3.1.1.1.6. A total of **1,131 pair-wise encounters** were ultimately extracted from the radar data, **of which 241 were identified as actual ACAS/RVSM encounters** with observable pilot reactions in response to probable ACAS RAs. These latter encounters were modified on a case-by-case basis to remove the aircraft deviations likely to result from the pilot responses to RAs. As far as practicable, late manoeuvres likely to result from either a late controller intervention or a visual acquisition of the threat by the pilot were maintained. This was necessary to enable the building of a safety encounter model that corresponds to a virtual, yet realistic, airspace without ACAS[11].

3.1.1.1.7. To support the specific study of multiple aircraft encounters (see section 4.3), an additional radar data processing was performed (using enlarged capture criteria based on TA-like thresholds) to extract multiple aircraft encounters that occurred in close proximity in time and space. The search for multiple aircraft encounters was also extended to operational TCAS monitoring data and Mode S monitoring data. Using all sources of data **a total of nine actual RVSM multiple aircraft encounters** were identified, **of which only two were actual ACAS/RVSM multiple aircraft encounters**.

3.1.1.2. RVSM pair-wise encounters

3.1.1.2.1. As shown in Figure 5, the pair-wise encounters extracted from the European radar data were distributed over all the RVSM flight levels. Greatest encounter likelihood was observed at FL330 and adjacent flight levels. This results from the conjunction of the large proportion of flights cruising at these altitudes, together with the increased likelihood for aircraft to fly through these flight levels. Although the number of observed flight-hours was greater at higher levels (i.e. between FL350 and FL370), the limited number of encounters in the upper part of the RVSM airspace is likely to result from the reduced likelihood of flight level changes at these altitude. The significant reduction when altitude increases is also due to the fact that the number of encounters is expected to vary as the square of the observed flight-hours.

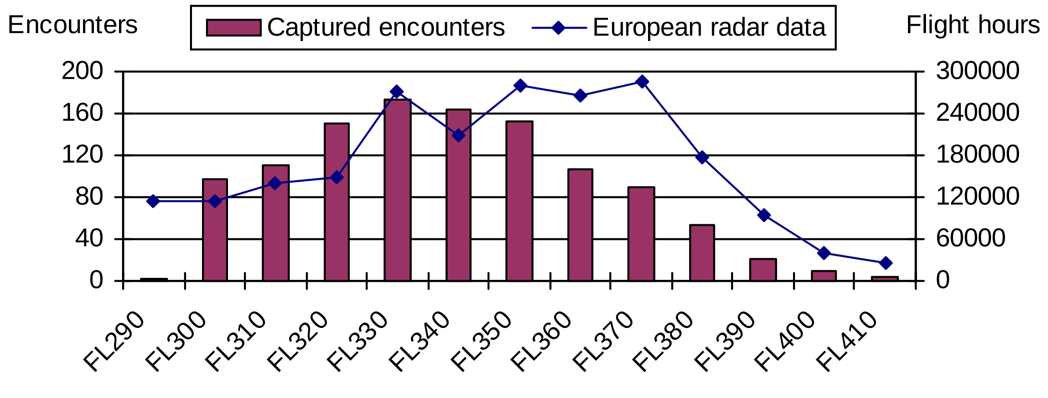

Figure 5: Altitude distribution of the post-RVSM radar encounters

[11] These radar encounters, which include any ACAS effect, can not be used directly to assess the risk of collision with ACAS, because the behaviour of ACAS is dependent on horizontal separation which, in most of these encounters, is significant in terms of collision avoidance.

Note: In the figure, the altitude of a given encounter refers to that of the highest aircraft at closest approach. This explains the relatively small number of encounters at FL290. Indeed, only those encounters with two aircraft flying at, or close to, FL290, are counted as being at this flight level.

3.1.1.2.2. Taking into account the number of observed flight-hours in the RVSM airspace, the captured encounters can be estimated to occur about once every 1,500 flight-hours. It should be understood that the capture criteria used to detect these encounters uses a logic and threshold parameters derived from, but slightly greater than, the ACAS logic. Hence, not all captured encounters were expected to correspond to actual ACAS/RVSM encounters. This was confirmed by the small proportion (about 21%) of encounters with an observable pilot reaction to a probable RA. When such a pilot reaction was observed, this was generally the case for only one aircraft (in about 18% of the encounters). Only a minor proportion (less than 3%) of the encounters included two observable pilot reactions to probable coordinated RAs.

3.1.1.2.3. The identification of probable pilot reactions to RAs was supported by observing the performance of ACAS in simulations on the radar encounters. Further, whenever possible, an attempt was made to correlate the captured encounters with known ACAS events already identified during ACAS operational monitoring. Figure 6 illustrates the operational background and knowledge that supported the processing of identified pilots' reactions to RAs in the radar encounters. In this specific ACAS/RVSM encounter corresponding to a separately reported incident, only the vertical trajectory of the descending aircraft (that followed its successive RAs to "Descend", then to "Climb") was modified, whereas the vertical trajectory of the climbing aircraft that followed an ATC instruction to descend (instead of its RA to "Climb") has been maintained in the modified encounter.

Note: The figure presents the vertical profiles of both aircraft versus time, as well as the simulated ACAS events for the aircraft that followed the resolution advisories: the sequence of RAs is shown by tags on the own trajectory and the intruder status is shown by a TCAS-like symbol on the intruder trajectory.

Initial radar encounter (with one pilot reaction to ACAS)	Modified radar encounter (with the pilot reaction to ACAS removed)

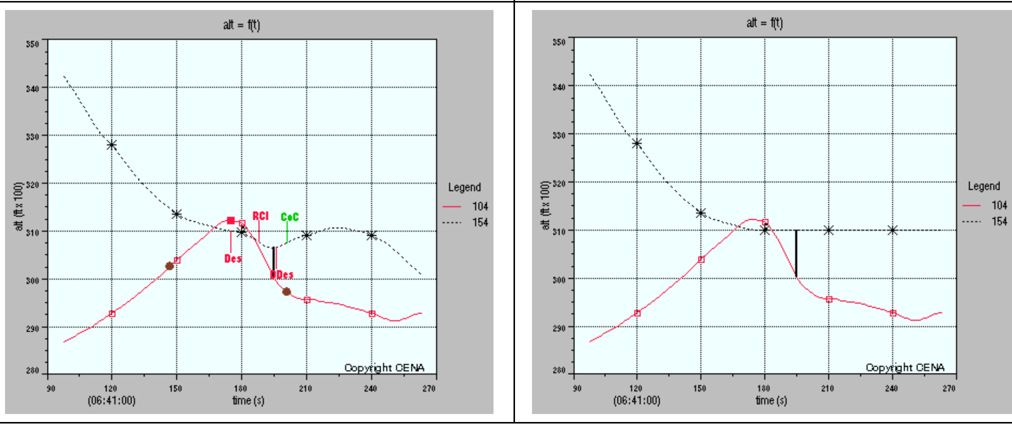

Figure 6: Illustration of an actual ACAS/RVSM encounter with coordinated RAs and a late controller intervention

3.1.1.2.4. A brief analysis of the captured, and subsequently modified radar encounters (i.e. with any observed pilot reactions to ACAS removed) showed that the encounter set was characterised by:

- a huge proportion (about 95%) of encounters between commercial air transport aircraft12, the remaining 5% of encounters being crossing encounters between commercial aircraft and military fighters;
- a great proportion (about 60%) of level-off encounters, i.e. encounters with either one or two aircraft levelling off at adjacent RVSM flight levels;
- a significant proportion (about 26%) of level/non-level encounters with vertical crossing close to closest approach. These encounters typically correspond to situations where one aircraft is flying through the flight level of a level aircraft without any visible change in either vertical trend;
- a noteworthy proportion (about 11%) of level-level encounters at distinct flight levels. These encounters typically result from poor altitude station keeping, possibly combined with a vertical offset from the standard flight level, on at least one aircraft involved;
- a small but non-negligible proportion (less than 1%) of encounters with a vertical separation at closest approach less than 100 ft. These encounters were of particular interest since they typically correspond to serious incidents.

3.1.1.2.5. Figure 7 shows the various combinations of vertical profile observed in the encounters involving two commercial air transport aircraft. The encounter set referred to as ‘other vertical profiles’ typically correspond to ATC or pilots errors including encounters between aircraft performing avoidance manoeuvres (apart from any pilot response to RAs). An example of such an avoidance manoeuvre is the late descent initiated by the climbing aircraft (in response to ATC late instruction) in the encounter presented in Figure 6.

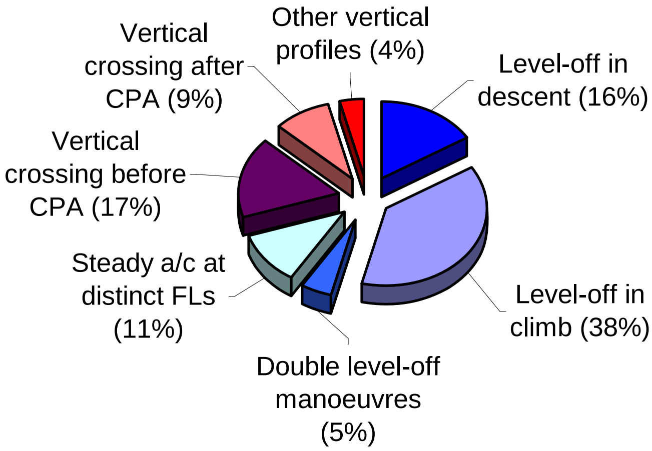

Figure 7: Actual encounters extracted from the post-RVSM radar data

[12] Hereafter, commercial air transport aircraft refers to all aircraft involving the transport of passengers, but also business aircraft that are provided with air traffic control services.

3.1.1.2.6. As shown, the majority of level-off encounters observed in the RVSM airspace consisted of climbing aircraft levelling-off below another aircraft. Level-off manoeuvres while in descent were less frequently observed and double level-off manoeuvres even less. These observations were consistent with operational expectations. More surprising was the significant proportion (17%) of level/non-level encounters where aircraft crossed vertically before closest approach. These encounters might reflect specific air traffic control practices in the observed airspace.

3.1.1.3. RVSM multiple aircraft encounters

3.1.1.3.1. When looking for multiple aircraft encounters that occurred in the European RVSM airspace, a set of nine encounters were identified that were distributed over all the RVSM flight levels. Although not very numerous, these nine encounters taken as a whole were considered a representative set of RVSM multiple aircraft encounters.

3.1.1.3.2. Only two of these encounters corresponded to actual incidents where the 'multi-aircraft logic[13]' component of the ACAS logic had been invoked. These encounters consisted of:

- an **actual ACAS/RVSM 'multi-aircraft logic' encounter** (from July 2004) involving three airliners flying level at adjacent RVSM flight levels (viz. FL340, FL350 and FL360) with suspect variations in the transmitted altitude data of the upper aircraft. This specific feature was confirmed by onboard downloaded TCAS data made available in the context of the operational TCAS monitoring. It is considered a key factor that contributed to the occurrence of undesirable RAs between aircraft that were actually vertically separated.
- a **recent (January 2005) ACAS/RVSM 'multi-aircraft logic' encounter** involving three airliners flying level at adjacent RVSM flight levels (viz. FL370, FL380 and FL390) with a conflicting descent of the middle aircraft some time before closest point of approach with the two other aircraft. This encounter, which was outside the period of radar data analysed in the ASARP study, was identified thanks to the operational TCAS monitoring.

3.1.1.3.3. Taking into account the number of flight-hours observed in the RVSM radar data, it can be estimated that the 'multi-aircraft logic' of ACAS is exercised about once every 500,000 flight-hours at the European RVSM airspace. This estimate was consistent with operational expectations since a very few cases of multiple threat RAs are being reported each year in Europe.

[13] The multi-aircraft logic of ACAS deals with simultaneous threats. This specific part of the logic was extensively modified in Version 7 of TCAS II to allow the determination of optimum resolutions against all simultaneous threats [TCAS7a].

3.1.1.3.4. Four other multiple aircraft encounters involved commercial air transport aircraft only. These encounters included three actual pair-wise ACAS/RVSM encounters (with observable pilot reactions) with a third traffic in close proximity either flying level or levelling-off at another RVSM flight level. The fourth one consisted of a reported[14] multiple aircraft ACAS encounter involving two level aircraft at co-altitude and a third one at an adjacent RVSM flight level.

3.1.1.3.5. The last three RVSM multiple aircraft encounters consisted of crossing encounters between commercial aircraft (typically, flying level at RVSM flight levels) and a military aircraft flying in close proximity.

3.1.2. Development of a post-RVSM European safety encounter model

3.1.2.1. Scope and approach

3.1.2.1.1. The **building of the post-RVSM European safety encounter** was supported by a specific analysis of the pair-wise RVSM encounters extracted from the European radar data, and the determination of the statistical distributions of each encounter parameter in this radar encounter set. The work then consisted of the update of the tables of the European safety encounter model developed in the ACASA project (to include the possible effect of RVSM operations). Although the present study focused on the safety of ACAS in the RVSM airspace, the ASARP safety encounter model (like the ACASA one) addresses the whole European airspace.

3.1.2.1.2. The opportunity was also taken to incorporate some improvements to the ASARP safety encounter model including: *a)* a refinement of the aircraft performance classes used by the model, *b)* the positioning of level aircraft close to standard cruising levels, *c)* an extension of encounter lead-in time in the case of slow closure rates to allow the ACAS tracking algorithms to settle down during ACAS simulations, and *d)* the inclusion of a trajectory perturbation model used to introduce realistic variations in aircraft positions (in accordance with the requirements of the RVSM MASPS for the vertical dimension and RNP-0.3 in the horizontal dimension).

3.1.2.1.3. The 'Vertical Miss Distance' (VMD) (i.e. the vertical separation at closest approach) is a key factor in determining the behaviour of ACAS in individual encounters. For this reason a specific analysis of the VMD tables was conducted to determine whether sparse and empty entries represented genuine properties of the airspace or whether they were due to statistical fluctuations. The VMD tables corresponding to each layer were modified on a case-by-case basis to provide tables that are more statistically representative while preserving the characteristics of the observed encounter set.

[14] This encounter was identified through the operational TCAS monitoring. The analysis performed in the study concluded that, despite the pilot declarations, the encounter was unlikely to be a multiple aircraft ACAS encounter.

3.1.2.1.4. The set of VMD tables were also analysed in conjunction with a model of altimetry error for the whole airspace (see section 3.3.3) to determine the NMAC rate implied by the encounter model without any ACAS simulations. This underlying NMAC rate is crucial to the determination of ACAS risk ratios. It was, therefore, essential that the VMD distributions could be adjusted where necessary to reproduce an NMAC rate believed to be operationally realistic. The NMAC rate that was imposed on the VMD distributions in the whole atmosphere was 3×10^{-7} NMACs per flight-hour – a rate already used in the earlier ACASA project.

3.1.2.1.5. Thanks to the improvements brought to the encounter capture process in the present safety study compared to the ACASA one, the NMAC rate implied by the VMD distribution of the encounters captured in the RVSM layer was consistent with operational expectations (viz. the value obtained was 1.7×10^{-7} NMACs per flight-hour). Therefore, only the VMD distributions in the non-RVSM layers were adjusted so that, when combined with the unadjusted VMD distribution for the RVSM layer, the European safety encounter model yields the imposed underlying NMAC rate.

3.1.2.2. Whole atmosphere safety encounter model

3.1.2.2.1. The ACASA and ASARP safety encounter models consist of five altitude layers with boundaries at operationally significant altitudes. With the introduction of RVSM from FL290 to FL410 inclusive, the lower boundary of layer 5 was shifted from FL295 to FL285, so that this fifth and last layer of the ASARP encounter model would correspond wholly to the RVSM levels.

3.1.2.2.2. Table 1 shows the proportions of ‘close encounters’ in the layers 1 to 4 and layer 5 as defined in the ASARP safety encounter model. To determine these proportions, the ACASA and ASARP radar data sets were adjusted so as to take into account the different periods of observation between the two studies, the slightly different encounter capture criteria thresholds used and the increase in traffic levels between both radar data collection exercises[15].

3.1.2.2.3. As shown, during 10,000 hours of observation (approximately 417 days) by a typical radar in the core ECAC area we expect to observe about 200 encounters of the type modelled by the ASARP safety encounter model. About two thirds of these encounters would occur in terminal airspace (i.e. below FL135, in layer 1 or layer 2 of the model). While the flight-hours at the RVSM altitudes correspond to about 61% of the overall flight-hours represented by the model, the encounters at such altitudes would represent slightly less than 9% of the encounters in the whole atmosphere.

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[15] The tables of the ACASA safety encounter model were populated using European radar data collected in 1998 and 2000. The increase in traffic levels between these dates and 2003 (taken as the reference date of the European radar data collected in ASARP) has been estimated at about 10%. If traffic increases by a factor of n then, all other things being equal, one would expect the number of encounters to increase by a factor of n^2.

Layer	Altitude range	Modelled flight-hours	Encounters per 10^4 hours	Proportion
1	1,000ft-FL50	0.50×10^6	73.11	0.365
2	FL50-FL135		61.16	0.306
3	FL135-FL215		28.50	0.142
4	FL215-FL285		19.82	0.099
5	FL285-FL415	0.78×10^6	17.56	**0.088**
Totals		1.28×10^6	**200.15**	1

Table 1: Layer proportions in the post-RVSM safety encounter model

3.1.2.2.4. The ACASA safety encounter model introduced the idea of aircraft performance classes. Seven classes covered civil and state aircraft depending on the aircraft propulsion type and maximum take-off mass (MTOM) with thresholds that correspond to the MTOM thresholds of the phased European ACAS mandate (viz. 5,700 kg and 15,000 kg). A eighth class was dedicated to high performance military jets that are outside the scope of the ACAS mandate. In the ASARP safety encounter model, the class corresponding to turbo-jet aircraft with MTOM in excess of 15,000 kg has been split into two new classes (viz. below and above 100,000 kg), so as to distinguish between the aircraft performances in the medium and heavy wake vortex categories.

3.1.2.2.5. Figure 8 provides an overall picture of the likelihood of each aircraft performance class per altitude layer as defined by the ASARP safety encounter model. As shown, the aircraft classes involved in 'close encounters' vary significantly depending on the altitude layers: light piston-engined aircraft being the most common type in encounters at low altitudes and medium jets with MTOM between 15,000 kg and 100,000 kg being the most common aircraft overall. It should be noted that neither light piston-engined nor turbo-prop aircraft are expected to be involved in encounters occurring in the RVSM airspace.

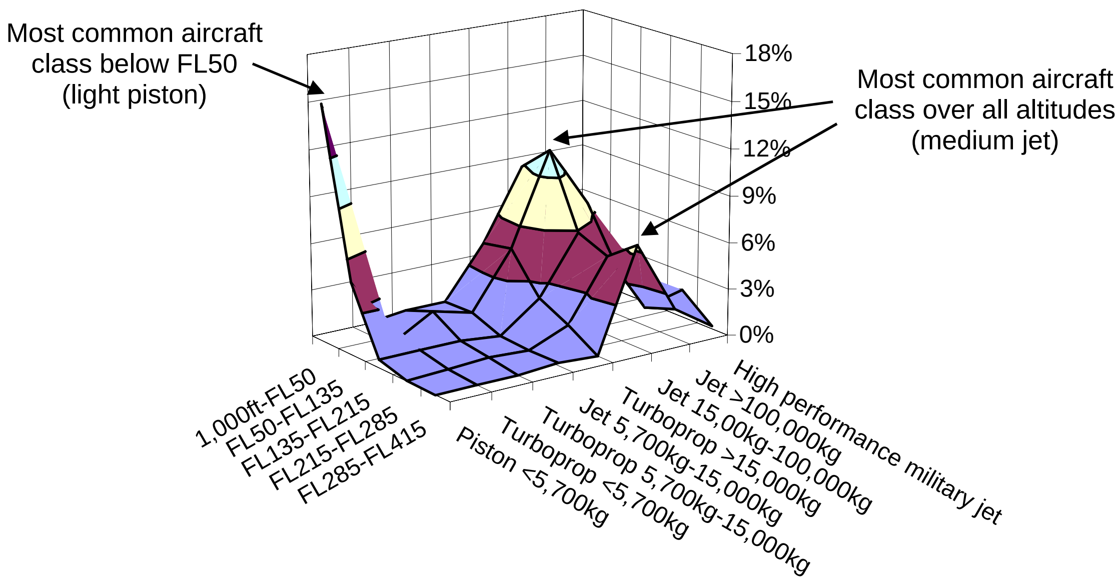

Figure 8: Aircraft performance classes and associated proportions

3.1.2.3. Encounter characteristics in the RVSM layer

3.1.2.3.1. The 'close' encounters observed at RVSM altitudes have specific characteristics captured in the layer 5 tables of the ASARP safety encounter model. A key characteristic is the encounter geometry in the vertical plane. The model distinguishes between 'crossing' and 'non-crossing' encounters (depending on whether or not the relative vertical position of the aircraft is reversed during the encounter time window[16], a characteristic referred to as 'cruxality'), and between two encounter types (viz. 'type-A' encounters involving level aircraft or aircraft that level-off and all the other encounters referred to as type-B).

3.1.2.3.2. Figure 9 shows the partition of the modelled encounters for the RVSM layer. As shown, the majority (53%) of the RVSM encounters corresponds to 'non-crossing' 'type-A' situations with both aircraft flying level at the end of the encounter. The 'crossing' encounters represent only 2% of the encounters in the RVSM layer.

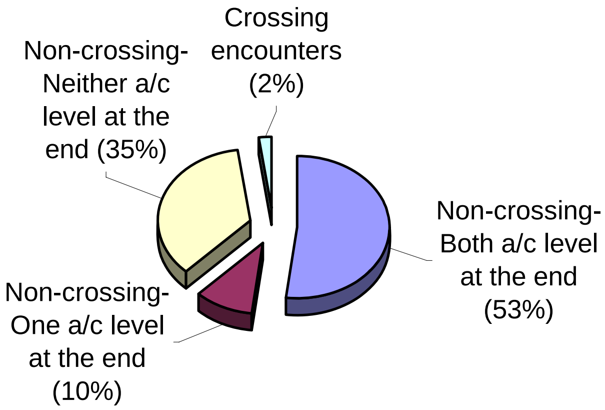

Figure 9: Proportions of encounter classes in the RVSM layer

3.1.2.3.3. Figure 10 shows the final VMD distributions (for each encounter type and 'cruxality', i.e. whether the encounter is crossing or non-crossing) that resulted from the statistical analysis of the post-RVSM radar encounters and the ad-hoc modifications introduced to smooth out statistical fluctuations. As expected, the vertical profiles corresponding to these four encounter sets tend to produce distinct VMD distributions (captured as separate tables in the encounter model). For 'non-crossing' 'type-A' encounters, the VMD distribution is skewed towards the applicable vertical separation minima of 1,000 ft in the RVSM airspace. More challenging situations can be observed for the 'crossing' 'type-B' encounters with a greater likelihood of small VMDs.

[16] The standard encounter window in the ASARP safety encounter model extends from 50 seconds before CPA to 10 seconds after CPA. This window is enlarged in the case of certain awkward encounter geometries requiring an extension of lead-in time for appropriate ACAS tracking initialisation.

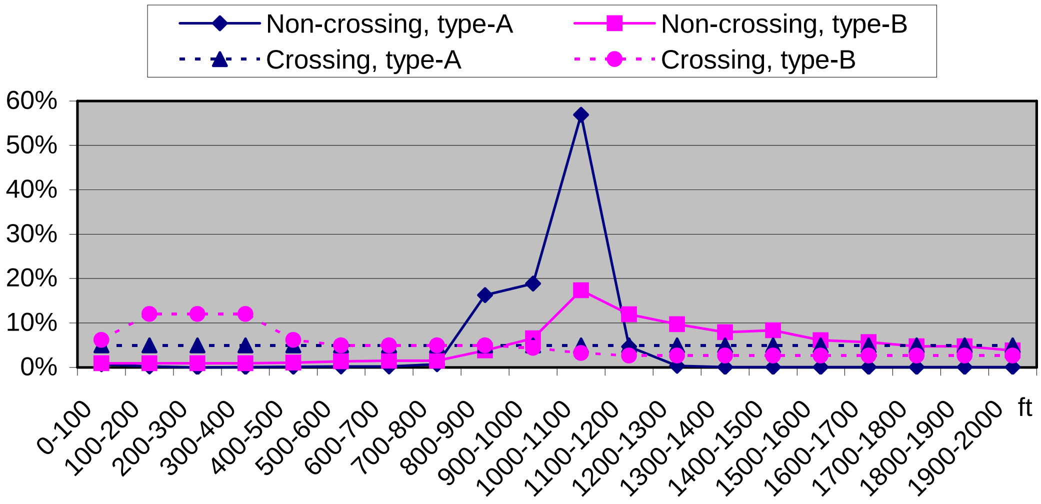

Figure 10: VMD distributions in the RVSM layer

3.1.3. Comparison with pre-RVSM European safety encounter model

3.1.3.1. The differences between the ASARP and ACASA safety encounter models are not limited to the tables corresponding to the RVSM levels, i.e. layer 5 of the encounter model. As already introduced, the VMD tables for layer 1 to 4 were adjusted so that the whole atmosphere encounter model still implies an underlying NMAC rate of 3×10^{-7} NMACs per flight-hours.

3.1.3.2. Another major difference is in the number of 'close encounters' that each encounter model represents assuming a given period of observation by a single radar. For 10,000 hours of observation, this number increased from about 150 encounters for the ACASA encounter model to about 200 encounters for the ASARP encounter model (see Table 1).

3.1.3.3. For the layers 1 to 4, this increase directly relates to the growth in traffic between the periods that the two models represent. The increase in the number of encounters in layer 5 is much greater reflecting the reduction in the vertical separation minimum and the increased number of encounters with VMD close to this minimum. This feature highlights the potential for more ACAS alerts in RVSM compared to CVSM, but should not be interpreted as RVSM airspace being less safe than CVSM airspace.

3.1.3.4. Finally, it should be noted that the much greater number of radar encounters used to populate the tables relating to the RVSM levels has greatly improved the statistical validity of the European safety encounter model produced in ASARP.

3.2. Actual pilot responses to ACAS

3.2.1. Analysis of airborne recorded data

3.2.1.1. The airborne-recorded data collected during the ASARP project consisted of about 80 RAs that occurred in 2001, 2002 and 2004. The data came from four European airlines, two being major airlines and the two others being regional airlines. It consisted of 'Quick Access Recorder' (QAR) data for three of the airlines and of TCAS II recorder data for one of the major airlines.

3.2.1.2. The available aircraft parameters, as well as the parameters' quality, varied depending on the origin of the data. To analyse the pilot reactions in response to RAs on comparable bases, it was, therefore, necessary to establish a set of basic parameters common to all data sets. These basic parameters were then used to compute three key parameters characterising the pilot reaction types. These consolidated parameters were: *a)* the pilot reaction time to a corrective RA, *b)* the vertical rate adopted by the pilot in response to the RA and *c)* the vertical acceleration applied to reach this vertical rate.

3.2.1.3. The analysis concentrated on the pilot responses to the initial corrective RAs, i.e. positive RAs (viz. 'Climb' and 'Descend' advisories), negative RAs (viz. 'Don't climb' and 'Don't descend' advisories) and 'Vertical Speed Limitations' (VSL) RAs. For the initial preventive RAs (which accounted for only 10% of the initial RAs), it was observed that, as expected, the pilots disengaged the autopilot, but did not deviate in response to the RAs. For the subsequent RAs, it was not possible to identify any significant trend since the number of RAs was not significant enough and the pilot reactions varied considerably.

3.2.1.4. In summary, pilots did react to their corrective RAs in most of the situations (about 90%). When responding to corrective RAs, their response was generally very close to the standard reaction expected from the ACAS logic, although the reactions adopted spanned a range of reaction times, vertical rates and vertical accelerations. It should be noted that no inappropriate reactions were observed (i.e. aircraft climbing instead of descending) in the case of positive RAs. A few inappropriate reactions were identified in case of VSL RAs, but these lasted only a few seconds and then the pilots adopted a correct vertical rate.

3.2.2. Definition of typical pilot models

3.2.2.1. From this analysis of airborne-recorded data, decision was taken to define a 'typical pilot' model that would consist of a combination of several (33) elementary pilot response models with associated probabilities of occurrence. Figure 11 provides an overall picture of the main pilot response characteristics and associated probabilities of each of these elementary models.

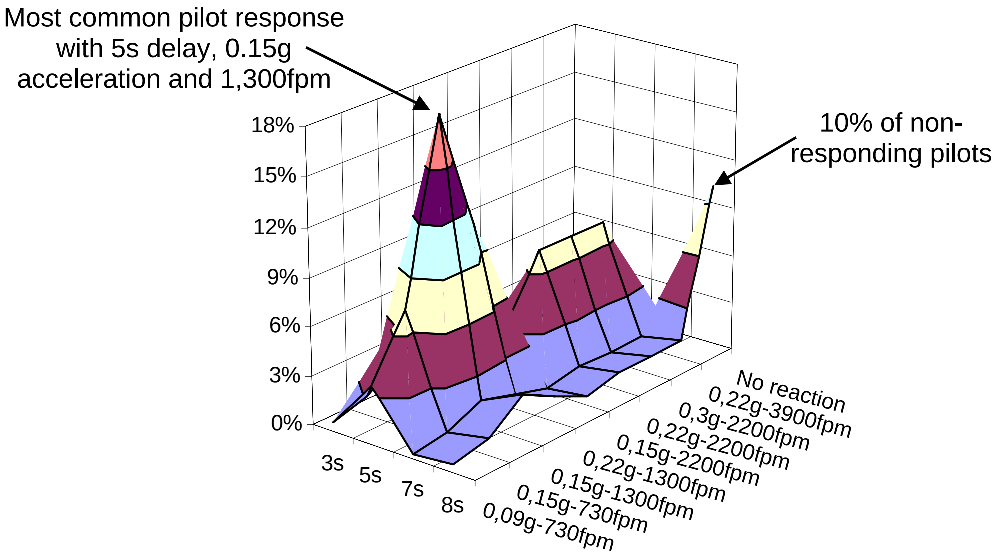

Figure 11: Typical pilot models and associated proportions

3.2.2.2. In line with the actual pilot behaviours observed in the airborne-recorded data, the 'typical pilot' model includes a 10% proportion of non-responding pilots. With regard to the elementary pilot responses, they combine four typical pilot reaction times in-between 3 and 8 seconds, with four typical vertical rates in response to positive RAs ranging from 730 fpm up to 3900 fpm and four vertical accelerations ranging from 0.08*g* and 0.30*g*. As shown in the figure, not all combinations of rates and accelerations were observed.

3.2.3. Comparison with former pilot models

3.2.3.1. Historically, ACAS studies have used the 'standard pilot' model specified in the ICAO SARPs to simulate aircraft deviations in response to RAs. The ACASA study[17] defined, and used, two additional pilot response models, i.e. the 'aggressive response' model and the 'slow response' model. These models were characterised by two distinct vertical rates (viz. 500fpm and 3700fpm) that were far from the standard one expected by the ACAS logic.

3.2.3.2. The present study demonstrated that such extreme pilot responses to RAs still exist, but are much less likely to occur. It should notably be noted that, on average, the 'typical pilot response' defined in ASARP is very close to the 'standard pilot response'. Another key result is the good ratio (90%) of pilot responses included in the ASARP 'typical pilot' model compared to the ACASA results. Generally, the ASARP results demonstrate the relatively good behaviour of European pilots when faced with RAs, most likely due to their increased knowledge of ACAS operation.

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[17] The ACASA pilot models were established using TCAS II recorded data provided by some airlines in the early 1990s in the framework of the European ACAS II operational evaluation. The data included about 60 exploitable RAs. Although most of them (95%) were corrective RAs, a pilot reaction was detected for less than half of the RAs.

3.3. Altimetry error assumptions

3.3.1. HMU data collection and analysis

3.3.1.1. As part of its on-going monitoring activities, EUROCONTROL continuously gathers data from the HMUs installed across Europe, and regularly assesses the altimetry error of specific aircraft types. Pre-RVSM data published in 2001 and post-RVSM data acquired during 2004 were made available for the ASARP project. Figure 12 shows the location and operating range of the three HMUs that provided the operational RVSM data used in the study.

Figure 12: Location of the Height Monitoring Units used in the study

3.3.1.2. By comparing measurements of the geometric altitudes of individual aircraft with their reported pressure altitude (corrected for the known surface pressure), HMUs are able to determine the ‘Altimetry System Error’ (ASE) of the aircraft. Since any single aircraft does not fly close to HMUs sufficiently frequently, the individual aircraft are grouped into HMU monitoring classes based on aircraft types. For each monitoring class, very many measurements of the ASE are then made and an average ASE distribution for these classes is derived. The ASE of each monitoring class is approximated by a linear combination of a Laplacian distribution (also known as a ‘double exponential’) and a Gaussian distribution.

3.3.1.3. The HMU monitoring classes were matched to the aircraft performance classes defined in the European safety encounter model. For the three performance classes present in the RVSM layer (viz. jet aircraft with MTOM in the range 5,700kg to 15,000kg, 15,000kg to 100,000kg, and above 100,000kg), no statistically significant differences in altimetry performance were observed from the HMU data available. Consequently, it was decided to define a single ASE distribution for RVSM that would apply to all three performance-classes in the present study.

3.3.2. Definition of a post-RVSM Altimetry Error Model

3.3.2.1. Taking into account the proportion of the observed traffic for each monitoring class, the post-RVSM HMU data was used to derive numerically the average altimetry error distribution applicable to individual aircraft. This distribution constituted the ASARP AEM ('altimetry error model') for post-RVSM operations. It has a mean of 0.6ft and a standard deviation of about 65ft with more than 99% of the distribution within ±269ft. The proportion of the distribution with an altimetry error in excess of 150ft is 2.25%.

3.3.3. Comparison with former Altimetry Error Models

3.3.3.1. Previous studies, including those carried out in the ACASA project, have used the altimetry error model specific in the ICAO SARPs. The SARPs AEM consists of a set of Laplacian distributions, with mean zero and different parameters in different altitude layers for ACAS equipped aircraft and unequipped aircraft. For each aircraft equipage, the standard deviation increases monotonically with increasing altitude.

3.3.3.2. In view of the results of the HMU data analysis, it was concluded that a more consistent AEM for the whole European airspace would be formed from a combination of the SARPs AEM and the post-RVSM AEM defined in ASARP. Essentially, ACAS equipped aircraft above FL100 should have applied to them the post-RVSM AEM, whereas ACAS equipped aircraft below FL100 and unequipped aircraft at all altitudes still have applied to them the SARPs AEM. The extended range of applicability (down to FL100) of the post-RVSM AEM maintained a consistent and continuous behaviour of altimetry error with increasing altitude. This feature is illustrated in Figure 13, which presents the standard deviations of each of the AEM depending on the altitude layers of the SARPs AEM.

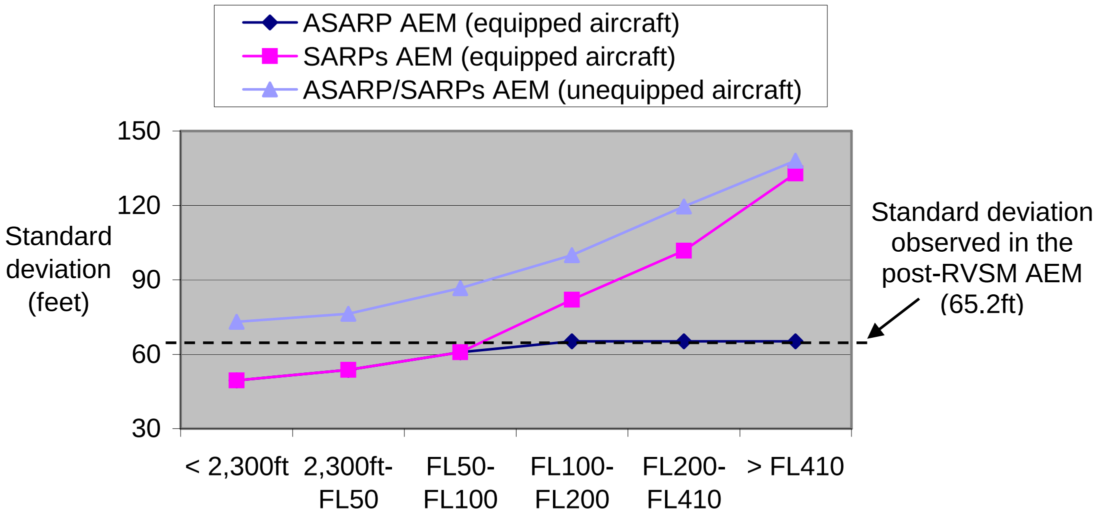


Figure 13: Standard deviations in the various altimetry error models

3.3.3.3. This combined ASARP AEM for the whole airspace was used when adjusting the VMD tables of the post-RVSM safety encounter model to the imposed NMAC rate (see section 3.1.2).

4. Efficacy of ACAS in the European RVSM environment

4.1. Scope and approach

4.1.1. In the safety analysis presented hereafter, the focus is on the question: "does ACAS reduce the risk of mid-air collision in the European RVSM airspace?".

4.1.2. To answer this question, the approach adopted consisted in computing an **airspace-centred risk ratio attributable to ACAS in the European RVSM airspace** (see section 2.1). Using the underlying NMAC rate observed for the RVSM airspace, the level of risk achieved with ACAS (in terms of NMAC rate) was also estimated. Two operational scenarios were investigated, which built upon each other and took into account increasing level of details:

- a 'reference scenario' addressing typical ACAS operations in RVSM airspace (in terms of aircraft equipage[18] and pilot responses to ACAS in 'close' encounters representative of the airspace) by end of March 2006, that is after completion of the transition period for the implementation of Phase II of the ACAS mandate;

  The 'reference scenario' was also evaluated for the whole European airspace to allow comparison between the RVSM altitudes and other altitude layers.

- a 'full-system scenario' addressing contingencies that can arise during typical operations of the ACAS system in RVSM airspace (including events related to equipment limitations, late controller involvement and visual acquisition of the collision threat by the pilot).

4.1.3. In addition, **aircraft-centred risk ratios were computed for various "pilot behaviour scenarios"** to assess the safety benefit of being ACAS equipped for an individual aircraft flying in the RVSM airspace (assuming all other mandated aircraft are already equipped). This was done on the basis of the 'full system scenario' where equipment and human factors events were considered.

4.1.4. These airspace-centred and aircraft-centred risk ratios focus on RVSM encounter situations involving two aircraft only (see section 4.2). The specific case of multiple aircraft encounters in RVSM airspace was assessed separately (see section 4.3). The remainder of the chapter presents the main conclusions of the ASARP study. Detailed results can be found in the study reports [WP5], [WP6] and [WP7].

[18] In the time horizon under consideration, it has been assumed that all civil aircraft flying in RVSM would be ACAS equipped, the only non-ACAS equipped aircraft being military aircraft. It was also anticipated that 92% of the Mode S aircraft would transmit their altitude in 25-feet increments. This value was consistent with the latest figures given by the Mode S monitoring in Europe. In addition to all ACAS equipped aircraft, these Mode S aircraft were assumed to include 20% of the military aircraft. This estimate was in line with EUROCONTROL predictions for state aircraft at the end of 2006. Finally, all ACAS equipped aircraft were assumed to supply their ACAS logic with the finest own altitude quantisation (i.e. one foot).

4.2. Evaluation of the safety benefits of ACAS

4.2.1. Scenarios of ACAS operations in RVSM airspace

4.2.1.1. Although using similar assumptions with regard to the main factors that influence the safety benefits of ACAS (see section 2.2), the two scenarios investigated had distinct focuses and were assessed using different approaches:

- The **'reference scenario' was assessed through the performance of ACAS simulations** (see section 2.3.5) on a large set of encounters generated from the post-RVSM European safety encounter model (limited to the RVSM layer). The focus was on evaluating the risk reduction provided by ACAS during typical operations and identifying those encounter geometries that influence most the safety of ACAS in RVSM airspace.
- The '**full-system scenario' was assessed using the 'contingency tree'** adapted to ACAS operations in European RVSM airspace with ad-hoc event probabilities (see section 2.3.6). The focus was on assessing the risk reduction provided by ACAS in RVSM airspace taking into account the contingency events that can occur assuming aircraft are in a collision course.

4.2.1.2. In both cases, aircraft were assumed to be ACAS equipped according to the European ACAS mandate (i.e. all civil aircraft operating at RVSM altitudes) and similar assumptions were used with regard to the equipment characteristics (viz. ACAS, transponder and altitude report quantisation). However, while the 'reference scenario' assumed nominal functioning of ACAS and transponder equipment, the 'full-system scenario' included a small proportion of aircraft with equipment that was unserviceable or providing limited information[19]. Furthermore, the 'full-system scenario' considered a non-standard, yet realistic, operating scenario of the ACAS equipment by the pilot (i.e. mix of standby, TA-only and full TA/RA-mode).

4.2.1.3. With regard to the pilot behaviour and performance, both scenarios assumed typical pilot responses to ACAS RAs including 10% of non-responding pilots (as described in section 3.2.2). However, while the 'reference scenario' did not distinguish between the reasons for not responding to RAs, the 'full-system scenario' considered a complex scenario in which a pilot occasionally ignores the RA outright, or notes the RA but gives preference to a controller instruction (but most frequently follows the RAs). Furthermore, the 'full-system scenario' considered the possibility that the pilot exercises "see-and-avoid" following visual acquisition (prompted by ACAS) of a potential collision threat. For all these specific circumstances, probabilities were defined as inputs to the 'contingency tree' from best available evidence and were checked for operational validity through expert judgement.

[19] Equipment limitations taken into account included unserviceable ACAS, ACAS tracking limitations, ACAS unequipped aircraft with unserviceable Mode C or Mode S transponder or with non-altitude reporting transponder.

4.2.1.4. It should be noted that, although not explicitly defined as such, late controller instructions followed by the pilots to the detriment of ACAS were taken into account to a certain extent in the 'reference scenario' through the encounters that already included late avoidance manoeuvres (see example presented in Figure 6) by aircraft for which no pilot response to RAs was simulated.

4.2.2. Risk reduction delivered by ACAS in RVSM airspace

4.2.2.1. Table 2 presents the airspace-centred risk ratios computed for the European RVSM airspace on both the 'reference scenario' and the 'full-system scenario', as well as the whole European airspace risk ratio computed on the 'reference scenario' extended to all layers.

	RVSM layer		All layers
	Reference scenario	Full-system scenario	Reference scenario
Airspace risk ratio	1.7%	1.7%	19.6%

Table 2: Airspace risk ratios for the reference and full-system scenarios

4.2.2.2. As shown, no significant variation in the RVSM airspace risk ratio (of about 1.7%) was observed between the two scenarios. This means that the effect of non-nominal events included in the full-system analysis were found negligible compared to the typical ACAS operations addressed in the 'reference scenario'. In practice, **the risk of mid-air collision can, therefore, be expected to be reduced by a factor of about sixty** as a result of the deployment of ACAS in European RVSM airspace**.**

4.2.2.3. It should be noted that **this risk reduction was estimated to be more than ten times greater at the RVSM altitudes than over all altitudes**. This can be explained by two main features:

- the greater proportion of ACAS equipped aircraft in RVSM airspace compared to the whole airspace. Previous ACAS safety studies [ACA1], [ACAe] have shown how the overall risk with ACAS is very sensitive to the proportion of aircraft that are equipped and to the pilot response rate to ACAS RAs. We would therefore expect maximum safety benefits in the European RVSM airspace where the ACAS system is expected to be operated by all civil aircraft flying in the airspace.
- the traffic characteristics in each portion of airspace. In this regard, we would expect encounters occurring in RVSM (with a tendency for aircraft to fly straight and level) to correspond to situations more easily solved by ACAS system than other situations at lower altitudes (with fewer ACAS-equipped aircraft and more manoeuvring aircraft).

4.2.2.4. These expectations were confirmed by the ACAS simulations performed on the 'reference scenario'. As an illustration Figure 14 shows the characteristics of the NMAC encounters that remained at the RVSM altitudes following the simulation of the operation of ACAS in the encounter set generated from the ASARP encounter model.

Note: In the figure, "ACAS response" corresponds to a typical pilot response to ACAS onboard an equipped aircraft, "no ACAS response" refers to a non-responding pilot in an ACAS equipped aircraft and "no ACAS" refers to a non-ACAS equipped aircraft (i.e. in RVSM, high performance military jet aircraft).

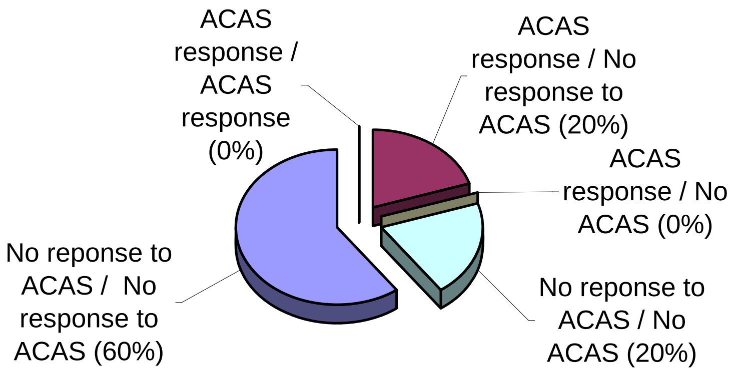


Figure 14: Component of the RVSM airspace risk with ACAS for the reference scenario

4.2.2.5. As shown, the majority (60%) of the remaining NMAC encounters consisted of encounters involving two equipped aircraft without any pilot responses to RAs. When pilot reactions were simulated in both aircraft, no encounters resulted in an NMAC with ACAS. The other remaining NMAC encounters consisted of either encounters involving only one ACAS equipped aircraft with a non-responding pilot (20%) or coordinated ACAS-ACAS encounters with only one pilot responding to ACAS (20%). The influence of aircraft equipage and pilot response rate to RAs is further discussed later on (see section 4.2.4).

4.2.3. ACAS efficacy and induced collision risk in RVSM airspace

4.2.3.1. Taking into account the underlying NMAC rate derived from the RVSM radar data, the estimated risk ratio (of 1.7%) represents an NMAC rate of about 3×10^{-9} NMACs per flight-hour (i.e. about three mid-air collisions every 10^{10} flight-hours). Using the flight-hour statistics that the post-RVSM safety encounter model represents, this would correspond to one NMAC every 500 years within the typical coverage of a single en-route radar.

4.2.3.2. In the overall risk with ACAS, distinction should be made between its unresolved and induced components. For the 'reference scenario' and as shown in Figure 14, the ACAS simulations showed that about 20% of the risk actually results from the operation of ACAS inducing NMACs that would not have occur if ACAS were not deployed. For the 'full-system scenario', this induced risk was estimated to constitute about one third of the overall risk with ACAS. This corresponds to an induced risk ratio of 0.5%, i.e. about one induced mid-air collision every 10^{10} flight-hours. Such a level of risk is acceptable in the context of the overall vertical TLS for RVSM operations (viz. 5×10^{-9} fatal accidents per flight-hour).

4.2.3.3. The ACAS simulations conducted on the ‘reference scenario’ showed that these induced NMACs all correspond to an inadequate use of ACAS, as described in the remainder of this paragraph. In a coordinated ACAS-ACAS encounter, one pilot ignores the RAs generated by ACAS and follows a vertical profile that is contrary to the sense of the RAs. In the other aircraft, the pilot responds to ACAS and follows the RAs that it generates in a typical manner. In these circumstances, the RAs are coordinated and the fact that one pilot does not respond to ACAS can thwart the collision avoidance logic. An example of such a circumstances is presented in Figure 15. This example is similar to the situation that occurred in the Überlingen accident.

Note: The figure presents the vertical profiles of both aircraft versus time, as well as the simulated ACAS events for the red aircraft complying with the RAs: the RA updates are shown by tags on the own trajectory and the intruder status is shown by a TCAS-like symbol on the intruder trajectory.

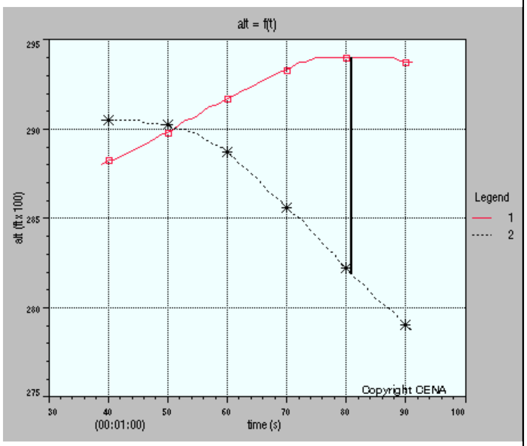
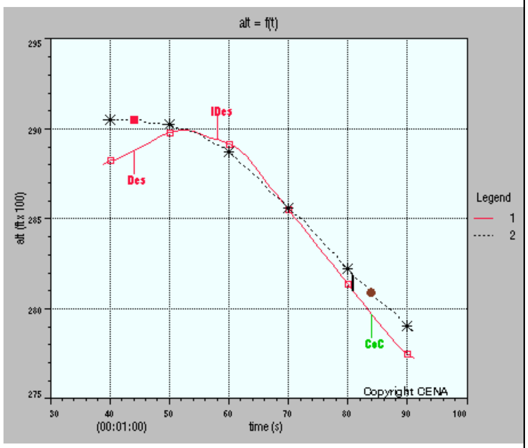
Initial encounter (without ACAS contribution)	Final encounter (with only one pilot following the RAs)
	

Figure 15: Illustration of an induced NMAC encounter with only one responding pilot

4.2.3.4. A change proposal to the ACAS logic addresses this issue[20], referred to as the ‘SA01’ issue, and is currently being progressed in RTCA[21] [CP112E]. If implemented, the performance of ACAS, particularly when one or other pilot does not comply with the RAs, would be significantly improved. In the European RVSM airspace, this would potentially remove most of the negative side-effect of ACAS on the overall safety.

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[20] Version 7.0 of the TCAS II logic permits sense reversal of coordinated RAs. However, this mechanism has some limitations that prevent it from being fully effective in all situations. This has led to a proposed change to the TCAS reversal logic known as the CP112E. This change proposal addresses three specific scenarios among which are the issue of late reversal RAs or no reversal RAs in coordinated encounters. EUROCONTROL contributed to both the design of the new reversal logic and its validation [SIR], [SIRE].

[21] RTCA Special Committee 147 is the body in charge of TCAS equipments standardisation. Its current terms of reference include an update of the Minimum Operational Performance Standards (MOPS) of [TCAS] that will address a final fix to the SA01 issue.

4.2.4. Influence of various factors on the airspace-centred risk ratio

4.2.4.1. The various factors that proved to influence, or not, the safety benefits of ACAS in the European RVSM airspace are further discussed hereafter.

4.2.4.2. Aircraft equipage and pilot response to RAs

4.2.4.2.1. As already mentioned (see section 2.2), the nature of aircraft equipage and the pilot behaviour in response to ACAS are key influencing factors. A series of 'basic scenarios' were simulated for each distinct situation (in terms of equipment and pilot response) that appears in the 'reference scenario' with appropriate weights. Figure 16 shows the risk ratios computed for the RVSM layer for each of these specific scenarios.

Note: Here again, "ACAS response" corresponds to a typical pilot response to ACAS, "no ACAS" still refers to a non-ACAS equipped aircraft with distinction between the aircraft reporting their altitude in 100-feet and 25-feet increments respectively.

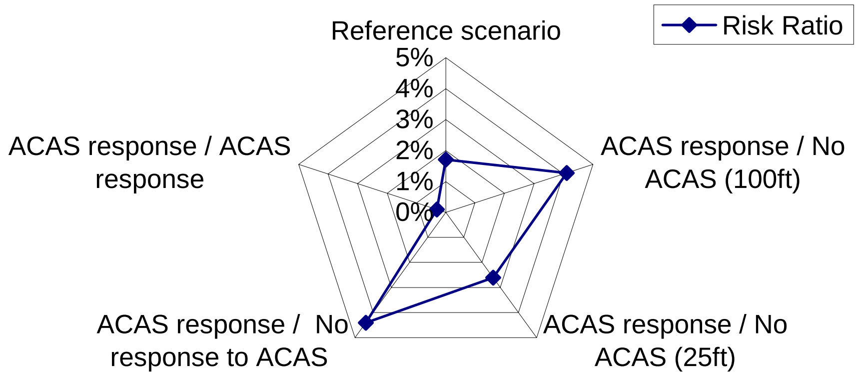

Figure 16: Influence of aircraft equipage and pilot response on the risk ratio

4.2.4.2.2. Assuming full ACAS equipage with all pilots responding to RAs in a typical manner, the ACAS collision avoidance algorithms could ideally achieve a risk ratio of 0.3%. An increased, yet still fairly good, risk ratio of 4.4% was observed in the case of full ACAS equipage when only one pilot in each encounter responds to RAs. The increase occurs principally because if one pilot does not follow his RA the selection of the RA in the other aircraft is constrained and its effectiveness can be reduced. Assuming only one ACAS equipped aircraft in every encounter, the altitude report quantisation of the non-ACAS equipped aircraft proved to affect the safety benefit of ACAS with the risk ratio changing from 2.6% with 25-feet reports to 4.1% with 100-feet reports.

4.2.4.2.3. In summary, the **risk reduction achievable in RVSM is all the more significant when aircraft are ACAS equipped, pilots of ACAS equipped aircraft follow their RAs and non-ACAS equipped aircraft report their altitude in 25-feet increments**.

4.2.4.3. Pilot response type

4.2.4.3.1. To assess the influence of the pilot response characteristics, a ‘simplified reference scenario’ was simulated in which typical pilots were replaced by ‘standard pilots’ as defined in [ACAS], but still with 10% of non-responding pilots. Under this simplified assumption, the risk ratio was estimated to be 1.8% (instead of 1.7% for the ‘reference scenario’), thus demonstrating that the safety benefit of ACAS in RVSM is not very sensitive to the small proportion of slow or aggressive responses included in the continuum response model of typical pilots.

4.2.4.3.2. In addition, it was observed that the typical pilot responses to RAs generally cause a small increase in the achieved vertical miss distances with ACAS compared to the standard pilot responses. This feature is illustrated in Figure 18 which shows a density plot of the VMDs observed in simulations with each pilot model. As shown, on average, the achieved VMDs with ACAS were greater with typical pilot responses than with standard ones.

Note: In the figure, the colour intensity reflects the number of encounters for each combination of VMDs assuming either ‘standard’ or ‘typical’ responses to RAs. The diagonal line indicates the area where there is no difference in VMD.

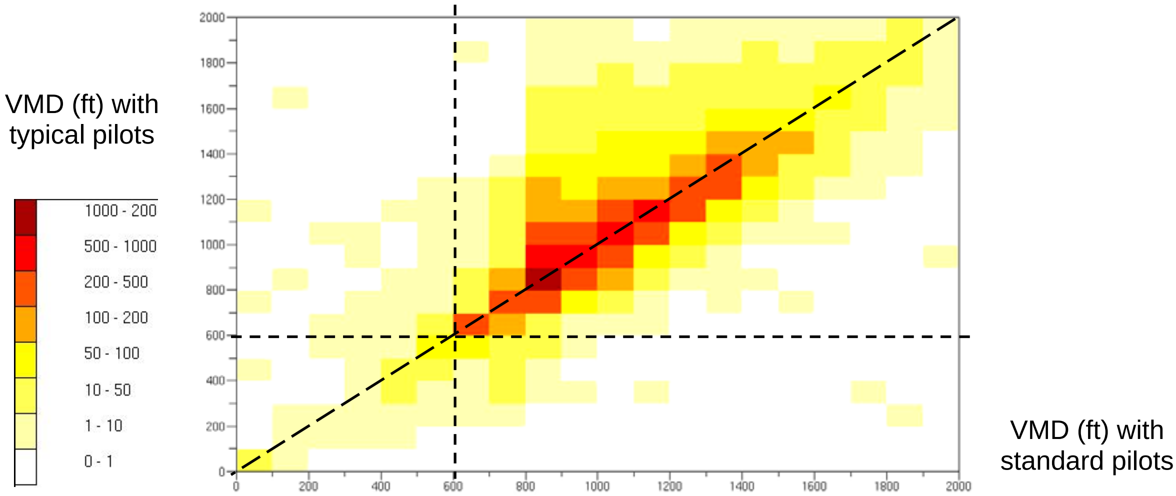

Figure 17: Change of VMDs between ‘standard’ and ‘typical’ pilot responses to RAs

4.2.4.4. Pilot response rate to RAs

4.2.4.4.1. The percentage of typical pilots responding to their RAs proved to be much more important than the precise characteristics of the response. This feature is illustrated in Figure 18, which presents the risk ratios computed for the RVSM layer on ‘modified reference scenarios’ where the proportion of responding pilots in ACAS equipped aircraft was varied between 0% and 100%. When responding to RAs, pilots were assumed to respond in a typical manner.

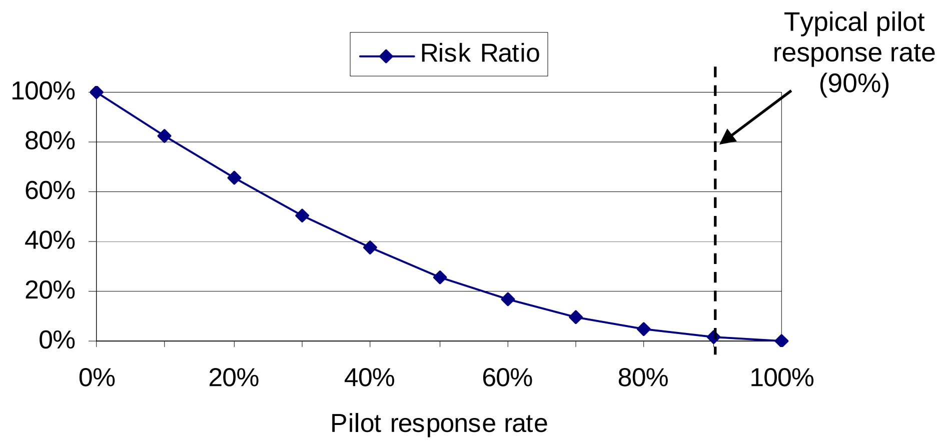

Figure 18: Influence of the pilot response rate to RAs on the risk ratio

4.2.4.4.2. As shown, **the risk reduction achievable with ACAS depends strongly on the rate of compliance of pilots to RAs.** The greater the proportion of responding pilots, the greater the safety benefits delivered by ACAS. It should be noted that twice as many non-responding pilots than estimated from the operational data (i.e. 20% instead of 10%) would increase by three times the risk with ACAS (i.e. risk ratio of 4.9% instead of 1.7%). When less than half of the pilots on average respond to their RAs, the risk reduction is more or less proportional to the percentage of responding pilots.

4.2.4.5. Altimetry error

4.2.4.5.1. As already mentioned (see section 2.2), the altimetry errors need to be considered when determining the overall risk with ACAS. Risk ratios were therefore computed on the 'reference scenario' for RVSM with and without the inclusion of altimetry errors. This was done following the ACAS simulations on the post-RVSM safety encounter set using either the AEM (Altimetry Error Model) established for RVSM environment (based on the HMU data) or the former AEM defined in the ACAS SARPs.

	Reference scenario (for RVSM)		
	With AEM (for RVSM)	With former AEM	Without AEM
Airspace risk ratio	1.7%	2.4%	1.6%

Table 3: Influence of the altimetry error on the risk ratio

4.2.4.5.2. From the results presented in Table 3, it is evident that the effect of typical RVSM altimetry errors on the effective VMDs achieved with ACAS is almost negligible. If the altimetry of aircraft flying in RVSM were only as good as the traditional SARPs AEM[22] the risk with ACAS would be 50% greater than that estimated with the post-RVSM AEM.

[22] Which would imply that the aircraft were not compliant with the RVSM MASPS.

4.2.4.6. Other environmental and human factors

4.2.4.6.1. The effect of equipment limitations, late controller involvement and visual acquisition on the RVSM airspace risk ratio was evaluated through the 'full-system scenario'. Figure 19 shows the variations observed in the risk ratio calculated using the 'contingency tree' as more factors were taken into account in the overall risk reduction delivered by the ACAS system in RVSM airspace. This risk reduction was evaluated for both 'typical pilots' (who sometimes do not respond to their RAs) and for 'conscientious pilots' (who always follow their RAs).

4.2.4.6.2. The full-system risk ratio goes beyond the mere operation of the ACAS collision avoidance logic. Factors can be introduced progressively in three main groups:

- Allowing for the non-perfect operation of ACAS surveillance and tracking, together with possible limitations of transponders (e.g. failure to report altitude) produces an 'equipment risk ratio',
- Allowing for the involvement of ATC and possible avoidance instructions from the controller produces a risk ratio appropriate to IMC ('Instrument Meteorological Conditions'),
- Finally, allowing for the possibility of visual acquisition in VMC (prompted by ACAS and aided by the traffic display) and "see-and-avoid" manoeuvres produces the 'full-system risk ratio'.

Note: Typical pilots occasionally ignore their RAs even if no external factors (i.e. controller involvement or visual acquisition) induce them to do so. The RA compliance rate assumed when considering the operation of the ACAS system alone was 98.6%. This compliance rate decreased to 90% when taking into account controller involvement and visual acquisition.

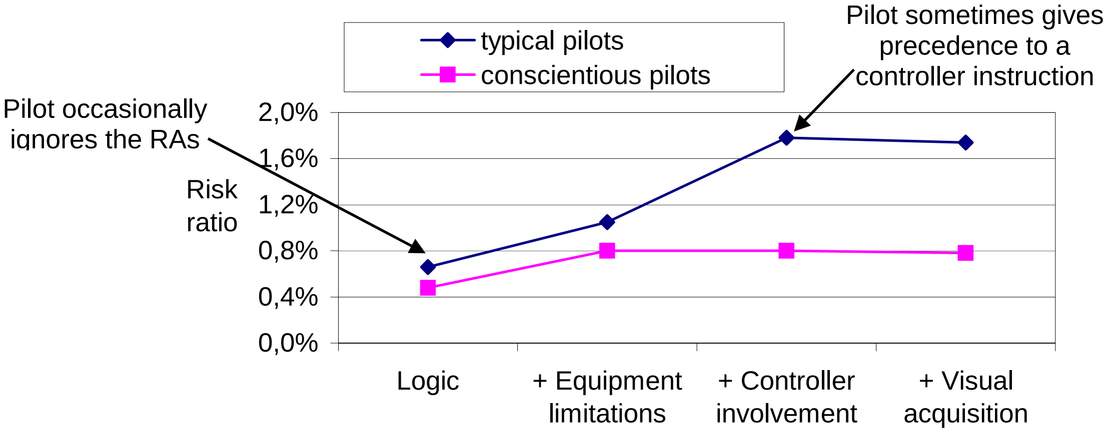

Figure 19: Influence of the environmental and human factors on the risk ratio

4.2.4.6.3. Assuming an ACAS equipage in accordance with the European mandate, and with all pilots responding to RAs in a typical manner, the ACAS collision avoidance algorithms could ideally achieve a logic risk ratio of 0.7%. In practice, limitations of equipment performance would limit the benefits of operating ACAS and an 'equipment risk ratio' of 1.0% would be a more realistic estimate.

4.2.4.6.4. The possible interaction between ACAS and controller avoidance instructions would result in a large increase of the risk ratio to 1.8%. This corresponds to **a reduction by about a factor of two of the safety benefit that ACAS could deliver if all pilots would respond to the RAs.** Finally, the possibility of visual acquisition slightly decreases this risk ratio to a full-system risk ratio of 1.7%.

4.2.4.6.5. Assuming 'conscientious pilots' who always respond to their RAs, the logic and equipment risk ratios were smaller, yet very similar, to the corresponding values for 'typical pilots'. However, when the possibility of contact with the controller was included, the significant increase in risk observed with 'typical pilots' disappears (because regardless of controller instruction the conscientious pilot will follow any RA). This serves to emphasise that pilots should follow RAs in preference to any controller instruction. Finally, when visual acquisition was taken into account, the risk ratio slightly decreased to a full-system value of 0.8%. This slight decrease corresponds to the small proportion of cases where a see-and-avoid manoeuvre prevents ACAS from generating an RA.

4.2.5. Safety benefit of individual ACAS equipped aircraft

4.2.5.1. To assess the safety benefits of deploying ACAS for an individual aircraft flying in RVSM, aircraft-centred risk ratios were calculated for several pilot behaviour scenarios. Even when unequipped the individual aircraft enjoys some measure of protection due to the ACAS equipage of the other aircraft in the airspace (except if the aircraft happens to encounter a similarly unequipped aircraft).

4.2.5.2. The aircraft-centred risk ratios presented in Table 4 indicate the further risk reduction that an individual aircraft can enjoy if it operates ACAS in full TA/RA mode (compared to the risk to which it is exposed if ACAS is operated in TA-only mode). All these risk ratios were computed assuming the other aircraft in the airspace are ACAS equipped according to the mandate and pilots comply with the RAs in a typical manner.

Scenario of individual pilot behaviour	Logic risk ratio	Full-system risk ratio
Ignores RAs	**114.6%**	**109.0%**
Typically responds to RAs	8.0%	12.4%
Conscientiously responds to RAs	6.5%	10.6%

Table 4: Aircraft-centred risk ratios for the full-system scenario

4.2.5.3. **Being in full TA/RA mode but ignoring the RAs, an individual pilot would place himself (and the unwitting pilot of any ACAS equipped aircraft he might encounter) in more danger than if his own aircraft was operating ACAS in TA-only mode**. This is highlighted by a full-system risk ratio (of 109.0%) greater than unity. A 'typical pilot' who would generally comply with the RAs, and only occasionally ignore them, significantly increases the level of protection afforded by ACAS as shown by a full-system risk ratio of 12.4%. Finally, a 'conscientious pilot' who always follows the RAs (even when the rest of the fleet still only respond in a typical manner) can further reduce this full-system risk ratio to 10.6%.

4.3. Investigation of multiple aircraft encounters

4.3.1. Scope and approach

4.3.1.1. The ASARP study also investigated the performance of ACAS in typical multiple aircraft encounters occurring in European RVSM airspace. This investigation approach was two-fold and consisted of assessing both:

- the **operational performance of ACAS** based on the small, yet representative, set of (9) actual RVSM multiple aircraft encounters extracted from the European radar data (see section 3.1.1.3), and
- the **safety efficacy of ACAS, and particularly of its multi-aircraft logic component**, in reducing the risk of mid-air collision in multiple aircraft ‘close’ encounters likely to occur in RVSM.

4.3.1.2. The operational assessment was supported by a detailed analysis of ACAS simulation results for each actual encounter in several steps as follows: *a)* an initial analysis of the radar encounter with the observable pilot reactions to ACAS, *b)* a complementary analysis of a modified radar encounter in which the pilot responses to any RAs were removed and replaced by either standard or typical responses, and *c)* a sensitivity analysis of jittered radar encounters resulting from the introduction of acceptable trajectory perturbations[23] (in either the initial or the modified radar encounter).

4.3.1.3. The safety assessment was supported by ACAS simulations on several sets of (100,000) three-aircraft ‘close’ encounters. These encounters were generated using the post-RVSM safety encounter model of pair-wise encounters by combining two probable pairs of aircraft with a common aircraft. Each encounter set corresponded to a given maximum time shift[24] between the time of closest approach of the two first pairs.

4.3.2. Performance of ACAS in actual RVSM multiple aircraft encounters

4.3.2.1. Based on the various analyses of actual multiple aircraft encounters, the ACAS logic has proven to positively contribute to the safety of flight operations in RVSM airspace and no safety issue has been identified from the real-life data.

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[23] To be operationally realistic, the trajectory perturbations were required not to result in a reduction of the safety margins that would be improbable in the initial encounter. But this does not mean that the perturbations were necessarily very small. Their ranges were defined on a case-by-case basis so as to increase the potential occurrence of multiple ACAS conflicts.

[24] For a given encounter set, the time shift used when generating the two first pairs was uniformly distributed between zero and a given maximum time shift value no greater than 40 seconds. The time of closest approach of the third pair of aircraft was unconstrained and could happen after a time period greater than this maximum time shift value.

4.3.2.2. Sequential RAs versus multiple-threat RAs

4.3.2.2.1. For an individual aircraft, a multiple aircraft encounter may result either in sequential RAs against two distinct threats or in a composite RA against two simultaneous threats. The ACAS collision avoidance algorithms proved to perform efficiently in both circumstances (when pilots respond in a standard manner).

4.3.2.2.2. As an illustration, Figure 20 shows the result of ACAS simulations performed on two jittered radar encounters that resulted respectively in two sequential ACAS resolutions for a given aircraft (see black aircraft on the left-hand diagram) and a multiple threat RA for another given aircraft (see black aircraft on the right-hand diagram).

Note: The figure presents the vertical profiles of the aircraft versus time, as well as the simulated ACAS events for one particular aircraft: the RA updates are shown by tags on the own trajectory and the intruder status is shown by a TCAS-like symbol on the intruder trajectory. The 'CoC' tags indicate the 'Clear of Conflict' advisories that end each ACAS resolution. In the right-hand diagram, the 'MTE' tag indicates the occurrence of the multiple threat RA.

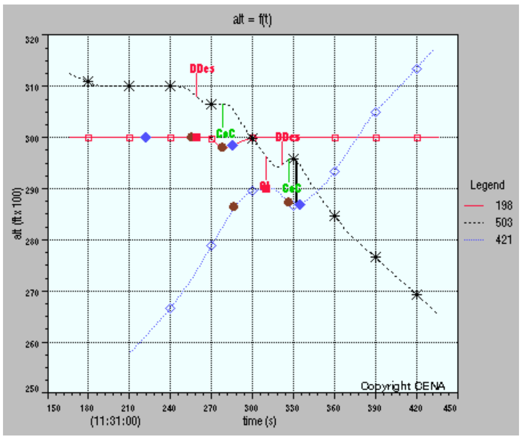
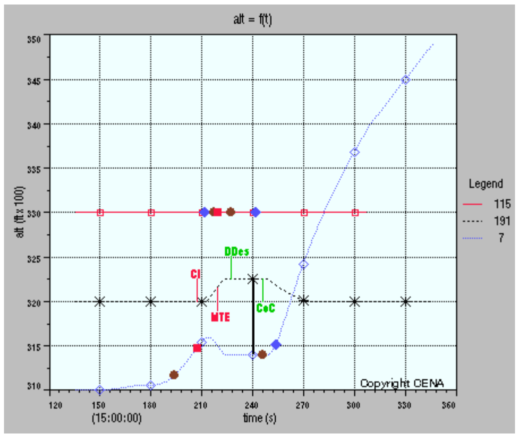
Sequential RAs against distinct threats (with standard pilot responses)	Simultaneous multiple threat RA (with standard pilot responses)
	

Figure 20: Illustration of sequential and simultaneous RAs against multiple threats

4.3.2.2.3. The study demonstrated that, assuming prompt and accurate pilot responses to RAs, **one should expect sequential RAs to be less frequent in RVSM airspace than multiple threat RAs**. Indeed, if the pilots return back to their initial clearance promptly after the 'Clear of conflict' advisory terminating an initial ACAS conflict (against a single threat), the occurrence of subsequent ACAS conflict with a third party aircraft would mean that two losses of ATC separation have occurred in a very short timescale in the same area. A more probable scenario is the occurrence of an ACAS conflict with a third party aircraft at an adjacent RVSM flight level, while the aircraft involved in the initial ACAS conflict are deviating from their initial path in response to their RAs.

4.3.2.3. Performance of the ACAS multi-aircraft logic

4.3.2.3.1. Version 7.0 of TCAS II equipment [TCAS7a] incorporates a multi-aircraft logic that aims to optimise resolution against all threats. When a new threat is declared, the resolution is not constrained by the initial RAs issued against a single threat. It also includes a specific mechanism to delay subsequent RA annunciation until adequate separation has been assured against the initial threat. Finally, it allows both sense reversal and increase rate RAs to deal with worsening situations.

4.3.2.3.2. **In the context of multiple threat encounters likely to occur in the RVSM airspace this sophisticated multi-aircraft logic has proven to issue stable and effective RAs**, typically “Adjust Vertical Speed” RAs that require own aircraft to level-off in-between the two simultaneous threats. When pilots respond in a standard manner, the VMDs achieved at closest approach were generally greater than the minimum vertical separation targeted by the ACAS logic (i.e. 600 ft at the RVSM altitudes).

4.3.2.3.3. Figure 21 shows the ACAS contribution observed for the most relevant[25] pairs of aircraft of the whole set of jittered radar encounters, as well as in the original radar encounter before jittering.

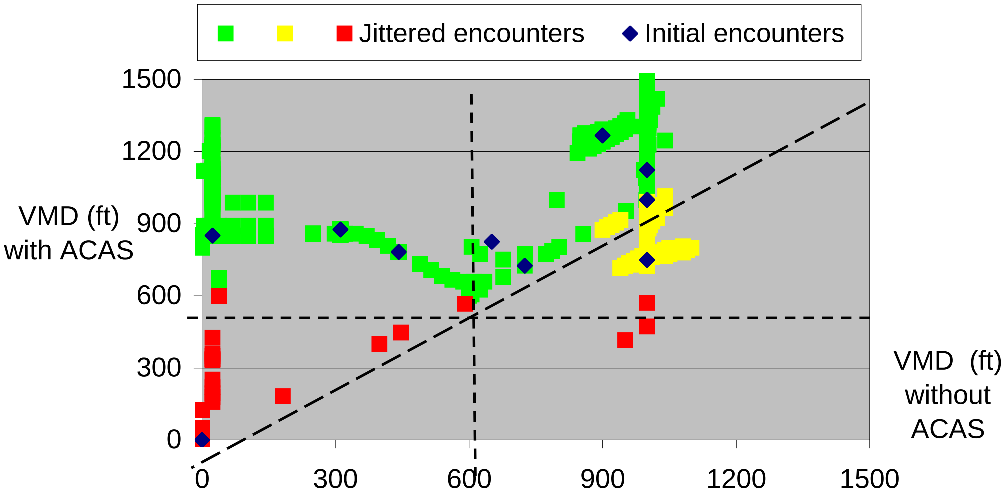


Figure 21: Vertical miss distances in the jittered radar encounters with multiple threat RAs

4.3.2.3.4. As shown (by the green plots in the figure), the VMDs with ACAS contribution generally increases the safety margins between the conflicting aircraft. The slightly reduced VMDs with ACAS contribution (the yellow plots in the figure) are generally due to the absence of coordinated RA in one aircraft involved due to a specific feature of Version 7.0 of the TCAS II logic, which reduces the alert time threshold for triggering an RA onboard level aircraft.

[25] The relevant pairs of aircraft typically correspond to those aircraft that are vertically separated by 1,000 feet or less at closest approach without ACAS contribution.

4.3.2.3.5. The cases where the achieved VMDs are lower than the ACAS targeted minimum separation (the red plots in the figure) correspond either to encounters that are characterised by a significant horizontal separation at closest approach in terms of collision avoidance or a few encounters in which a vertical crossing RA is issued against the third party aircraft (see further details hereafter).

4.3.2.4. Influence of the pilot response to RAs

4.3.2.4.1. The **pilot response to the initial RA (against a single threat) strongly influences the occurrence of an induced conflict with a third party aircraft** at an adjacent RVSM FL, and therefore, the occurrence of a multiple threat RA.

4.3.2.4.2. The left-hand diagram of Figure 22 is an illustration of an actual multiple threat RA (MTE in the diagram) experienced by a pilot who over-reacted to an initial "Climb" RA received during his conflicting descend towards an occupied flight level. As shown in the right-hand diagram, a standard pilot response would have reduced the aircraft deviation and prevented the occurrence of the multiple-threat RA.

Note: The figure presents the vertical profiles of the aircraft versus time, as well as the simulated ACAS events for the middle aircraft.

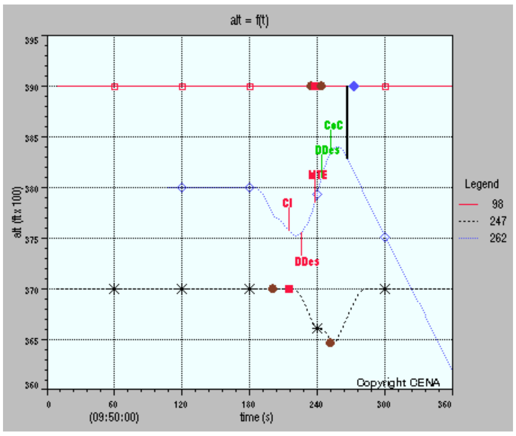
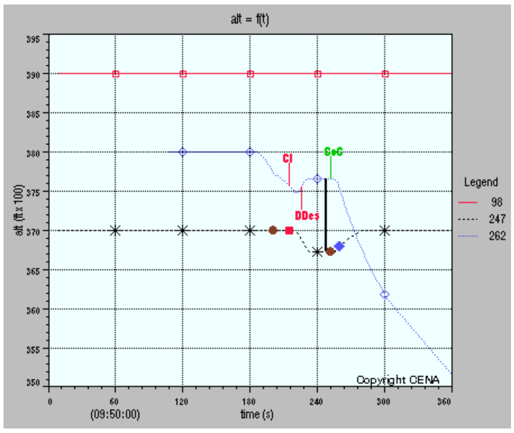
Multiple threat RA to level-off (with actual pilot responses)	Single threat RA (with standard pilot responses)
	

Figure 22: Illustration of an actual multiple aircraft ACAS/RVSM encounter with suspect altitude reports

4.3.2.4.3. If, however, such a conflict with a third aircraft occurs, the **pilot response to the multi-threat RA then influences the occurrence of an ACAS domino-effect on the third party aircraft**. From an operational perspective, domino-effects are likely to be considered as disruptive, although appropriate safety margins are maintained between all the aircraft. Prompt and accurate pilot responses to RAs are unlikely to induce such domino-effects, except when the initial RAs occur between aircraft at co-altitude.

4.3.2.4.4. **The most challenging situation identified corresponds to a scenario where the pilot response to the initial RA (against a single threat) induces a multiple threat RA with a third party aircraft that requires a crossing in altitude** between these two last aircraft. Such disruptive vertical crossing RAs have only been simulated for typical pilot responses with a vertical rate greater than the one expected by the ACAS logic (viz. greater than 1500 fpm in the case of "Climb" or "Descend" RAs). From an operational perspective, vertical crossing RAs are likely to be considered as disruptive by both the pilots and the controller even though they can result in appropriate safety margins if followed by the pilots.

4.3.2.4.5. Figure 23 further illustrates the influence of the pilot responses to RAs as observed in a jittered radar encounter when simulating various typical pilot responses to RAs characterised by more or less important vertical rates. In the left-hand diagram, the slight over-reaction of the pilot to the multiple-threat RA (MTE in the diagram) induced a coordinated "Climb" RA onboard the third upper aircraft. In the right-hand diagram, the aggressive pilot response to the initial "Climb" RA (against the lower aircraft) induced a multiple threat "Maintain Crossing Climb" RA (MCl in the diagram) coordinated with a "Crossing Descend" RA onboard the upper aircraft.

Note: The figure presents the vertical profiles of the aircraft versus time, as well as the simulated ACAS events for the middle aircraft.

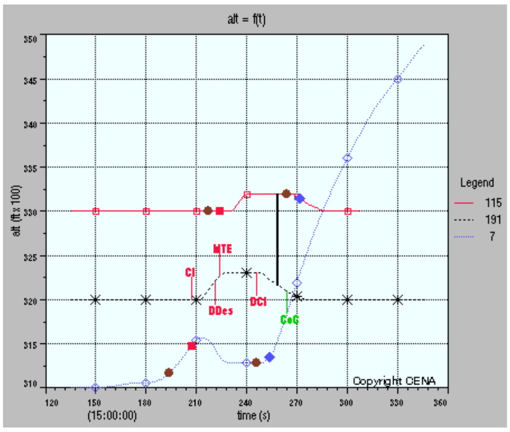
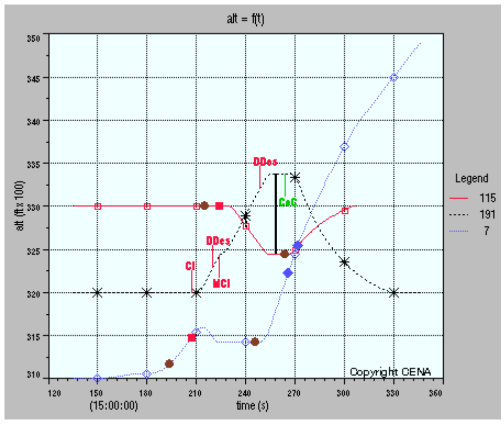
Multiple threat RA to level-off with a domino effect on the upper aircraft (due to slight pilot over-reaction)	Vertical crossing RA against multiple threats (due to an aggressive pilot response)
	

Figure 23: Illustration of the possible effects of typical pilot responses to multiple threat RAs

4.3.2.5. Influence of altitude station keeping and altitude report accuracy

4.3.2.5.1. The analysis of an actual multiple aircraft ACAS/RVSM encounter involving three aircraft flying at adjacent FLs underlined **how essential is good altitude station keeping performance and correct altitude reports to prevent the issuance of undesirable RAs** (both initial RAs against a single threat, subsequent multiple threat RAs involving a third aircraft and possible induced domino-effect on this aircraft).

4.3.2.5.2. This analysis was supported by a full set of data including the ATC report, Mode S RA downlink data, onboard downloaded TCAS data of the aircraft that experienced a multiple threat RA, and its Airline Flight Safety Operations comments on the incident. The analysis of the downloaded TCAS data showed that the aircraft flying level at the adjacent RVSM flight level just above, which announced an ability to report its altitude with 25 feet quanta, actually reported a few suspect altitude changes of 100 feet in one or two seconds.

4.3.2.5.3. Such discrepancies between altitude quantization and altitude reporting capability announcement are a known issue, observed during the TCAS operational monitoring in Europe in the EMOTION-7 project of EUROCONTROL [EMO7]. However, there is no evidence that such an issue occurred during this actual multiple aircraft ACAS/RVSM encounter. It is known from the airline incident analysis that the variations in the altitude transmitted by the intruder aircraft were not linked to any wake turbulences.

4.3.2.5.4. As shown in Figure 24, the perceived vertical rate associated with one of these suspect altitude changes induced a "Descend" RA onboard the own aircraft, rapidly updated into a multiple-threat RA to level-off (MTE in the diagram) coordinated with a "Descend" RA onboard a third aircraft just below. It should be noted that standard pilot responses to RAs would have reduced the aircraft deviation and prevented the occurrence of the domino effect observed on the third aircraft (as shown in the right-hand diagram).

Note: The figure presents the vertical profiles of the aircraft versus time, as well as the simulated ACAS events for the middle aircraft.

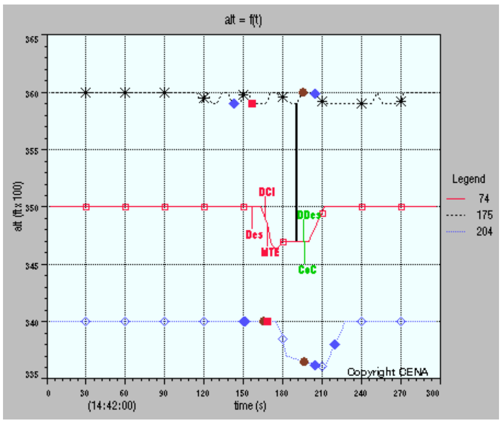
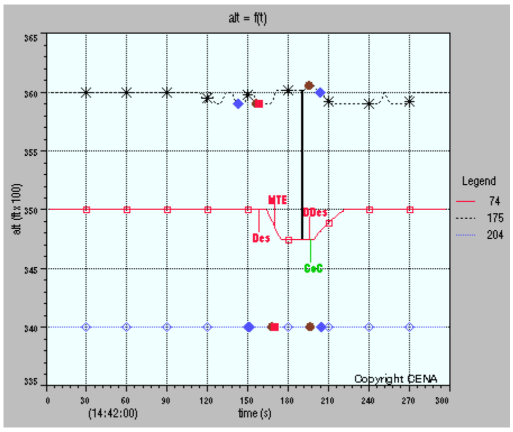
Multiple threat RA (with actual pilot responses)	Multiple threat RA (with standard pilot responses)
	

Figure 24: Illustration of an actual multiple aircraft ACAS/RVSM encounter with suspect altitude reports

4.3.3. Safety efficacy of the ACAS multi-aircraft logic in RVSM encounters

4.3.3.1. Figure 25 presents the risk ratios computed for the various sets of multiple aircraft close encounter generated using the post-RVSM safety encounter model (see section 4.3.1.3) assuming either a typical or a full pilot response rate to RAs (regardless of whether the ACAS multi-aircraft logic was invoked or not).

4.3.3.2. As shown, the risk ratios computed with a typical pilot response rate (of 90%) varied between 3% and about 8%[26] depending on the encounter set. When typically operated, **ACAS is therefore estimated to reduce the risk of mid-air collision during RVSM multiple aircraft encounters by a factor of about 15** (i.e. a risk ratio of 6% on average). This risk reduction was shown not to be sensitive to the typical altimetry errors observed at RVSM altitudes.

4.3.3.3. It should be noted that the small proportion (10%) of non-responding pilots resulted in a large decrease of the estimated safety benefits of ACAS (by a factor between 6 and 9) when compared to a full pilot response rate.

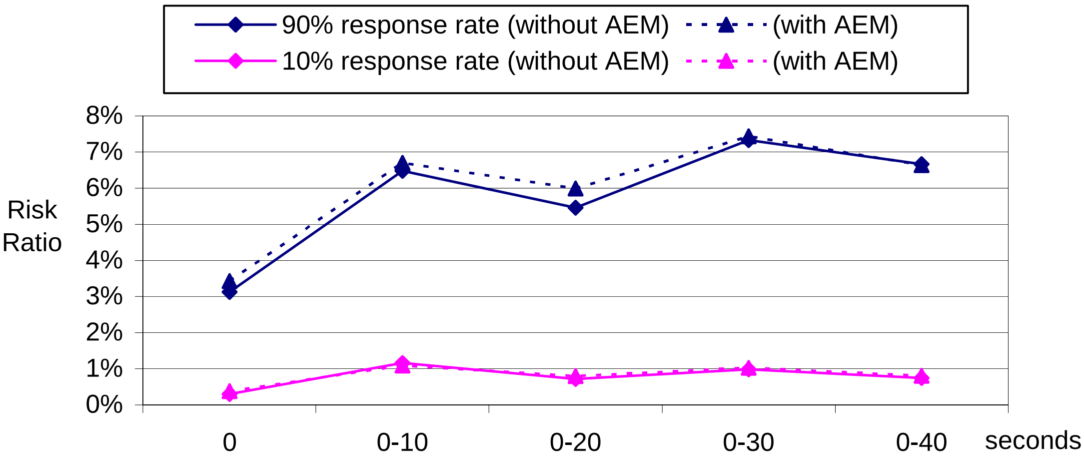


Figure 25: Risk ratio in multiple aircraft close encounters likely to occur in RVSM

4.3.3.4. It was also noticeable that, except for the encounter set without any time shift, the induced risk ratio was much higher than the unresolved risk ratio by a factor between 2 and 3 (assuming a 90% pilot response rate). This induced risk was found even greater, i.e. between 2 and 5 times higher than the unresolved risk, when the ACAS multi-aircraft logic was invoked.

4.3.3.5. Comparatively, the ACAS logic showed better safety performances on the individual pairs of aircraft that compose the multiple aircraft close encounters than in the multiple aircraft close encounters themselves. This result is not surprising since multiple aircraft encounters are more complex situations to solve than pair-wise encounters.

[26] Similar results were obtained when looking specifically at the safety efficacy of the ACAS multi-aircraft logic (with risk ratios between 2% and about 6% depending on the maximum time shift used for the encounter generation).

4.3.3.6. Finally, some geometries were identified in which the ACAS multi-aircraft logic does not achieve its design purpose. The following issues were observed recurrently:

- Multiple threat RAs to level-off were sometimes not triggered on time or not updated, leading to unsafe situations;
- The multiple aircraft reversal logic has the same behaviour as the single intruder reversal logic on SA01 geometries (see paragraph 4.2.3.3);
- The multiple aircraft logic can trigger positive RAs without setting the green arc bit required for positive RAs. This safety issue has an impact on some displays and was already highlighted in the EMOTION-7 project [EMO7].
- The multiple aircraft logic can trigger unexpected “Climb, Descend” RAs, which might have uncertain results on some displays and aural annunciations.

4.3.3.7. These deficiencies are however tolerable since they are likely to occur in a small proportion of multiple aircraft ACAS/RVSM encounters, which are already rare events (one every 500,000 flight-hours).

5. Conclusions and recommendations

5.1. Conclusions

5.1.1. As the last resort safety net, ACAS is an essential component of the ATM system. It must deliver its safety benefits whatever the nature of ATM operations. The effect of any change in ATM on the performance of ACAS should therefore be given appropriate consideration. A previous EUROCONTROL study was conducted prior to RVSM introduction in Europe using operational assumptions. The present safety study replaces these assumptions by actual RVSM operational data.

5.1.2. The ASARP study was conducted using the validated methodology and tools that support the analysis of ACAS safety. These tools were first refined using up-to-date RVSM operational data, so as to ensure an accurate modelling of ACAS operations in RVSM airspace. In summary, the study results demonstrated that:

- **ACAS, as actually observed to be operated, provides substantial safety benefits in the European RVSM airspace**. The reduction of the mid-air collision risk (by a factor of about 60) achieved by ACAS was estimated to be ten times greater at the RVSM altitudes than in the airspace as a whole.

  Furthermore, the level of protection provided by ACAS is not very sensitive to altimetry errors actually observed in RVSM airspace, based on operational HMU data.

- **Prompt and correct pilot response to the RAs that ACAS generates is key to achieve maximum safety benefits**. This is particularly true for the European RVSM airspace where all civil aircraft are expected to be ACAS equipped. The typical pilot response rate observed in real operations (based on recent airborne recorded data) was found to be quite good (90%). However, if all pilots would follow the RAs instead of sometimes giving preference to late controller instructions, the level of protection delivered by ACAS could be further increased by about a factor of 2 in RVSM airspace.

  Additionally, this level is not very sensitive to the small proportion of slow or aggressive responses observed in the range of typical pilot responses to RAs. Nonetheless, an aggressive reaction increases the likelihood of an ACAS event with a third aircraft at an adjacent RVSM flight level. This may have operational consequences, but ACAS continues to provide effective collision avoidance protection.

- **In the context of the TLS for RVSM, the induced ACAS risk is small** (i.e. about one mid-air collision every 10^{10} flight-hours). The induced risk when ACAS is deployed in RVSM results from an inadequate use of the system, i.e. when one pilot manoeuvres contrary to the RA. This risk could be further reduced by modifying the ACAS collision avoidance logic as described in a change proposal (CP112E) currently being progressed.

- **Safety benefits delivered by ACAS in RVSM multiple aircraft encounters are also significant**. The risk of mid-air collision in those multiple aircraft encounters that might occur in RVSM airspace was found to be reduced by a factor of about 15 with ACAS. Some geometries were identified in which the ACAS multi-aircraft logic does not achieve its design purpose. However, this is considered tolerable since they constitute a small proportion of multiple aircraft ACAS/RVSM encounters, which are already rare events (estimated to occur about once every 500,000 flight-hours in RVSM airspace).

5.1.3. The safety performance of ACAS highly depends on the airspace in which it is operated. It is therefore important to note that the above conclusions relate to the European RVSM airspace.

5.2. Recommendations

5.2.1. Safety of ACAS

5.2.1.1. For the safety benefits of ACAS to be maximised, it is essential that all adhere to the standardised ACAS operational procedures, and that ACAS best practice is always applied:

a) Pilots when flying in RVSM airspace, as at all other times, should operate ACAS in RA-mode and the RAs that are generated must be followed promptly and accurately;

b) Controllers must not interfere with pilots' response to RAs.

5.2.1.2. Pilots and controllers are reminded that:

a) An accurate response to RAs reduces the possibility of a domino effect with a third aircraft at an adjacent RVSM flight level;

b) ATC collision avoidance instructions in the horizontal plane eliminate the risk of incompatibility with any vertical manoeuvres required by ACAS.

5.2.1.3. To reduce the residual risk with ACAS in the European RVSM airspace, as in the whole airspace, it is essential to proceed with the implementation of change proposal CP112E to the ACAS collision avoidance logic.

5.2.2. Future safety studies

5.2.2.1. Work should be conducted to investigate further the shortcomings identified with the ACAS multi-aircraft logic and to propose solutions. (In this context, the potential of the ASARP multi-aircraft encounter model should be noted.)

5.2.2.2. Future ACAS safety studies should exploit the enhanced tools developed in the ASARP project. In addition, the enhanced European safety encounter model could be used to support the evaluation of ATM safety nets in general.

6. References

6.1. ASARP main deliverables

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[WP1] ASARP Project – Final report on the post-RVSM radar data processing – ASARP/WP1/18D, version 1.0, March 2005

[WP2] ASARP Project – Final Report on post-RVSM European safety encounter model – ASARP/WP2/34D, version 1.1, January 2006

[WP3] ASARP Project – Final report on the update of altimetry-error assumptions – ASARP/WP3/16D, version 2.0, January 2006

[WP4] ASARP Project – Final report on the analysis of airborne recorded data and pilot model specification – ASARP/WP4/19D, version 1.0, April 2005

[WP5] ASARP Project – Final report on the computation of post-RVSM logic risk ratios and associated values – ASARP/WP5/57D, version 1.1, February 2006

[WP6] ASARP Project – Final report on post-RVSM full system safety study using the contingency tree method – ASARP/WP6/58D, version 1.0, February 2006

[WP7] ASARP Project – Final report on the investigation of the multiple aircraft encounter issue – ASARP/WP7/53D, version 1.0, February 2006

[WP8] ASARP Project – ACAS induced collision risk in RVSM airspace – ASARP/WP8/68D, version 1.0, February 2006

6.2. External references

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[ACA1b] ACASA Project – European Encounter Model: Part 1/2 – EUROCONTROL ACAS Programme – Specifications, ACASA/WP1.1/186, Version 2.1, December 2001

[ACA3] ACASA Project – Final Report on ACAS / RVSM interaction –- EUROCONTROL ACAS Programme – ACASA/WP3.6/185D, Edition 3, September 2001

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[DOC9433] ICAO – Interception manual – Doc9433-AN/926, second edition

[EMO7] EMOTION-7 Final Report – EUROCONTROL ACAS Programme – ACAS/03-003 – Edition 1.0, January 2003

[OSCAR] DSNA – OSCAR test-bench, User's Manual – Version 2.0, October 1996

[PANS-OPS] ICAO – Procedures for Air Navigation Services - Aircraft Operations – Doc8168-OPS/611, November 2003

[PISC] The EUR RVSM Pre-Implementation Safety Case – EUROCONTROL RVSM Programme – RVSM 691 – Edition 2.0, August 2001

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