

TCAS II performance in European TMAs

Part 1: Analysis

Safety Issue Rectification Extension 2006-2008 Project

SIRE+ Project

CND/CoE/CNS/09-047

Edition Number	:	1.1
Edition Date	:	03rd February 2009
Status	:	Released
Intended for	:	EATM Stakeholders

DOCUMENT CHARACTERISTICS

TITLE			
TCAS II performance in European TMAs Part 1: Analysis Safety Issue Rectification Extension 2006-2008 Project SIRE+ Project			
ALDA Reference: 09/04/14-09			
Document Identifier			
Edition Number:		1.1	
Edition Date:		03 rd February 2009	
Abstract			
<p>The objective of this study was to analyse TCAS II version 7.0 performance in European Terminal Control Areas (TMAs), both from an operational standpoint and from a safety standpoint. The study has been conducted using radar and Resolution Advisory (RA) downlink data collected in three major TMAs over three months during 2007-2008 winter period.</p> <p>Part 1 of the report describes statistical results of the monitoring effort. Approximately 200 RAs were recorded. The most common types of RAs were Adjust Vertical Speed and Monitor Vertical Speed, each corresponding to over a third of all RAs. The majority of RAs were against unequipped intruders below TMA. The compliance rate of flight crews to Climb and Descend RAs was 60%. Because of non-compliance with TCAS RAs, five very close encounters have been identified. The large number of RAs against unequipped intruders should be addressed through airspace design.</p>			
Keywords			
TCAS	TMAs	SIRE	
ACAS		Analysis	
Contact Person(s)		Tel	Unit
Stanislaw Drozdowski		+32.2.729.3760	Mode S & ACAS Programme
John Law		+32.2.729.3766	Mode S & ACAS Programme

STATUS, AUDIENCE AND ACCESSIBILITY				
Status	Intended for		Accessible via	
Working Draft	<input type="checkbox"/>	General Public	<input type="checkbox"/>	Intranet <input type="checkbox"/>
Draft	<input type="checkbox"/>	EATMP Stakeholders	<input checked="" type="checkbox"/>	Extranet <input type="checkbox"/>
Proposed Issue	<input type="checkbox"/>	Restricted Audience	<input type="checkbox"/>	Internet (www.eurocontrol.int) <input type="checkbox"/>
Released Issue	<input checked="" type="checkbox"/>			

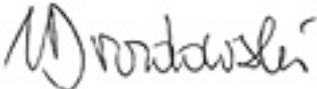
ELECTRONIC SOURCE		
Path:	Software	Size
Host System Windows_XP	Microsoft Word / Adobe Acrobat	3.76 MB

EUROCONTROL Headquarters
Mode S & ACAS Programme
96 Rue de la Fusée
B-1130 BRUSSELS

Tel: +32 (0)2 729 3766
E-mail: acas@eurocontrol.int

DOCUMENT APPROVAL

The following table identifies all management authorities who have successively approved the present issue of this document.

AUTHORITY	NAME AND SIGNATURE	DATE
ACAS Operational Expert	 Stanislaw Drozdowski	20 April 2009
Mode S & ACAS Programme Manager	 John Law	20 April 2009

TCAS II performance in European TMAs Part 1: Analysis

**Safety Issue Rectification Extension 2006-2008 Project
SIRE+ Project**

Drafted by: Hervé Dréville

Authorised by: Thierry Arino on 03-02-2009

RECORD OF CHANGES

Issue	Date	Detail of changes
0.1	08-12-2008	Initial draft
0.2	08-12-2008	Revised version following internal review
0.3	11-12-2008	Complete draft following progress meeting
1.0	19-01-2009	Initial version delivered to EUROCONTROL
1.1	03-02-2009	Revised version following EUROCONTROL review

IMPORTANT NOTE: ANY NEW VERSION SUPERSEDES THE PRECEDING VERSION, WHICH MUST BE DESTROYED OR CLEARLY MARKED ON THE FRONT PAGE WITH THE MENTION OBSOLETE VERSION

TABLE OF CONTENTS

1. INTRODUCTION.....	6
1.1.CONTEXT	6
1.2.SCOPE AND OBJECTIVES	6
1.3.DOCUMENT OVERVIEW	7
2. DATA AND METHODOLOGY.....	8
2.1.OVERVIEW OF DATA	8
2.2.METHODOLOGY USED	8
3. OPERATIONAL PERFORMANCE OF TCAS II.....	9
3.1.INTRODUCTION	9
3.2.RA FREQUENCY	9
3.3.RA TYPE DISTRIBUTION	9
3.4.CHARACTERIZATION OF RAS	13
3.4.1. RA altitude distribution.....	13
3.4.2. Miss distance distribution.....	17
3.5.OTHER ISSUES	20
3.5.1. Conflict caused by go around	20
3.5.2. Level-off below holding pattern	24
4. SAFETY PERFORMANCE OF TCAS II.....	26
4.1.RA COMPLIANCE RATE	26
4.2.ACHIEVEMENT OF ALIM	30
5. CONCLUSIONS AND RECOMMENDATIONS	33
5.1.GENERAL	33
5.2.OPERATIONAL PERFORMANCE	33
5.3.SAFETY PERFORMANCE	34
5.4.RECOMMENDATIONS	34
6. REFERENCES.....	35
7. ACRONYMS.....	36

LIST OF FIGURES

Figure 1: Distribution of RA types.....	10
Figure 2: VTT feature preventing the issuance of RA onboard level aircraft.....	11
Figure 3: MDF creating dissymmetry in TCAS-TCAS encounter (no RA in red aircraft).....	12
Figure 4: Altitude distribution of RAs	13
Figure 5: Aircraft on approach receiving MVS RA against traffic below TMA	14
Figure 6: Departing aircraft receiving AVSA RA in 1,000ft level-off situation.....	15
Figure 7: Altitude distribution of Climb/MVS and AVSA RAs	16
Figure 8: HMD distribution.....	17
Figure 9: VMD distribution.....	18
Figure 10: Combined altitude, HMD and VMD distribution.....	19
Figure 11: Combined RA type, HMD and VMD distribution	20
Figure 12: RAs received onboard aircraft performing go around	22
Figure 13: RAs received onboard departing aircraft.....	23
Figure 14: Induced RAs in aircraft in holding pattern	25
Figure 15: Compliance rate to corrective positive RAs	26
Figure 16: Characteristics of RAs complied and not complied with	27
Figure 17: Non-compliance with Climb RA against unequipped threat	29
Figure 18: Combined HMD-VMD distributions per altitude layer.....	30
Figure 19: RAs received onboard non-responding aircraft.....	32

GLOSSARY

ACAS	Airborne Collision Avoidance System – a system standardised in the ICAO SARPs that uses transponder replies from other aircraft to warn the pilot of a risk of impending collision. Hereafter, ACAS always refers to ACAS II – a system that generates traffic advisories (TAs) and also generates resolution advisories (RAs) in the vertical plane.
RA downlink	A communication channel enabling a TCAS-equipped aircraft to transmit detailed information about on-going RAs. These data can notably be collected by Mode S ground stations.
Resolution Advisory	A resolution advisory (RA) is an ACAS alert instructing the pilot on how to modify or regulate his vertical speed in order to reduce the risk of collision diagnosed by the system.
Safety issue	An issue that has the potential to debase the safety benefits brought by ACAS, possibly leading to reduced vertical separations or even NMACs.
SIR SIRE SIRE+	Safety Issue Rectification and Safety Issue Rectification Extension – a series of studies commissioned by EUROCONTROL in order to improve TCAS safety performance. SIRE+ addresses two safety issues: <ul style="list-style-type: none">- SA01: inappropriate reversal logic operation,- SA-AVSA: misinterpretation of AVSA RAs leading to unintentional responses in the opposite sense.
TCAS	Traffic alert and Collision Avoidance System – an aircraft equipment that is an implementation of an ACAS.
Threat	A transponder-equipped aircraft within the surveillance range of ACAS and that is tracked by ACAS.
TMA	A volume of controlled airspace set up at the confluence of airways in the vicinity of one or more major airports to protect inbound and outbound traffic. A TMA is generally defined as a series of areas around approaching and departing routes, constrained both horizontally and vertically. A TMA typically spans over a few tens of NM around the airport(s) and rises from a few thousands of feet above the ground to a defined FL.

1. Introduction

1.1. Context

- 1.1.1. The **Airborne Collision Avoidance System (ACAS)**¹ has been introduced in order to reduce the risk of mid-air collisions. It serves as a last resort safety net irrespective of any separation standards.
- 1.1.2. From 1st January 2005 in the European Civil Aviation Conference (ECAC) area, all civil fixed-wing turbine-engined aircraft having a Maximum Take-Off Mass (MTOM) exceeding 5,700 kg or a maximum approved passenger seating configuration of more than 19 shall be equipped with an ACAS II compliant equipment (i.e. the Traffic alert and Collision Avoidance System (TCAS) II version 7.0).
- 1.1.3. Following the identification of two severe safety issues in TCAS II version 7.0, EUROCONTROL has commissioned the Safety Issue Rectification (SIR) initiative, culminating with the present SIRE+ project, to address these two issues. This initiative has proposed to resolve these safety issues through two changes to the TCAS II Minimum Operational Performance Standards (MOPS) ([DO185A]), identified as Change Proposals (CP) 112E and 115. Both EUROCAE Working Group 75 (WG75) and RTCA Special Committee 147 (SC147) have evaluated and endorsed these proposals.
- 1.1.4. As part of the validation of CP112E and CP115 conducted within RTCA SC147 and EUROCAE WG75, the SIRE+ project has assessed the performance of TCAS II version 7.0 in two US Terminal Control Areas (TMAs); i.e. New York ([SIRE+1]) and Boston ([SIRE+2]). The objective of these studies was notably to gain some insight in the current operation of TCAS in busy US TMAs, enabling to assess the operational and safety effect of CP112E and CP115 introduction. As radar data from several European Air Navigation Service Providers (ANSPs) became available to EUROCONTROL, the opportunity arose to conduct a similar assessment of TCAS II version 7.0 operational and safety performance in major European TMAs.

1.2. Scope and objectives

- 1.2.1. The objectives of the study are to perform an analysis of TCAS II version 7.0 performance in European airspace, both from an operational standpoint and from a safety standpoint. The study has been conducted using radar and Resolution Advisory (RA) downlink data collected in three major Terminal Control Areas (TMAs) over three months during the 2007-2008 winter period.
- 1.2.2. Operational performance of TCAS II version 7.0 has been assessed through the analysis of the typical situations that led to the issuance of RAs and of the characteristics of these RAs.

¹ In this document, ACAS refers to ACAS II, as it is the only version which use has been mandated in Europe.

1.2.3. Safety performance of TCAS II version 7.0 has assessed of the crew compliance rate with TCAS alerts and if the safety benefits expected from TCAS were actually achieved. This assessment resulted in the computation of the rate with which very close encounters occur in European TMAs and, ultimately, of the risk of mid-air collision in operational environment.

1.3. *Document overview*

1.3.1. Section 1 is the present introduction.

1.3.2. Section 2 gives an overview of the data and the methodology used to conduct the present study.

1.3.3. Section 3 is an analysis of TCAS II operational performance conducted in some major European TMAs. It provides the frequency of TCAS alerts and details the typical issues that have been observed.

1.3.4. Section 4 is an analysis of TCAS II safety performance in these TMAs. It estimates the rate of compliance with RAs and assesses the level of safety benefits brought by TCAS in an operational environment.

1.3.5. Section 5 is the conclusion of this report, also providing some recommendations based on the issues observed within this study.

2. Data and methodology

2.1. Overview of data

- 2.1.1. The radar data used to conduct the operational and safety analysis of TCAS II version 7.0 performance have been collected in three major European TMAs by Mode S stations between November 2007 and March 2008. Because of the period during which radar data have been collected, fewer flights under Visual Flight Rules (VFR) have been observed than for a comparable amount of data recorded during the summer. This results in less frequent RA events against VFR flights than would be anticipated with summer data.
- 2.1.2. The amount of radar data available to perform the study was about 140,000 Mode S flight hours. This figure might seem low but is a consequence of the short time where aircraft are actually flying within a TMA (typically less than 30 minutes for a departure or an arrival). This averages to a total of about 1,500 flight hours per day in the three TMAs under study.

2.2. Methodology used

- 2.2.1. When assessing the operational performance of TCAS in a given airspace through radar data, two methodologies are available depending on the availability of RA downlink information for this airspace. These two methodologies have been compared in Part 2 of the present report and been found to produce equivalent performance indicators.
- 2.2.2. The first methodology only uses radar data and has been used in the past on Secondary Surveillance Radar (SSR) data. It consists in identifying close encounters using TCAS-like criteria and in simulating the behaviour of TCAS on these encounters off line. This methodology was noticeably used for the assessment of the operational performance of CP115 in New York airspace ([SIRE+1]), as RA downlink data were not available for this study.
- 2.2.3. With this methodology, radar tracks, which are generally updated every 4 to 12 seconds, are interpolated into 1-second update rate trajectories. Because of the sensitivity of the collision avoidance logic to altitude and vertical speed, this interpolation step sometimes leads the TCAS simulation to miss RAs that actually occurred or issue RAs when none actually were. To cope with this issue, jittering the encounters before applying the TCAS simulation can improve confidence in the simulation result
- 2.2.4. The second methodology bases the identification of encounters of interest on RA downlink data, through the RA reports contained in BDS30. This methodology has been applied when assessing the performance of CP115 in Boston TMA ([SIRE+2]). As RA downlink information was available for the present study, this methodology has been used.

3. Operational performance of TCAS II

3.1. *Introduction*

- 3.1.1. The operational performance of TCAS II in European TMAs has been assessed through the computation of the frequency with which RAs are issued and through the analysis of the typical geometries that led to the issuance of these RAs. This analysis allowed identifying some types of operations, commonly used in the three TMAs under study, which have the potential to frequently generate TCAS alerts.
- 3.1.2. In addition, the observation of individual RA events found in the radar data also identified noticeable encounters resulting from less frequent procedures and where TCAS was also involved.

3.2. *RA frequency*

- 3.2.1. The amount of Mode S data available for the study ranged between 13,500 and 68,400 flight hours for the different TMAs under study. These radar data have been collected over three months during the 2007-2008 winter period. Within these radar data, from 7 to 127 valid RAs² have been identified in the RA downlink data, depending on the TMA being considered, for a total of 191 valid RAs.
- 3.2.2. Given the amount of flight hours for each TMA, this is equivalent to a frequency of one RA per 540 to 1,900 flight hours.

3.3. *RA type distribution*

- 3.3.1. Figure 1 provides a distribution of the types of RAs that have been identified in the various European TMAs through RA downlink data.

² Valid RAs are those RAs indicated by RA downlink for aircraft that are actually on collision course. This excludes empty or erroneous RA messages transmitted through RA downlink, as well as RAs generated against non-threat aircraft as a result of garbled responses to TCAS interrogations.

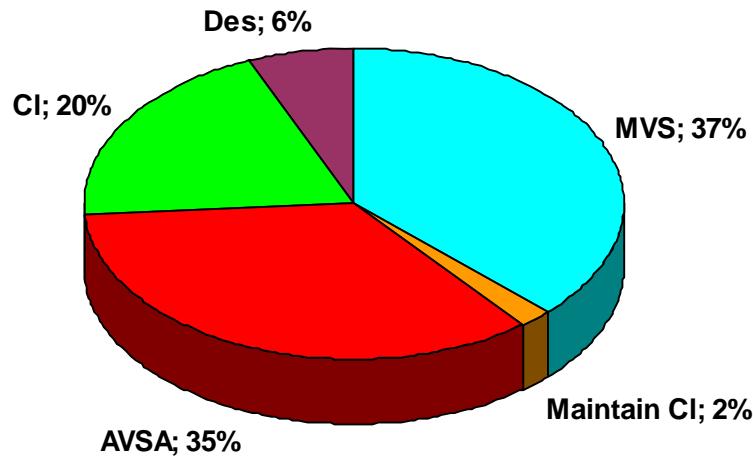


Figure 1: Distribution of RA types

- 3.3.2. As indicated in Figure 1, the more common types of RAs are Monitor Vertical Speed (MVS) RAs and Adjust Vertical Speed Adjust (AVSA) RAs, which each correspond to about one third of the total number. Then, Climb RAs make up about one fifth of all RAs.
- 3.3.3. It should also be noted that corrective RAs (i.e. RAs that require the pilot to change the vertical rate of the aircraft: Climb, Descend, AVSA RAs) are issued 61% of the time, with Climb and Descend RAs occurring in 26% of cases.
- 3.3.4. If considering events (i.e. close encounters between two aircraft in which at least one aircraft received an RA) rather than RAs, analysis of the RA downlink data shows that both aircraft receive an RA in only 4% of the cases. It essentially results from the fact that 60% of RAs are issued against aircraft not equipped with TCAS³. In the other cases, either the Vertical Threshold Test (VTT) feature (cf. Figure 2) or a dissymmetry in the behaviour of each aircraft Miss Distance Filter (MDF) feature (cf. Figure 3) can result in a TCAS-equipped aircraft not receiving an RA while the threat does.

³ In New York airspace, this proportion was estimated to 97% ([SIRE+2]).

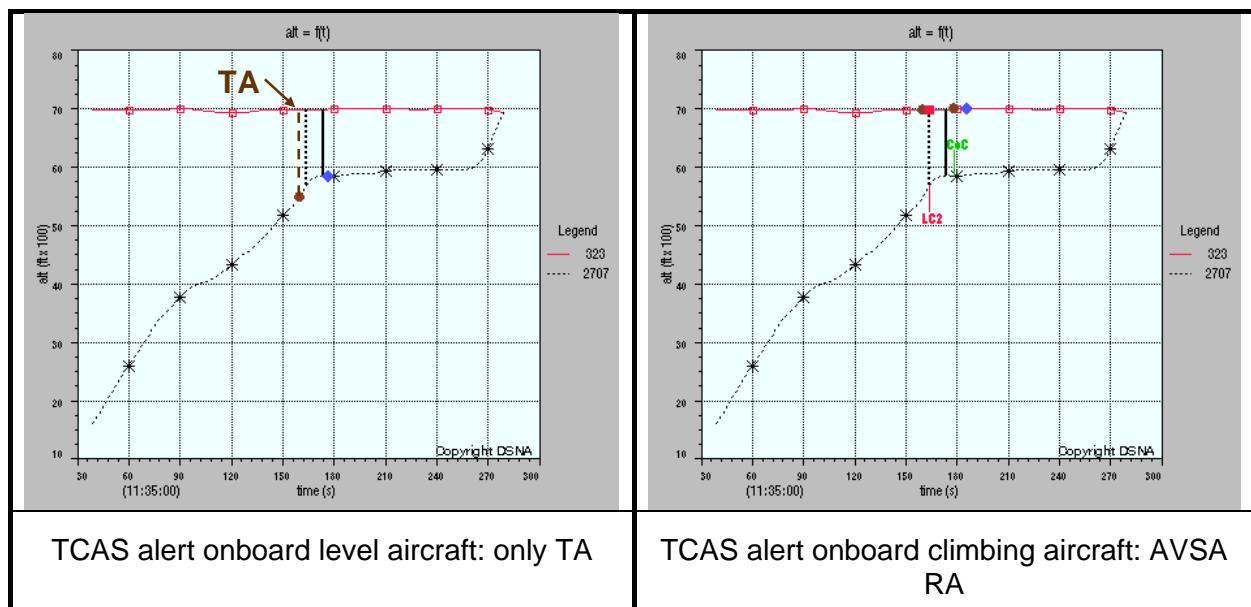


Figure 2: VTT feature preventing the issuance of RA onboard level aircraft

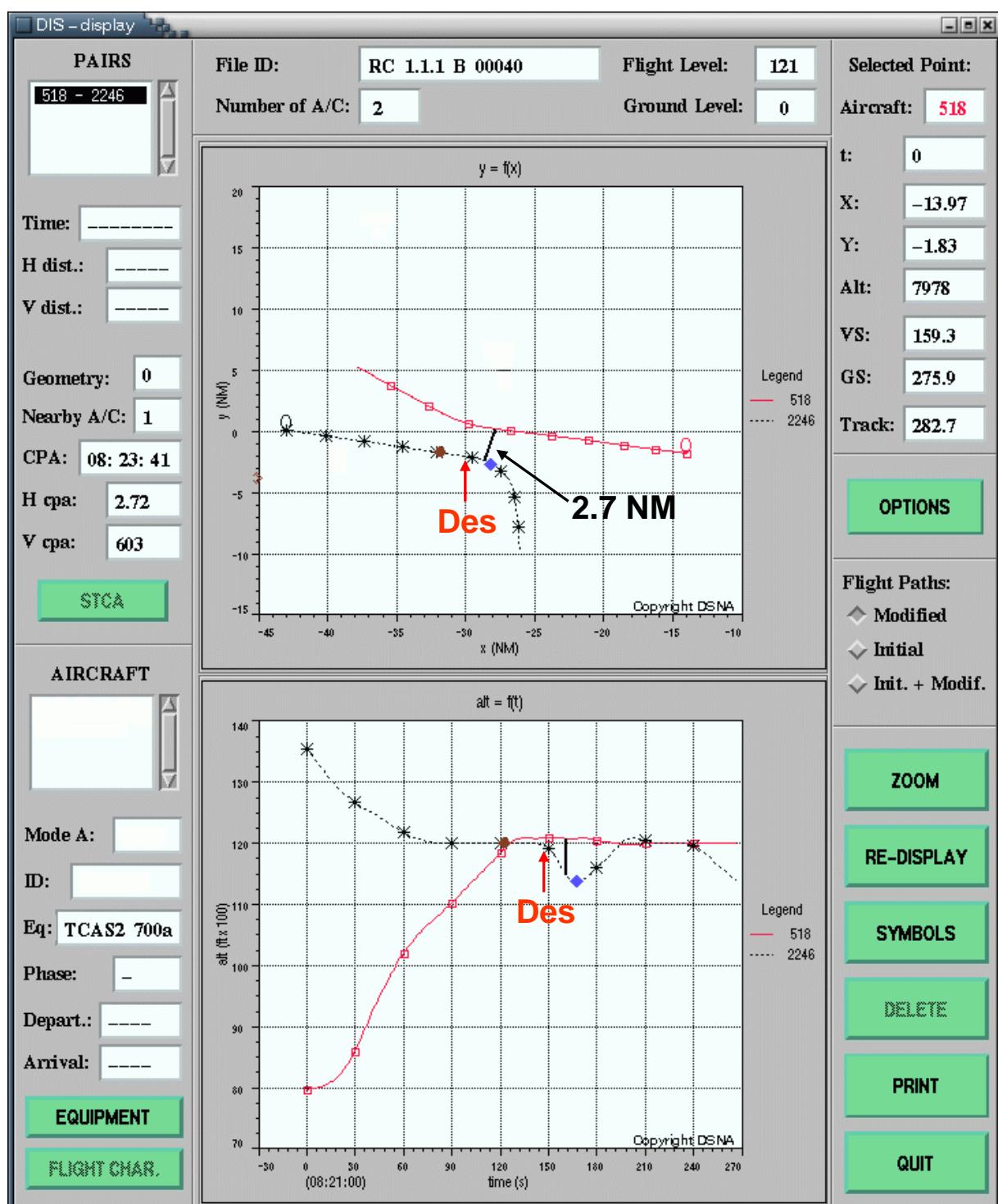


Figure 3: MDF creating dissymmetry in TCAS-TCAS encounter (no RA in red aircraft)

3.4. ***Characterization of RAs***

3.4.1. **RA altitude distribution**

3.4.1.1. Figure 4 provides the distribution of RAs by altitude, given in Flight Levels (FLs).

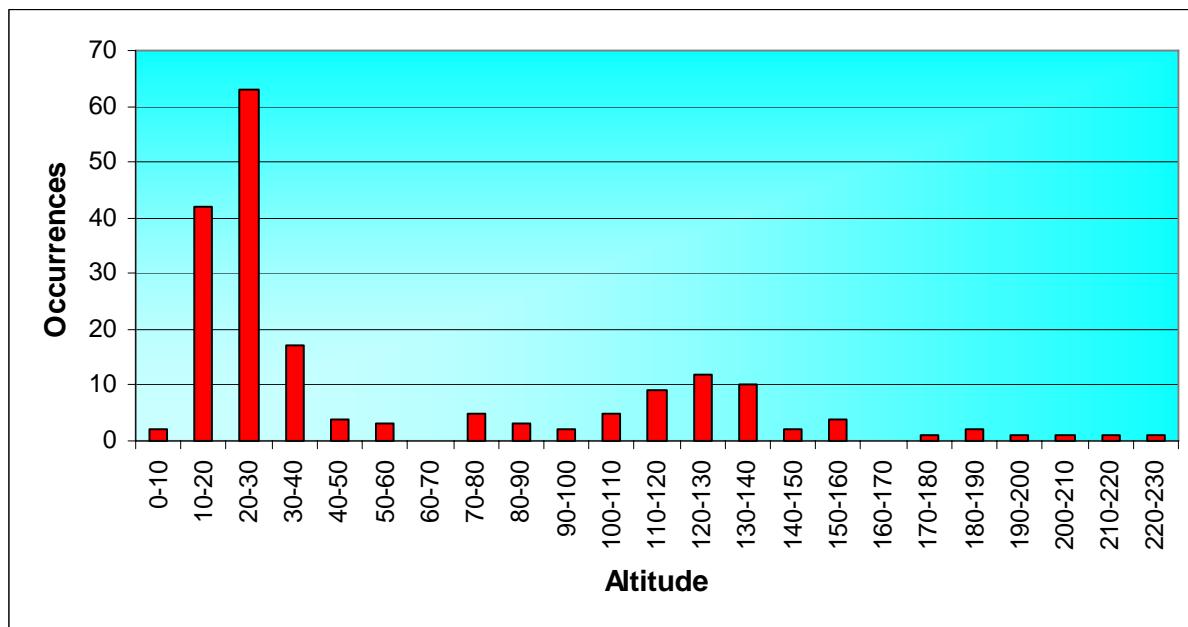


Figure 4: Altitude distribution of RAs

3.4.1.2. As indicated in Figure 4, two thirds of RAs are issued below 5,000 ft, with a peak between 2,000 and 3,000 ft. This generally corresponds to aircraft on approach at low altitude and crossing a traffic flying below the TMA (cf. example provided in Figure 5).

3.4.1.3. A secondary peak appears between FL100 and FL140 and corresponds to RAs issued in departing aircraft about to level-off below a level aircraft (cf. example provided in Figure 6). This situation generally occurs in TMAs including several major airports and where departing and arriving flows of traffic are separated by 1,000ft. Such a situation is particularly favourable to the issuance of RAs as departing aircraft typically approach their assigned flight level with high vertical rates, creating the conditions for both vertical and horizontal convergence with a threat above, and as TCAS is not aware of the aircraft intent to level-off below the threat.

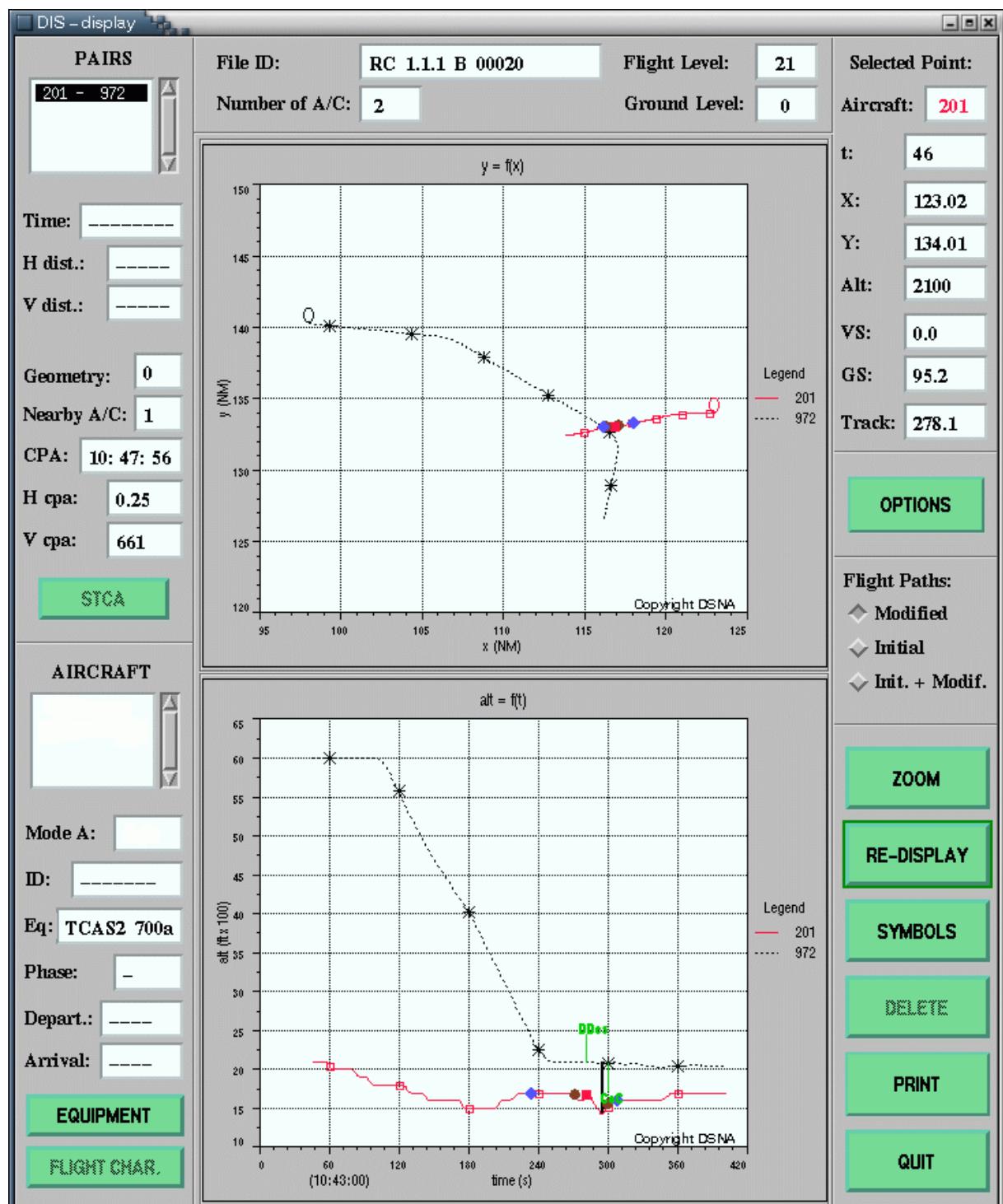


Figure 5: Aircraft on approach receiving MVS RA against traffic below TMA

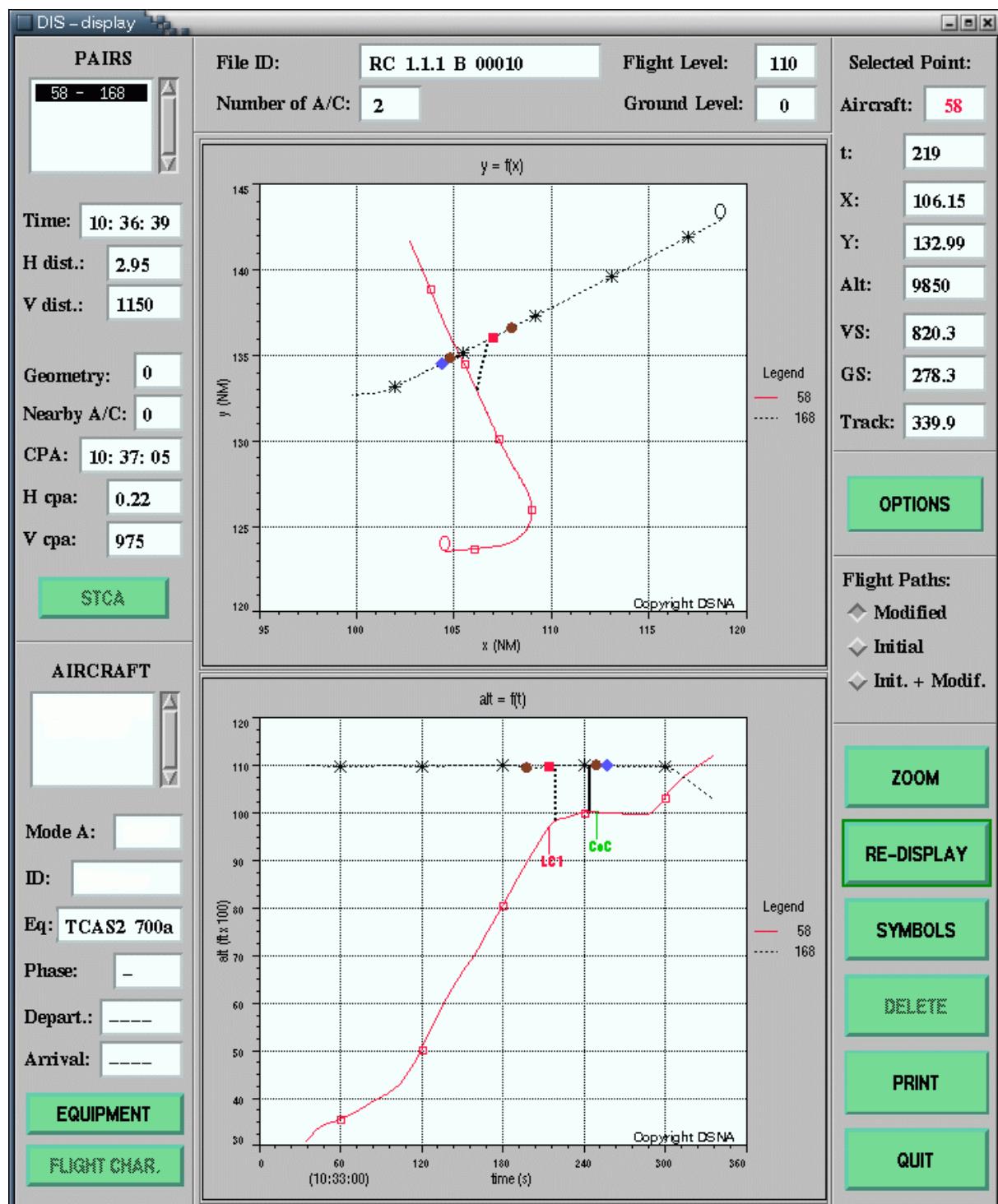


Figure 6: Departing aircraft receiving AVSA RA in 1,000ft level-off situation

3.4.1.4. Analysing the altitude distributions of Climb and MVS RAs on one hand, and AVSA RAs on the other hand (i.e. 90% of all RAs) clearly highlights the two types of geometries described above and the behaviour of TCAS in each of them.

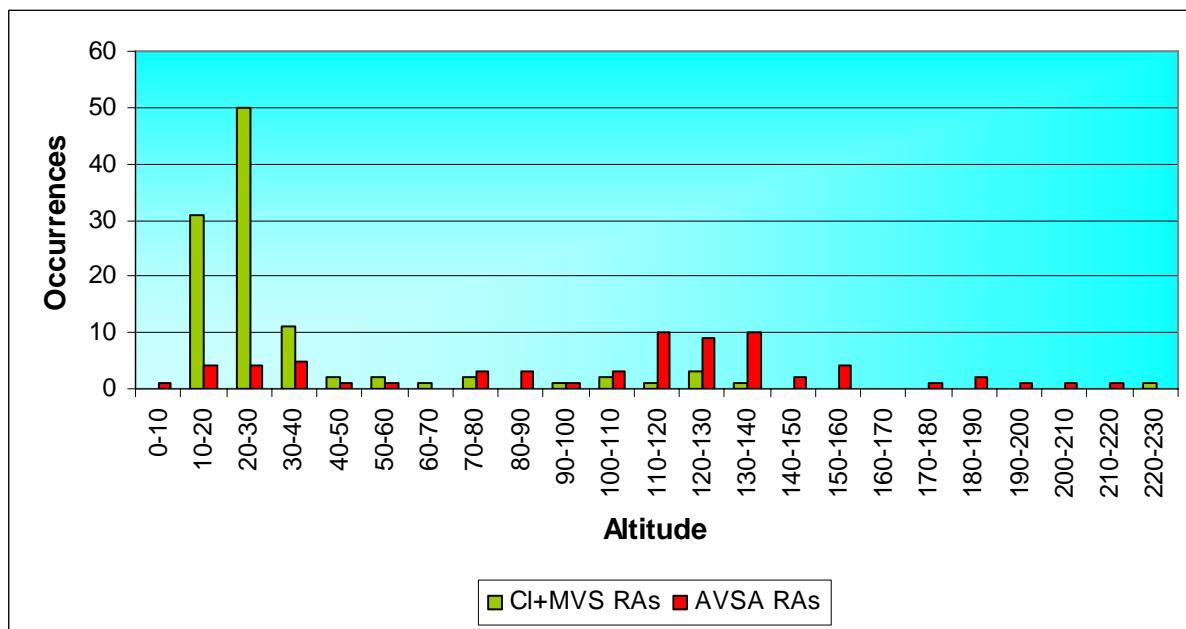


Figure 7: Altitude distribution of Climb/MVS and AVSA RAs

3.4.1.5. Figure 7 shows a clear correlation between type of RA and altitude, as a consequence of the typical geometries found at various altitudes in TMAs. Climb and MVS RAs are typically issued onboard aircraft descending or level on approach against general aviation aircraft flying below the TMA. AVSA RAs are typically issued in 1,000ft level-off geometries intended to separate outbound traffic flows from either inbound flows or other outbound flows.

3.4.1.6. Furthermore, this distribution of encounters into two main geometries also explains the dissymmetry in the number of Climb and Descend RAs (respectively 20% and 6% of all recorded RAs).

3.4.1.7. Indeed, aircraft on approach descending towards a threat level at about 1,500 to 2,500ft have little time to implement the manoeuvre required by TCAS, as the collision avoidance logic works with tight thresholds at this altitude range. Once the 5 second delay allowed for the pilot initial reaction is deduced, the aircraft is expected to achieve a 300ft separation from the threat in about 10 to 15 seconds. Depending on its rate of descent, this might require a rather aggressive manoeuvre and thus a Climb RA.

3.4.1.8. On the other hand, aircraft about to level-off 1,000 ft below a threat at FL110 or FL140 have more time to implement their required manoeuvre, as the logic thresholds are relaxed. Typically, the climbing aircraft will have about 25 seconds to achieve a 400ft separation from the threat and, given the vertical rates involved in this geometry, a Descend RA is unnecessarily strong in most cases. A simple reduction in the rate of climb through an AVSA RA is generally sufficient to meet the separation targeted by the collision avoidance logic.

3.4.2. Miss distance distribution

3.4.2.1. Figure 8 shows the distribution of Horizontal Miss Distances (HMD) at closest approach in encounters where at least one aircraft received RAs.

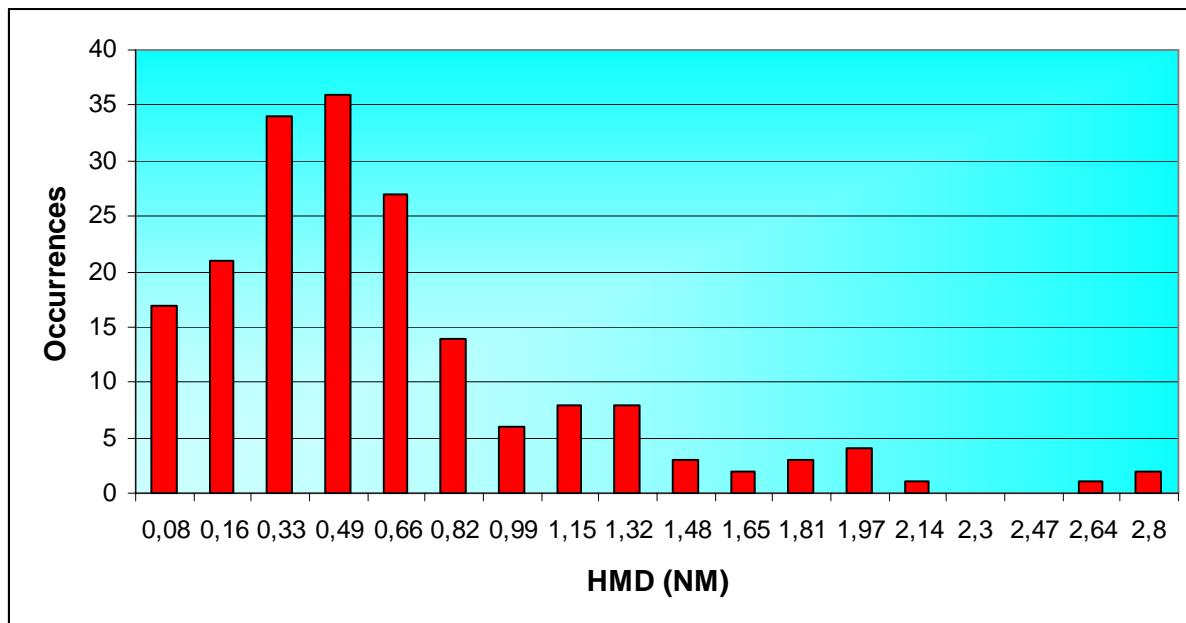


Figure 8: HMD distribution

3.4.2.2. As could be expected, HMDs are generally low, with an average value of 0.6 Nautical Miles (NM). Indeed, in the altitude range typically found in TMAs, the MDF feature of the collision avoidance logic filters RAs in encounters where the HMD is predicted to be more than twice the range of the protected volume used by TCAS (i.e. roughly from 0.4 NM below 2,350 ft up to 1.6 NM below FL200). Manoeuvres from aircraft might thwart the MDF prediction though, which explains why HMDs up to 2.8 NM have been found.

3.4.2.3. Figure 9 provides the distribution of Vertical Miss Distances (VMD) at closest approach in encounters where at least one aircraft received RAs. It has to be noted that VMDs shown in Figure 9 include TCAS contribution.

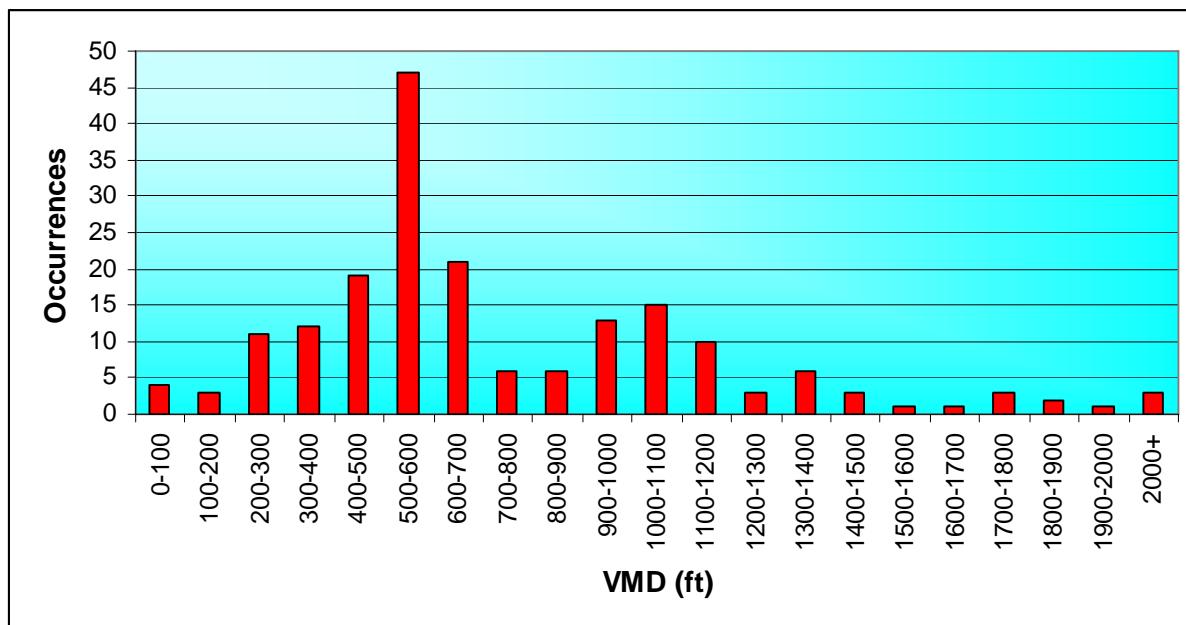


Figure 9: VMD distribution

3.4.2.4. Figure 9 shows a distinct peak around 500ft, which is a direct consequence of the number of RAs issued in aircraft on approach against general aviation threats flying under the TMAs, with which a 500ft separation is commonly used by Air Traffic Control (ATC). There is also a secondary peak around 1,100ft resulting from RAs being issued in 1,000ft level-off situations.

3.4.2.5. Figure 10 provides as a 3-dimension graph the combined distribution of altitude, HMD and VMD at closest approach in encounters where at least one aircraft received RAs.

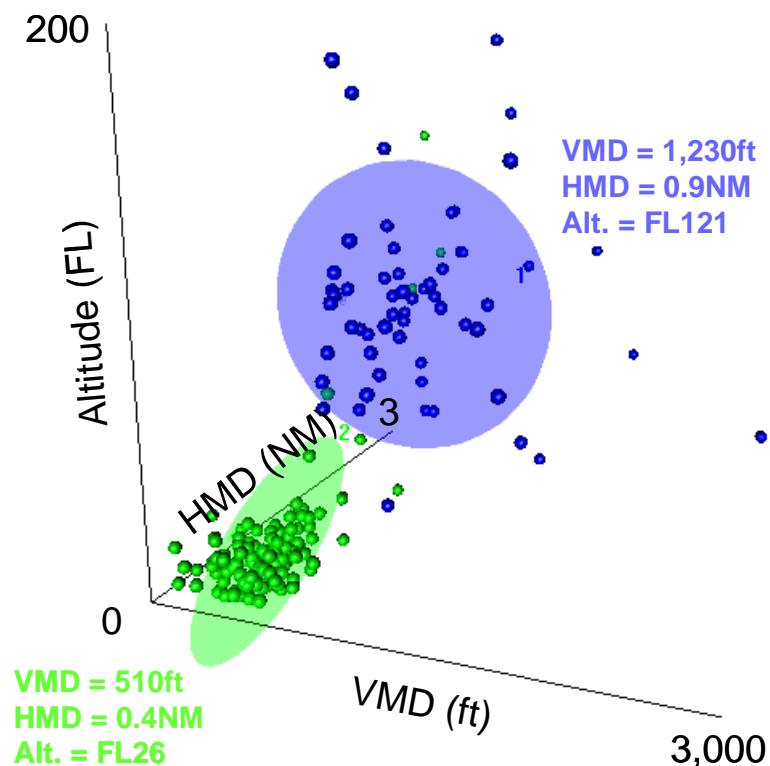


Figure 10: Combined altitude, HMD and VMD distribution

3.4.2.6. Figure 10 shows that the encounters can be grouped in two main categories, corresponding to the two typical geometries illustrated through Figure 5 and Figure 6:

- Low altitude encounters, with HMDs of about 0.4 NM and VMDs of about 510 ft on average. These encounters typically involve VFR aircraft flying close to the bottom of the TMA.
- Higher altitude encounters (around FL121), with HMDs of about 0.9 NM and VMDs of about 1,230 ft on average.

3.4.2.7. Figure 11 provides as a 3-dimension graph the combined distribution of RA type, HMD and VMD at closest approach in encounters where at least one aircraft received RAs. MVS RAs are indicated by light blue dots, Maintain Climb RAs by orange dots,

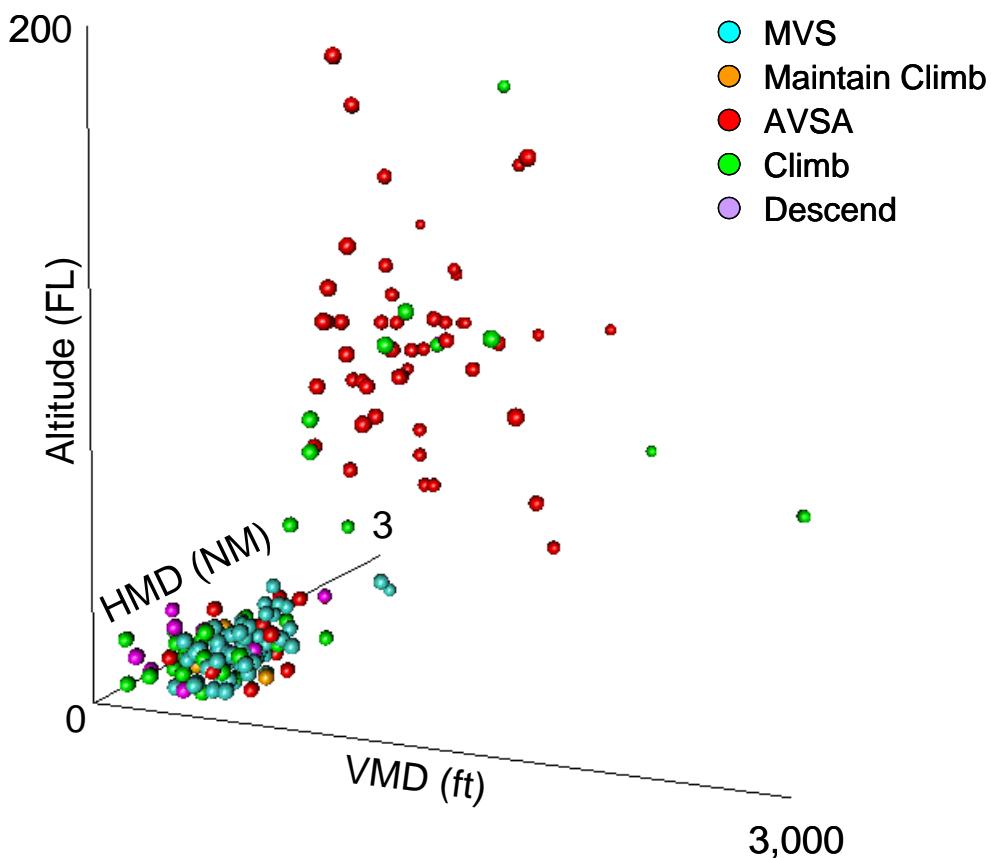


Figure 11: Combined RA type, HMD and VMD distribution

3.4.2.8. Figure 11 also highlights the two distinct geometries that have been illustrated through Figure 5 and Figure 6. MVS RAs and Climb/Descend RAs are issued in encounters where the VMD is around 600 ft and where HMDs are small (i.e. typically involving VFR aircraft below the TMA). On the other hand, AVSA RAs are issued in encounters with VMDs slightly above 1,000 ft and larger HMDs (i.e. typically between a departing aircraft and arriving or departing aircraft).

3.5. **Other issues**

3.5.1. **Conflict caused by go around**

3.5.1.1. This event occurred between two TCAS-equipped aircraft arriving to and departing from a same airport, which uses perpendicular tracks. One aircraft was scheduled to land on a southerly runway, but had to perform a go around which made it cross the path of another aircraft departing from a westerly runway.

3.5.1.2. This event is similar to the two near misses incidents which occurred in quick succession at JFK airport in July 2008, when an aircraft making a go-around crossed the path of an aircraft departing from a perpendicular runway. These incidents led the Federal Aviation Administration (FAA) to terminate converging operations at JFK airport pending a procedural review ([NTSB]).

- 3.5.1.3. On the following figures, the trajectory of the arriving aircraft performing the go around is shown in red, while the trajectory of the departing aircraft is shown in black. The solid black line between both trajectories materializes the closest point of approach and the positions of the aircraft at this time. The dotted black line represents the time when initial RAs were issued onboard the two aircraft.
- 3.5.1.4. The collision avoidance logic issued coordinated RAs onboard both aircraft 14 seconds before their closest approach. Because of this short warning time and of the significant vertical rate of climb of the departing aircraft, located below the aircraft going around at this time, crossing RAs were determined as being best able to achieve the vertical separation targeted by TCAS (i.e. 300ft at the altitude the event occurred).
- 3.5.1.5. This resolution is particularly stressful for flight crews as they have to accept that they will cross the altitude of the threat in order to avoid a potential collision. The successful resolution of this particular collision risk highly relies on the timely execution of TCAS commands by both flight crews, which was the case in this event. As a result the miss distances at closest approach were 0.2NM and 300ft according to radar data.

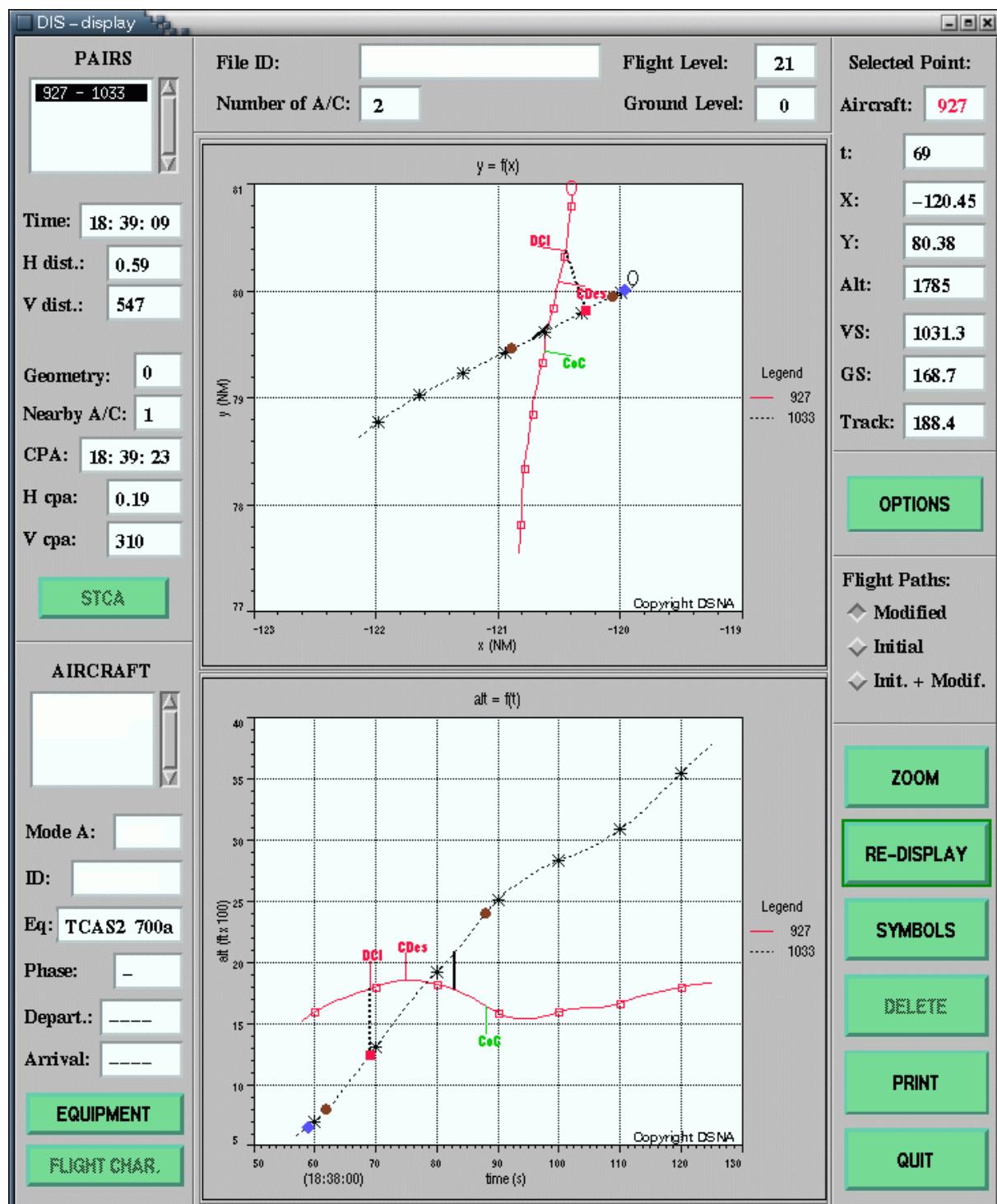


Figure 12: RAs received onboard aircraft performing go around

3.5.1.6. As indicated in Figure 12, the red aircraft received an initial Crossing Adjust Vertical Speed RA requiring a level-off. This RA was strengthened 6 seconds later to a Crossing Descend RA requiring a 1,500 feet per minute (fpm) rate of descend. The flight crew complied precisely with these RAs.

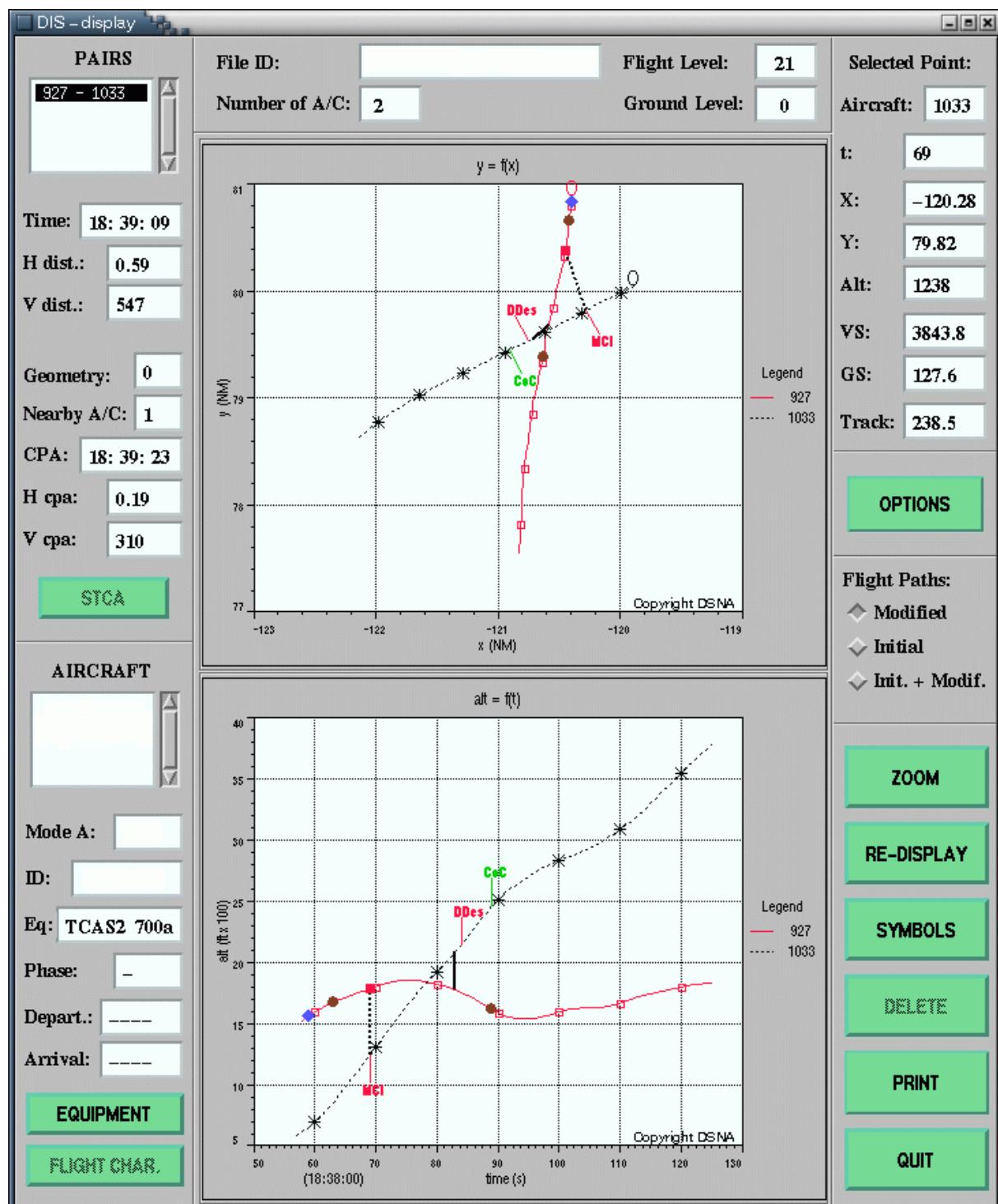


Figure 13: RAs received onboard departing aircraft

3.5.1.7. As indicated in Figure 13, the black aircraft received an initial Crossing Maintain Climb RA requiring the crew to maintain their 4,000fpm rate of climb. Shortly after the aircraft had crossed in altitude, this RA was weakened to an AVSA RA requiring a level-off. The flight crew also complied precisely with this initial Maintain Climb RA.

3.5.2. Level-off below holding pattern

3.5.2.1. This event involves three TCAS-equipped aircraft. Two of them are on top of each other in a holding pattern, respectively at FL80 and FL90. The third aircraft is climbing towards FL70, intending to stop 1,000ft below the stack.

3.5.2.2. Because of the vertical speed of the climbing aircraft and the proximity of the two aircraft in the holding pattern, an AVSA RA is issued onboard the climbing aircraft. Shortly after, each TCAS unit in the two level aircraft issues a Climb RA against the climbing aircraft. The RA in onboard the top aircraft is thus **not** induced by the RA response from the middle aircraft. All three flight crews comply with these RAs and the vertical separations at closest approach are well above the minimum spacing targeted by the collision avoidance logic.

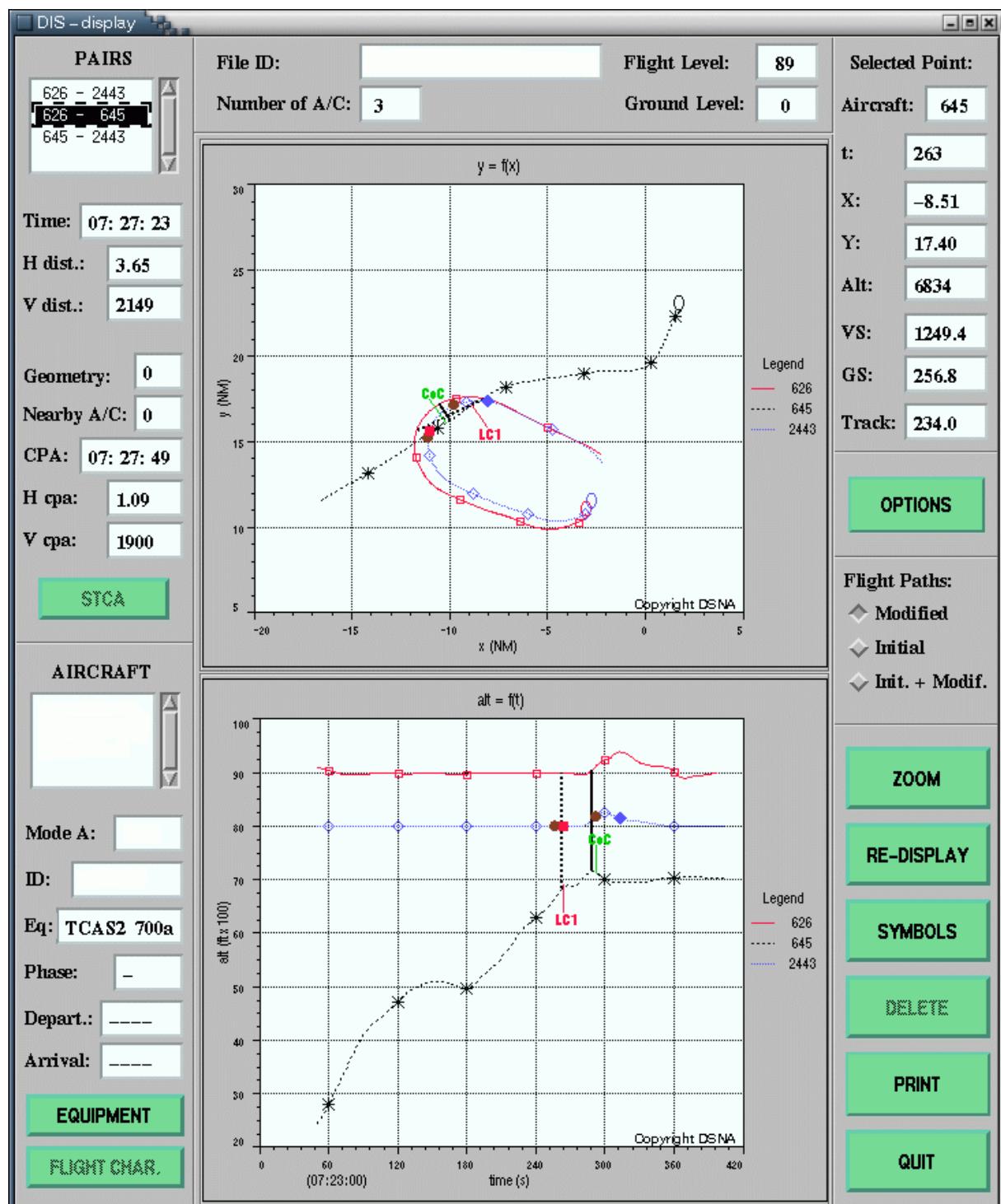


Figure 14: Induced RAs in aircraft in holding pattern

4. Safety performance of TCAS II

4.1. RA compliance rate

4.1.1. The overall compliance rate of pilots to RAs has been assessed, using only corrective positive RAs (i.e. Climb and Descend). Compliance with AVSA RAs is more difficult to observe in radar data, as changes in observed vertical rates before and after the RAs can also result from radar altitude measurement imprecision. Actual pilot compliance to AVSA RAs is better assessed using onboard data. As for preventive RAs, non-compliance would come from a pilot manoeuvring his aircraft into the red arc and no such situation has been observed.

4.1.2. Figure 15 provides a distribution of compliant responses and non responses to the 46 Climb, Crossing Climb and Descend RAs used in the compliance rate assessment.

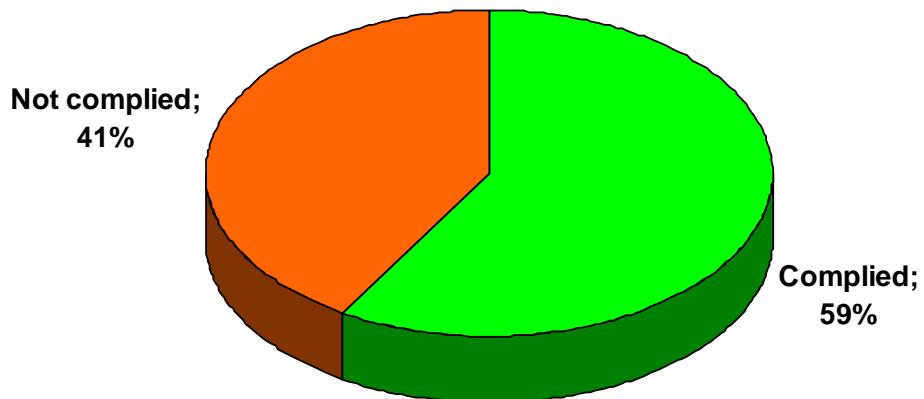


Figure 15: Compliance rate to corrective positive RAs

4.1.3. **The overall compliance rate to corrective positive RAs is about 60%.** All non-compliant responses have occurred against TCAS-unequipped threats, meaning that in 40% of cases, collision avoidance only relied on ATC (if provided) or on see-and-avoid. In 63% of non-compliant responses, the threat was squawking 7000 and flying below the TMA, which makes it unlikely that it was a controlled flight. Consequently, it is likely that **in 25% of encounters where a Climb or Descend RA was issued, collision avoidance relied on see-and-avoid only.** See-and-avoid has been demonstrated to be of limited efficacy as a means to avoid collisions ([BASI]).

4.1.4. Assuming that the threat was under VFR in the 19 encounters where corrective positive RAs were not complied with, the commonly used 500ft vertical spacing was lost in 80% of cases. This issue results from the airspace structure, as the spacing between controlled aircraft in the TMA and uncontrolled aircraft flying under the TMA can be less than 500ft (because of inaccurate vertical navigation or poor altitude

keeping notably). The RAs generated in these 19 encounters were all required to resolve a potential risk of collision. Because they were not complied with, the operation of TCAS did not provide the expected safety benefits. Indeed, ALIM (i.e. 300ft at the altitudes where the encounters occurred) was not achieved at closest point of approach in about 50% of cases.

4.1.5. Figure 16 provides the characteristics of Climb and Descend RAs as a combined distribution of altitude, HMD and VMD. RAs that the flight crew complied with are indicated as green dots, while RAs that the flight crew did not comply with are indicated as red dots.

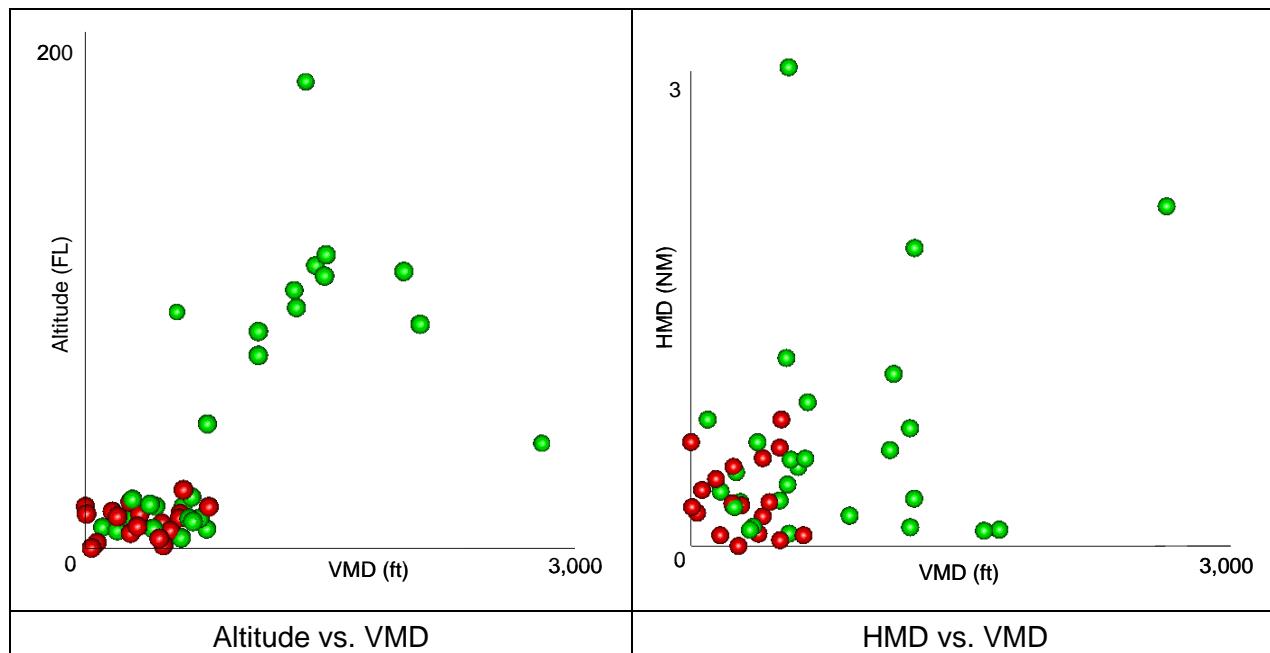


Figure 16: Characteristics of RAs complied and not complied with

4.1.5.1. As indicated in Figure 16, RAs that were not complied with have been issued in low altitude encounters, i.e. below 3,500 ft. On average, the encounters where RAs were not complied with end up with a 330 ft VMD, while encounters where RAs were followed end up with an 860 ft VMD. If focusing on encounters below 3,500 ft, the average VMD in encounters where RAs were followed is 440 ft, which is still significantly higher than the 330 ft average observed in non-compliance cases.

4.1.6. Aircraft not responding to corrective positive RAs are in a vast majority operated by companies providing on-demand charter on business jets. A significant, but reduced, proportion of these aircraft are also privately owned (i.e. by non-airline companies or individuals). The few remaining aircraft belong to airlines.

4.1.7. When considering the compliance rates to Climb RAs on one hand and to Descend RAs on the other hand, no significant difference has been observed. Climb RAs are complied with in 38% of cases while Descend RAs are complied with 50% of cases. Because this figure has been computed on few cases, there is however a larger uncertainty on it.

4.1.8. As an illustration, Figure 17 shows a non-compliance to a Climb RA that has been identified. This event involves a TCAS-equipped business jet which flight path crosses an unequipped aircraft below the TMA. Because of the very small altitude difference between the two aircraft and of their convergence in the horizontal

dimension, the business jet receives a Climb RA while both aircraft are 0.4NM and 150ft apart.

- 4.1.9. For unknown reasons, the pilot decides to perform a slight descent, opposite to the sense requested by the RA, and to cross the other aircraft altitude with this manoeuvre. According to radar data, the resulting miss distance at closest approach is 0.2NM and 60ft.
- 4.1.10. Figure 17 provides both the horizontal view and the vertical view of this event, with the TCAS-equipped business jet trajectory shown in black and the unequipped aircraft trajectory depicted in red. The solid black line between both trajectories materializes the closest point of approach and the positions of the aircraft at this time. The dotted black line represents the time when initial RAs were issued onboard the two aircraft.

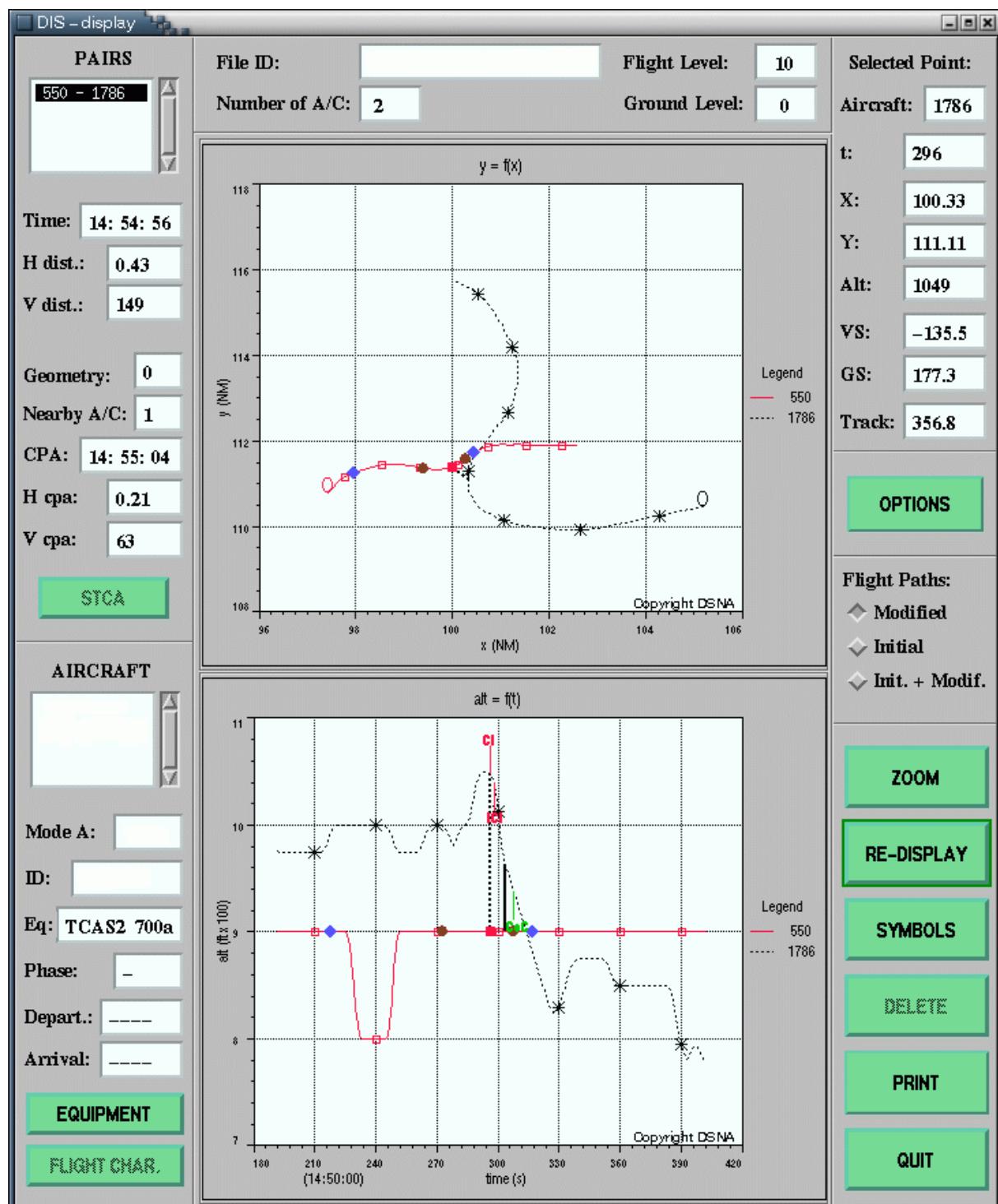


Figure 17: Non-compliance with Climb RA against unequipped threat

Note: altitude bumps in the vertical view of trajectories in Figure 17 result from the quantization (either in 25 ft increments for the black aircraft or in 100 ft increments for the red aircraft) of the altitude data.

4.2. Achievement of ALIM

4.2.1. Figure 18 a combined distribution of HMD and VMD values into four altitude bands (from bottom of TMA to FL50, from FL50 to FL100, from FL100 to FL200 and above FL200). Values for the minimum separation targeted by the collision avoidance logic (i.e. ALIM) are also indicated for these four altitude bands as solid lines in matching colours.

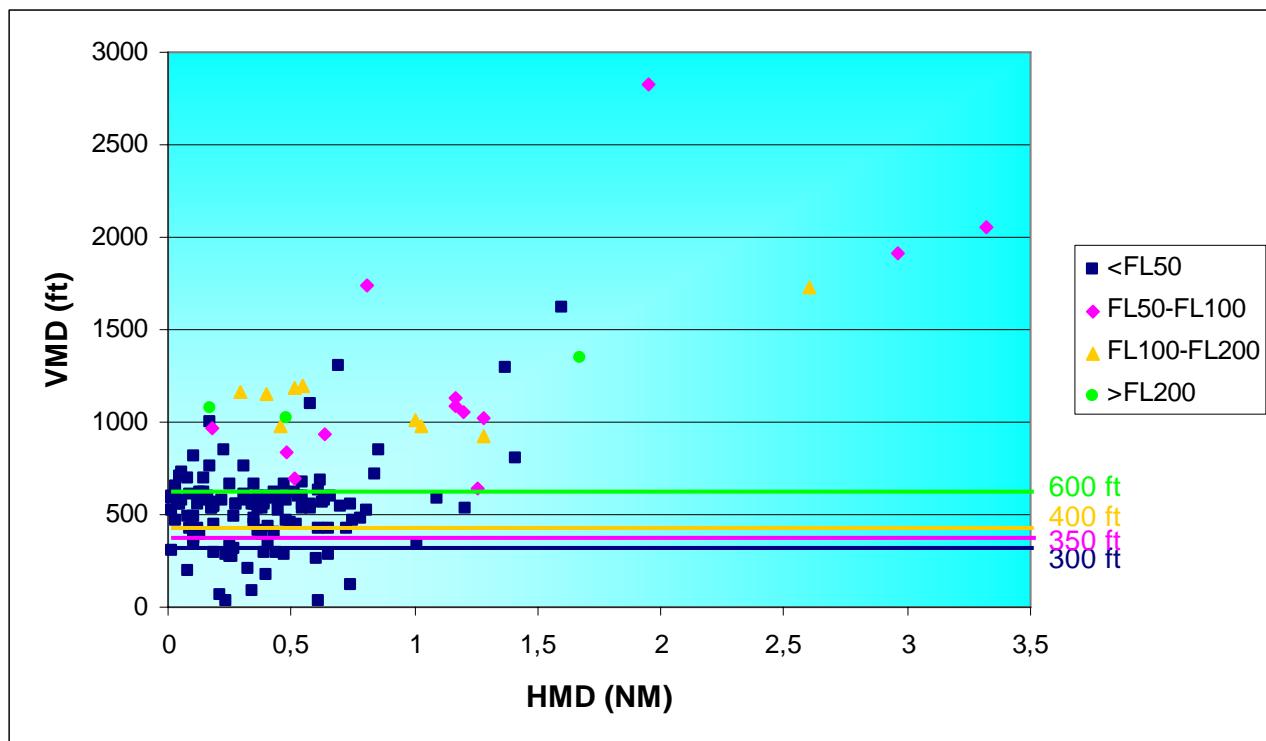


Figure 18: Combined HMD-VMD distributions per altitude layer

4.2.2. As indicated in Figure 18, 17 encounters, or 9% of all encounters where an RA has been issued, end up with a vertical miss distance less than the separation targeted by the collision avoidance logic. All these encounters occur below FL50, where ALIM is 300ft, and correspond to severe losses of ATC separation, as the HMD is always less than 0.75NM.

4.2.3. As an illustration, Figure 19 provides an example of an encounter where ALIM was not achieved because of non-compliance with the RA. This encounter involves a business jet aircraft departing from a secondary airport and crossing the path of an unequipped aircraft flying below the TMA. Because of the very small altitude difference between the aircraft and of their convergence in the horizontal dimension, the TCAS onboard the business jet issues a Climb RA when the aircraft are 0.5NM and 50ft apart.

4.2.4. The pilot does not comply with this RA and remains level. Consequently, the collision avoidance logic strengthens this initial RA to an Increase Climb RA, which is not followed by the pilot either. Because of this lack of pilot compliance, the vertical miss distance at closest approach is only 50ft according to radar data, while the horizontal miss distance is 0.25NM.

- 4.2.5. Figure 19 provides both the horizontal view and the vertical view of this event, with the TCAS-equipped business jet trajectory shown in black and the unequipped aircraft trajectory depicted in red. The solid black line between both trajectories materializes the closest point of approach and the positions of the aircraft at this time. The dotted black line represents the time when initial RAs were issued onboard the two aircraft.
- 4.2.6. As a side note, the TCAS-equipped aircraft was involved in a similar situation 2 minutes earlier in its flight. A Climb RA was also issued in this first event, which the pilot did not comply with either. According to radar data, miss distances were marginally larger in this case.

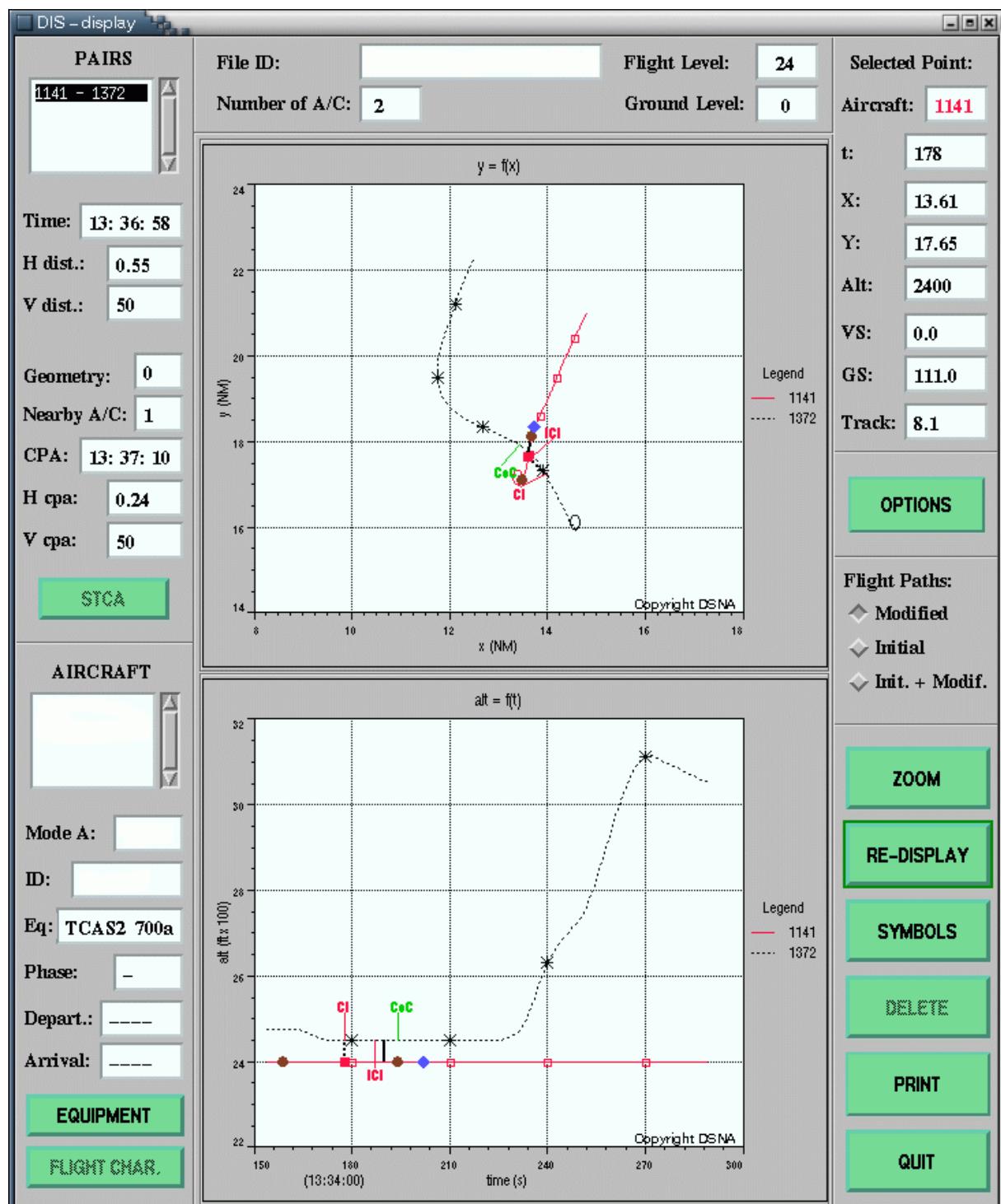


Figure 19: RAs received onboard non-responding aircraft

5. Conclusions and recommendations

5.1. General

- 5.1.1. This study has analysed the operational performance of TCAS II in three major European TMAs using three months of Mode S data collected for each of the TMAs during the 2007-2008 winter period. The Mode S data contained RA downlink information, which enable the precise identification of close encounters in which TCAS RAs were issued.
- 5.1.2. Close to 200 RA events have been identified, corresponding to about 190 pair-wise encounters. This means that in only 4% of encounters did both aircraft receive an RA. This is largely due to the fact that the majority of these encounters (60%) involve a threat aircraft not equipped with TCAS. Among TCAS-TCAS encounters, only one aircraft generally receives an RA, primarily because of the VTT feature included in the collision avoidance logic and, to a lesser extent, because of a dissymmetry in the behaviour of the MDF feature onboard each aircraft.
- 5.1.3. The most common types of RAs are Adjust Vertical Speed and Monitor Vertical Speed RAs, each corresponding to over a third of all RAs. Climb and Descend RAs are totalling about one fourth of the total number of RAs. Other types of RAs only represent a very small part of observed RAs.

5.2. Operational performance

- 5.2.1. The distribution of RAs by altitude showed that a significant majority of them occurred close to the bottom of the TMA when aircraft on approach cross traffic flying below the TMA. A noticeable proportion of RAs have been found to occur around FL120 where the strategic 1,000ft separation of inbound and outbound flows is generally made.
- 5.2.2. Analysing the geometries involved in these RAs showed two recurring types of encounters. The first one involves an inbound TCAS flight on approach crossing the path of an unequipped threat flying under the TMA. This generally results in a Climb or Monitor Vertical Speed RA, depending on whether the TCAS aircraft is descending or level. The second frequent geometry corresponds to TCAS-TCAS encounters where an aircraft is cleared by ATC to level off 1,000ft below a level aircraft. This generally leads to an AVSA RA for the climbing aircraft, while the RA onboard the other aircraft is ultimately filtered by the VTT feature.
- 5.2.3. Given that the majority of RAs are issued against aircraft flying under VFR below the TMAs, the miss distances at closest approach are generally small, typically 500ft and less than 0.5NM. Comparing the vertical miss distance to the vertical separation targeted by the collision avoidance logic (i.e. ALIM) highlighted that this target was not achieved in 9% of all the encounters. All of these occurred below FL50 against threats not equipped with TCAS and flying below the TMA.

5.3. Safety performance

- 5.3.1. The compliance rate of flight crews to TCAS alerts has been assessed on a subset of Climb and Descend RAs, as compliance with other types of RAs is difficult to assess in radar data. Overall, 60% of these RAs were complied with. In two thirds of the remaining encounters, the threat was under the TMA and squawking 7000, which makes it unlikely that it was under ATC. Consequently, in 25% of the encounters where a Climb or Descend RA was issued, collision avoidance might have relied on see-and-avoid only.
- 5.3.2. Because of non-compliance with TCAS RAs, five very close encounters have been identified, where miss distances at closest approach were less than 0.5 NM horizontally and 200 ft vertically. More generally, 9% of encounters where an RA has been issued did not achieve the vertical spacing targeted by the collision avoidance logic and the operation of TCAS thus did not provide the expected safety benefits.

5.4. Recommendations

- 5.4.1. Resulting from the monitoring effort within SIRE+ project:
- 5.4.2. It is recommended that the issue of TCAS-unequipped aircraft flying under TMAs and generating RAs against TCAS-equipped on approach be addressed strategically through the design of airspace around major airports. As these RAs become frequent, pilots tend to consider them as nuisances and to ignore them, thus reducing safety in TMA.
- 5.4.3. It is recommended that a monitoring effort, similar to what was conducted within the SIRE+ project, be continued, notably to further assess the issue of uncontrolled traffic below TMAs on summer data (i.e. when VFR traffic is higher).
- 5.4.4. It is recommended that pilots should continue to be informed about the need to comply with TCAS RAs in order to maximise the safety benefits brought by TCAS. This information effort should notably be directed towards on-demand charter operators and companies offering fractional ownership of business jets, which pilots have been observed to comply less frequently with TCAS RAs than for commercial airlines.

6. References

- [ACA1] ACASA – ‘NMAC rate’ – EUROCONTROL ACAS Programme – WP1.1.7/115, Version 2.2, October 2000
- [BASI] ‘Limitations of the See-and-Avoid Principle’ – Australian Bureau of Air Safety Investigation – April 1991
- [DO185A] ‘Minimum operational performance standards for Traffic alert and Collision Avoidance System II airborne equipment’ – RTCA – 1997
- [NTSB] ‘Factual Report on incident OPS08IA008B from 5th July 2008’ – National Transportation Safety Board – July 2008
- [SIRE+1] SIRE+ – ‘Operational performance of CP115 in New York airspace’ – EUROCONTROL Mode S & ACAS Programme – SIRE+/WP6/59/D, Version 1.1, December 2005
- [SIRE+2] SIRE+ - ‘Operational performance of CP115 in Boston airspace’ – EUROCONTROL Mode S & ACAS Programme – SIRE+/WP5/37/D, Version 1.0, March 2007

7. Acronyms

ACAS	Airborne Collision Avoidance System
ACASA	ACAS Analysis
ANSP	Air Navigation Service Provider
ATC	Air Traffic Control
AVSA	Adjust Vertical Speed, Adjust
BDS	Comm-B Data Selector
CP	Change Proposal
DSNA	Direction des Services de la Navigation Aérienne
ECAC	European Civil Aviation Conference
EUROCAE	European Organisation for Civil Aviation Equipment
EUROCONTROL	European Organisation for the Safety of Air Navigation
FAA	Federal Aviation Administration
FL	Flight Level
fpm	feet per minute
HMD	Horizontal Miss Distance
ICAO	International Civil Aviation Organization
MDF	Miss Distance Filter
MOPS	Minimum Operational Performance Standards
MTOM	Maximum Take-Off Mass
MVS	Monitor Vertical Speed
NM	Nautical Mile
NMAC	Near Mid-Air Collision
RA	Resolution Advisory
SA01	SAfety issue 01
SA-AVSA	SAfety issue AVSA
SARPs	Standards And Recommended Practices
SC147	Special Committee 147

SIR	Safety Issue Rectification
SIRE	Safety Issue Rectification Extension
SSR	Secondary Surveillance Radar
TCAS	Traffic alert and Collision Avoidance System
TMA	Terminal Control Area
VFR	Visual Flight Rules
VMD	Vertical Miss Distance
VTT	Vertical Threshold Test
WP	Work Package
WG75	Working Group 75

*** END OF DOCUMENT ***