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Work Package 3
Final Report on ACAS/RVSM Interaction

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Abstract

This Study report is a deliverable from work package (WP) 3 of the ACAS Analysis (ACASA) Project, part of the ACAS Programme. The study focusses on technical and operational issues of ACAS/RVSM interaction. It utilises ACAS performance indicators to underline potential improvements, or drawbacks, in the area of safety, pilot acceptance and ATC compatibility. Finally, recommendations are made.

Keywords

ACAS TCAS RVSM TA RA

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Prepared by Christian Aveneau and Béatrice Bonnemaison

Executive summary

In view of the ACAS (‘Airborne Collision Avoidance System) and future RVSM (‘Reduced Vertical Separation Minima’) implementations in Europe respectively by beginning of 2000 and 2002, the purpose of the ACASA/WP3 (‘Work Package ’ 3) was to ascertain:

- Whether there are any significant operational implications for ACAS II performance due to European RVSM implementation, and also,
- Whether the benefits expected from RVSM could be compromised due to the operation of ACAS II.

The ACAS/RVSM interaction study was to focus not only on technical issues, but also on identifying potential operational issues and providing recommendations. In order to cope with a larger set of issues, and not to be limited in scope, the study was based on different sources of data:

- **Modified radar data**.
- Data extracted from **real-time simulations**,
- Non-automatic **artificial encounters**,
- Automatic **artificial encounters**
- Data extracted from **fast-time simulations**,

The main principle of the study was to perform, for each source of data, a pair-wise comparison of the ACAS performances within the future RVSM environment and the current CVSM (‘Conventional Vertical Separation Minima’) environment, based on the same level of traffic.

For each source of data, a large set of ACAS performance indicators were analysed in order to highlight potential improvements or drawbacks in terms of **safety**, **pilot acceptance**, and **compatibility with ATC**.

The ACASA partners involved in the study were : EEC (‘Eurocontrol Experimental Centre’), DERA (‘Defence Evaluation Research Agency’) and CENA (‘Centre d'Etudes de la Navigation Aérienne’) which had the leadership on WP3.

This report first describes the methodology and tools used in the different studies. Then, the hypothesis and results of the ACAS simulations based on each specific source of data are presented. The main features of ACAS and RVSM interaction are finally discussed and recommendations are made.

The different studies have shown that the introduction of RVSM is expected to affect TCAS II performance above FL290. Issues related to TCAS II operations in continental RVSM airspace should be very similar to those already identified for altitudes between FL200 and FL290.

The main issue from the ATC point of view is the occurrence of nuisance RAs, which is particularly high with TCAS II version 6.04a. In an RVSM environment, these nuisance RAs are expected to occur in particular for oscillating level aircraft flying 1,000 feet apart, and for aircraft in level-off manoeuvre 1,000 feet from another aircraft. The first issue was already identified during previous ACAS and RVSM studies for the North Atlantic Traffic. The second issue was already identified below FL290 during the TCAS II operational evaluations. The CVSM and RVSM simulations performed in this study have shown to what extent, these issues should apply above FL290.

As expected, the TCAS II logic version 7.0 demonstrated a greater compatibility with ATC by providing a reduction of the number of RAs. This contribution of TCAS II version 7.0 is due to the introduction of the 'Miss Distance Filtering' in case of large HMD, to the performances of the 25 feet vertical tracker and to the less disruptive behaviour of the logic in case of level-off geometry.

The main issue for pilots is the high frequency of TAs with TCAS II version 6.04a in RVSM (due to the incompatibility of version 6.04a TA thresholds with RVSM separation). This incompatibility is a known problem highlighted in a number of previous ACAS and RVSM studies.

From the pilots' point of view, TCAS II version 7.0 reduces the interaction between TCAS II and RVSM, the most important contribution being the suppression of TAs between aircraft perfectly steady and vertically separated. **Nevertheless, the high proportion of nuisance TAs is an operational issue for the RVSM introduction, irrespective of the TCAS II logic version**. The substantial proportion of repetitive TAs could also be an ACAS operational issue for the RVSM introduction, irrespective of the TCAS logic version.

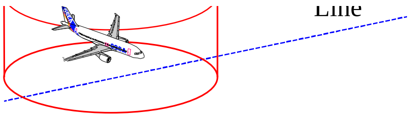
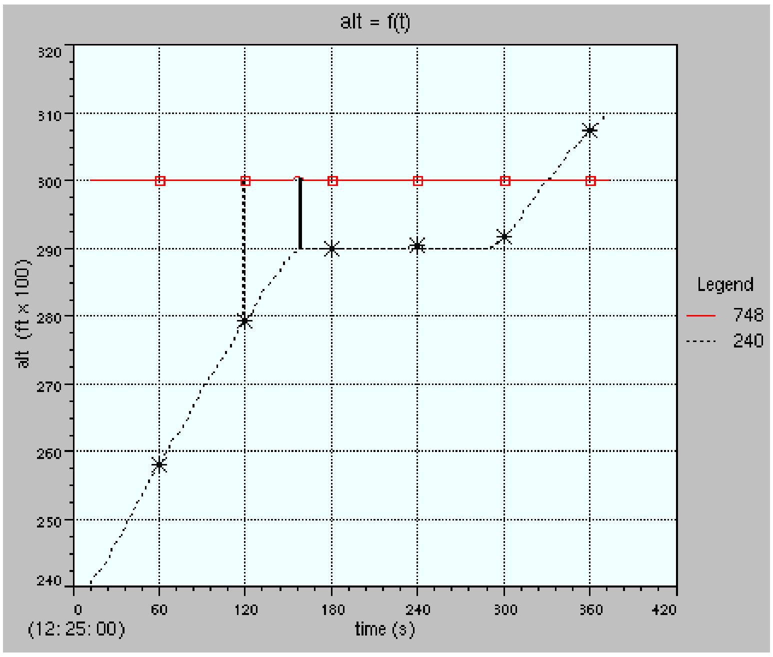
Finally, **the study did not reveal any ACAS safety issues related to the introduction of RVSM in Europe** and showed that going from a non-ACAS airspace to an ACAS airspace improves the level of safety whatever the VSM conditions.

The ACAS/RVSM interaction presented in this report relies on the results of the ACAS simulations conducted using various sources of data. It was not always possible to clearly conclude on the ACAS/RVSM interaction due to some discrepancies in the results obtained from each source of data. Nevertheless, the study provides an overview of the main features of the ACAS/RVSM interaction that are expected to occur in the future European RVSM airspace.

List of Acronyms

ACAS	Airborne Collision Avoidance System
ACASA	Airborne Collision Avoidance Systems Analysis
ADC	Air Data Computer
ATC	Air Traffic Control
CPA	Closest Point of Approach
CVSM	Conventional Vertical Separation Minima
FL	Flight Level
FLAS	Flight Level Allocation Scheme
FLOS	Flight Level Orientation Scheme
FMS	Flight Management System
HMD	Horizontal Miss Distance
MASPS	Minimum Aircraft System Performance Specification
MOPS	Minimum Operational Performance Standard
NAT	North Atlantic Traffic
NM	Nautical Miles
NMAC	Near Mid Air Collision
RA	Resolution Advisory
RVSM	Reduced Vertical Separation Minima
RWG	RTCA (Radio Technical Commission on Aeronautics) Working Group
SARPS	Standard and Recommended Practices
SICASP	SSR Improvements and Collision Avoidance Systems Panel
TA	Traffic Advisory
TCAS	Traffic alert and Collision Avoidance System
TOD	Top Of Descent
TSO	Technical Standard Order
TVE	Total Vertical Error
VMD	Vertical Miss Distance

List of Definitions

ALIM	A parameter of the TCAS logic, which defines the targeted minimum vertical distance between aircraft. This value depends on the altitude layer where the own aircraft flies. It is used when determining the initial strength of an RA. For example, it is equal to 600 ft in the [FL200; FL420] altitude layer, for TCAS II logic version 7.0.
Encounter	An encounter is an air traffic situation involving two or more aircraft, and potentially generating an ACAS alert (either a TA or an RA) in either the CVSM or RVSM environment. For example, converging aircraft separated by 2,000 feet in CVSM could become a TCAS encounter in RVSM where the separation would potentially be reduced to 1,000 feet. 
Level-off encounter	Encounter where at least one aircraft in vertical evolution is getting steady at some flight level, separated by more than 2,000 feet in CVSM, and 1,000 feet in RVSM, from the other aircraft. The figure below (see Appendix A for display explanations) is an example of a level-off at FL290 issued by ATC for separation from another aircraft flying level above at the next available FL (i.e. FL310 in CVSM and FL300 in RVSM). 

Nuisance Alert	A TCAS alert (TA or RA) is defined as a nuisance if normal standard ATC separation is not clearly lost (i.e. the horizontal separation exceeds 5 NM, or the vertical separation without the TCAS contribution exceeds 2,000 feet in CVSM and 1,000 feet in RVSM, with a 200 feet tolerance). It should be noted that the definition of nuisance alerts is only related to the loss of ATC separation, and does not necessarily mean a low risk of collision. For example, the TCAS II alerts issued during a level-off encounter are nuisance alerts for air traffic controllers, but they are sometimes qualified as useful alerts by pilots.

1 Introduction

1.1 Objectives

1.1.1.1 In view of the implementations of ACAS ('Airborne Collision Avoidance System) and of RVSM ('Reduced Vertical Separation Minima') in Europe, the purpose of the ACAS/RVSM interaction study was to ascertain:

- Whether there are any significant operational implications for ACAS II performance due to European RVSM implementation, and also,
- Whether the benefits expected from RVSM could be compromised due to the operation of ACAS II.

1.1.1.2 The study was to focus not only on technical issues, but also on identifying potential operational issues and providing recommendations.

1.2 Background and context

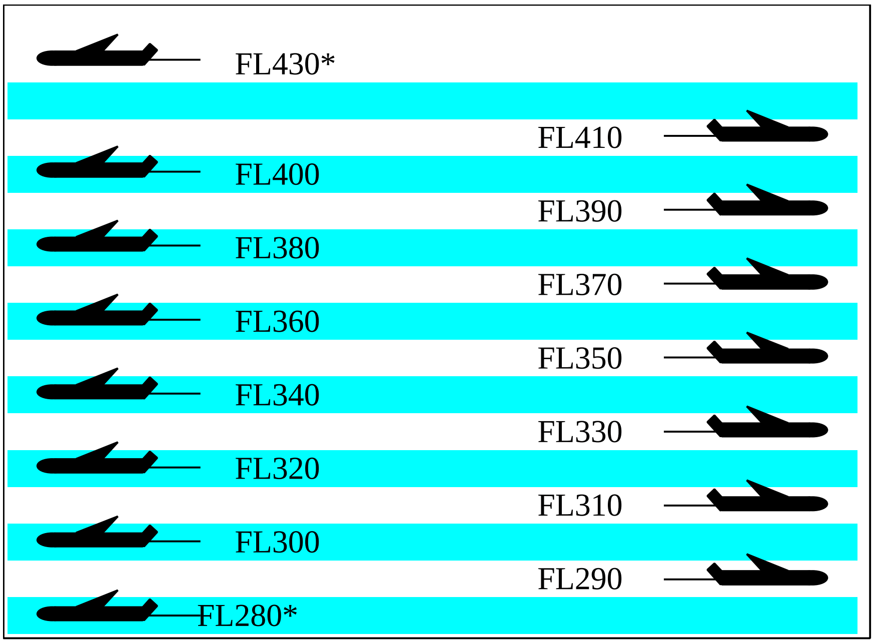
1.2.1 ACAS and RVSM in Europe

1.2.1.1 The carriage and operation of ACAS II is mandatory in Europe from 1st January 2000 for all civilian aircraft with more than 30 passenger seats or more than 15,000 kg. The mandatory carriage of ACAS II for aircraft with more than 19 passengers or more than 5,700 kg is only applicable from 1st January 2005.

1.2.1.2 Due to the late availability of the ACAS II compliant equipment TCAS II ('Traffic Alert and Collision Avoidance System') version 7.0, an ACAS II implementation transition period is scheduled from 1st January 2000 until 31 March 2001. During this transition period, aircraft fitted with TCAS II version 6.04a will continue to operate in Europe

1.2.1.3 The implementation of RVSM in European RVSM airspace between FL290 and FL410 is planned for January 2002. At this date, the RVSM of 1,000 feet will be applied between RVSM MASPS ('Minimum Aircraft System Performance Specification') approved aircraft.

1.2.1.4 Regarding the orientation and application of the RVSM levels, the single alternate FLOS ('Flight Level Orientation Scheme') configuration will be implemented in accordance with ICAO Annex2, Appendix 3.



* non-RVSM level

Figure 1: Cruising flight levels in European RVSM airspace

1.2.2 Previous ACAS/RVSM studies

1.2.2.1 The ACAS community had already started to work on ACAS and RVSM interaction. However, with one exception [Hag96] the work done only concerns the NAT RVSM area, where the majority of aircraft are flying in the same direction and are operating in broadly the same speed range.

1.2.2.2 Some working and information papers have been presented to ICAO SICASP (‘SSR Improvements and Collision Avoidance Systems Panel’) WG 2 (‘Working Group’). According to these initial studies, the two main conclusions were that:

- TCAS II (‘Traffic Alert and Collision Avoidance System’) version 6.04a is not compatible with RVSM [Cas95] and,
- it was not possible to draw any firm conclusions about TCAS - RVSM operations from operational experience to date [Mat97].

1.2.2.3 In particular, the issues related to repeated TAs (`Traffic Advisories’) and to nuisance RAs (‘Resolution Advisories’) have been highlighted. The importance of specific pilot training [Til96] has also been underlined.

1.2.2.4 Furthermore, these previous studies have shown the interest of using several sources of data: real-time simulation data [Hag96], artificial data [Cas95] & [Car96a], adapted radar data [Car96b] & [Lub96] and - TCAS recorder data from NAT RVSM operations [Mat97].

1.2.3 ACASA project

1.2.3.1 The TEN (‘Trans European Network’) / ACASA (‘Airborne Collision Avoidance Systems Analysis’) project investigates several areas related to ACAS II operations in Europe [WP001].

1.2.3.2 The ACASA/WP3 (‘Work Package’) is dedicated to the study of ACAS/RVSM interaction in continental Europe. Indeed, the European RVSM airspace was considered as a more ‘hostile’ operating environment for ACAS than the NAT, and thus meriting particular attention.

1.2.3.3 From the early stage of the ACASA project, the scope of the ACAS/RVSM interaction study was:

- To only investigate the single alternate FLOS configuration;
- To concentrate on the continental RVSM, and not to investigate the RVSM / non-RVSM transition area.

1.2.3.4 The study was intended to address neither non-MASPS aircraft nor military aircraft. Indeed, only the MASPS compliant aircraft will use the RVSM of 1,000 feet and should have an impact on the overall performances of ACAS II in Europe.

1.2.3.5 It was decided to analyse the impact of aircraft fitted not only with TCAS II version 7.0, but also with version 6.04a, as a pre-operational RVSM implementation was envisaged between years 2000 and 2002. Besides, RVSM MASPS compliant aircraft not subject to the European mandatory carriage of ACAS II until 2005, but potentially equipped with version 6.04a, will be allowed to fly within the European RVSM airspace by the beginning of 2002.

1.2.3.6 The ACASA partners involved in this study are : EEC (‘Eurocontrol Experimental Centre’), DERA (‘Defence Evaluation Research Agency’) and CENA (‘Centre d'Etudes de la Navigation Aérienne’) which has the leadership on WP3.

1.3 Scope of the document

1.3.1.1 All ACAS/RVSM interaction studies planned for WP3 of the ACASA project have been completed. This final report is based on the results of all of them

1.3.1.2 The methodology and tools used in these different studies are described in section 2. The third section deals with the hypothesis and results of the ACAS simulations based on each specific source of data. The main features of ACAS and RVSM interaction are discussed in section 4. This report ends with some concluding remarks about the study and recommendations prior to the simultaneous ACAS and RVSM operations in Europe.

2 Methodology and tools

2.1 Approach overview

2.1.1.1 This study of ACAS/RVSM interaction in Europe is based on different sources of data:

- **Modified radar data**;
- Data extracted from **real-time simulations**;
- Non-automatic **artificial encounters**,
- Automatic **artificial encounters**
- Data extracted from **fast-time simulations**.

Note: An encounter is an air traffic situation involving two or more aircraft, and potentially generating an ACAS alert (either TA or RA).

2.1.1.2 The rationale for using different sources of data to investigate the ACAS/RVSM interaction was to compensate the limitations related to each source of data, and to cope with a larger set of issues.

2.1.1.3 Indeed, the study was intended to address both safety and operational issues, for each source of data. In particular, the following items have been identified as issues meriting study in an European RVSM environment, but they are not necessarily exclusive:

- the 1,000 ft level-off geometry,
- the occasional incompatibility between RAs and ATC clearance,
- the altitude station keeping, and more generally,
- the nuisance TCAS II alerts.

2.1.1.4 The main principle of the study [WP002] was to perform, for each source of data, a pair-wise comparison of the ACAS performances within the future RVSM environment and the current CVSM ('Conventional Vertical Separation Minima') environment, based on the same level of traffic.

2.1.1.5 For that purpose, ACAS simulations with different scenarios of TCAS II equipage were run for both CVSM and RVSM traffic samples obtained from the various sources of data. At the outcome of these ACAS simulations, a large set of ACAS performance indicators were analysed in order to highlight potential improvements or drawbacks in terms of **safety**, **pilot acceptance**, and **compatibility with ATC** above FL290 in Europe.

2.2 Different sources of data

2.2.1 Modified radar data

2.2.1.1 European radar data have been used both to assess the impact of RVSM on ACAS performances on the [FL290; FL410] layer, and to make a comparison between the current situation below FL290 and the future situation (after RVSM introduction) above FL290.

2.2.1.2 The advantage of radar data was to provide realistic aircraft trajectories that nevertheless needed to be MASPS compliant in order to be taken into account in the study. The amount of radar data recordings was also greater than that that could be extracted from real-time simulation archives.

2.2.1.3 Nevertheless, the use of current radar data to simulate the future RVSM traffic implied the modification of the original radar data, and in particular, the reduction of the vertical separation from 2,000 feet to 1,000 feet when required. Such approach had some limitations, the major one being that the behaviour of air traffic controllers was assumed similar in both CVSM and RVSM environments.

2.2.2 Real-time simulation data

2.2.2.1 Continental RVSM real-time simulations provided data for both the current and future Vertical Separation Minima in Europe. The original traffic samples were created from real traffic samples supplied by the participating ATC Centres. These traffic samples were also adjusted to represent increased traffic loads that could be met in the future RVSM airspace.

2.2.2.2 The main advantage expected from real-time simulations was to take into account the behaviour of air traffic controllers. Of course, due to the training issues related to each new ATC improvement like RVSM, the real time simulations may not necessarily reflect the actual controllers’ behaviour in future RVSM operations.

2.2.2.3 An anticipated limitation of real-time simulations was that they represent a few hours of ATC, and specific ATC sectors, due to the expensive cost of such simulations. Besides, due to the simplified flight trajectories used in simulations, the introduction of trajectory deviations were required in order to obtain more realistic aircraft trajectories to be used in the ACAS simulations. The trajectory deviation model was pessimistically designed to maximise the number of encounters and look at the worst case interactions between ACAS and RVSM.

2.2.3 Non-automatic artificial encounters

2.2.3.1 A small set of artificial encounters representative of situations that could generate ACAS alerts in the European RVSM airspace, has also been defined. This approach had already been used for the introduction of RVSM in the Northern Atlantic.

2.2.3.2 This qualitative set of encounters had been used to allow identifying issues related to the introduction of continental RVSM, and to analyse in deeper details the ACAS and RVSM interaction based on relevant situations. Of course, such approach was not expected to provide any quantitative assessment of the impact of RVSM on ACAS performances.

2.2.4 Automatic artificial encounters

2.2.4.1 In order to study the ACAS/RVSM interaction in Europe, it had been proposed to develop a theoretical encounter model for the future European RVSM airspace.

2.2.4.2 Such theoretical safety encounter model could have been derived from fast-time simulation data, real-time simulation data or existing radar data, as far as these data allow identifying the relevant conflict situations specific to the European RVSM airspace. The option taken in this study was to derive an RVSM safety encounter model from the existing CVSM safety encounter model (built in ACASA Work Package 1 from European radar data). The idea was to apply to the CVSM encounter model the differences found between CVSM and RVSM real-time simulations.

2.2.4.3 The most obvious alternative strategy was to build the two models, for CVSM and RVSM, directly from the simulation data. This was not favoured for two reasons: it was feared that the details of the encounters in the simulations would be insufficiently realistic; and it was feared that there would be insufficient encounter data to build the encounter models. In the event, there were sufficient encounters, the models were built and risk ratios were calculated from them. The results are consistent with those reported here for the preferred strategy described in the previous paragraph. However, for many reasons, this approach is still considered less reliable than that first chosen.

2.2.4.4 The main advantage of a theoretical encounter model for RVSM would be to study the ACAS/RVSM interaction based of a huge set of encounters, and in particular to address the potential safety issues related to ACAS in the RVSM environment. Of course, the confidence one can have in the results obtained using the model depends on the amount of input data and the soundness of the method used to build the model.

2.2.5 Fast-time simulation data

2.2.5.1 Fast-time simulation data were collected through fast-time simulations performed at the Eurocontrol Experimental Centre using RAMS (‘Reorganised ATC Mathematical Simulator’). Such fast-time simulator allows simulating an ATC environment in which simulated traffics follow their flight plans under simulated air traffic control.

2.2.5.2 Usually, fast-time simulators are used to study new airspace structure based on large traffic samples. Due to non-availability of both CVSM and RVSM fast-time simulation data, the traffic samples used in the study were the same as those used for the real-time simulations, and as such, were limited to a small set of flight plans.

2.2.5.3 It was also necessary to enable the ATC conflict detection and resolution in order to perform the ACAS simulations on controlled flights. Unfortunately, the ATC behaviour provided by such fast-time simulators could not be considered as realistic as that obtained in real-time simulations. And, this is particularly the case for new ATC concepts like RVSM, which may have an impact on the methods of air traffic control.

2.3 ACAS simulation scenarios

2.3.1 General

2.3.1.1 For each source of data (except in the study based on non-automatic artificial encounters), total of six scenarios were run three each for CVSM and RVSM. The three basic scenarios differed in the relative proportions of TCAS II equipage and in the altitude reporting quantization.

2.3.1.2 Although the original data used in the study might also have included aircraft flying at altitudes below FL290, only those encounters involving TCAS alerts between FL290 and FL410 were considered in the ACAS simulation analyses. Besides, only MASPS compliant aircraft trajectories were considered in the ACAS simulations.

2.3.2 TCAS II equipage

2.3.2.1 The following three TCAS II equipage scenarios have been investigated:

- **Scenario #1:** Whole TCAS II fleet fitted with version 7.0
- **Scenario #2:** Mixed TCAS II fleet fitted with version 7.0 (90%) and version 6.04a (10%);
- **Scenario #3:** Whole TCAS II fleet fitted with version 6.04a.

2.3.2.2 Each scenario was composed of a similar proportion of aircraft fitted or not with TCAS II. The proportion of aircraft flying at high altitude and not subject to the European mandatory carriage of ACAS II before 2005 was estimated to be around 10%.

2.3.2.3 It was anticipated that most of the TCAS aircraft within RVSM airspace will be fitted with an ADC ('Air Data Computer'). Therefore in each scenario, the TCAS aircraft will supply its logic with the finest own altitude quantization (i.e., one foot).

2.3.2.4 Each scenario was also composed of a similar proportion of aircraft reporting altitude in 25-ft increments. Based on preliminary statistics about Mode S equipped aircraft in Europe, this proportion was set to 50%.

Note: It should be noted that, for aircraft fitted with TCAS II version 6.04a, the intruder altitude has been supplied to the TCAS logic with a 100-ft quantization whatever the report quantization, because no 25-ft vertical tracker is included in TCAS II version 6.04a.

Proportions	No TCAS 25ft	No TCAS 100 ft	Version 7.0 25 ft	Version 7.0 100 ft	Version 6.04a 25 ft	Version 6.04a 100 ft
Scenario #1	5%	5%	45%	45%	0%	0%
Scenario #2	5%	5%	40.5%	40.5%	4.5%	4.5%
Scenario #3	5%	5%	0%	0%	45%	45%

Table 1: Scenarios of aircraft TCAS II equipage

2.3.2.5 A standard pilot model [SARPS] conformed to the SARPS for ACAS II was applied to TCAS equipped aircraft.

2.3.3 MASPS compliant aircraft

2.3.3.1 An aircraft trajectory was considered as MASPS compliant [TGL_6] if:

- The TVE (‘Total Vertical Error’) is lesser than 190 feet;
- The altitude is controlled within ±65 feet when the aircraft is operated in straight and level flight. This threshold can go up to ±130 feet under specific conditions.
- When changing levels, the aircraft does not overshoot or undershoot the supposed flight level by more than 150 feet.

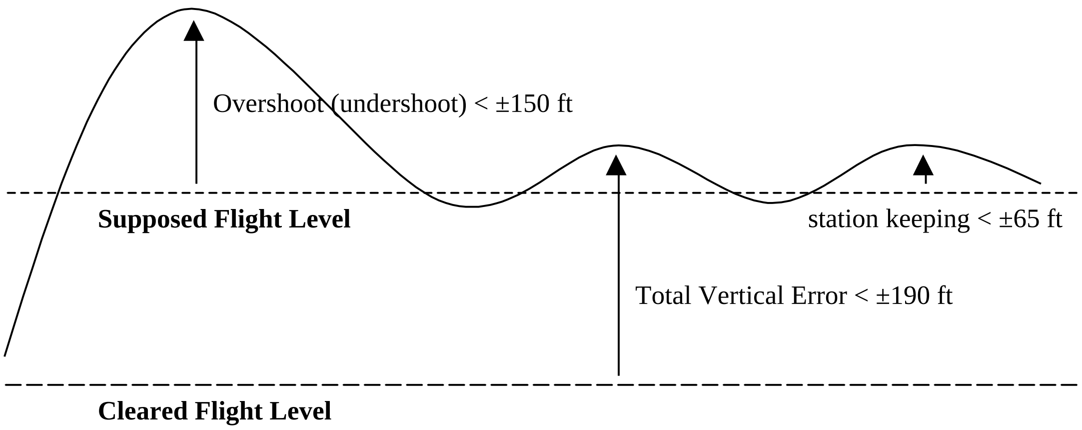


Figure 2: MASPS compliant trajectory

2.3.3.2 In the modified radar data simulations, trajectories of a level aircraft involving vertical variations of up to ±130 feet were kept when selecting encounters extracted from radar data.

2.3.3.3 In the real-time and fast-time simulations, a vertical deviation model was introduced, which can alter vertical trajectories by adding oscillations of up to 130 ft.

2.4 ACAS performance indicators

2.4.1 General

2.4.1.1 The various ACAS performance indicators used in the study was split into three sets: safety, pilot acceptance, and compatibility with ATC. However, it should be noted that some indicators are not specifically related to only one kind of issues.

2.4.1.2 On one hand, it was anticipated that each performance indicator is not necessarily relevant. On the other hand, the list of performance indicators should not be considered exhaustive enough to cope with specific potential issues.

2.4.1.3 These ACAS performance indicators were proposed for encounters involving only two aircraft, and only one TCAS alert by aircraft were considered during an encounter.

2.4.2 Safety indicators

2.4.2.1 The potential safety issues were addressed through the analysis of specific RAs such as: RAs not providing sufficient vertical separation despite a standard pilot reaction, non-initial RAs that are opposite to the aircraft trajectory.

2.4.2.2 The whole set of performance indicators related to safety consisted in:

- the number of RAs without provision of version 7.0 ALIM at CPA (i.e., 600 ft) despite a standard pilot reaction;
- the number of subsequent RAs which are opposite to the aircraft trajectory (i.e., an RA to climb when the aircraft was descending (VS < -300 fpm) at the time of the initial RA and vice versa);
- the number of increase rate RAs;
- the number of RAs during which the sense of the RA is reversed;
- the distribution of encounters without TCAS contribution versus VMD (‘Vertical Miss Distance’) at CPA (‘Closest Point of Approach’) in 100 ft bins and HMD (‘Horizontal Miss Distance’) at CPA in 1 NM bins;
- the distribution of encounters with TCAS contribution versus VMD at CPA in 100 ft bins and HMD at CPA in 1 NM bins.

2.4.3 Pilot acceptance indicators

2.4.3.1 The pilot acceptance issues were addressed through the analysis of both:

- The **RAs characteristics** in both CVSM and RVSM simulations. In particular, positive RAs (climb or descend RAs) or RAs that are opposite to the aircraft trajectory can be used to assess the potential stress caused to pilots by ACAS;
- The **occurrences of TAs** issued by the TCAS II logic in CVSM compared to RVSM simulations. Indeed, the number of TAs can be used to quantify the disruption caused to pilots by ACAS, particularly when the traffic advisories are not followed by any resolution advisory.

2.4.3.2 The whole set of ACAS performance indicators related to pilot acceptance consisted in:

- the number of RAs qualified as crossing by the TCAS logic;
- the number of positive RAs (climb or descend RAs);
- the number of initial RAs which are opposite to the aircraft trajectory (i.e., an RA to climb when the aircraft is descending (VS < -300 fpm) and vice versa);
- the number of split RAs;
- the number of RAs with more than two advisories in the sequence;
- the number of TAs;
- the distribution of TAs versus HMD at CPA in 1 NM bins;
- the number of nuisance TAs when the own aircraft is level (|VS| < 300 fpm) at the time the TA is first issued;
- the number of nuisance TAs when the own aircraft is non-level (|VS| > 300 fpm) at the time the TA is first issued;
- the number of repetitive TAs;
- the average of TA duration;
- the average of TA duration for the 10% longest TAs.

2.4.4 Indicators of compatibility with ATC

2.4.4.1 The compatibility of ACAS alerts with ATC was studied through the comparison between the occurrences of RAs in both CVSM and RVSM simulations. Particular attention was paid to the number of **nuisance RAs, particularly for level-off geometry**.

2.4.4.2 An RA was considered a nuisance if normal standard ATC separation were not clearly lost (i.e., if the separations without a TCAS contribution exceed 5 NM or 1,000 ft) at some point in the encounter. With the CVSM environment, the vertical separation threshold will be set to 2,000 ft instead of 1,000 ft. For both environments, a 200-ft tolerance on the vertical separation threshold was used.

2.4.4.3 A level-off encounter was defined as an encounter where at least one aircraft in vertical evolution is getting steady at some flight level, separated by more than 2,000 feet in CVSM, and 1,000 feet in RVSM, from the other aircraft.

2.4.4.4 It should be noted that the definition of nuisance RAs is only related to the loss of ATC separation, and does not necessarily mean a low risk of collision. For instance, in case of aircraft in vertical evolution, RAs triggered before a level-off manoeuvre 1,000 feet apart another aircraft are sometimes qualified as useful RAs by pilots. Such RAs for level-off geometry are nevertheless considered as nuisance alerts by air traffic controllers.

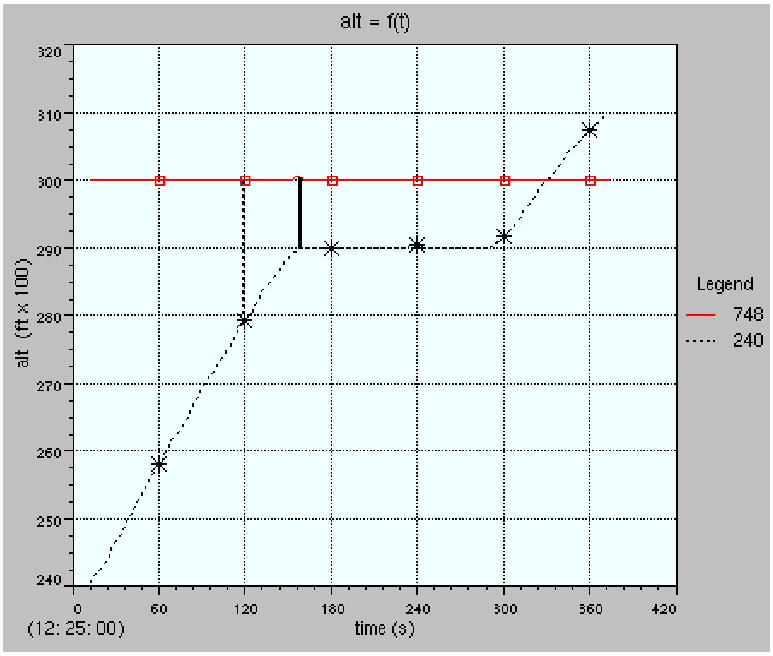


Figure 3: Level-off encounter between aircraft at adjacent flight levels

2.4.4.5 The whole set of ACAS performance indicators related to compatibility with ATC consisted in:

- the number of RAs;
- the number of RAs for level-off geometry only;
- the distribution of RAs versus HMD at CPA in 1 NM bins;
- the number of nuisance RAs when the own aircraft is level (|VS| < 300 fpm) at the time the RA is first issued;
- the number of nuisance RAs when the own aircraft is non-level (|VS| > 300 fpm) at the time the RA is first issued;
- the number of nuisance RAs for level-off geometry only;
- the distribution of RAs versus vertical deviation (> 0 ft) in 300 ft bins;
- the average of vertical deviations (> 0 ft);
- the average of vertical deviations (> 0 ft) only for level-off geometry;
- the number of RAs with incompatible sense selection (i.e., an RA which can disrupt ATC or the normal operation of the aircraft by inverting the vertical separation of two aircraft);
- the average of RA duration;
- the average of RA duration for the 10% longest RAs.

2.4.4.6 The deviations were computed as specified in [Ari98]. A box is modelled between the points at which the aircraft deviates from and then resumes its original flight path. A positive deviation was only considered if the modified flight path goes outside the box (an aircraft that is limiting its rate of descent or climb does not deviate from its original flight path in the ATC general sense).

2.5 ACAS simulation tools

2.5.1.1 The execution and analysis of the ACAS simulations were conducted using the available tools in each ACASA partner's organisation. These tools included InCAS ('Interactive Collision Avoidance Simulator') and the ACAS Server at the EUROCONTROL Experimental Centre, and the OSCAR ('Off-line Simulator for Collision Avoidance Resolution') test bench [OSCAR] at CENA.

2.5.1.2 These ACAS simulation tools are a set of integrated tools to prepare, execute and analyse scenarios of encounters involving TCAS II equipped aircraft. They include an implementation of the TCAS II logic version 6.04a and 7.0 conformed to the MOPS. The TCAS II logic version 7.0 also includes RWG approved changes 1 to 92 and 98.

2.5.1.3 The execution of an ACAS simulation means:

- For each TCAS II equipped aircraft, the performance of the ACAS computations and co-ordination mechanism, as well as, the simulation of the pilot response to the advisories issued by the ACAS logic.
- Recording of the ACAS simulation results for further analysis, in particular, the computation of the ACAS performance indicators.

2.5.1.4 The ACAS simulation tools also include a set of facilities to display the encounters and scenarios, to replay the encounters and to visualise the scenario results in a graphical and textual way.

3 ACAS simulations and results

3.1 Introduction

3.1.1.1 The following sections present and illustrate the most significant results obtained during the study of ACAS/RVSM interaction using the various sources of data [WP056] & [WP057] & [WP110] & [WP111].

3.1.1.2 For each source of data (except for automatic artificial encounters), the simulation results are used to make a comparison between :

- The current situation in the [FL290; FL410] layer (labelled CVSM) and;
- The future situation in the [FL290; FL410] layer (labelled RVSM).

3.1.1.3 Furthermore, the section dealing with modified radar data makes a comparison between:

- The future situation in the [FL290; FL410] layer (labelled RVSM) and;
- The current situation in the [FL250; FL295] layer (labelled below)

3.1.1.4 Finally, the simulation results for each scenario of TCAS II equipage (v6.04a, mixed versions and v7.0) are used to outline the impact of the TCAS II logic versions.

3.2 *Simulations based on modified radar data*

3.2.1 Data collection and preparation

European radar data

3.2.1.1 The European radar data used in the study are 16 days of radar data recordings including:

- Four days of multi-radar data from UK,
- Five days of multi-radar data from Maastricht, and
- Seven days of mono-radar data from France.

3.2.1.2 The figure below is an overview of the coverage of the overall radar data. The coloured tracks represent two hours (from 7am to 9am) of one day of UK, Maastricht and France radar data. The X,Y co-ordinates of the tracks, initially expressed in the local radar system using different projection, have been translated in the same reference to visualise roughly the European radar data coverage.

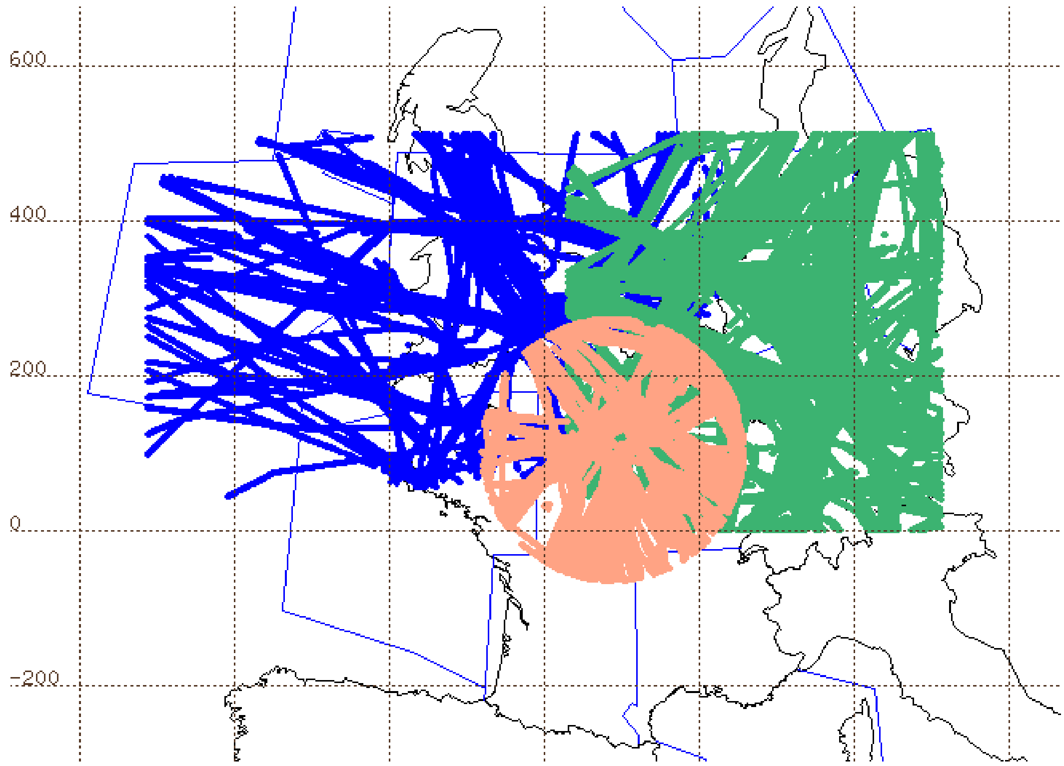


Figure 4: European radar data coverage

Extraction of encounters from radar data

3.2.1.3 Before the ACAS simulations, relevant encounters were extracted from radar data. These encounters involve pairs of aircraft whose geometry match some space and time-related parameters, which depend on the separation standard and the TCAS sensibility level applicable in the studied layer.

3.2.1.4 These encounters are not necessarily associated with a TCAS II alert, or a loss of ATC separation. But, they were defined so as to include all the encounters that could be associated with a TCAS alert in the RVSM environment (e.g. converging aircraft separated by 4,000 feet in CVSM could become a TCAS encounter in RVSM where the separation would potentially be reduced to 2,000 feet).

Modification of encounters extracted from radar data

3.2.1.5 Only for French radar data, the horizontal separation has been reduced for encounters with large HMD. The objective was to simulate the current (but not at the time of the radar data collection) horizontal separation standard of 5 NM in all simulations.

3.2.1.6 In the simulations where an RVSM environment was simulated, a strategy was designed to modify the flight level allocation in order to obtain a single alternate FLOS configuration, while not altering the flight profile and preserving the possible blunders. The following tables sum up this strategy.

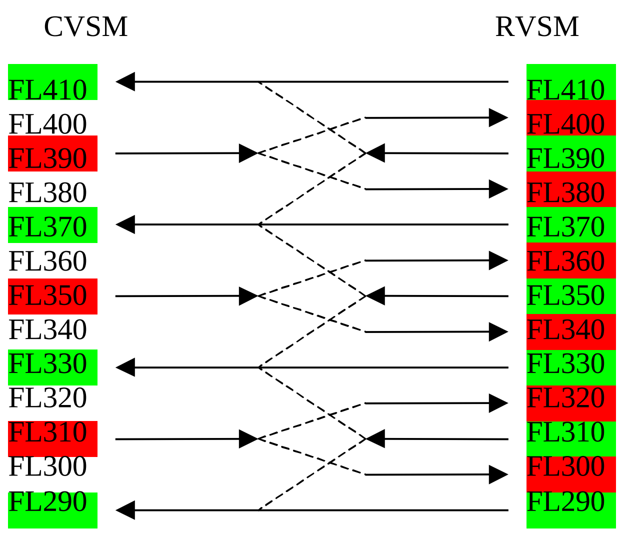


Figure 5: Flight level change strategy for RVSM

FL in CVSM	**FL in RVSM**												
	FL290	**FL300**	**FL310**	**FL320**	**FL330**	**FL340**	**FL350**	**FL360**	**FL370**	**FL380**	**FL390**	**FL390**	**FL410**
FL410											10%		90%
FL390										80%		20%	
FL370							20%		60%		20%		
FL350						60%		40%					
FL330			20%		60%		20%						
FL310		20%		80%									
FL290	40%		60%										

Table 2: Flight level changes probabilities for modified radar data study

3.2.1.7 The unresolved conflicts (i.e. losses of ATC separation) extracted from the radar data have been maintained in both the CVSM and RVSM simulations whatever the actual flight levels, in order to preserve the same level of ATC performances in both environments, and not to artificially modify it in the future RVSM environment.

3.2.2 Main results for [FL290; FL410] layer

3.2.2.1 The reader must be aware that the results of the scenarios ran under RVSM environment depend on the probabilities used for the flight level change strategy, which might turn out to differ from those used in these simulations when RVSM will be introduced. Also, some figures are to be taken carefully as the number of resolution advisories is not very large in some cases.

Occurrence of RAs

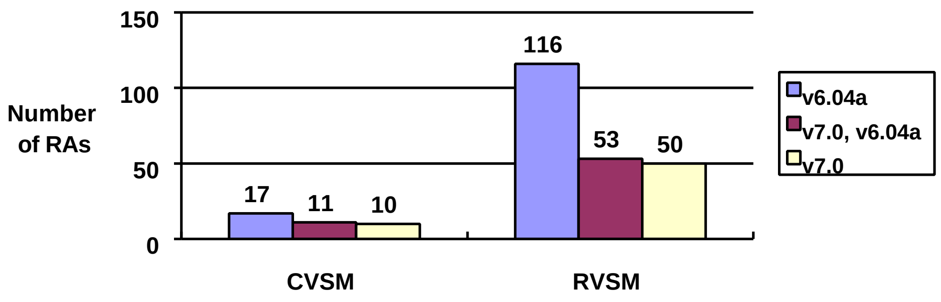


Figure 6: Occurrence of RAs (modified radar data)

3.2.2.2 The number of RAs is greater in RVSM than in CVSM scenarios, whatever the TCAS II logic version. The ratio of RAs between CVSM and RVSM is particularly high with the TCAS II logic version 6.04a with about 7 times more RAs in RVSM than in CVSM. **This ratio of RAs between CVSM and RVSM is reduced with the logic version 7.0, but there are still 5 times more RAs in RVSM than in CVSM**.

3.2.2.3 When compared to the TCAS II version 6.04a, the **version 7.0 produces an RA reduction rate** of 41% in CVSM, and up to 57% in RVSM. This contribution of the TCAS II logic version 7.0 is consistent with previous studies performed on the current European airspace [Ari98].

3.2.2.4 The average of RA duration is slightly reduced in RVSM when compared to CVSM, whatever the TCAS II logic version (from 27 seconds to 23 seconds with v7.0).

RAs during 1,000 ft level-off

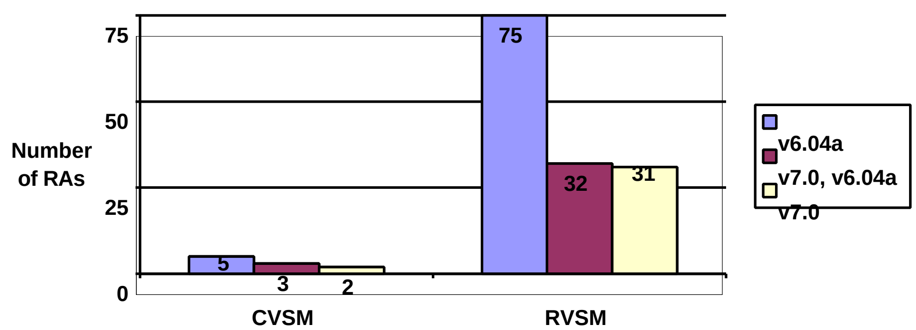


Figure 7: Occurrence of RAs for level-off geometry (modified radar data)

3.2.2.5 **The number of RAs for level-off geometry is significantly increased in RVSM, particularly with the TCAS II logic version 6.04a**. When compared to the number of RAs, the proportion of such RAs is much lower in CVSM than in RVSM, whatever the TCAS II logic version (from 29% to 67% with v6.04a, from 27% to 60% with mixed v6.04a/v7.0 and from 20% to 62% with v7.0).

3.2.2.6 In both CVSM and RVSM environment**,** the TCAS II logic version 7.0 provides the following benefits :

- **the number of RAs for level-off is significantly reduced with the TCAS II logic version 7.0** when compared to version 6.04a (60% in CVSM and 59% in RVSM). This more efficient behaviour of TCAS II version 7.0 in level-off geometry is consistent with the performances expected when designing the logic [Lov98].
- the proportion of level-off encounters which induce an RA for both aircraft is reduced (from 44% with v6.04a to 14% with mixed v6.04a/v7.0 or v7.0 in RVSM).
- the compatibility with the flight profile is improved, due to the logic's ability to issue an initial 'level-off' RA (i.e. Don't Climb or Don't Descend) instead of a positive RA (i.e. Climb or Descend RAs) in case of TCAS-TCAS encounters when the intruder has a modest vertical rate [Lov98].

<u>**Nuisance RAs**</u>

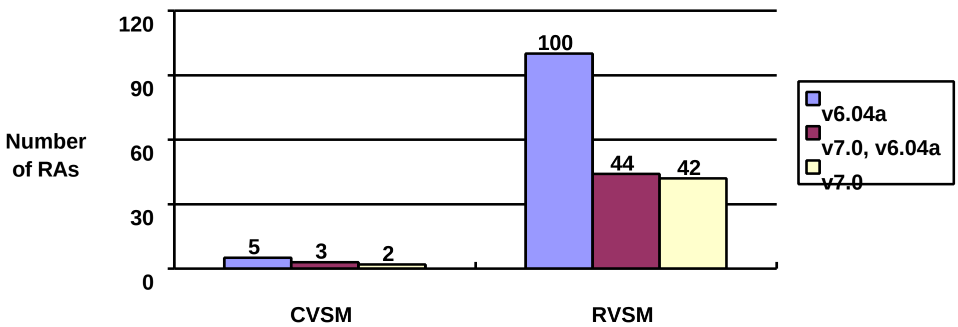


Figure 8: Occurrence of nuisance RAs (modified radar data)

3.2.2.7 The number of nuisance RAs is significantly increased in RVSM when compared to CVSM, particularly with the TCAS II logic version 6.04a. **The proportion of nuisance RAs is significantly increased from CVSM to RVSM, whatever the TCAS II logic version** (from 29% to 86% with v6.04a, from 27% to 83% with mixed v6.04a/v7.0 and from 20% to 84% with v7.0).

3.2.2.8 The proportion of nuisance RAs for level aircraft is slightly reduced with the TCAS II logic version 7.0 when compared to version 6.04a (e.g. from 21% to 12% in CVSM and from 76% to 53% in RVSM). This result is related to the reduction of the proportion of RAs for level-off geometry previously noticed with the TCAS II logic version 7.0.

Vertical deviations

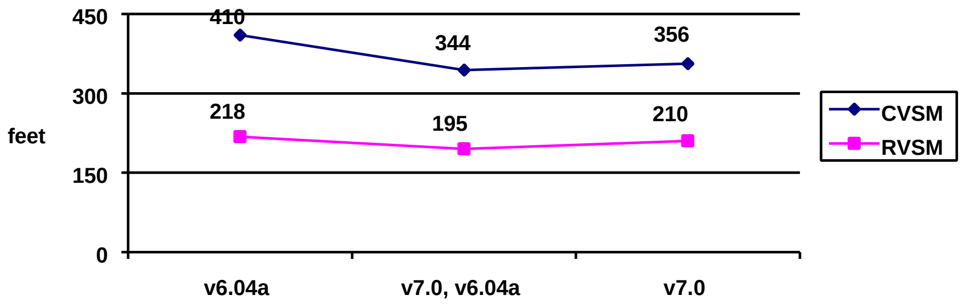


Figure 9: Average of vertical deviation (modified radar data)

3.2.2.9 **The greater proportion of useful RAs in CVSM induces a greater proportion of RAs with positive deviation than in RVSM**. For instance, the proportion of RAs causing vertical deviations of more than 300 feet is about two thirds of the RAs with positive deviation in CVSM, and less than 13% in RVSM whatever the TCAS II logic version. This explains the greater average deviation in CVSM.

3.2.2.10 In both CVSM and RVSM environment, the average of vertical deviation is lower with the TCAS II logic version 7.0 when compared to version 6.04a, particularly in case of level-off geometry. For instance in RVSM, the average of vertical deviation is reduced by 46% for level-off geometry, and only by 3% overall, when introducing the TCAS II logic version 7.0 instead of version 6.04a. These results highlight the greater ATC compatibility provided by the TCAS II version 7.0 in level-off geometry.

3.2.2.11 It shall be noted that operational deviations are usually higher than the deviations measured in this study since actual pilots' reaction is often less ideal than the one implemented by the standard pilot model.

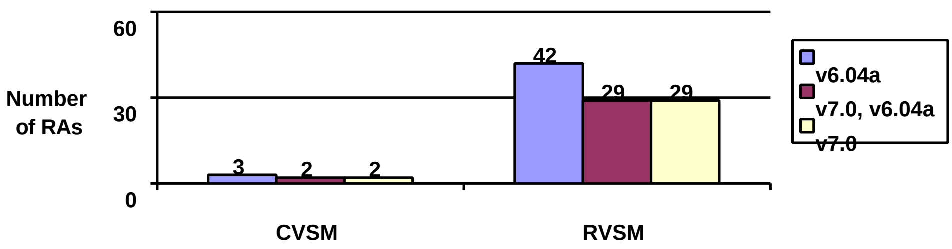


Figure 10: Occurrence of RAs with no deviation (modified radar data)

3.2.2.12 The low proportion of RAs with no deviations in CVSM (around 19% with all equipage scenarios) compared with those in RVSM is also explained by the greater proportion of useful RAs in CVSM. The positive impact of version 7.0 is shown by the increase of the proportion of RAs with no deviation in RVSM (from 30% to 51%). TCAS II logic version 7 is more compatible with ATC.

Occurrence of TAs

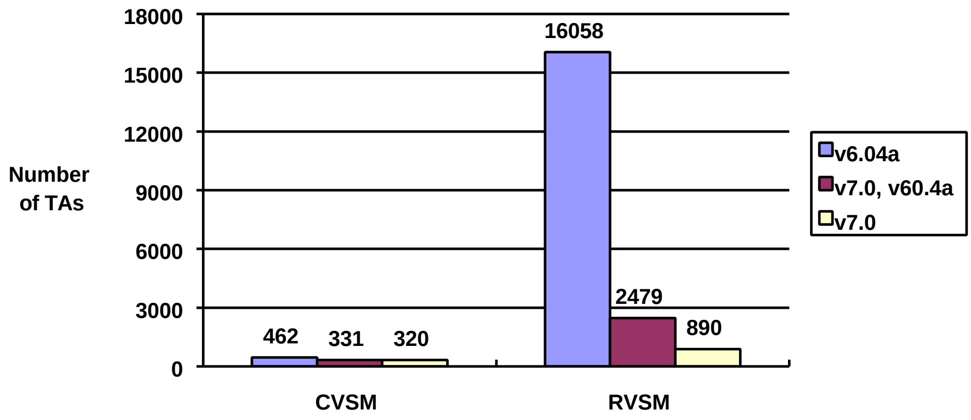


Figure 11: Occurrence of TAs (modified radar data)

3.2.2.13 The number of TAs is much greater in RVSM than in CVSM scenarios, whatever the TCAS II logic version. The ratio of TAs between CVSM and RVSM is particularly high with the TCAS II logic version 6.04 with about 35 times more TAs in RVSM than in CVSM. This ratio of TAs between CVSM and RVSM is reduced to less than 3 with the logic version 7.0.

3.2.2.14 Besides, the average of TA duration is greater in RVSM than in CVSM, particularly with the TCAS II logic v6.04a with only 20 seconds in CVSM, and up to 47 seconds in RVSM.

3.2.2.15 When compared to version 6.04a, **the TCAS II logic version 7.0 produces an TA reduction rate of 30% in CVSM, and up to 94% in RVSM**. This contribution of the TCAS II logic version 7.0 is mainly due to the reduction of the vertical detection threshold, which has been introduced for altitudes between FL300 and FL420 to support RVSM [Lov98].

Nuisance TAs

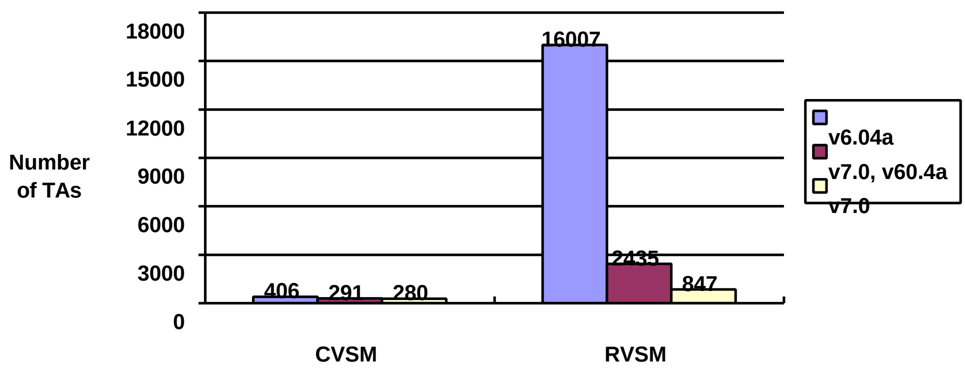


Figure 12: Occurrence of nuisance TAs (modified radar data)

3.2.2.16 The number of nuisance TAs is dramatically increased in RVSM when compared to CVSM with the TCAS II logic version 6.04a. Actually, when compared to the number of TAs, the proportion of nuisance TAs is very high in CVSM/RVSM whatever the TCAS II logic version (e.g. 87% in CVSM and 95% in RVSM with v7.0).

3.2.2.17 In CVSM, the proportion of nuisance TAs is similar for both versions of TCAS II logic, whereas in RVSM, this proportion is slightly reduced, but is still higher than in CVSM, with the logic version 7.0 (more than 99% with v6.04a, 98% with mixed v6.04a/v7.0 and 95% with v7.0).

Repetitive TAs

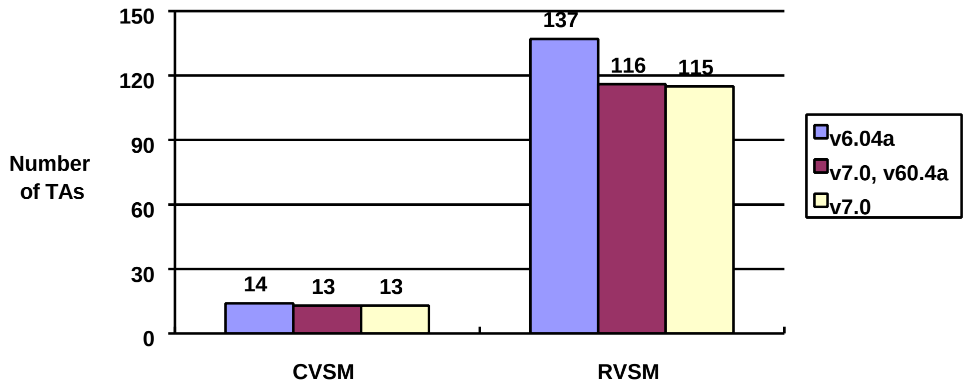


Figure 13: Occurrence of repetitive TAs (modified radar data)

3.2.2.18 The number of repetitive TAs is greater in RVSM than CVSM like the number of TAs. **With the TCAS II logic v7.0, the proportion of repetitive TAs grows up from 4 percent in CVSM to 12 percent in RVSM**. On the other hand, due to the high number of TAs, this proportion reduces from 3 to one percent with version 6.04a.

3.2.2.19 However, **the high proportion of repetitive TAs produced by the TCAS II version 7.0 needs to be further investigated and carefully monitored** as some changes have actually been made in the logic in order to reduce the likelihood of issuing such repetitive TAs.

Safety aspects

3.2.2.20 None of the ACAS performance indicators computed in the study revealed a safety issue. However, the total number of resolution advisories triggered in the ACAS simulations is small enough that such a rare event as one that highlights safety problems does not appear.

3.2.3 Comparison with current [FL250; FL290] layer

<u>Occurrence of RAs</u>

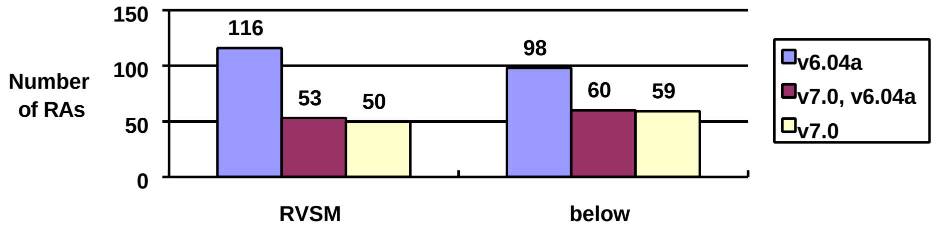


Figure 14: Occurrence of RAs (modified radar data)

3.2.3.1 Between the current situation below FL290 and the future situation above FL290, the number of RAs is quite similar. The slightly inferior reduction rate (40% versus 57%) achieved by TCAS II logic version 7.0 below FL290 seems to indicate that there are more useful RAs in this layer.

<u>RAs during 1,000 ft level-off</u>

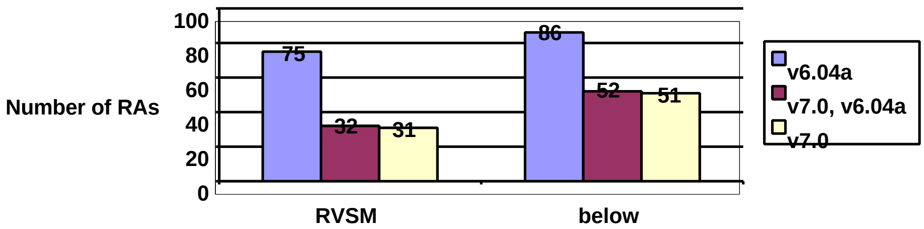


Figure 15: Occurrence of RAs for level-off geometry (modified radar data)

3.2.3.2 A higher number of RAs for level-off geometry occurs currently in the [FL250; FL290] layer than above, whatever the TCAS logic. Likewise, the proportion of RAs for level-off geometry is higher (87% versus around 65%). These figures reflect that below FL290 aircraft are more often in vertical evolution whereas the above layer is more occupied with cruising aircraft.

<u>Nuisance RAs</u>

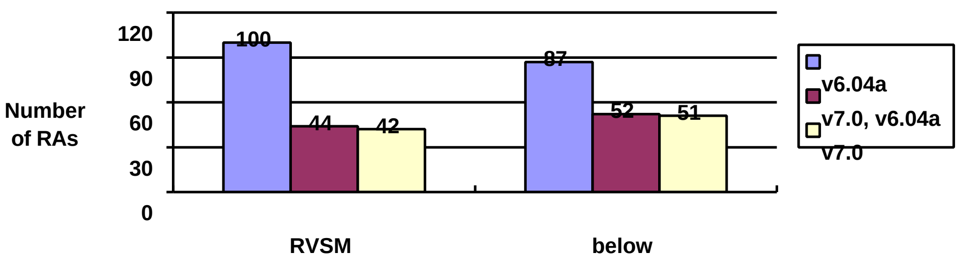


Figure 16: Occurrence of nuisance RAs (modified radar data)

3.2.3.3 The current proportion of nuisance RAs in the [FL250; FL290] layer is nearly equal to the expected proportion of nuisance RAs in the [FL290; FL410] layer (87% versus around 84%). It must be noted that the proportions of nuisance RAs and of level-off RAs are equal in the layer below FL290 because all level-off RAs are nuisance RAs.

Vertical deviation

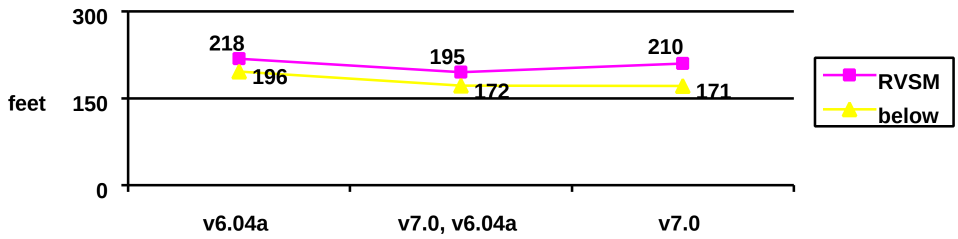


Figure 17: Average of vertical deviation (modified radar data)

3.2.3.4 The curve of average vertical deviation for the current situation below FL290 parallels the one for the expected situation above FL290, with a difference of 20 to 40 ft.

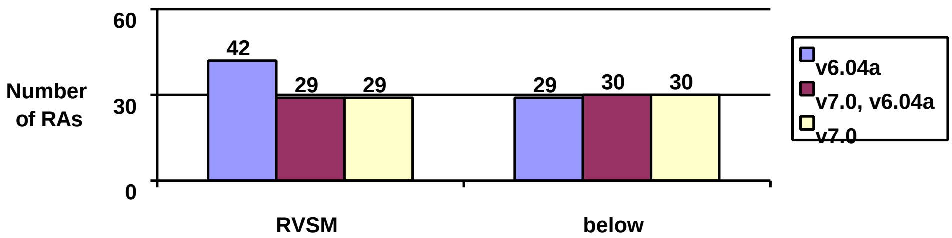


Figure 18: Occurrence of RAs with no deviation

3.2.3.5 In absolute numbers, the current situation below FL290 is identical to the future situation with TCAS II logic version 7.0. In percentiles, the current situation below FL290 (with v6.04a then) is worse than the future situation above FL290 (with v7.0) : 30% of RAs induce no deviation instead of 58%. However, the introduction of v7.0 below FL290 will equalise the situations, with a proportion of 51% of RAs with no deviation.

RA duration

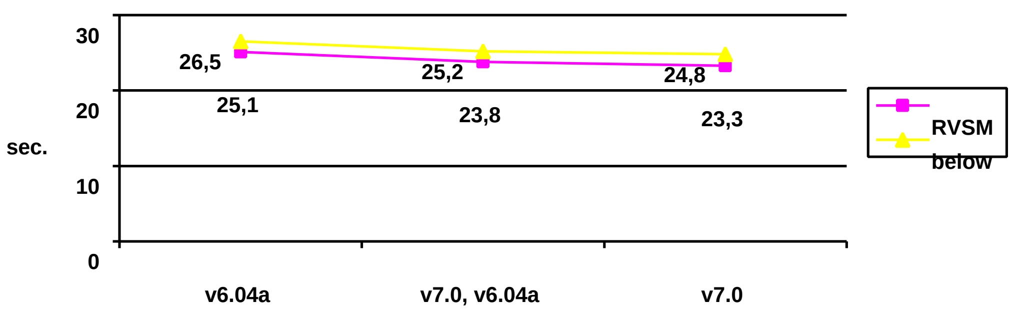


Figure 19: Average of RA duration (modified radar data)

3.2.3.6 The resolution advisories occurring currently below FL290 last around 1.5 seconds longer than those expected to occur above FL290, after the introduction of RVSM.

Characteristics of RAs

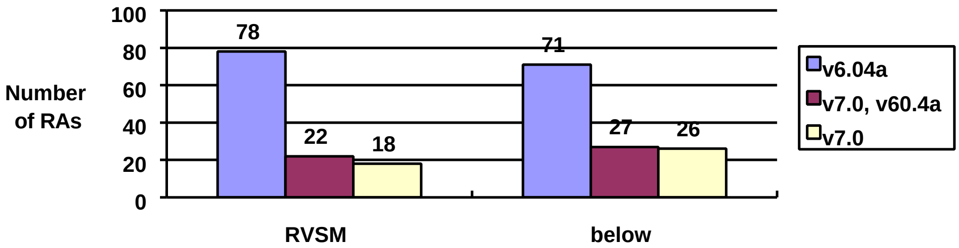


Figure 20: Occurrence of positive RAs (modified radar data)

3.2.3.7 Relatively to the total number of RAs, the proportions of positive RAs are not very different (67% versus 74% with v6.04a; 36% versus 46% with v7.0). The higher proportion below FL290 can be explained by the greater occurrence of situations where an RA is useful.

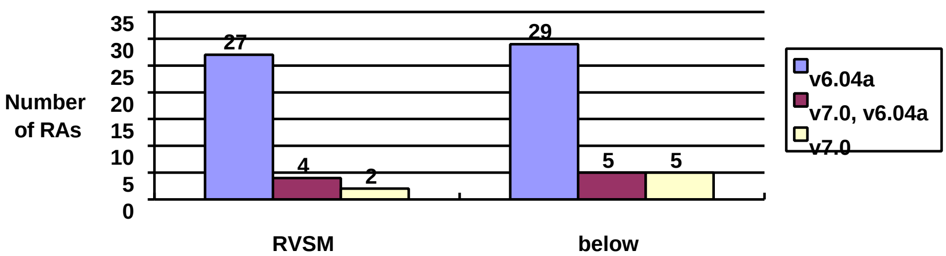


Figure 21: Occurrence of rate-reversing RAs (modified radar data)

3.2.3.8 As with the positive RAs, the proportions of rate-reversing RAs are a bit higher in the [FL250; FL290] layer (23% versus 30% with v6.04a; 4% versus 9% with v7.0)

3.2.3.9 Neither crossing RAs nor secondary RAs are found in both studies.

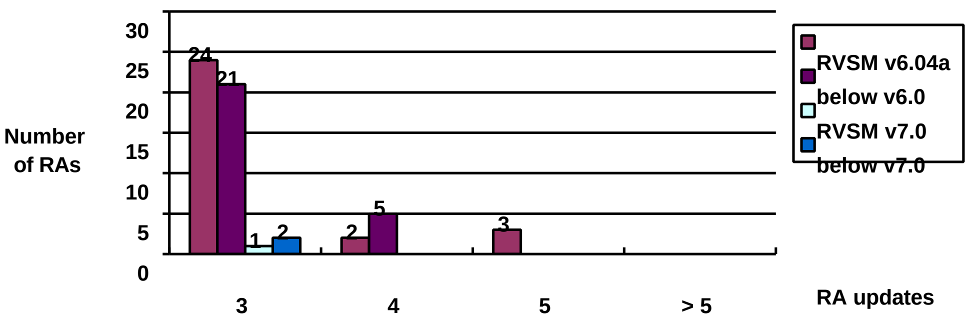


Figure 22: Occurrence of RAs with multiple advisories (modified radar data)

3.2.3.10 The proportions of RAs with multiple advisories are similar in both layers: around 26% have more than 3 advisories with v6.04a and only around 3% with v7.0.

Occurrence of TAs

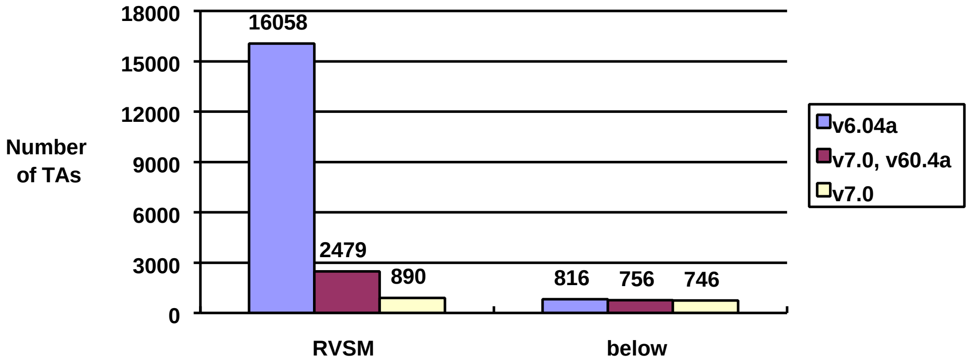


Figure 23: Occurrence of TAs (modified radar data)

3.2.3.11 The high number of TAs, which is expected in the RVSM environment with version 6.04a, does not exist currently below FL290 because the vertical detection threshold that version is inadequate only above FL290. When comparing both situations with version 7.0, there are only 16% more TAs with the introduction of RVSM.

Nuisance TAs

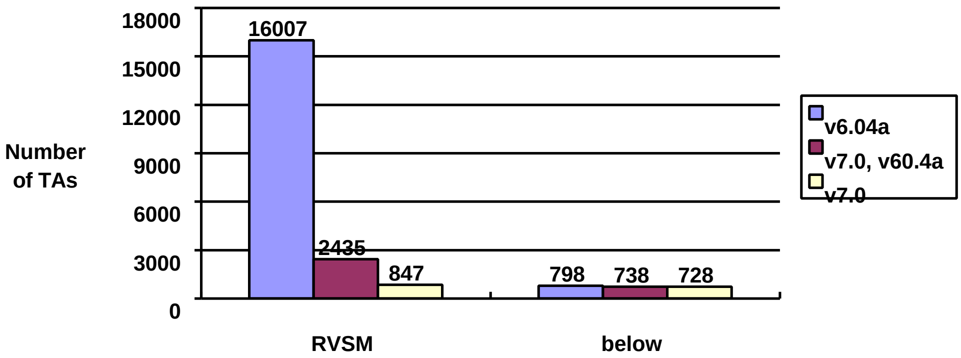


Figure 24: Occurrence of nuisance TAs (modified radar data)

3.2.3.12 Regarding v6.04a, the situation is the same as in the 'occurrence of TAs' section. Relatively to the total number of TAs, the proportion of nuisance TAs remains at 98% in the current situation below FL290, whatever the TCAS logic version, which is a close to the proportion expected above FL290 in the RVSM environment.

Repetitive TAs

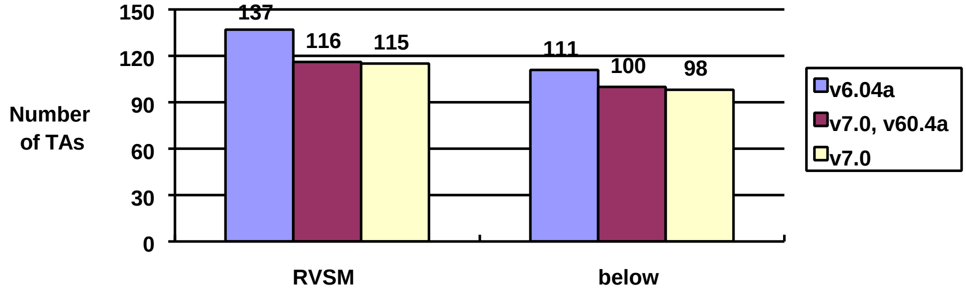


Figure 25: Occurrence of repetitive TAs (modified radar data)

3.2.3.13 Repetitive TAs exist also in the current situation below FL290 with the same proportion as expected in the RVSM environment (13%), at least with version 7.0. This is a well-known result for the layer below FL290.

TA duration

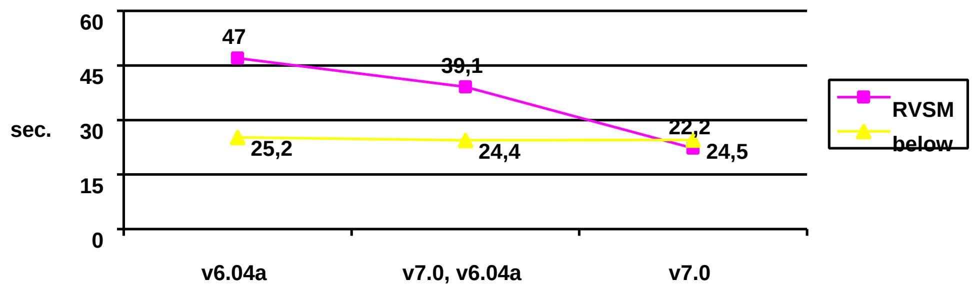


Figure 26: Average of TA duration (modified radar data)

3.2.3.14 Going from full v6.04a equipage to full v7.0 equipage, the average TA duration in the current [FL250; FL290] layer and in the future [FL290; FL410] layer converge to around 23 seconds. As with the average RA duration, the figure is slightly higher in the current situation below FL290.

3.3 Simulations based on real-time data

3.3.1 Data collection and preparation

<u>Third Continental RVSM simulation</u>

3.3.1.1 The data come from the Third Continental RVSM simulation [Lan97] that dealt with an area comprising ATC Centres from France, Germany, and Switzerland.

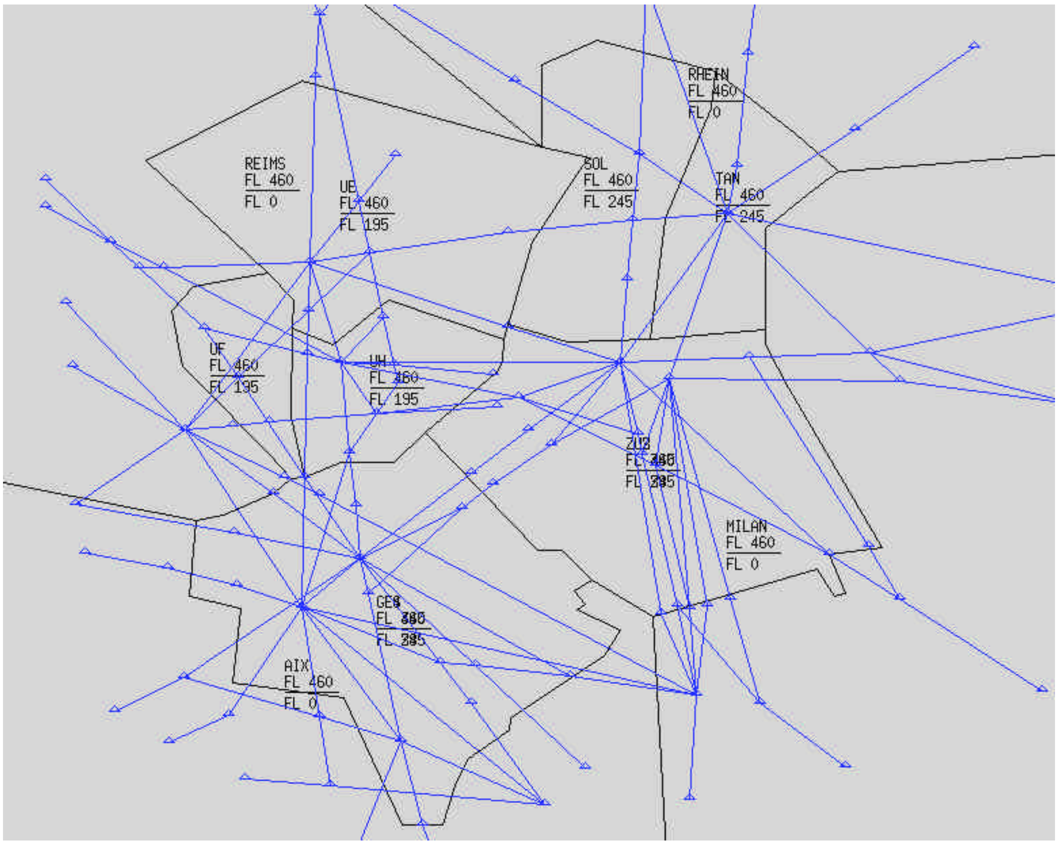


Figure 27: Sectors and route structure in the real-time study

3.3.1.2 The original CVSM traffic samples were created at the EEC. They were based upon a morning and afternoon traffic recording from Friday 24th May 1996 supplied by the participating ATCCs. A morning and afternoon traffic sample was created to reflect the traffic flow variation according to the time of day. The samples were then adjusted to include conflicting traffic situations within the measured sectors and to represent traffic loads equivalent to the 1996 published sector capacity +35%, +55%, and +65%.

3.3.1.3 The original RVSM Single Alternate traffic samples were created from the CVSM traffic samples. The flight levels were adjusted using the rules proposed by EUROCONTROL. The flights were chosen taking into account aircraft performance, and the distance of the flight.

3.3.1.4 Typically, each real-time simulation exercise lasted one hour and a half, during which all aircraft trajectories were recorded. These recorded trajectories form the starting point for the ACAS studies and are referred to as the "traffic samples" (which should not be confused with the "original" traffic samples, referred to above).

3.3.1.5 Traffic samples taken for this study were representative of 1996 + 35%, and +55% (the 65% traffic loading samples were not used since they were for RVSM only, and do not have corresponding CVSM exercises). Only exercises from Organisation 1 (sectorisation and route network in use as of November 1996) CVSM, and Single Alternate FLOS, were used. CVSM and RVSM exercises based on the same original traffic samples were taken to enable a pair-wise comparison. Table 1 lists the S08 real-time simulation exercises used for this study.

Exercise	**Recorded interval**	**VSM**	**1996 Traffic increased by**	**Total flight hours**	**Flight hours FL290-410**
210197A	0900:1030	CVSM	+35%	119	61
210197B	1100:1230	CVSM	+35%	109	55
210197C	1400:1530	CVSM	+35%	118	61
240197A	0900:1030	CVSM	+35%	108	56
240197B	1100:1230	CVSM	+35%	116	60
240197C	1400:1530	CVSM	+35%	110	58
060297A	0900:1030	CVSM	+55%	139	71
060297B	1100:1230	CVSM	+55%	137	70
220197A	0900:1030	RVSM	+35%	111	58
220197B	1100:1230	RVSM	+35%	116	61
220197C	1400:1530	RVSM	+35%	106	56
230197A	0900:1030	RVSM	+35%	113	58
230197B	1100:1230	RVSM	+35%	105	54
230197C	1400:1530	RVSM	+35%	109	56
290197B	1100:1230	RVSM	+55%	124	65
040297A	0900:1030	RVSM	+55%	130	68

Table 3: S08 simulation exercises used for the real-time study

3.3.1.6 At the beginning and end of a real-time simulation traffic levels were not representative of the target level. In addition, traffic enter and leave the main simulation area through feed-sectors, during which time they are not in controlled airspace and consequently are not realistically separated. Therefore, to avoid these effects, the first and last 15 minutes of each exercise were excluded from the study.

3.3.1.7 In the resulting traffic samples issued from the real-time simulations, it should be noted that:

- Aircraft are mainly in level flight. In RVSM, the traffic was, on average, only 8% of the time in vertical evolution, and only 7% of the time in CVSM.
- The occurrence of loss of ATC separation, between FL290 and FL410, was 54 (1 per 9 flight hours) in CVSM, and 27 (1 per 18 flight hours) in RVSM.

<u>Trajectory Error Model</u>

3.3.1.8 During the ACAS simulations a Trajectory Error Model in accordance with [WP043] was applied to the aircraft trajectories to render them more realistic. This model is outlined as follows:

- The altitude keeping error in straight and level flight is modelled by a sinusoid with period between 70 and 90 seconds. Its amplitude is a random value between 30 and 130 feet for older aircraft (pre 1997) and between 30 and 65 feet for newer aircraft.
- The altitude keeping overshoot error is modelled as a continuation of the climb/descent followed by a short period of level flight and then a return to correct altitude at 500 ft per minute. Its amplitude is a random value between 0 and 30 ft for older aircraft and between 0 and 95 ft for newer aircraft.
- 13% of the aircraft population are assumed to be newer aircraft with superior altitude keeping performance.

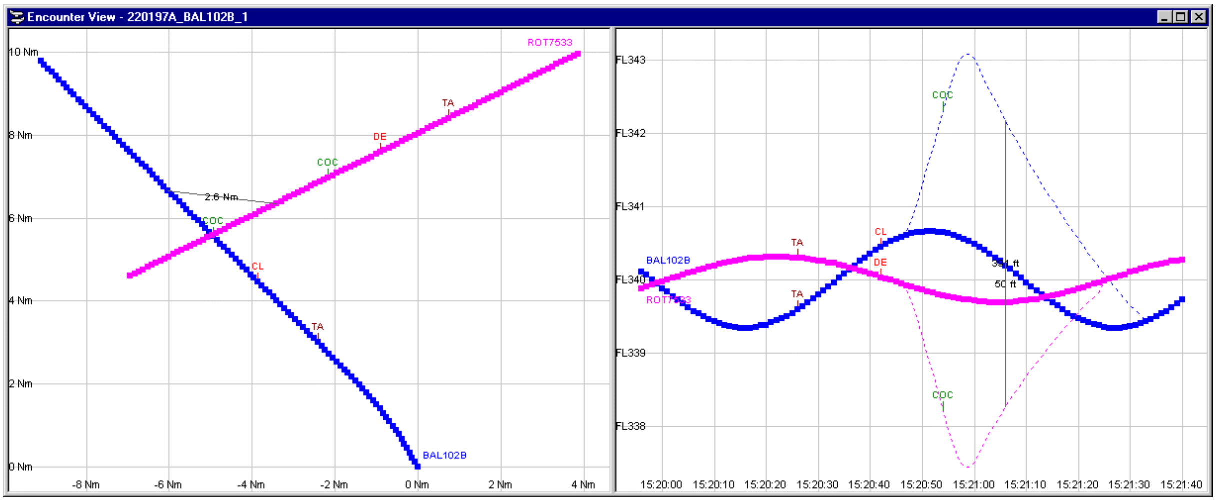


Figure 28: Illustration of the Trajectory Error Model (real-time simulation data)

3.3.1.9 Despite the somewhat pessimistic error model, the generated trajectories were still MASPS compliant.

3.3.2 Main Results

3.3.2.1 The following results were obtained from a combination of the ACAS simulation results based on the 35% traffic loading exercises (amounting to 343 flight hours in RVSM) and the 55% traffic loading exercises (amounting to 133 flight hours in RVSM).

3.3.2.2 Due to the lack of 55% traffic loading exercises, it was not relevant to breakdown the results obtained with the different traffic loading. Consequently, the effect of increased traffic loading on ACAS performance was not investigated.

3.3.2.3 Besides, due to the rather small number of flight hours included in the real-time simulations and due to the pessimistic trajectory error model, the reader must be aware that some figures are to be taken carefully.

Occurrence of RAs

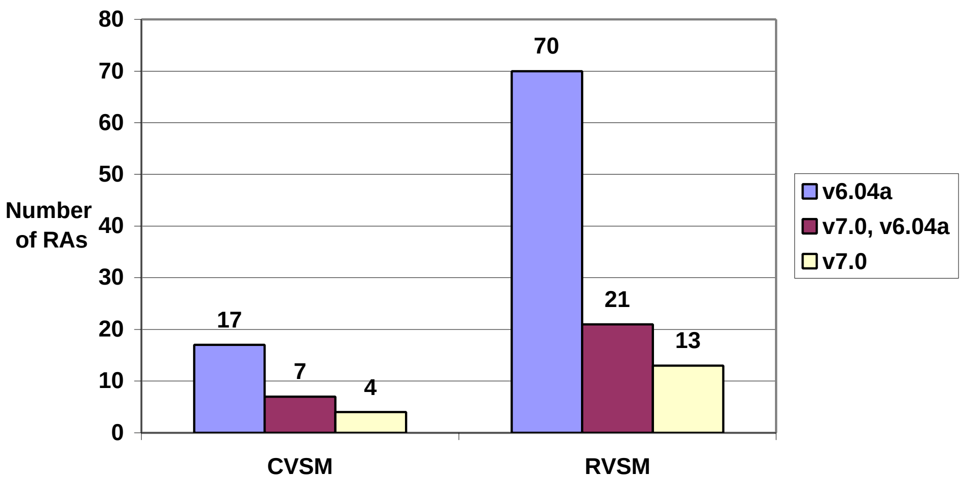


Figure 29: Occurrence of RAs in CVSM / RVSM (real-time simulation data)

3.3.2.4 The number of RAs is greater in RVSM than in CVSM scenarios, whatever the TCAS II logic version. The ratio of RAs between CVSM and RVSM is high with version 6.04a with about 4 times more RAs in RVSM than in CVSM. **This ratio of RAs between CVSM and RVSM is reduced with the logic version 7.0, but there are still 3 times more RAs in RVSM than in CVSM**.

3.3.2.5 On the other hand, the average of RA duration is reduced in RVSM when compared to CVSM, whatever the TCAS logic (from 32 seconds to 21 seconds with v7.0).

3.3.2.6 In both environments, the TCAS II logic v7.0 provides a marked reduction in the number of RAs compared with version 6.04a (from 76% in CVSM to 81% in RVSM). This improvement is probably owing to v7.0's Horizontal Miss Distance Filter, and also, to the reduction of the vertical detection threshold, which has been introduced for altitudes between FL300 and FL420 to support RVSM [Lov98].

3.3.2.7 Despite this reduction, the occurrence of RAs with version 7.0 is of the order of 1 per 37 flight hours in the RVSM airspace. This rather high ratio of RAs is consistent with the number of loss of ATC separation present in the simulation data.

RAs during 1,000 ft level-off

3.3.2.8 **In RVSM, the proportion of RAs for level-off geometry is very low: 8% (1) with version 7.0, and 4% (3) with version 6.04a**, and non occur in CVSM. These figures are far from the two-third proportion that operational studies demonstrated below FL290.

3.3.2.9 The relatively small number of RAs for level-off geometry are probably due to:

- The low proportion (8%) of traffic in evolution in the [FL290; FL410] layer relatively to the layers below,
- The low occurrence of level-off manoeuvres, which are dependent on the behaviour of the controllers (how they choose to separate aircraft).

Nuisance RAs

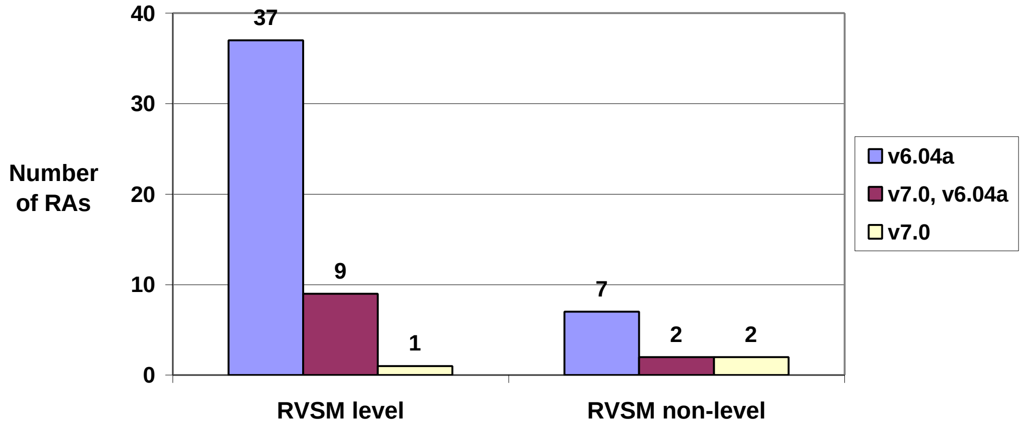


Figure 30: Occurrence of nuisance RAs in CVSM / RVSM (real-time simulation data)

3.3.2.10 There are no nuisance RAs in CVSM, and some exist in RVSM, especially with the version 6.04a. Since these RAs are mainly for level aircraft, and since a few RAs were triggered for level-off geometry, **most of the nuisance RAs in RVSM are probably related to aircraft flying level, 1,000 feet apart, with some altitude keeping error.**

This hypothesis is based on the high proportion of RAs without provision of ATC horizontal separation (HMD < 5NM) and with a VMD around 1,000 feet in RVSM, as illustrated on the following figure.

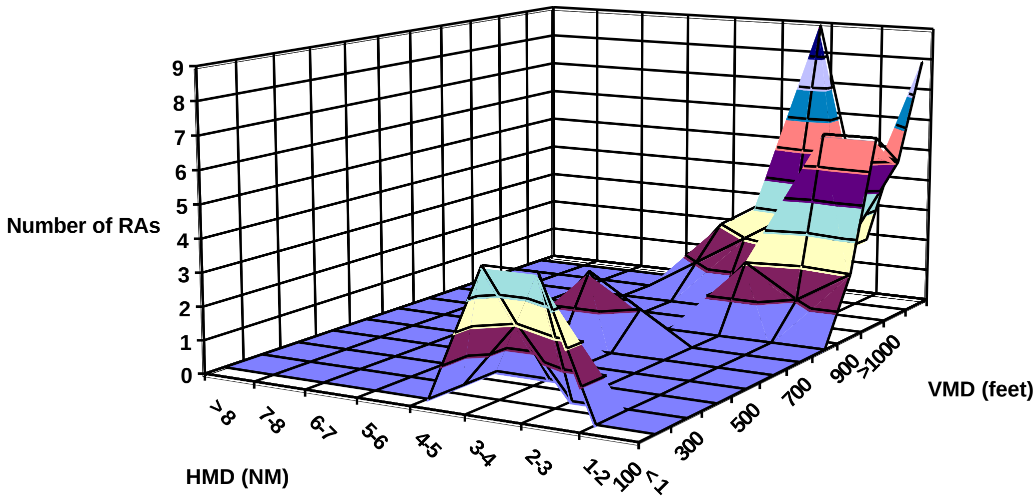


Figure 31: Distribution of RAs in RVSM against separation at CPA

3.3.2.11 **The proportion of nuisance RAs is greatly reduced with the TCAS II logic version 7.0 when compared to version 6.04a** (63% with v6.04a and 23% with v 7.0 in RVSM). This result is probably owing to the quality of the TCAS surveillance provided by the 25 feet vertical tracker.

Vertical deviations

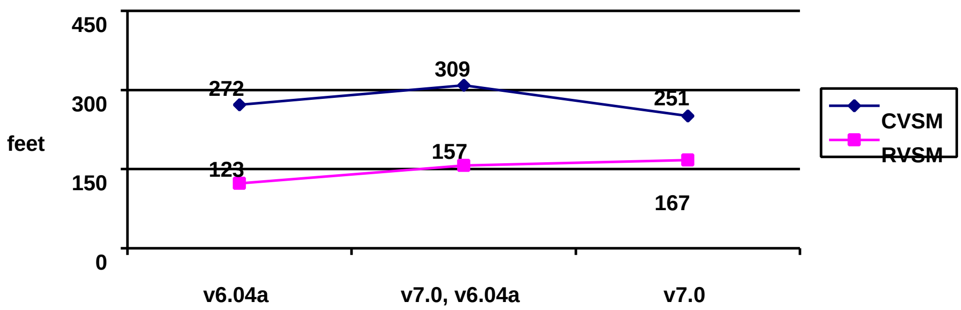


Figure 32: Average of vertical deviation (real-time data)

3.3.2.12 **The greater proportion of useful RAs in CVSM induces a greater proportion of RAs with positive deviation than in RVSM**. For instance, the proportion of RAs causing vertical deviations of more than 300 feet is about two thirds of the RAs with positive deviation in CVSM, and around one fifth in RVSM whatever the TCAS II logic version. This explains the greater average deviation in CVSM.

3.3.2.13 The average deviation in RVSM is very low: 167 ft in the worst case (with TCAS II logic version 7.0). The majority of RAs from the real-time data are caused by a poor vertical station keeping for level aircraft. The oscillations introduced by the vertical error model trigger a temporary convergence situation with an aircraft above or below. Then, the level aircraft receives a resolution advisory which is opposite to the aircraft trajectory. A weakened resolution advisory comes quickly since the convergence was not strong. This would explain why the deviations are so low. Furthermore, in such situations version 7.0 may not trigger an RA; this tends to increase the average deviation measured for version 7.0.

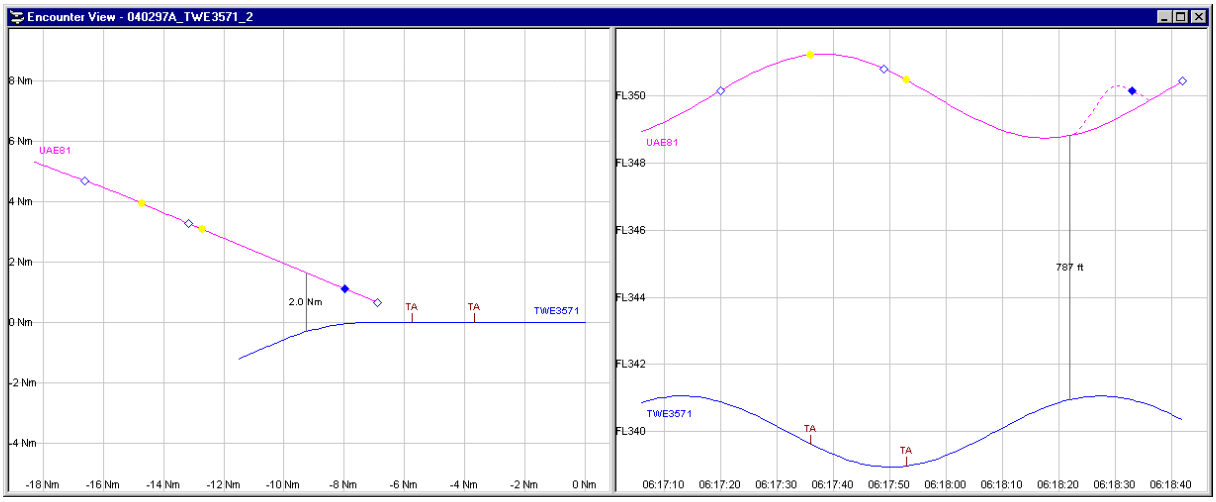


Figure 33: Low deviation RA triggered by poor vertical station keeping

3.3.2.14 It shall be noted that operational deviations are usually higher than the deviations measured in this study since actual pilots' reaction is often less ideal than the one implemented by the standard pilot model.

RAs with more than two advisories

3.3.2.15 **A relatively high number of RAs with more than two advisories occur in the CVSM environments.** In RVSM, the proportion of RAs with more than two advisories is 8% (1) with v7, 19% (4) with a mix, and 39% (27) with v6.04a. In CVSM, 25% (1) occur with v7, 29% (2) with a mix, and 71% (12) with v6.04a.

Multi-aircraft situations

3.3.2.16 Multi-aircraft encounters were also considered in this study. The criterion for qualifying an encounter as multi-aircraft was the loss of ATC separation (i.e., 5 NM and 1,000 feet) of an ACAS equipped aircraft with TCAS contribution, with a third aircraft. With the CVSM environment, the vertical separation threshold is set to 2,000 ft. For both environments, the calculation allows a 200 feet tolerance on the vertical separation threshold.

3.3.2.17 The RVSM introduction triggers the appearance of multi-aircraft encounters (3 with v6.04a and 4 with v7) that did not occur in CVSM. This occurrence could prove disturbing for air traffic controllers since an RA in a pair of aircraft might lead to a loss of separation with a third aircraft. However, this trend needs to be confirmed since the sample of encounters with RAs is small.

Occurrence of TAs

3.3.2.18 The number of TAs is much greater in RVSM than in CVSM scenarios, whatever the TCAS II logic version. The ratio of TAs between CVSM and RVSM is particularly high with the TCAS II logic version 6.04 with about 15 times more TAs in RVSM than in CVSM. This ratio of TAs between CVSM and RVSM is reduced to less than 5 with the logic version 7.0.

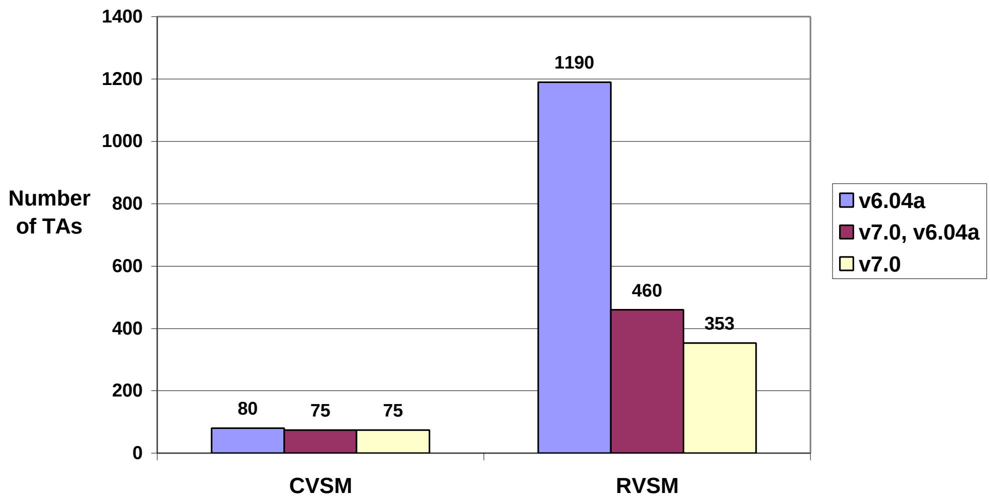


Figure 34: Occurrence of TAs in CVSM / RVSM (real-time simulation data)

3.3.2.19 When compared to the TCAS II version 6.04a, the version 7.0 produces a TA reduction rate of 7% in CVSM, and up to 70% in RVSM. This contribution of the TCAS II logic version 7.0 is mainly due to the reduction of the vertical detection threshold, which has been introduced for altitudes between FL300 and FL420 to support RVSM [Lov98].

3.3.2.20 Besides, the TCAS logic v7.0 decreases the average TA duration by 27 seconds (from 47 seconds with v6.04a to 20 seconds with v7.0) in the RVSM environment.

Nuisance TAs

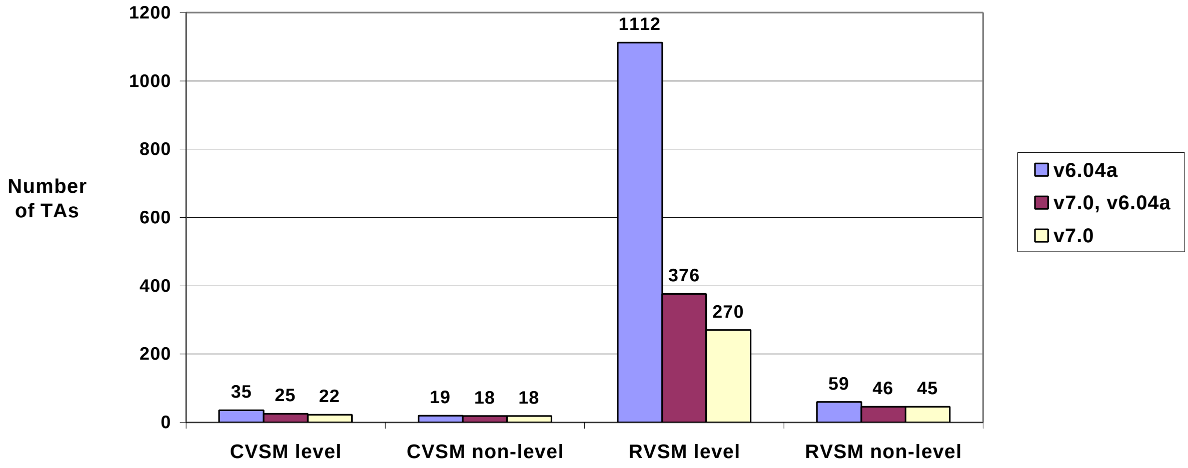


Figure 35: Occurrence of nuisance TAs in CVSM / RVSM (real-time simulation data)

3.3.2.21 The number of nuisance TAs is dramatically increased in RVSM when compared to CVSM with the TCAS II logic version 6.04a. Overall, the occurrence of nuisance TAs in RVSM is most significant when own aircraft is level, with both versions of TCAS II. However, this is most noticeable with version 6.04a, compared to version 7.0, which shows a clear benefit.

3.3.2.22 Actually, when compared to the number of TAs, the proportion of nuisance TAs is very high in RVSM whatever the TCAS II logic version (greater than 90%) although it is much more acceptable in CVSM (no more than 63%).

3.3.2.23 In CVSM as well as in RVSM, the proportion of nuisance TAs is reduced when going from version 6.04a to version 7.0. The reduction rate is much more important in RVSM (73%) than in CVSM (26%).

Repetitive TAs

3.3.2.24 In RVSM, the proportion of repetitive TAs is 5% (16) with version 7.0, 4% (20) with a mix, and 4% (53) with version 6.04a. In CVSM, none occur with version 7.0, or a mix, and 3% (1) occur with version 6.04a.

3.3.2.25 **Overall, repetitive TAs are more likely to occur in RVSM than in CVSM, with both versions of TCAS II**, at a frequency of the order of 1 per 30 flight hours with version 7.0 in RVSM. This relatively high frequency probably reflects the somewhat pessimistic Trajectory Error Model used in this study.

Safety aspects

3.3.2.26 None of the ACAS performance indicators computed in this study revealed a safety issue. However, the total number of resolution advisories triggered in each simulation is small therefore rare events that highlight safety problems do not appear.

3.4 Simulations based on non-automatic artificial encounters

3.4.1 Set of artificial encounters

3.4.1.1 In order to evaluate the impact of the reduction of the vertical separation from 2,000 feet to 1,000 feet, two types of encounter have been simulated:

- Two aircraft in level flight, at adjacent flight levels, and
- One aircraft in level flight and one levelling off at an adjacent flight level.

3.4.1.2 Some of the artificial encounters were derived from those used to study the use of ACAS in the NAT RVSM area [Cas95]. Additional ones have been created to simulate continental RVSM environment.

3.4.1.3 These artificial encounters have been created either with the OSCAR's generator of artificial trajectories, or by the modification of real trajectories extracted from the radar data.

3.4.1.4 The constraints of the OSCAR's generator of artificial trajectories are:

- constant ground speed for each aircraft during an encounter,
- life time lower than 1000 seconds (16 minutes and 40 seconds),
- up to two horizontal manoeuvres,
- up to two vertical manoeuvres with a possible overshoot of the final level.

3.4.1.5 Furthermore, these artificial trajectories are very smooth, almost perfect.

3.4.1.6 To compensate these constraints, some trajectories extracted from European radar data described in section 3.1.1.4 have been used to create additional encounters. Several types of modification have been brought for the generation of the new encounters: altitude translation, altitude extension, time translation, horizontal trajectory alteration, etc.

3.4.2 Main Results

3.4.2.1 Detailed analysis the TCAS II behaviour for each the type of encounter can be found in [WP056]. The main results of the ACAS simulations and analyses performed are summarised hereafter.

<u>For encounters involving steady aircraft</u>

3.4.2.2 With the CVSM of 2,000 feet:

- **Both TCAS II versions** do not generate any advisory;

3.4.2.3 With the RVSM of 1,000 feet:

- **TCAS II version 6.04a** generates TAs on-board both aircraft, which can have a long duration in case of low relative speed between aircraft;

  TCAS II version 6.04a can also generate RAs in case of large amplitudes of oscillation in altitude station keeping;

- **TCAS II version 7.0** prevents the generation of TAs between aircraft perfectly steady 1,000 ft apart;

  TCAS II version 7.0 also generates TAs on-board both aircraft in case of vertical offsets from the cleared flight level or oscillations in altitude station keeping;

  TCAS II version 7.0 should prevent the generation of RAs even in the case of vertical offsets and oscillations in altitude station keeping;
- **Both TCAS II versions** may generate several secondary short-duration TAs;
- **25-ft altitude reports** contribute in the reduction of advisory generation with TCAS II version 7.0 by reducing its sensitivity to altitude data.

For encounters involving a steady aircraft and a levelling off one

3.4.2.4 With the CVSM of 2,000 feet:

- **TCAS II version 6.04a** generates a few TAs mainly on-board the steady aircraft;
- **TCAS II version 7.0** generates TAs in extreme cases: vertical overshoot or very large amplitudes of oscillation in altitude station keeping;

3.4.2.5 With the RVSM of 1,000 feet:

- **TCAS II version 6.04a** generates a large number of RAs in addition to TAs;

  TCAS II version 6.04a generates long duration RAs if aircraft are on the same route with a low relative speed, which induce large vertical deviations;
- **TCAS II version 7.0** reduces the number of TAs and RAs, but it does not remove all of them;

  TCAS II version 7.0 also generates long duration RAs if aircraft are on the same route with a low relative speed, but with low vertical deviations;

  TCAS II version 7.0 can generate RAs because of horizontal manoeuvres, which inhibit the MDF, even if these manoeuvres increase HMD;
- **Both TCAS II versions** generate numerous split TAs;
- **25-ft altitude reports** contribute slightly in the reduction of advisory generation by TCAS II version 7.0.

3.5 Simulations based on automatic artificial encounters

3.5.1 Introduction

3.5.1.1 The offline ACAS simulations on automatic artificial encounters involve the production of a theoretical safety encounter model for European airspace above FL290 that has parameter distributions appropriate to European RVSM airspace [WP063].

3.5.1.2 The purpose of a theoretical safety encounter model for analysing ACAS / RVSM interaction is to enable the computation of a risk ratio specific to RVSM airspace and to enable its comparison with a risk ratio computed on the current CVSM environment above FL290.

3.5.1.3 The ACAS simulations based on automatic artificial encounters only address safety aspects. Indeed, computing performance indicators to assess the compatibility with ATC using a theoretical encounter model is not worth the effort because:

- the other studies provide good estimates of these performance indicators; and
- the relatively low confidence in the performance indicators that could be obtained using a theoretical encounter model.

3.5.1.4 Taking into account the RVSM specific features extracted from the RVSM real-time simulations, the European RVSM safety encounter model has been derived from the European safety encounter model produced for the current CVSM environment, using European radar data. The set of encounters generated by those safety models include a number of NMACs (Near Mid Air Collisions - encounters where the vertical separation is less than 100ft, and the horizontal separation less than 500ft) and enables a determination of the number of NMACs present when the effect of ACAS is simulated. The risk ratio is then given by :

$$risk\ ratio = \frac{NMACs\ with\ ACAS}{NMACs\ without\ ACAS}$$

3.5.1.5 A summary of the process based on the existing CVSM safety encounter model for computing risk ratios for RVSM is given in the following sections. A more complete description can be found in [WP177]

3.5.2 Preparation and use of the encounter models

Construction of simulation-based encounter models

3.5.2.1 The data used come from the Third Continental RVSM simulation (cf 3.3). For each of the vertical separation minima (current and reduced), the following steps were followed.

3.5.2.2 Encounters between aircraft which were close enough were extracted through a coarse filter. At this stage, the number of encounters was increased by creating 20 slightly different copies of each pair of original trajectories, through a stochastic modification of timing and horizontal position of their plots. The goal was to obtain a large enough sample of encounters.

3.5.2.3 Each encounter then underwent a 1 second-interpolation. A finer filter was applied to select the encounters which were either already NMACs before any ACAS intervention or which were liable to lead ACAS to induce NMACs. Modifications of the vertical component of the selected trajectories enabled a more realistic flight profile with the introduction of overshoots/undershoots, phugoïdal motion and offsets with regard to the standard flight level.

3.5.2.4 The final set of encounters was analysed in order to determine the relative frequency of each parameter of the model (encounter class, cruxality, vertical miss distance,…). For each parameter, a probability table was filled. The full sets of tables make up the encounter models which are representative of the studied airspace, either CVSM or RVSM.

Construction of a pseudo radar-based RVSM encounter model

3.5.2.5 Firstly, a comparison between the CVSM simulations-based model and the RVSM simulations-based model was made. The goal was to identify the differences between the two airspaces. A statistical method (computing the c^2 value) was used for each parameter of the model in order to detect which differences were statistically significant (i.e. with a low probability of being there just by chance).

3.5.2.6 The level of statistical significance used in this comparison was not high; a probability of 5% was treated as 'significant'. Because the statistical sample was small, subjective judgement was an important part of the process. The differences that were identified were significant (at 5%), but also credible.

3.5.2.7 A method to implement the identified differences when going from CVSM to RVSM was built and applied to the radar-based CVSM safety encounter model from ACASA Work Package 1. Using this method was necessary because, of course, no radar data on an RVSM environment was available, and also because it was felt that more reliable results would come from an RVSM model derived from pseudo radar data, rather than risk ratios computed directly from simulation-based models.

3.5.2.8 As noted in section 2.2.4, models were also built directly from the two sets of real-time simulations. This meant that these two models contained structural differences between CVSM and RVSM encounters that were neither subjectively credible nor statistically significant. Some of these differences appeared to affect the risk ratio results, confirming the initial view that direct use of the simulation data would be unwise.

Adjustment of the models

3.5.2.9 Each encounter model had to be calibrated to ensure that a set of encounters generated through the model would give an NMAC rate as expected for the studied airspace. The model is adjusted so that there is a given probability that an individual encounter produced by the model will be an NMAC. It is this probability, that an encounter from the model will be an NMAC, multiplied by the rate at which the encounters produced by the model occur in the airspace of interest that gives the NMAC rate.

3.5.2.10 The NMAC rate that is imposed is 3 NMACs in 10^8 flying-hours for both CVSM and RVSM.

Risk ratio calculations

3.5.2.11 The scenarios described in section 2.3 imply that several combinations of equipage (ACAS and quantisation) can exist for the same encounter, each aircraft of the encounter being equipped independently. The idea was to run ACAS simulations on the same set of encounters generated by one of the models, each time with one of the different combinations of equipage. This gave an NMAC rate for each combination of equipage. The global NMAC rate for the scenario was then computed as the sum of the probability of each combination of equipage (given by the scenario) times the NMAC rate for this combination of equipage.

3.5.3 Discussion on the method

3.5.3.1 Several assumptions had to be made which have an impact on the computed risk ratios:

- The capture criteria had to be wide enough to capture all significant encounters but not too large to avoid capturing encounters which had no impact on the safety level of the airspace. The final values were best guesses based on the experience of the ACASA team.

- The determination of whether the perceived separation is, in fact (due to altimeter error), an NMAC is dependent upon the assumed form of the aircraft altimetry error. The aircraft altimetry error model specified for use with the encounter model in the SARPS is such that if it truly characterised the performance of aircraft altimeters then they would not be compliant with the MASPS. Consequently a new aircraft altimetry error model, one that does imply MASPS compliance, has been assumed when making calculations for RVSM airspace.

- The adjustment of the model relies on an NMAC rate which is assumed to be realistic for the studied airspace. The one chosen ($3 \text{ in } 10^8$ flying-hours) here is consistent with the Target Level of Safety of 2.5×10^{-9} fatal accidents per aircraft flight hour used by the RGCSP in their initial assessment of the feasibility of RVSM.

- The CVSM and RVSM were assumed to be equally safe without the use of ACAS. Doing it another way would have required another study, and it is not the purpose of ACASA to investigate the level of collision risk in either CVSM or RVSM.

3.5.3.2 Also the following limitations must be borne in mind :

- Whatever the source of data, there were so few encounters that many entries in the encounter models were left empty. In other words, there are many possible configurations, which probably occur in the real world, that happened not to be captured and were thus not modelled in the calculations.

- An effort was made to exclude non-MASPS and military aircraft from the original simulation data. However, it was found in the course of the study that a small number of them remained and their effect pervades the building of the RVSM safety encounter model. This is not necessarily a problem: encounters between a civil aircraft and a military aircraft are relevant to the study and it is desirable to include these; encounters between two military aircraft (particularly two fast jets) are not relevant to the study, but these types of encounter are not the encounters that have the most significant effect on the calculations.

- Some encounters were captured for which the values observed for some model parameters were outside the range of values defined for the model. These encounters impact the model in some parameter tables and not in others. However, there is no evidence that this is a significant problem.

3.5.4 Results

3.5.4.1 Resource constraints mean that results are available for equipage with TCAS II version 7.0 only. Unless otherwise stated, the results presented here assume that 90% of aircraft are ACAS equipped and (independently) that 50% of aircraft report altitude with 100ft quantisation and 50% of aircraft report altitude with 25ft quantisation.

3.5.4.2 The results need to be treated with great care, not only because of the caveats mentioned in paragraph 3.5.3.1 but also because the basic CVSM model is based on only 26 radar data encounters. For this reason the results given below, for the reader's information, are not authoritative.

	CVSM	RVSM
Risk ratios	17.5%	35.7%

Table 4: Risk ratios computed from the safety encounter models

3.5.4.3 The techniques that have been used in order to arrive at these comparative figures were specifically developed to evaluate the effect on ACAS of the introduction of RVSM. They were not intended to allow the calculation of definitive absolute values of the risk ratio in either airspace environment. Nevertheless, the techniques have been developed so that the risk ratios are as realistic as the limitations allow. Bearing in mind the comments of the preceding paragraph, the following conclusions can be drawn from the figures presented in Table 4:

- That the introduction of RVSM may, to some extent, adversely affect the benefit in safety that is accrued solely by virtue of ACAS being deployed within the airspace.

- However, in both cases the risk ratio is well below 100% and so, even though the precise values may not be accurate, we can be confident that, once RVSM is introduced, ACAS continues to provide a safety benefit.

3.5.4.4 The risk ratios presented in Table 4 are for the scenario in which 90% of aircraft are equipped with ACAS. Consequently 81% of encounters are between two ACAS equipped aircraft. However, the risk of collision (when ACAS is deployed) in these encounters accounts for less than 1% of the total risk in both the CVSM and RVSM environments. The overwhelming contribution to the risk of collision comes from encounters in which at least one aircraft is unequipped. Increasing the level of ACAS equipage from 90% to 95% is found almost to halve the risk of collision, in both CVSM and RVSM.

3.5.4.5 The preceding calculations are based upon the assumption that the pilots of all aircraft that are equipped with ACAS respond to any RAs that are generated and with the standard response. An investigation into the effect, on risk ratio, of a proportion of pilots ignoring RAs has been performed for a scenario in which 90% of aircraft are equipped with ACAS (and in which all aircraft report altitude with 100ft quantisation). The results indicate that if only 10% of RAs are ignored the risk of collision would be more than doubled for both CVSM and RVSM. In the case of RVSM, the effect would be such that the risk ratio could be close to 100%, i.e. the effect of 10% of RAs being ignored would negate the safety benefit that was gained from the 90% of RAs that were followed.

3.5.5 Conclusions

3.5.5.1 The computed risk ratios, even though the exact figures cannot be trusted, confirm that ACAS will continue to provide a significant safety benefit, as expected, when RVSM is introduced. However the introduction of RVSM could reduce the benefit in safety that is accrued solely due to the deployment of ACAS within the airspace.

3.5.5.2 The overall risk of collision, in either CVSM or RVSM, is very sensitive to the proportion of aircraft that are equipped with ACAS.

3.5.5.3 The great importance of pilots following the RAs if the benefit from ACAS is to be gained has been confirmed. Indeed, an individual pilot who ignores RAs will be at greater risk than if his aircraft were unequipped – as will (unwittingly) the well-behaved pilots of ACAS equipped aircraft he encounters.

3.6 Simulations based on fast-time data

3.6.1 Data collection and preparation

3.6.1.1 The fast-time study was based on the EEC RVSM real-time simulation (S08) flight-plan data, which was itself based on real radar recordings from Friday 24th May 1996, as described in section 3.1.1.4. Four real-time simulation exercises were chosen, representative of morning and afternoon recordings prepared for CVSM and RVSM with +35% and +55% traffic loading.

3.6.1.2 To increase the number of traffic samples available for ACAS simulations the original traffic entry times were jittered 9 times, producing a total of 10 samples from each of the original exercises (1 with original entry times, and 9 with entry times varying randomly between 0 and +-15 minutes).

3.6.1.3 Thus, from the original 4 exercises, a total of 40 traffic samples were made available for ACAS simulations. Table 2 gives the total of ATC hours and flight hours for the 40 samples used in the ACAS simulations.

Original exercise	**VSM**	**Traffic loading**	**Number of samples**	**Total ATC hours**	**Total flight hours**
210197A	CVSM	35%	10	13.9	795
220197A	RVSM	35%	10	14.0	735
060297A	CVSM	55%	10	13.9	882
290197A	RVSM	55%	10	13.7	819

Table 5 : ATC hours and flight hours in the fast-time study

3.6.1.4 During the ACAS simulations, the trajectory error model described in section 3.1.1.4 was also applied to the aircraft trajectories to render them more realistic, while still MASPS compliant.

3.6.2 Main Results

3.6.2.1 The fast-time simulator (RAMS) used for this study has two main deficiencies, which were unknown to the ACASA project at the start of this study :

- The ATC conflict detection and resolution algorithm is inefficient, mainly when dealing with aircraft which are slowly converging, leading to losses of separation (and ACAS alerts), which would not have occurred under real ATC.
- The output trajectory software is flawed, which corrupts a significant proportion of aircraft trajectories. Affected aircraft typically fly, trombone-like, to and from along the same trajectory, and this often produces spurious ACAS alerts.

3.6.2.2 In an attempt to use the RAMS data, a filter (based on ACAS alert duration) was applied to the final results. However, this filter, though removing the worst cases of unrealistic ATC conflicts, does not remove all of them, and it is considered that the filter itself introduces its own kind of bias to the results.

3.6.2.3 The above deficiencies explain that most of the results obtained in the fast-time study are considered unrealistic. Here are some examples :

- ATC separation is lost on 782 occurrences per day of control, which is a bad performance on a controlled area of the size of the traffic samples. Indeed, this rate is ten times as high as the actual rate measured in the real-time simulations (with real controllers).
- Resolution advisories occur more often in CVSM than in RVSM whereas the contrary is expected.
- A resolution advisory occurs every 3 flight-hours in CVSM with TCAS II logic version 6.04a, which is far above what was found in the operational studies.
- Vertical deviations over 600 feet are more numerous than expected: the average deviation is 100 ft higher than in the real-time study. This also has an impact on alerts' duration, which are a few seconds longer.
- Safety-related events (such as sense reversal RAs) occur with a worrying rate, whereas they should be almost non-existent on a sample of this size.

3.6.2.4 In view of these unrealistic results, the ACAS performances based on the fast-time simulations data will not be taken into account when discussing the interaction between ACAS and RVSM in section 4 of this report.

4 Main features of the ACAS/RVSM interaction

4.1 General

4.1.1.1 This section provides a synthesis of the ACAS/RVSM interaction study, and puts the emphasis on the changes and potential issues that are expected to occur in the future European RVSM airspace.

4.1.1.2 The impact of aircraft fitted only with TCAS II version 6.04a in the RVSM environment is described first. Then, the section presents the effects of a homogeneous TCAS II version 7.0 equipage. Finally, the transition period where both versions of TCAS II will operate in the European RVSM airspace is addressed.

4.1.1.3 The features of the ACAS/RVSM interaction presented in this section rely on the results of the studies based on real-time simulation data, on modified radar data and on non-automatic artificial encounters. As stated in section 3, the results of the study based on fast-time simulation data were not judged realistic enough to be taken into account.

4.1.1.4 It was not always possible to clearly conclude on the ACAS/RVSM interaction due to some discrepancies in the results obtained from the real-time simulations and those obtained from the modification of radar data. In such cases, the feature is nevertheless discussed, but the discrepancy in the ACAS simulation results is explicitly stated.

4.1.1.5 When required, the features of the ACAS/RVSM interaction are compared to what is happening in the [FL250; FL295] layer according to the study based on European radar data.

4.1.1.6 Illustrations of the most characteristic TCAS II behaviour in the European RVSM airspace are also provided, based on artificial or real encounters used in the study. Some of the figures are screen dumps from the OSCAR display that is briefly presented in Appendix A.

4.2 Full v6.04a equipage scenario

4.2.1 Compatibility with ATC

4.2.1.1 With the introduction of RVSM and the whole TCAS II fleet fitted with version 6.04a, **the number of RAs above FL290 is expected to increase by 5 to 7 times**.

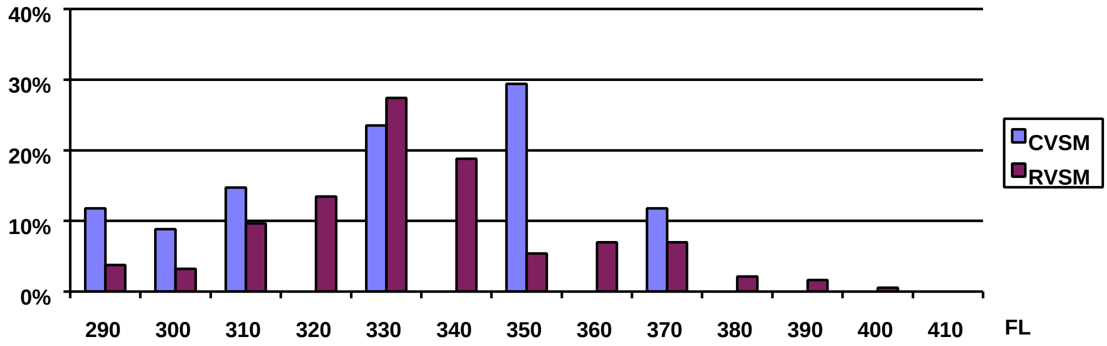


Figure 36: Altitude distribution of RAs with TCAS II version 6.04a

4.2.1.2 The newly available flight levels will get their share of RAs. According to previous operational studies, the peak of RA occurrence should be around FL290. Since the study of ACAS/RVSM interaction did not take into account encounters below FL290, the figure only shows a secondary peak of RA occurrence, which is expected to exist around FL330 rather than FL350 in a CVSM environment.

4.2.1.3 The distribution of RAs among nuisance (i.e. occurring while the standard ATC separation exists) and non-nuisance categories is very different between the two quantitative studies used for this analysis. As shown in the figure below, **the proportion of nuisance RAs is nevertheless very high: from 63% to 86%,** but for different reasons.

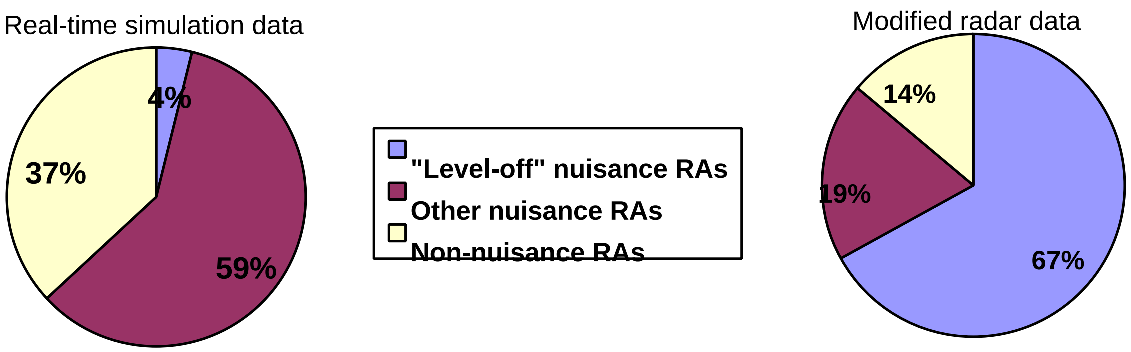


Figure 37: Distribution of RA types with TCAS II version 6.04a in RVSM environment

4.2.1.4 In the study based on real-time data, the majority of nuisance RAs does not involve a levelling-off aircraft. Since no RA has occurred beyond 5 NM of horizontal separation (i.e. the standard horizontal separation) , the nuisance can only come from a loss of vertical separation. In the layer [FL290; FL410] aircraft are mainly in level flight. Moreover, the level aircraft having nuisance RAs are predominant over non-level aircraft. So the majority of nuisance RAs seem to be caused by interactions between level aircraft, which oscillate around their flight level while still MASPS compliant.

4.2.1.5 The following figure illustrates the geometry of such encounters and the RA they can trigger.

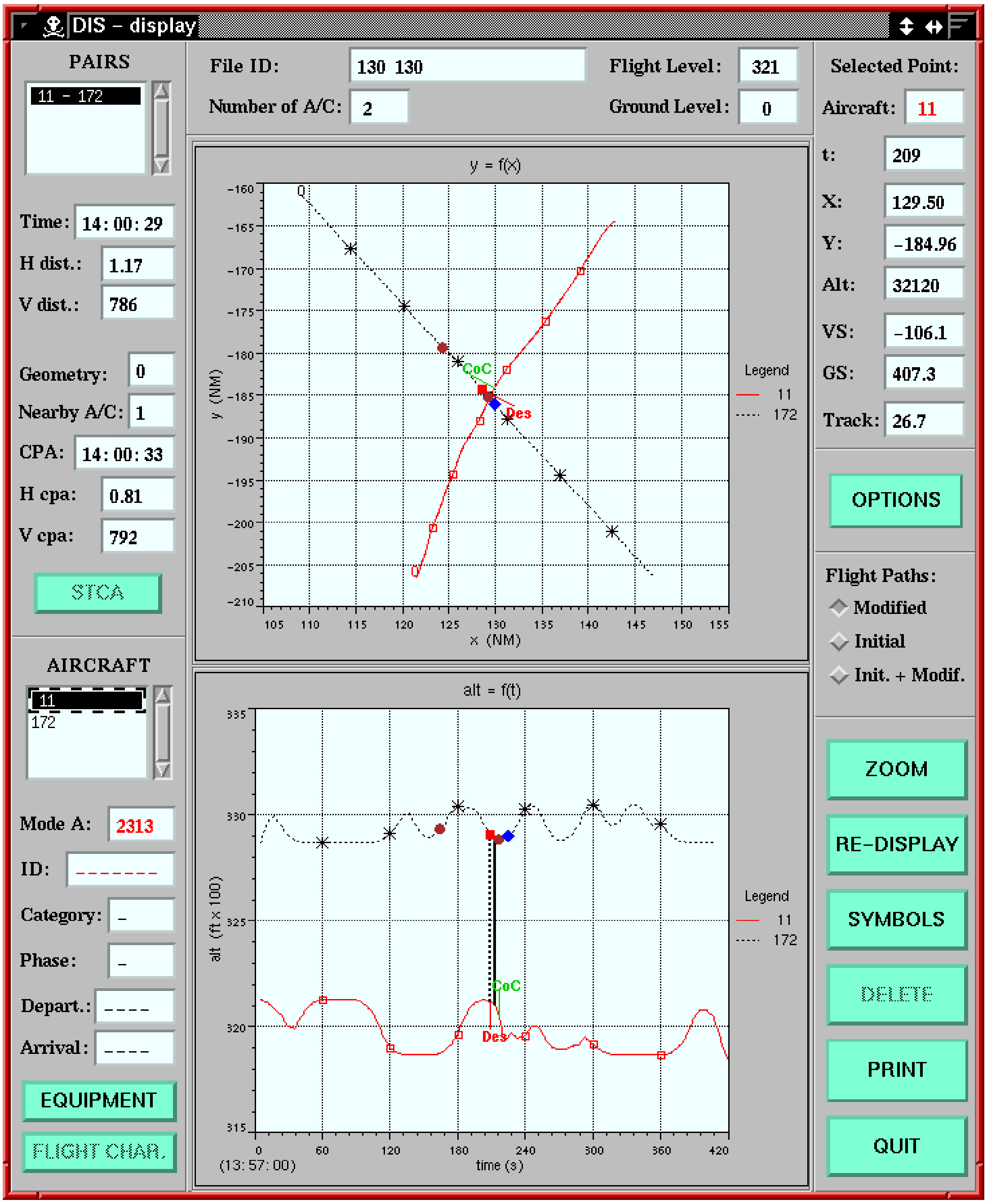


Figure 38: Nuisance RA (version 6.04a) for oscillating aircraft on adjacent RVSM levels

4.2.1.6 In the study based on modified radar data, the majority of nuisance RAs is triggered for level-off encounters between aircraft separated by 1,000 feet. Such geometry is further discussed and illustrated in the section 4.3.1.5 about TCAS II version 7.0.

4.2.1.7 Among the RAs, those considered as nuisances by air traffic controllers will make up the majority: from 63% to 86% of the total. This proportion is also greatly increased relatively to the CVSM data.

4.2.1.8 After the introduction of RVSM, the average RA duration above FL290 is expected to decrease by 5 seconds. This is linked to the greater proportion of nuisance RAs in an RVSM environment: they tend to end sooner than the other RAs. For example, the Trajectory Error Model applied to the real-time simulation data has an oscillation period of around 80 seconds. Thus, the time needed to climb from the average altitude to the maximum altitude is 20 seconds. Then, the aircraft begins to descend and the potential RA triggered by the climb is likely to be weakened.

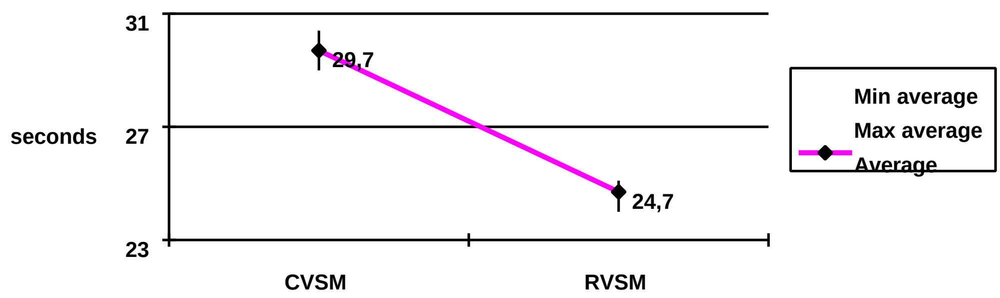


Figure 39: Average RA duration above FL290 with TCAS II version 6.04a

4.2.1.9 After the introduction of RVSM, the average deviation above FL290 is expected to decrease by 160 feet. The reduced duration is mainly responsible for this decrease (as 5 seconds at 1,500 ft/min. represents 125 feet).

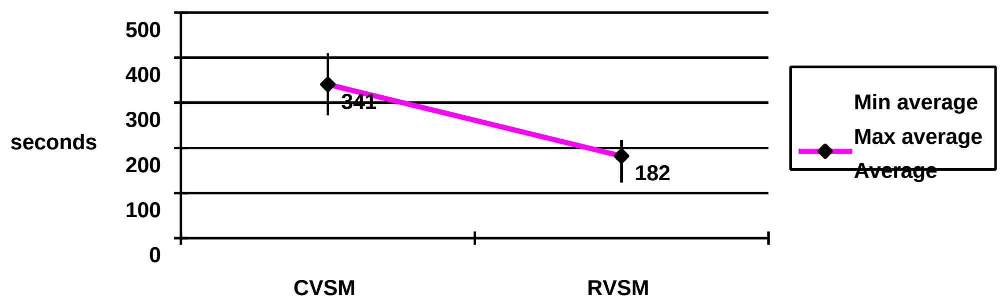


Figure 40: Average deviation above FL290 with TCAS II version 6.04a

4.2.1.10 The results about average RA duration and average deviation in RVSM converge towards the figures currently observed in the [FL250; FL290] layer (25.1 s and 196 ft).

4.2.2 Pilot acceptance

4.2.2.1 **A great majority (from 67% to 77%) of RAs will be positive advisories** (i.e. climb or descend). This means that pilots will most of the time have to alter their trajectory to comply with the advisory. Combined with the greater frequency of RAs, the increasing stress and workload will certainly have a negative impact on pilots.

4.2.2.2 The number of RAs whose initial advice requires that the pilot reverses the aircraft vertical rate is expected to be significant: from 9% to 23% depending on the data used for the study. Such an advisory happens mainly in the aircraft about to level off. It is disturbing because reversing the vertical rate is a harder decision to take and longer to implement than a simple vertical rate limitation.

4.2.2.3 Only in the study based on real-time data, RAs with more than 2 advisories are predicted to make up 39% of the whole set. This result has not been confirmed by the other studies and needs to be further investigated. If it is true, the higher number of actions to be taken will be more stressful for the pilot.

4.2.2.4 **The number of TAs should skyrocket with a multiplication factor of 15 to 35. Around 99% of them are considered as nuisance**. The reason is that TCAS II logic version 6.04a can issue a TA when aircraft are vertically separated by less than 1200 ft, which was an appropriate threshold for a CVSM airspace, but no more for an airspace where the standard ATC vertical separation becomes 1000 ft. Such a high frequency of TAs is likely to cause pilots to lose confidence in their ACAS, which is not acceptable.

4.2.2.5 As shown in the figure below, the TAs issued by the TCAS II version 6.04a above FL290 are expected to be located along the major traffic flows in Europe. The relatively lower density of traffic flows over England results from a less important amount of data for this area.

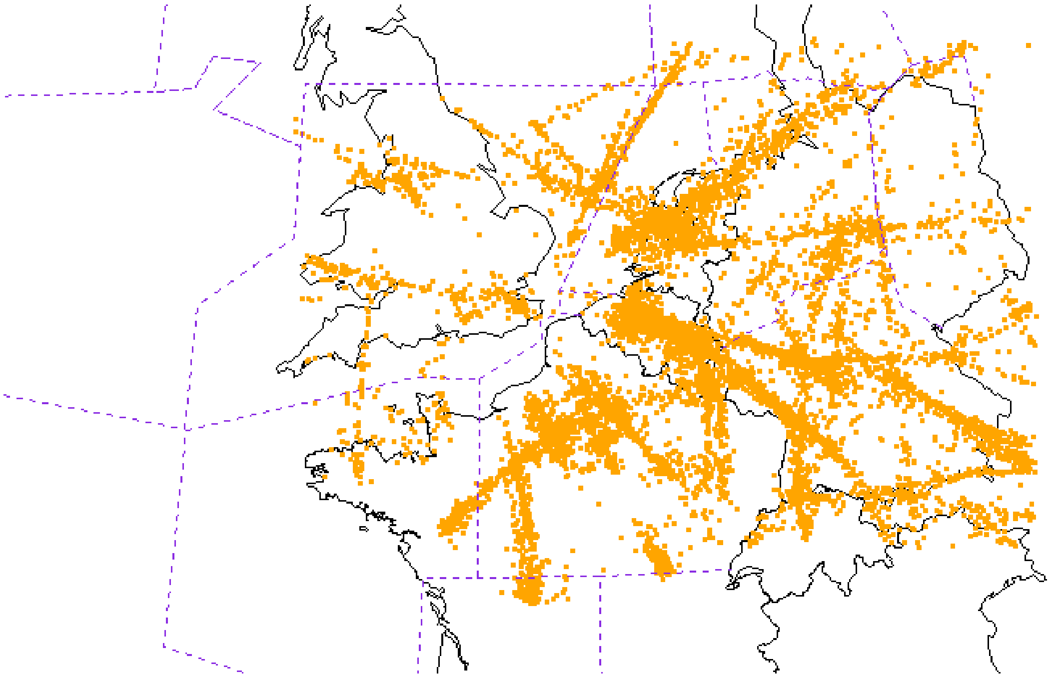


Figure 41: Traffic advisories in RVSM with TCAS II version 6.04a

4.2.2.6 After the introduction of RVSM, **the average TA duration is expected to significantly increase**, but still be reasonable and close to the time threshold to trigger a TA at those altitudes: 47 seconds.

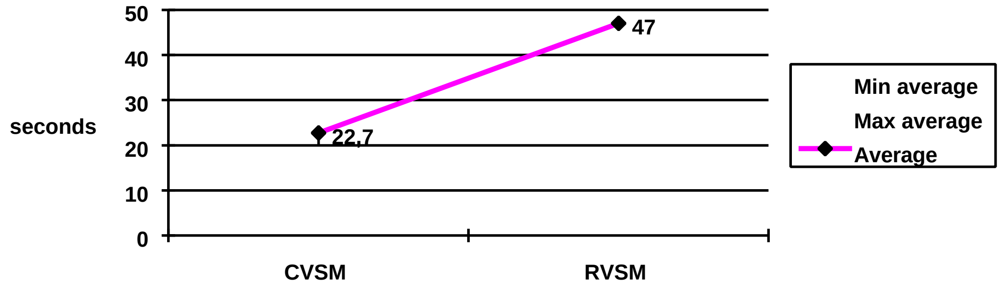


Figure 42: Average TA duration above FL290 with TCAS II version 6.04a

4.2.2.7 The study based on non-automatic artificial encounters analysed theoretical cases that induced long-duration TAs. The encounters involved two aircraft on the same track, 1,000-ft apart with some speed differential. Normally, such geometry should not exist with the single alternate FLOS configuration, where aircraft flying on one-way routes should be separated by 4,000 ft. However, for strategic or tactical reasons, the semi-circular rule may not be applied, leading aircraft to be separated by 2,000 ft in CVSM (and consequently 1,000 in RVSM). An example of long-duration TA is provided in the following figure.

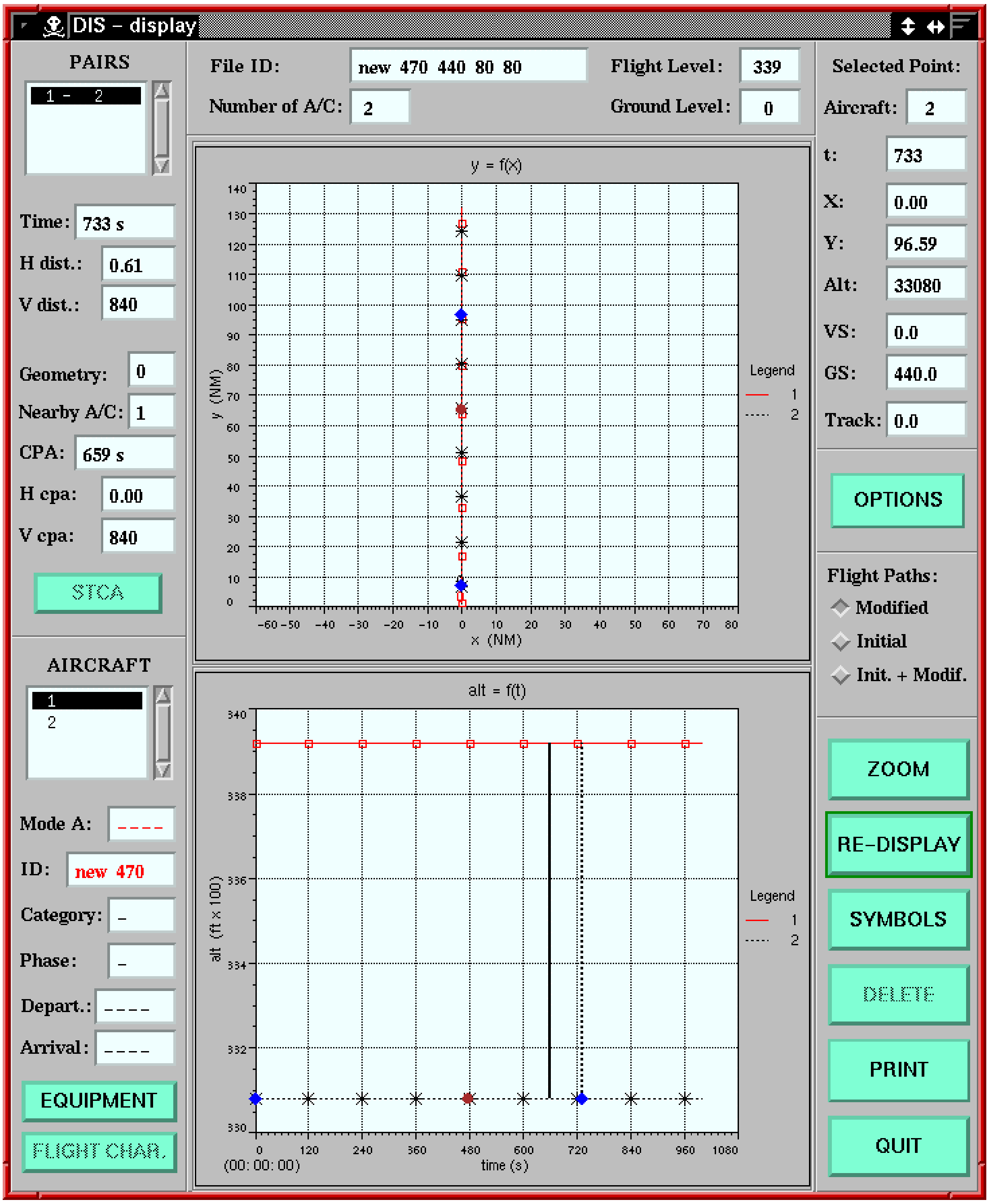


Figure 43: Long-duration TAs (version 6.04a) between steady aircraft on adjacent RVSM levels

4.2.2.8 The average result of 47s does not mean that no long-duration TAs exist, but rather, that they are hidden in the large set of TAs. Long-duration TAs are an operational issue which will appear with the introduction of RVSM.

4.2.3 Safety

4.2.3.1 No ACAS safety issues are expected to appear related to the introduction of RVSM in Europe.

4.3 Full v7.0 equipage scenario

4.3.1 Compatibility with ATC

4.3.1.1 With the introduction of RVSM and the whole TCAS II fleet fitted with version 7.0, **the number of RAs above FL290 is expected to increase by 3 to 5 times**. This increase in the rate of RAs is not insignificant, but it is nevertheless smaller than that obtained with version 6.04.

4.3.1.2 The newly available flight levels will get their share of RAs. Since the study of ACAS/RVSM interaction did not take into account encounters below FL290, the figure only shows a secondary peak of RA occurrence, which is expected to exist around FL330 rather than FL350 in CVSM. Nevertheless, in view of previous operational studies, and according to the study of the [FL250; FL295] layer, a peak of RA occurrence should also exist around FL290.

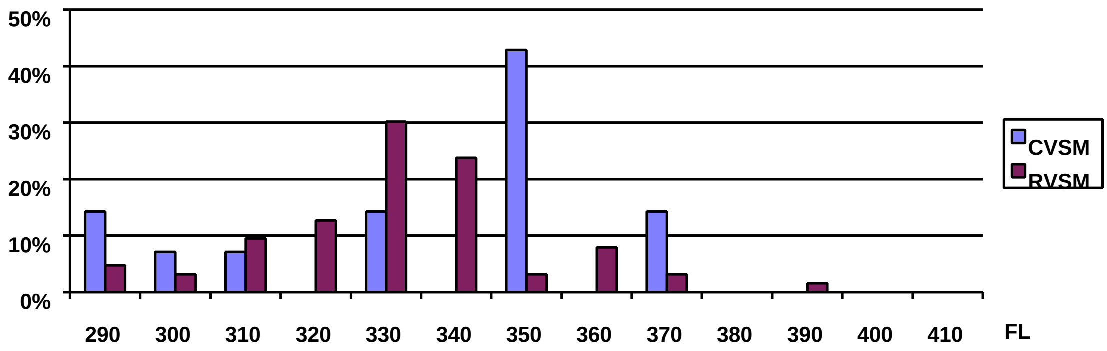


Figure 44: Altitude distribution of RAs with TCAS II v7.0

4.3.1.3 The distribution of RAs among nuisance (i.e. occurring while the standard ATC separation exists) and non-nuisance categories is very different between the two quantitative studies used for this analysis, as shown in the following illustration.

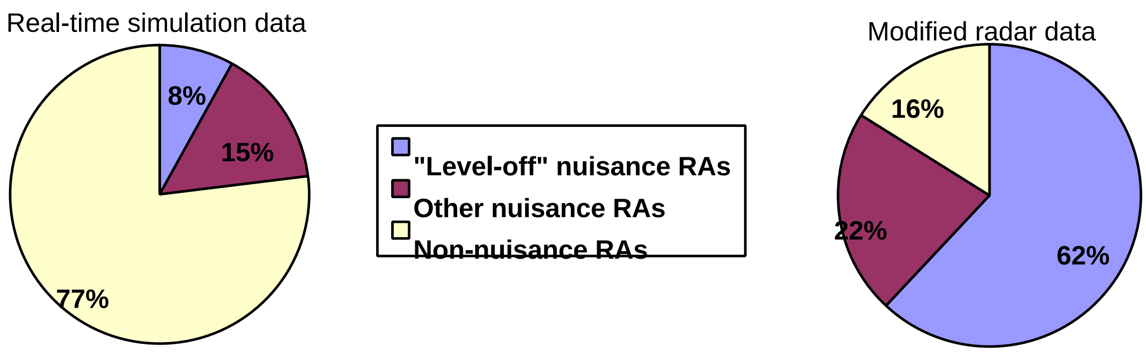


Figure 45: Distribution of RA types with TCAS II version 7.0 in RVSM environment

It shall be noted that the number of RAs in the real-time study is not very high. This could explain the discrepancy between both studies.

4.3.1.4 In the study based on real-time data, the majority of nuisance RAs is caused by level-level encounters (already illustrated in section 4.2.4 for TCAS II version 6.04a). However, their number has been greatly reduced by the existence of a better altitude tracker in TCAS II logic version 7, which no longer sees small oscillations greater than they are. Furthermore, 25-ft altitude reports by aircraft also contribute in the reduction of advisory generation with TCAS II version 7.0 by reducing its sensitivity to altitude data.

4.3.1.5 In the study based on modified radar data, the majority of nuisance RAs involves an aircraft levelling-off, 1,000 ft above or below a level aircraft. The following figure illustrates the geometry of such encounters and the RA they can trigger.

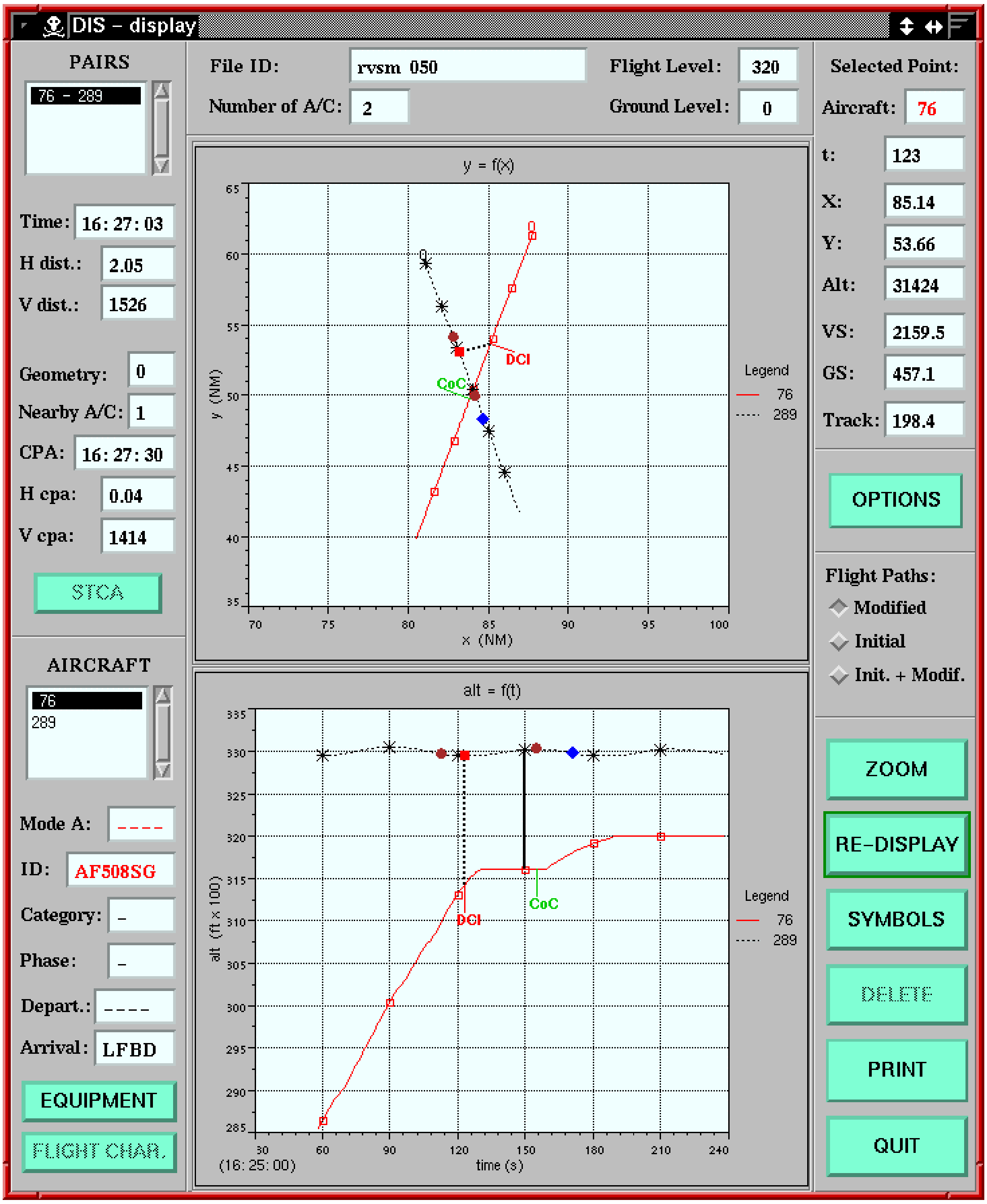


Figure 46: Nuisance RA (version 7.0) caused by an aircraft in level off manoeuvre

4.3.1.6 If the study based on modified radar data is closer from what is going to happen in the RVSM airspace, the number of RAs considered as nuisances by air traffic controllers will make up 84% of the total. This proportion is also greatly increased relatively to the CVSM data.

4.3.1.7 The increased number of RAs combined with the increased proportion of nuisance might seem worrying for air traffic controllers. However, with the same ACAS equipment, the same levels of occurrence are already currently experienced in the [FL250; FL295] layer without adverse effect on ATC performance. And, the proportion of nuisance RAs in this layer is estimated to be around 87%.

4.3.1.8 After the introduction of RVSM, the average RA duration above FL290 is expected to be slightly reduced, and lower than the time threshold for triggering RAs in this layer: around 22 seconds. This is identical to what is expected for the [FL250; FL295] layer (23 s) with the current vertical separation minima.

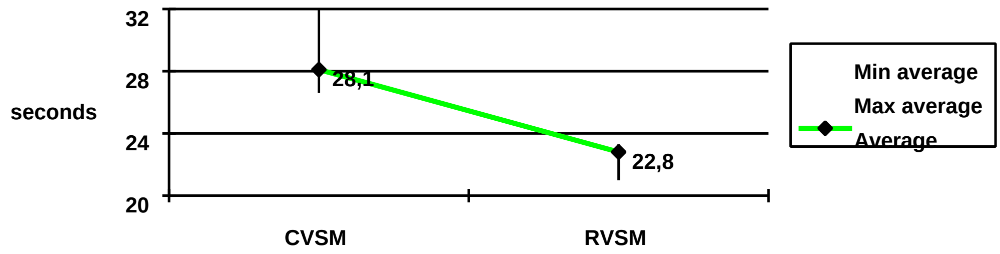


Figure 47: Average RA duration above FL290 with TCAS II version 7.0

4.3.1.9 After the introduction of RVSM, the average deviation above FL290 is expected to decrease by 120 feet. The reduced RA duration noticed above is mainly responsible for this decrease. The average deviation in RVSM is close to what is expected for the [FL250; FL295] layer (171 ft) with the current vertical separation minima.

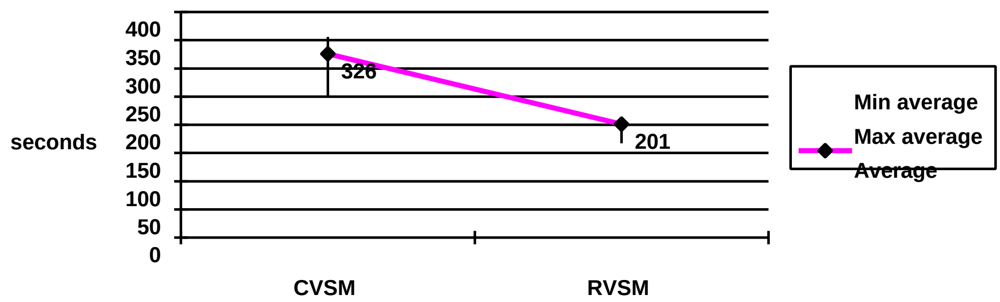


Figure 48: Average deviation above FL290 with TCAS II version 6.04a

4.3.2 Pilot acceptance

4.3.2.1 **The number of TAs is expected to increase by a factor of 3 to 5. Around 90% of them are considered as nuisance**. These figures are expected to be more acceptable than with v6.04a, because this rate is currently experienced in the [FL250; FL290] altitude band. Indeed, 98% of the TAs are nuisance TAs below FL290. However, it is still an operational issue since, most of the time, pilots will be alerted and sometimes tempted to request traffic information about an aircraft, which will be clearly separated.

4.3.2.2 The ratio between TAs and RAs is expected to increase by a factor of around 1.5 : one RA should occur for 18 to 27 TAs. This confirms the operational issue with TAs discussed above : the majority of TAs will not be followed by an RA, whereas one of their main functions is precisely to prepare the pilot for an RA.

4.3.2.3 Positive RAs are expected to increase by 2 to 3 times. However, their proportion is predicted to become alarming only in the study based on real-time data (77%). This is explained by the low proportion of nuisance RAs in this study : in the 67% of non-nuisance RAs, a good deal is probably made up of useful RAs, which involve the selection of "strong" advisories more often than happens for nuisance RAs.

4.3.2.4 However this proportion of positive RAs is not confirmed by the study based on modified radar data below FL290 where it reaches only 47%. So, 77% must be taken as a pessimistic result.

4.3.2.5 **The proportion of repetitive TAs is expected to increase, reaching between 5% and 12%.** This high proportion exists already below FL290. It is nonetheless an ACAS operational issue that should extend to the airspace above FL290 after the introduction of RVSM and needs to be closely monitored. Indeed, pilots may consider repeated occurrences of the 'traffic, traffic' aural annunciation as disruptive alerts.

4.3.2.6 An example of secondary TA triggered by poor station keeping performances is presented below.

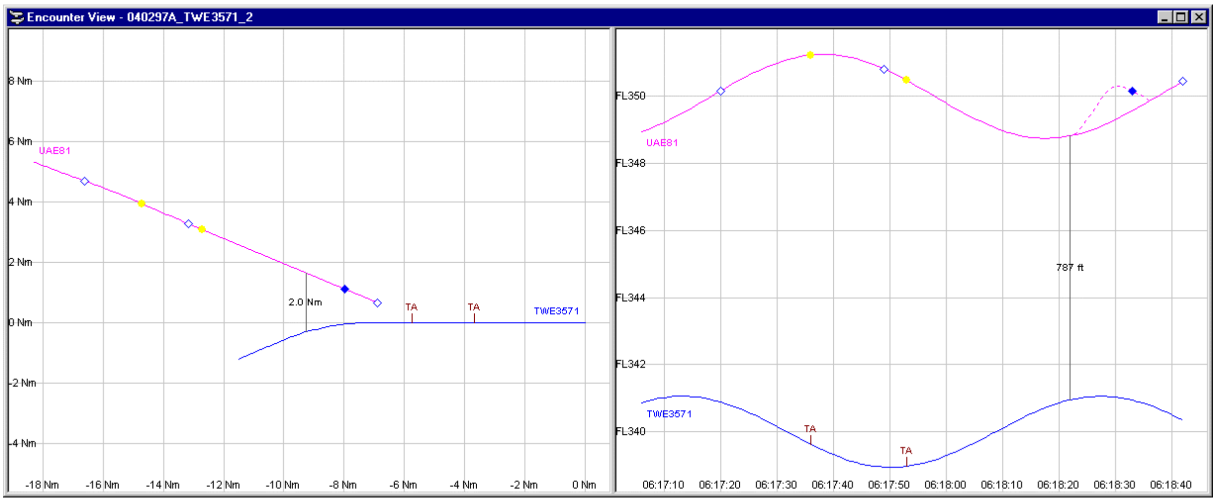


Figure 49: Split TA (version 7.0) caused by oscillating aircraft on adjacent RVSM levels

4.3.2.7 After the introduction of RVSM, the average TA duration is expected to be slightly reduced and well below the time threshold for triggering TAs in this layer: around 21 seconds. This is slightly different from what is currently happening in the [FL250; FL295] layer (24,5s).

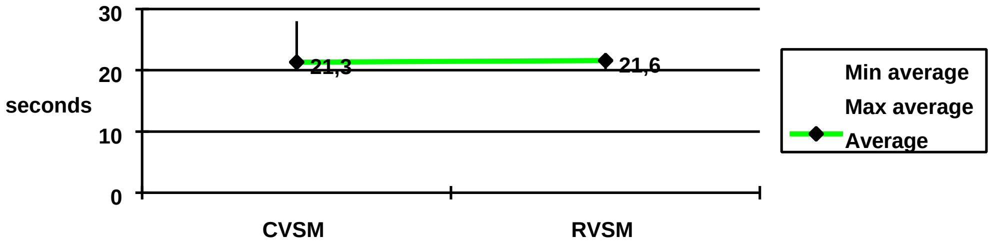


Figure 50: Average TA duration above FL290 with TCAS II version 7.0

4.3.2.8 Compared with version 6.04a, long-duration TAs still exist but are more rare events since version 7.0 does not issue TAs between aircraft perfectly steady and vertically separated.

4.3.3 Safety

4.3.3.1 No ACAS safety issues, related to the introduction of RVSM in Europe, were revealed.

4.4 Mixed equipage scenario

4.4.1 General

4.4.1.1 When RVSM is implemented in ECAC airspace, it is possible that some aircraft will still be equipped with TCAS II V6.04a. Simulations on a mixed equipage scenario (10% of aircraft equipped with version 6.04a) have been run in order to assess ACAS and RVSM interaction in such a case.

4.4.2 Compatibility with ATC

4.4.2.1 The results obtained (on RAs) for the scenarios involving a mix of aircraft fitted with TCAS II v6.04a and of aircraft fitted with TCAS II v7.0 are nearly identical to the results for the full version 7.0 equipage scenario.

4.4.3 Pilot acceptance

4.4.3.1 If aircraft equipped with version 6.04a fly in RVSM airspace, their pilots will receive RAs at approximately twice the rate received by aircraft equipped with V7.0. Nevertheless, based on current experience below FL290 this rate can be considered to be operationally tolerable both to pilots and to ATC.

4.4.3.2 The following figure gives an idea of the rate at which the number of TA increases in RVSM according to the proportion of aircraft equipped with version 6.04a. It is computed relatively to the number of TAs issued by version 7.0 in RVSM.

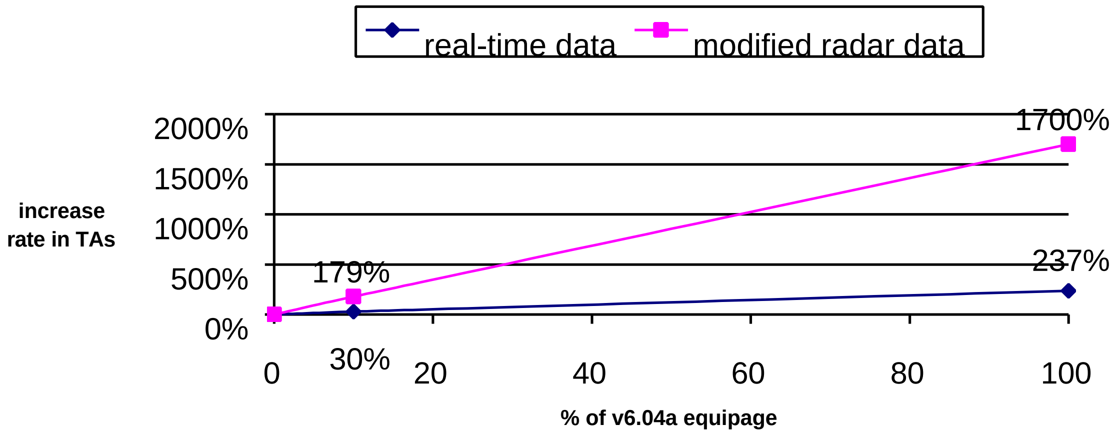


Figure 51: TA increase rate in RVSM

4.4.3.3 However, for 6.04a pilots the rate of receiving TAs may be as much as 20 times higher than in CVSM. Extrapolating this to TA rates implies that any aircraft fitted with 6.04a in RVSM will have an unacceptably high TA rate.

4.4.3.4 Furthermore, experience with ACAS operations has shown that pilots sometimes ask for traffic information when receiving a TA. This increases the use of an often already busy radio frequency and requires the controller an additional check of its radar display followed by a reply on the frequency. Thus an increase in the TA rate will have an impact on ATC workload.

4.4.3.5 In the subjective opinion of this study and in a conservative view, a 50% increase in the TA rate is the maximum that operational actors should be asked to accept. This implies that the maximum proportion of aircraft that ATC could allow to remain equipped with 6.04a in RVSM would range from 2.8% to 16.7%, assuming that pilots are willing to fly in RVSM with 6.04a.

4.4.4 Safety

4.4.4.1 No ACAS safety issues, related to the introduction of RVSM in Europe, were revealed.

4.5 TCAS II alert rates

4.5.1 General

4.5.1.1 The TCAS II alert rates presented in this section rely on the results of the studies based on real-time simulation data [WP111], and on modified radar data [WP057]. As stated in [WP123], the results of the study based on fast-time simulation data were not judged realistic enough to be taken into account.

4.5.1.2 For both modified radar data and real-time simulation data, the ACAS simulation results are used to make a comparison of the TCAS II alert rates between :

- The current situation in the [FL290; FL410] layer (labelled CVSM) and;
- The future situation in the [FL290; FL410] layer (labelled RVSM).

4.5.1.3 Furthermore, the section dealing with modified radar data makes a comparison between:

- The future situation in the [FL290; FL410] layer (labelled RVSM) and;
- The current situation in the [FL245; FL295] layer.

4.5.1.4 Finally, the TCAS II alert rates for different TCAS II equipage (v6.04a, mixed versions and v7.0) are presented to outline the impact of the TCAS II logic versions. The following three TCAS II equipage scenarios have been investigated for both the CVSM and the RVSM environment:

- **Scenario #1:** Whole TCAS II fleet fitted with version 7.0
- **Scenario #2:** Mixed TCAS II fleet fitted with version 7.0 (90%) and version 6.04a (10%);
- **Scenario #3:** Whole TCAS II fleet fitted with version 6.04a.

4.5.1.5 Each scenario was composed of a similar proportion of aircraft fitted or not with TCAS II. The proportion of aircraft not subject to the European mandatory carriage of ACAS II was estimated to be around 10%.

4.5.2 Study based on modified radar data

4.5.2.1 European radar data have been used both to assess the impact of RVSM on ACAS performances on the [FL290; FL410] layer, and to make a comparison between the current situation below FL290 and the future situation (after RVSM introduction) above FL290.

4.5.2.2 In the simulations where an RVSM environment was simulated, a strategy was designed to modify the flight level allocation in order to obtain a single alternate FLOS configuration, while not altering the flight profile and preserving the possible blunders.

4.5.2.3 The advantage of radar data was to provide realistic aircraft trajectories that nevertheless needed to be MASPS compliant in order to be taken into account in the study. The amount of radar data recordings was also greater than that that could be extracted from real-time simulation archives.

4.5.2.4 Nevertheless, the use of current radar data to simulate the future RVSM traffic implied the modification of the original radar data, and in particular, the reduction of the vertical separation from 2,000 feet to 1,000 feet when required. Such approach had some limitations, the major one being that the behaviour of air traffic controllers was assumed similar in both CVSM and RVSM environments.

4.5.2.1 Number of flight hours

4.5.2.1.1 The European radar data used in the study are 16 days of radar data recordings including:

- Four days of multi-radar data from UK,
- Five days of multi-radar data from Maastricht, and
- Seven days of mono-radar data from France (Palaiseau, near Orly).

4.5.2.1.2 The overall radar data recordings represent a total of 26541 flight hours for the [FL290; FL410] layer, and 9910 flight hours for the [FL245; FL295] layer, distributed has follows:

Origin	Total radar data recordings	Flight hours FL290-410	Flight hours FL245-295
England	4 days	7623	2304
Maastricht	5 days	12294	4615
Palaiseau	7 days	6624	2991
Total	16 days	26541	9910

Table 6 : Flight hours in the radar data recordings (modified radar data)

4.5.2.2 Encounters extracted from radar data recordings

4.5.2.2.1 Before the ACAS simulations, relevant encounters were extracted from the radar data. These encounters involve pairs of aircraft whose geometry match some space and time-related parameters, which depend on the separation standard and the TCAS sensibility level applicable in the studied layer.

4.5.2.2.2 These encounters are not necessarily associated with a TCAS II alert, or a loss of ATC separation. In particular, they were selected so as to include all the encounters that could be associated with a TCAS alert in the RVSM environment (e.g. converging aircraft separated by 4,000 feet in CVSM could become a TCAS encounter in RVSM where the separation would potentially be reduced to 2,000 feet).

<u>For the [FL290; FL410] layer</u>

4.5.2.2.3 Even though about 28% of the encounters initially extracted from the radar data have not been taken into account, the set of encounters used for the CVSM and RVSM simulations was still great (45001 encounters).

4.5.2.2.4 The majority of rejected encounters (59%) were potential conflicts near the limits of the RVSM airspace or at the limits of the radar data in time or space. In particular, some encounters extracted from the UK radar data and located in the oceanic airspace (4%) have been rejected.

4.5.2.2.5 The distribution of rejected encounters due to non MASPS aircraft is as follows: military aircraft (6%), altitude station keeping with variation greater than 130 feet (11%), TVE greater than 190 feet (18%), flight level change with overshoot greater than 150 feet (6%).

<u>For the [FL245; FL295] layer</u>

4.5.2.2.6 Below the future RVSM airspace, the amount of rejected encounters was relatively high: about 59% of the encounters initially extracted from the radar data. Nevertheless, the set of encounters used for the ACAS simulations was still great (14847 encounters).

4.5.2.2.7 The majority of rejected encounters (83%) were potential conflicts near the limits of the [FL245; FL295] layer or at the limits of the radar data in time or space.

4.5.2.3 TCAS II alerts per flight hour

4.5.2.3.1 As the ACAS simulations were only performed on the set of selected encounters extracted from the radar data, only rough estimates of TCAS II alert rates can be computed using the amount of flight hours included in the radar data.

4.5.2.3.2 Taking into account all flight hours (including the rejected encounters), the **minimum TCAS II alert rate** is as follows:

Min TCAS II alert rate = Number of TCAS II alerts / Total flight hours

4.5.2.3.3 Without taking into account the rejected encounters (-28% encounters above FL290, -59% encounters below), the **maximum TCAS II alert rate** is as follows:

Max TCAS II alert rate = Number of TCAS II alerts / Corrected flight hours

Corrected flight hours = Total flight hours * (1 - X)
Where X is the percent of rejected encounters.

Occurrence of RAs

4.5.2.3.4 In RVSM environment when compared to CVSM, the number of RAs per flight hour increases by at least by 2 to 4 times depending on the TCAS II logic version. In the worst estimates, the RA rate may increase by 3 to 6 times, respectively with TCAS II version 7.0 and version 6.04a.

4.5.2.3.5 Nevertheless, it should be noticed that the estimated RA rates above FL290, even in the RVSM environment, are much lower than those computed for the [FL245; FL295] layer. For instance, with TCAS II version 7.0, the mean RA rate goes from 1 RA every 1000 flight hours in CVSM, up to 1 RA every 400 flight hours in RVSM, while estimated at about 1 RA every 100 flight hours below FL290.

4.5.2.3.6 Finally, except within the CVSM environment, it should be noticed that the RA rates are about twice less great with TCAS II version 7.0 than with version 6.04a.

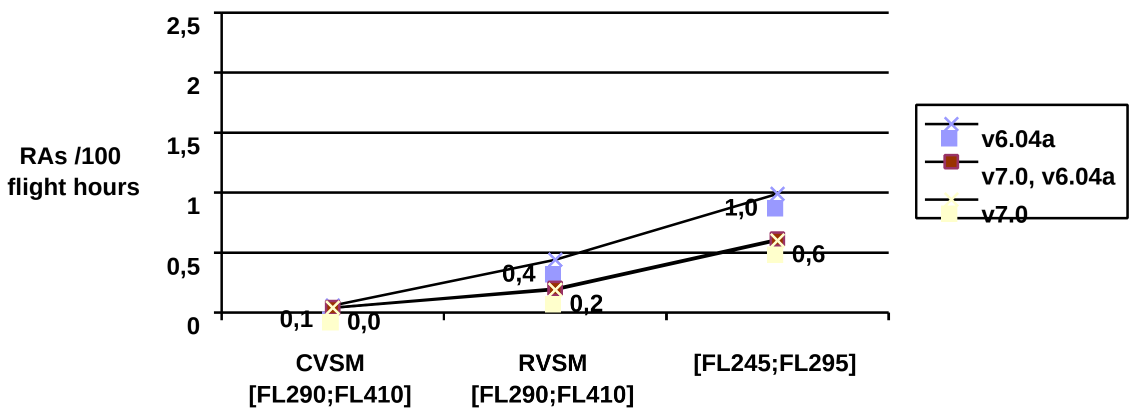


Figure 52: Minimum occurrence of RAs per flight hour (modified radar data)

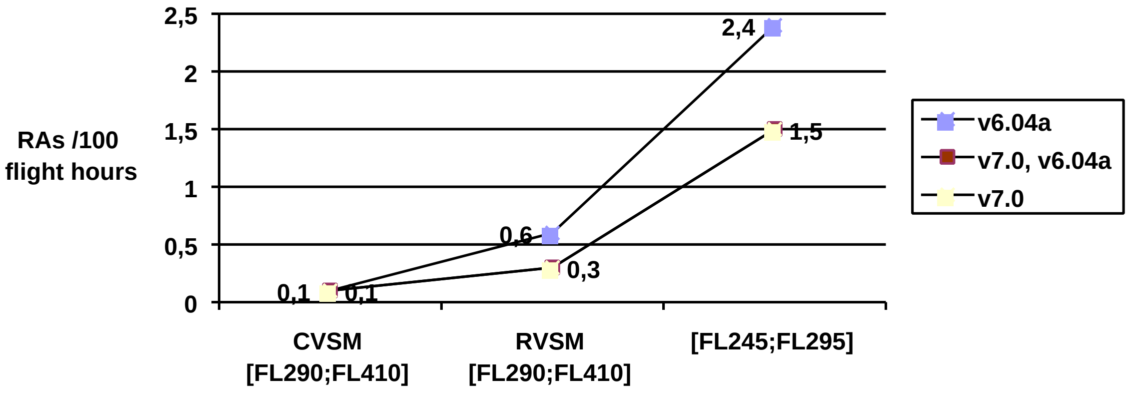


Figure 53: Maximum occurrence of RAs per flight hour (modified radar data)

<u>Occurrence of TAs</u>

4.5.2.3.7 The number of TAs per flight hour is much greater in RVSM than in CVSM environment, particularly with the TCAS II version 6.04a for which it increases from 1 TA every 50 flight hours in CVSM, up to nearly 1 TA every flight hour in RVSM. This significant TA rate is mainly due to the incompatibility between the vertical detection threshold of the logic version 6.04a and the reduced vertical separation minima of 1000 feet.

4.5.2.3.8 When compared to version 6.04, the TCAS II logic version 7.0 produces more acceptable TA rates, particularly within the RVSM environment with about 1 TA every 25 flight hours. Even though the TA rate with version 7.0 increases in RVSM when compared to CVSM, it should be noticed that it is about 2 to 4 times less than the TA rate simulated with the new TCAS II logic below FL290.

4.5.2.3.9 Finally, with only 10% of version 6.04a equipped aircraft, the mean TA rate in RVSM goes up to 1 TA every 10 flight hours.

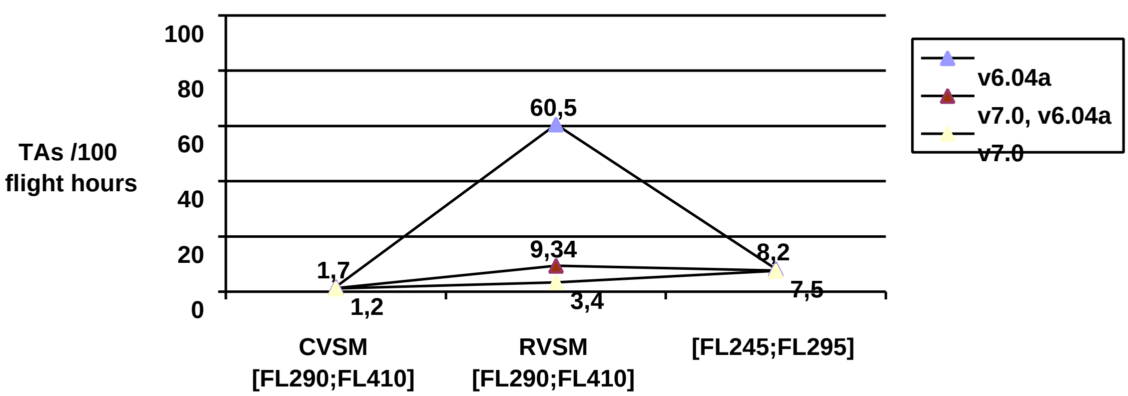


Figure 54: Minimum occurrence of TAs per flight hour (modified radar data)

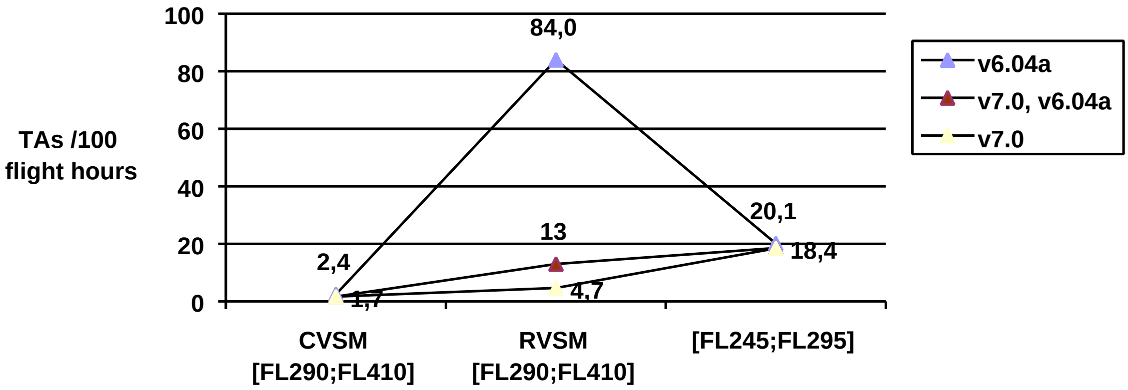


Figure 55: Maximum occurrence of TAs per flight hour (modified radar data)

4.5.3 Study based on real-time simulation data

4.5.3.1 Real-time simulation data

4.5.3.1.1 The Third Continental RVSM simulation [Lan97] provided data for both the current and future Vertical Separation Minima in Europe. The original traffic samples were created from real traffic samples supplied by the participating ATC Centres from France, Germany, and Switzerland. These traffic samples were also adjusted to represent increased traffic loads that could be met in the future RVSM airspace.

4.5.3.1.2 The main advantage expected from real-time simulations was to take into account the behaviour of air traffic controllers. Of course, due to the training issues related to each new ATC improvement like RVSM, the real time simulations may not necessarily reflect the actual controllers' behaviour in future RVSM operations.

4.5.3.1.3 Due to the simplified flight trajectories used in simulations, the introduction of trajectory deviations was required in order to obtain more realistic aircraft trajectories to be used in the ACAS simulations. The Trajectory Error Model was pessimistically designed to maximise the number of encounters and look at the worst case interactions between ACAS and RVSM [WP043]. This may partially explain the relatively high TCAS II alert rates simulated from the CVSM/RVSM real-time simulation data.

4.5.3.1.4 An anticipated limitation of real-time simulations was that they represent a few hours of ATC, and specific ATC sectors, due to the expensive cost of such simulations.

4.5.3.2 Number of flight hours

4.5.3.2.1 Traffic samples taken for this study were representative of 1996 + 35%, and +55%. Only exercises from Organisation 1 (sectorisation and route network in use as of November 1996) CVSM, and Single Alternate FLOS, were used: a total of 8 CVSM and 8 RVSM exercises based on the same original traffic samples and during 1h 30mn each.

4.5.3.2.2 At the beginning and end of a real-time simulation traffic levels were not representative of the target level. In addition, traffic enter and leave the main simulation area through feed-sectors, during which time they are not in controlled airspace and consequently are not realistically separated. Therefore, to avoid these effects, the first and last 15 minutes of each exercise were excluded from the study.

4.5.3.2.3 Taking into account only the amount of ATC hours used from the CVSM/RVSM real-time simulation data, the **corrected amount of flight hours** to be used to compute the TCAS II alert rates is as follows:

Corrected flight hours = Total flight hours * (1 - X)
Where X is the percent of rejected ATC hours.

Exercises with 1996 Traffic increased by	Corrected ATC hours	Total flight hours FL290-410	Corrected fight hours FL290-410
CVSM (+35%)	6 (from 9)	351	234
RVSM (+35%)	6 (from 9)	343	228, 7
CVSM (+55%)	2 (from 3)	141	94
RVSM (+55%)	2 (from 3)	133	88,7

Table 7 : Corrected ATC hours and flight hours in the S08 real-time simulation

4.5.3.3 TCAS II alerts per flight hour

4.5.3.3.1 The following results have been obtained from a combination of the ACAS simulation results based on the 35% traffic loading exercises (amounting to 343 flight hours in RVSM) and 55% traffic loading exercises (amounting to 133 flight hours in RVSM). Due to the lack of 55% traffic loading exercises, it was not relevant to breakdown the results obtained with the different traffic loading.

4.5.3.3.2 Besides, due to the rather small number of flight hours included in the real-time simulations and due to the pessimistic trajectory error model, the TCAS II alert rates derived from that source of data are to be taken carefully as they may not be statistically realistic.

4.5.3.3.3 Finally, it should be noted that the occurrence of loss of ATC separation, in the traffic samples issued from the real-time simulations between FL290 and FL410, was 54 (1 per 9 flight hours) in CVSM, and 27 (1 per 18 flight hours) in RVSM. These unrealistic ATC performances may partially explain the relatively high TCAS II alert rates simulated from the CVSM/RVSM real-time simulation data.

Occurrence of RAs

4.5.3.3.4 In RVSM environment when compared to CVSM, the number of RAs per flight hour increases by 3 to 4 times depending on the TCAS II logic version and the estimation method. Furthermore, the TCAS II logic version 7.0 provides a significant reduction of the RA rate by more than 5 times when compared to version 6.04a.

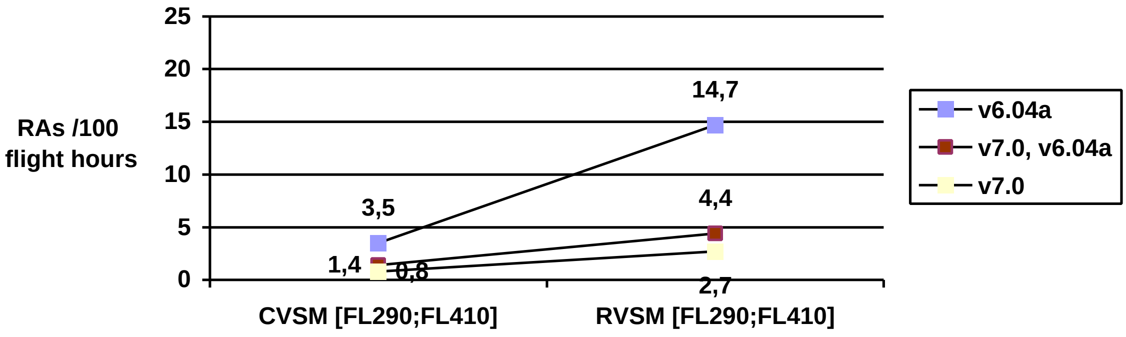


Figure 56: Minimum occurrence of RAs per flight hour (real-time simulation data)

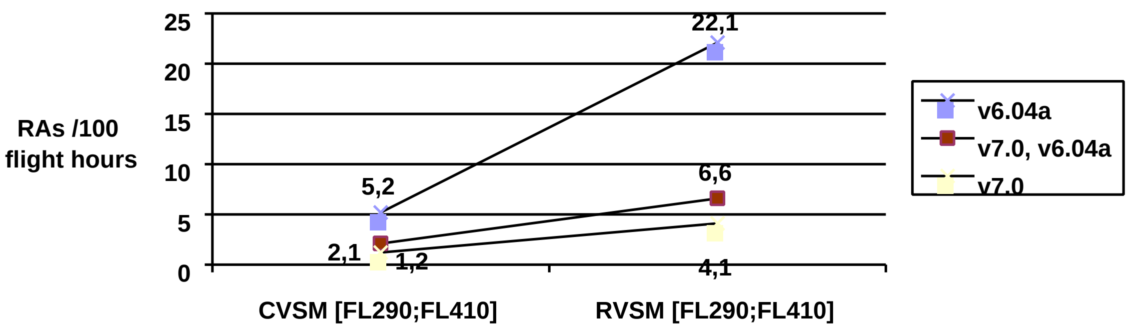


Figure 57: Maximum occurrence of RAs per flight hour (real-time simulation data)

4.5.3.3.5 Nevertheless, it should be noticed that these RA rates are much higher, and less realistic, than those computed from the European radar data. For instance with TCAS II version 6.04a, the mean RA rate based on the CVSM real-time simulations is about 1 RA every 25 flight hours (instead of 1 RA every 1000 flight hours based on the European radar data).

<u>Occurrence of TAs</u>

4.5.3.3.6 Like with the RA rate, the number of TAs per flight hour simulated from the CVSM/RVSM real-time simulation data are largely greater than those estimated from the European radar data, and cannot be used as such.

4.5.3.3.7 Nevertheless, it should be noticed that the same trends apply, in particular the similar TA rates in CVSM whatever the TCAS II logic version, and the significant increase in RVSM by 5 to 15 times, respectively with the logic version 7.0 and version 6.04a.

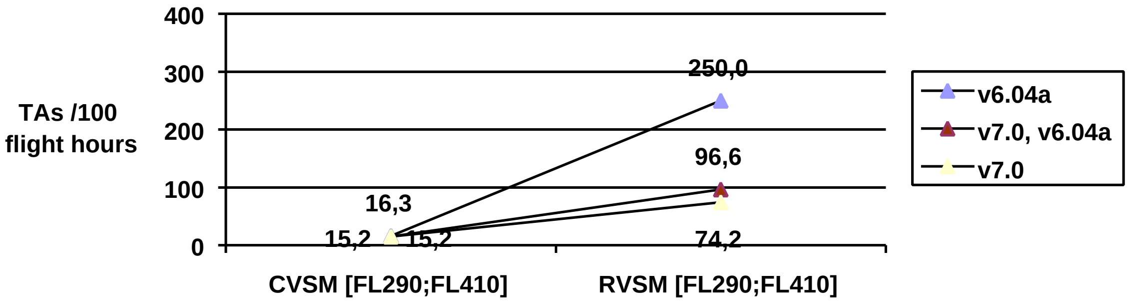


Figure 58: Minimum occurrence of TAs per flight hour (real-time simulation data)

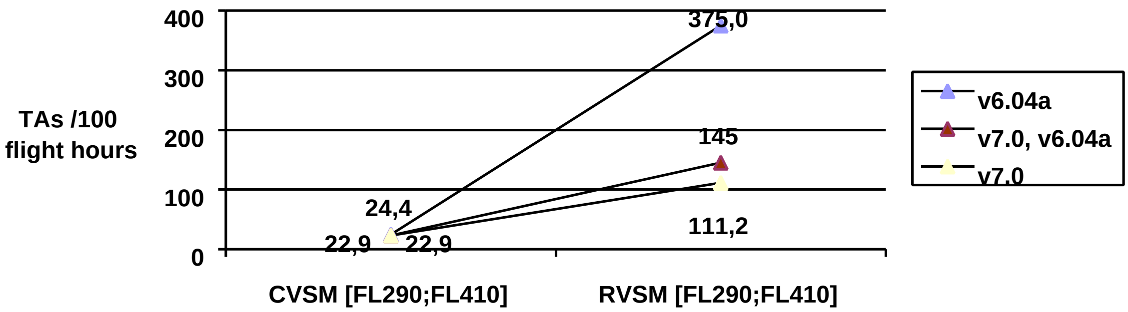


Figure 59: Maximum occurrence of TAs per flight hour (real-time simulation data)

4.5.4 Conclusions

4.5.4.1 The rationale for using different sources of data to investigate the ACAS/RVSM interaction was to compensate the limitations related to each source of data, and to cope with a larger set of issues. But, due to the discrepancies in the results obtained from the real-time simulations and those obtained from the modification of radar data, it is not possible to clearly determine the TCAS II alert rates that will be experimented in the European RVSM airspace.

4.5.4.2 Nevertheless, it is possible to conclude on the general trends that apply before and after the introduction of RVSM in the [FL290; FL410] layer, as well as to make a comparison with what is happening in the [FL245; FL295] layer according to the study based on modified European radar data.

4.5.4.3 These trends are summarised hereafter for each studied scenario of TCAS II equipage, and illustrated using the TCAS II alert rates estimated from the ACAS simulations based on the European radar data, as they were considered more operationally realistic.

4.5.4.1 Full version 6.04a equipage

4.5.4.1.1 In RVSM environment when compared to CVSM, the number of RAs per flight hour with full version 6.04a equipage increases by 4 to 6 times depending on the estimations. But, it should be noticed that the RA rates above FL290, even in the RVSM environment, are much lower than those computed for the [FL245; FL295] layer where the 1000 feet vertical separation minima already applies.

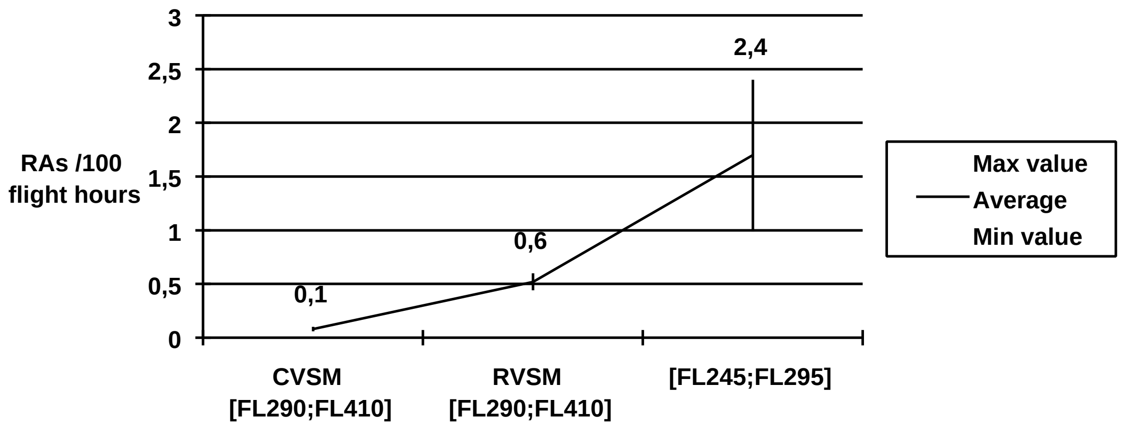


Figure 60: Occurrence of RAs per flight hour with TCAS II version 6.04a

4.5.4.1.2 With regard to the number of TAs per flight hour, it is expected to dramatically increase in RVSM when compared to CVSM, by 15 to 35 depending on the estimations. This incompatibility between version 6.04a and RVSM is considered as operationally unacceptable from the pilots' perspective.

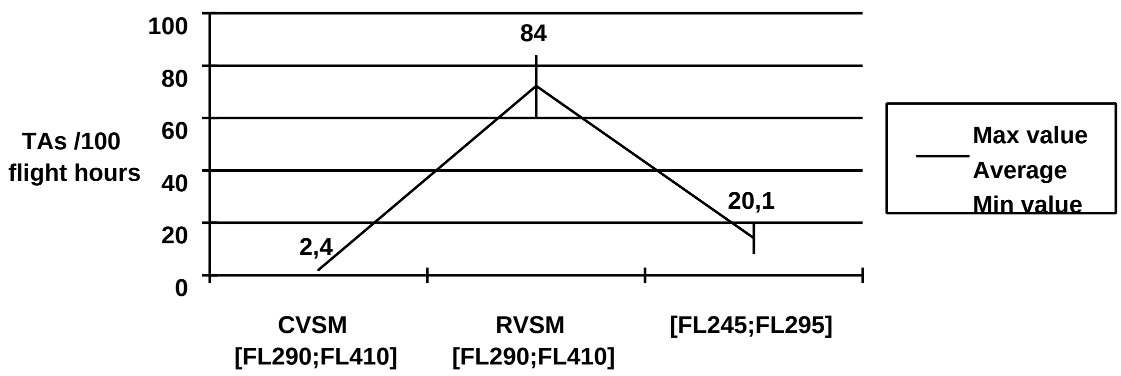


Figure 61: Occurrence of TAs per flight hour with TCAS II version 6.04a

4.5.4.2 Full version 7.0 equipage

4.5.4.2.1 With full TCAS II version 7.0 equipage, the number of RAs per flight hour increases in RVSM when compared to CVSM, by 2 to 3 times depending on the estimations. Nevertheless, the RA rates above FL290, even in the RVSM environment, are expected to be much lower than those estimated for the [FL245; FL295] layer.

4.5.4.2.2 Furthermore, it should be noticed that whatever the airspace, the RA rates with TCAS II version 7.0 are reduced when compared to full version 6.04a equipage.

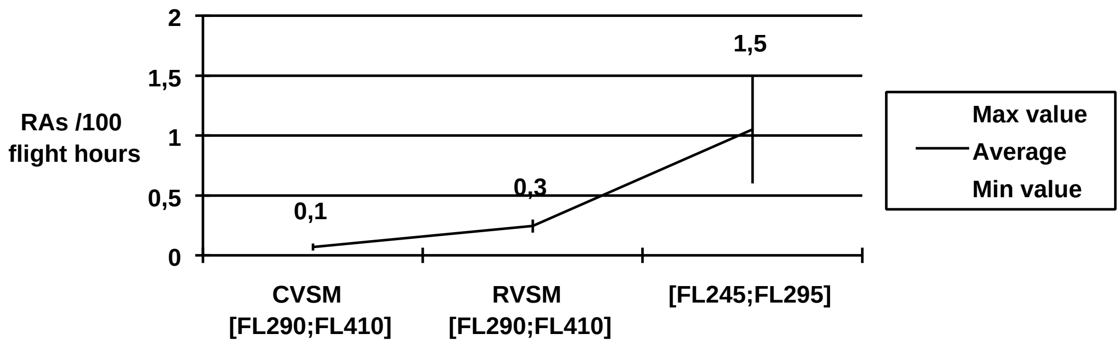


Figure 62: Occurrence of RAs per flight hour with TCAS II version 7.0

4.5.4.2.3 With regard to the number of TAs per flight hours in RVSM. The TCAS II version 7.0 provides a significant improvement when compared to version 6.04. Even though the TA rate is expected to increase by about 3 times in RVSM when compared to CVSM, it is expected to be 2 to 4 times less than the TA rate in the [FL245; FL295] layer.

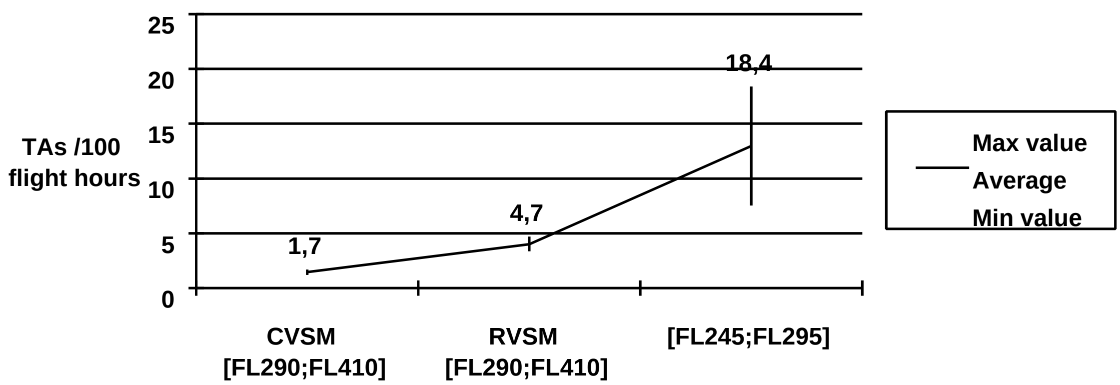


Figure 63: Occurrence of TAs per flight hour with TCAS II version 7.0

4.5.4.3 Mixed equipage scenario

4.5.4.3.1 The TCAS II alert rates obtained (on RAs and TAs) for the scenarios involving a mix of aircraft fitted with TCAS II v6.04a and of aircraft fitted with TCAS II v7.0 are nearly identical to the results for the full version 7.0 equipage scenario.

4.5.4.3.2 The only slight difference is in the higher TA alert rate experienced in RVSM by pilots of TCAS II version 6.04a equipped aircraft. Depending on the estimations, the mean TA alert rate in RVSM increases by 1,5 to 3 times with only 10% of version 6.04a equipped aircraft, when compared to full version 7.0 equipage.

4.5.4.4 Operational considerations

4.5.4.4.1 From the ACAS simulations performed on the modified European radar data and the CVSM/RVSM real-time simulation data, the TCAS II alert rates (on RAs and TAs) are expected to increase after the introduction of the RVSM above FL290 in Europe. As expected, the TCAS II logic version 7.0 demonstrated a better compatibility with RVSM than the version 6.04a.

4.5.4.4.2 Furthermore, the TCAS II alert rates in the future RVSM airspace are expected to be lower than those that are experienced in the [FL245; FL295] layer, whatever the TCAS II logic version. However, this feature may not be fully visible from an operational point of view due to the higher proportion of flight hours above FL290 (about 2 to 3 times more than below).

5 Conclusion

5.1 Methodology

5.1.1 A comparison of the ACAS performances within the future European RVSM environment and the current CVSM environment has been performed based on different sources of data. For each source of data, a large set of ACAS performance indicators has been used to highlight potential improvements or drawbacks in terms of safety, compatibility with ATC and pilot acceptance.

Advantages

5.1.2 The various sources of data used in this ACAS/RVSM interaction study had the advantage of covering the largest possible set of potential issues, both quantitatively and qualitatively without relying on only one type of study and its intrinsic limitations.

Limitations

5.1.3 All the studies are based on assumptions derived from the proposed operational procedures for RVSM. Nevertheless, those assumptions (for example, the ones linked to the way air traffic controllers will deal with RVSM) need to be tested against operational reality.

5.1.4 The number of events triggering an RA was not always as high as desirable for a statistical study.

5.2 ACAS/RVSM interaction

5.2.1 The study has shown that the introduction of RVSM affects ACAS performances above FL290. However the impact is quite different whether TCAS II version 6.04a or version 7.0 is in operation in the RVSM airspace.

5.2.2 The following sections sum up the teachings of the ACAS and RVSM interaction study for the three scenarios of ACAS equipage. However, it must be reminded that the full version 6.04a equipage scenario will not exist in the European RVSM environment. It has been studied only to give figures showing the benefit brought about by version 7.0.

TCAS II logic version 6.04a

5.2.3 The study has predicted the following behaviour with version 6.04a in the RVSM environment:

- A high level of RA occurrence combined with an increased number of nuisance RAs. The nuisance RAs are mainly caused by oscillating level aircraft flying 1,000 ft apart and by aircraft in a level-off manoeuvre 1,000 ft from another aircraft. This is the main issue from the ATC point of view.
- A high proportion of positive RAs (i.e. climb or descend) and of rate-reversing RAs.

- An excessive level of TA occurrence combined with an increased number of nuisance TAs due to the incompatibility between version 6.04a and RVSM. This is the main issue from the pilot's point of view as it may lead to a loss of confidence in the ACAS system.
- A risk of long duration TAs in case of exceptions (for ATC efficiency reasons) to the application of the semi-circular rule, bringing aircraft to fly 1,000 ft apart on the same track. When such two aircraft (even in perfectly steady flight) come closer horizontally a long-duration TA is bound to happen, which will seriously disturb the pilot.

5.2.4 In view of these results, TCAS II logic version 6.04a is considered to be incompatible with the future European RVSM from both the pilots' and air traffic controllers' point of view.

TCAS II logic version 7.0

5.2.5 Going from version 6.04a to version 7.0 improves the ACAS performances in the European RVSM airspace, in the following domains :

- The number of RA occurrences is reduced (and nuisance RAs accordingly) by the 'Miss Distance Filtering' mechanism, which suppress RAs when the HMD is large, by a less disruptive behaviour of the logic in case of level-off geometry. A better 25 feet vertical tracker and other changes also reduce the number of RAs.
- The number of TA occurrences is dramatically reduced (and nuisance TAs accordingly) by an adequate vertical detection threshold and thanks to a better 25 feet vertical tracker, the combination of both improvements suppressing TAs between perfectly steady (or even slightly oscillating) aircraft on adjacent flight levels.

5.2.6 Nevertheless, the study has foreseen the following issues with version 7.0 in the RVSM environment:

- An increased number of RAs when compared to the current CVSM environment;
- A high proportion of nuisance TAs which is an operational issue for the RVSM environment, from the pilots' point of view;
- A high proportion of repetitive TAs could also be an operational issue for the RVSM environment. Indeed, pilots may consider repeated occurrences of the 'traffic, traffic' aural annunciations as disruptive alerts.

5.2.7 However, the previous points have to be mitigated by the fact that they are already operational issues below FL290 in the current operational environment and the upgrade from version 6.04a to version 7.0 will be diminishing their impact.

5.2.8 Some issues have been identified using one source of data, but have not been confirmed by others. They are presented below, even if further investigation would be desirable:

- A high proportion of nuisance RAs caused by level-off encounters. This is an already-known ACAS behaviour below FL290 and steps have been taken to encourage pilots to reduce their aircraft vertical rate when approaching the cleared flight level while another aircraft is 1,000 ft above or below;
- A high proportion of RAs with more than 2 advisories. (To be confirmed)

5.2.9 Even with the previous issues, the interaction between TCAS II logic version 7.0 and RVSM can be considered as acceptable for both pilots and air traffic controllers, but the ACAS/RVSM compatibility could still be improved.

Mixed TCAS II logic

5.2.10 When both TCAS II versions will be in operation in the European RVSM airspace, the compatibility with ATC is expected to be nearly the same as the one described with the whole TCAS II fleet fitted with version 7.0.

5.2.11 Regarding pilot’s acceptance, even low proportions of TCAS version 6.04a equipped aircraft (10%) are likely to put a burden on pilots. This may even indirectly put a burden on controllers, if pilots send more requests for traffic information. These issues are expected to be exacerbated with a higher proportion of TCAS II version 6.04a equipped aircraft.

Safety considerations

5.2.12 No safety issues, related to the introduction of an RVSM environment, have been discovered.

5.2.13 The introduction of RVSM could adversely affect the benefit in safety that is accrued by virtue of ACAS being deployed within the airspace.

5.2.14 However, even though the exact figures cannot be trusted, the order of magnitude of the computed risk ratios confirm that ACAS will still continue to provide a safety benefit, as expected, when introducing RVSM.

5.2.15 The overall risk of collision, in either CVSM or RVSM, is very sensitive to the proportion of aircraft that are equipped, and it is important that all aircraft are equipped with ACAS.

5.2.16 The great importance of pilots following the RAs if the benefit from ACAS is to be gained has been confirmed. Indeed, an individual pilot who ignores RAs will be at greater risk than if his aircraft were unequipped – as will (unwittingly) the well-behaved pilots of ACAS equipped aircraft he encounters.

5.2.17 It is important that both aircraft are ACAS equipped and that both pilots follow their RAs accurately.

6 Recommendations

6.1 Aircraft equipments

Aircraft flying in RVSM environment should be equipped with TCAS II logic version 7.0.

6.1.1.1 TCAS II logic version 7.0 has been designed to be more compatible with an RVSM environment. It will bring many benefits in terms of reduction of alerts and compatibility with ATC clearances, which have been demonstrated in this study. Those benefits are all the greater than the proportion of aircraft fitted with version 6.04a is low.

Aircraft flying at 1000' separation in RVSM environment should be MASPS-compliant

6.1.1.2 Compliance with MASPS improves the vertical station-keeping of aircraft, thus reducing the amplitude of oscillations around the ideal trajectory. Smaller oscillations will offer less opportunities for ACAS to detect a dangerous closure rate, thus decreasing the number of nuisance advisories.

Transponders of Aircraft flying in RVSM environment should report their altitude with 25-feet increments.

6.1.1.3 Tracking other aircraft with a 25-foot accuracy instead of a 100-foot accuracy enables the ACAS logic to detect more accurately the position of aircraft. It will then not issue an advisory for an aircraft slightly oscillating around its flight level whereas a logic fed with 100-foot position report would have issued an advisory, because it would have seen the oscillating aircraft as closer and converging faster.

6.2 Management staff actions

Controllers should be provided ACAS/RVSM specific information and training

6.2.1.1 The number of advisories they will be confronted to in the [FL290; FL410] altitude band will increase. They should be prepared for this new situation. The level-off situations will occur more often and, in these situations, controllers should provide traffic information to the aircraft in evolution.

Pilots should be provided ACAS/RVSM specific information and training

6.2.1.2 The number of advisories they will be confronted to in the [FL290; FL410] altitude band will increase. They should be prepared for this new situation. When they receive traffic information that they are in a level-off situation, they should reduce the aircraft vertical rate when approaching the cleared flight level. Pilots should also be trained not to react with an excessive vertical rate when complying with a resolution advisory.

TCAS II logic version 7.0 performances in RVSM environment should be carefully monitored.

6.2.1.3 Some operational issues remain with version 7.0 in RVSM, in particular the presence of a substantial proportion of repetitive TAs. Also, no safety issues have been observed in the study, but that does not mean that none will appear. Therefore, an operational monitoring of version 7.0 behaviour in the RVSM environment would be useful.

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[WP022] ACASA/WP3.1-022 – 'Methodology for Study based on data extracted from real-time simulations' – EEC/David Powell - Version 1.2, 31 March 1999.

[WP023] ACASA/WP3.1-023 – 'Methodology for study based on data extracted from fast-time simulations' – David Powell – EEC/David Powell - Version 1.2, 31 March 1999.

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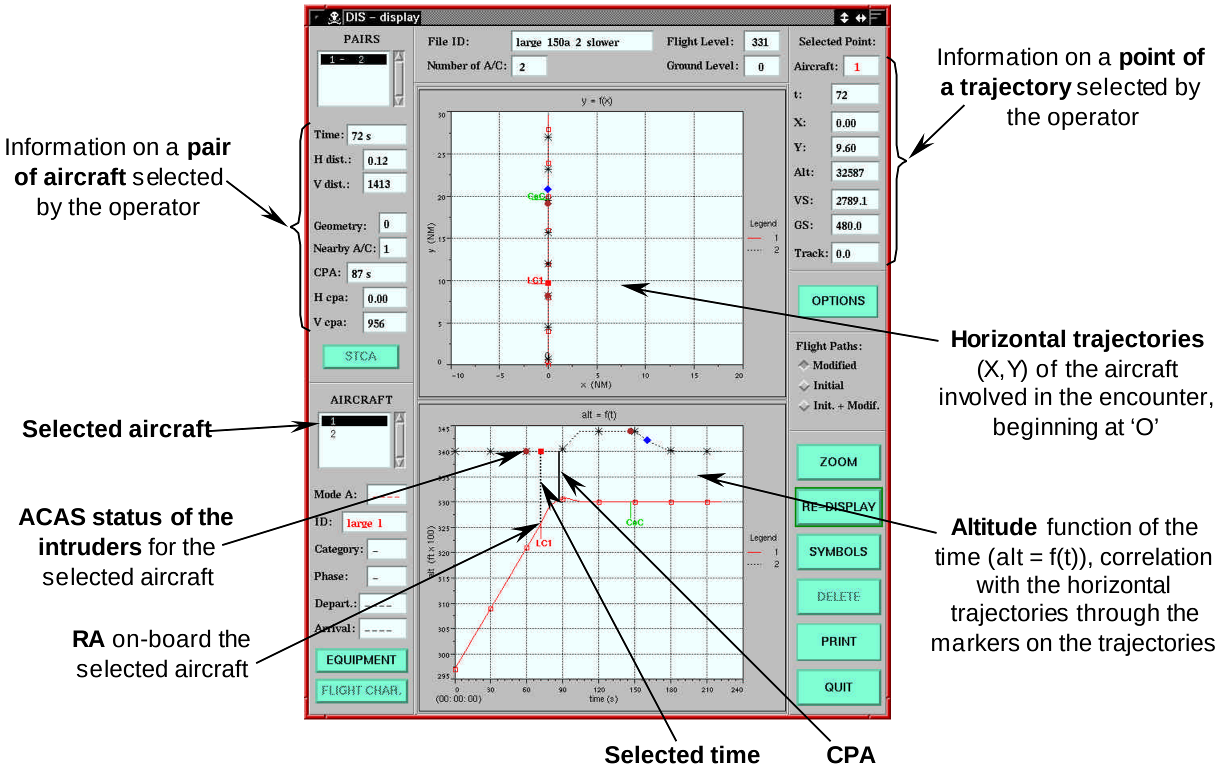
Appendix A : OSCAR display presentation



Note: The TCAS II simulation results are displayed on the horizontal and vertical trajectories: RAs are displayed on the trajectory of the selected aircraft and ACAS status of the intruders on their respective trajectories, according to the symbols described below: