



## **SIR Final Report**

## **Safety Issue Rectification SIR Project**

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## RECORD OF CHANGES

Issue	Date	Detail of changes
1.0	05-06-2004	Draft version Review by B.H, H.D (all but appendixes). Review by B.R (all but appendixes) Review by T.A. Review by J.Law
1.1	11-06-2004	First version delivered to EUROCONTROL
1.2	16-07-2004	Second version delivered to EUROCONTROL Modification of table 4 page 26 and of the CP112E pseudocode

**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**

## Executive summary

- Ex.1. The SIR project, which started in May 2003, builds upon the EMOTION-7 work methods and expertise to enable development in the CAS reversal logic. This EUROCONTROL project was conducted by Sofréavia with the support of the French CENA.

### **BACKGROUND**

#### **General**

- Ex.2. One major deliverable of the former EMOTION-7 project is CP112, a change proposal of the TCAS II version 7.0 reversal logic. This change has been developed in 2000 to address anomalies in the CAS reversal logic. These anomalies have been referenced as safety issue SA01 [EMO6]. Issue SA01 is composed of three sub-issues:
- Issue SA01a (Late reversal RAs or no reversal RAs in coordinated encounters) identified in early 2000;
  - Issue SA01b (Late reversal RAs or no reversal RAs in uncoordinated encounters) identified in the second half of 2002; and
  - Issue SA01c (Undesirable reversal RAs in coordinated encounters) identified in early 2000.
- Ex.3. CP112 only deals with issue SA01a and issue SA01c. It does not address issue SA01b, which was identified in 2002.

#### **Issue SA01a: Late reversal RAs or no reversal RAs in coordinated encounters**

- Ex.4. When compared with the previous TCAS II version 6.04a, one significant change included in the TCAS II version 7.0 is the sense reversals which are now permitted in TCAS-TCAS encounters. This change was introduced to cope with changing situations where the original sense has clearly become the wrong thing to do, in particular when one of the pilots decides not to follow his RA.
- Ex.5. An issue for this change has been identified in early 2000. This issue deals with either the non issuance or the late issuance of reversal RAs. The issue has been identified for an encounter set which is representative of operationally realistic scenarios (i.e. a pilot following a late ATC instruction opposite to his RA). The EMOTION-7 project has provided evidences that issue SA01a was indeed happening in operational use (e.g. Japanese event in January 2001, Belgian event in July 2001, French event in November 2001, German event in February 2002, Überlingen collision in July 2002).
- Ex.6. A first estimation (mid 2000) has indicated that one reversal RA is expected every two months in the French airspace. A more recent estimation (mid 2002) has shown that the probability for an aircraft subjected to the Phase I mandate to experience a late reversal RA, when the other aircraft is manoeuvring opposite to its RA, is  $4.7 \cdot 10^{-6}$  per flight hour in the European airspace.

### **Issue SA01b: Late reversal RAs or no reversal RAs in uncoordinated encounters**

- Ex.7. In the second half of 2002, the work in the CAS reversal logic area (conducted in parallel with the investigation of the TCAS aspects of the Überlingen collision) has also highlighted the potential for failure to initiate the reversal logic either in single equipage encounter or similarly in double equipage encounter but with one TCAS II either in stand-by mode or in TA-only mode.
- Ex.8. The geometries involved are comparable to those already described during the investigation of issue SA01a. In particular, one geometry is for two aircraft flying at the same FL and converging in range with a very late ATC instruction inducing an intruder manoeuvre which thwarts the initial RA issued onboard the own aircraft. This scenario was already identified in 1995 [SIC] but with TCAS II logic version 6.04a.

### **Issue SA01c: Undesirable reversal RAs in coordinated encounters**

- Ex.9. An other issue has been identified in early 2000. This issue deals with the undesirable issuance of reversal RAs in coordinated encounters when both pilots follow correctly their RAs. Indeed, in some cases not observed with TCAS II version 6.04a, the TCAS II version 7.0 contribution is decreasing the vertical separation at CPA.
- Ex.10. The issue has been identified for an encounter set which is representative of operationally realistic scenarios (i.e. altitude bust scenarios).

### **Initial change proposal CP112**

- Ex.11. CP112 was developed in 2000 to address both issue SA01a and issue SA01c. It does not address issue SA01b, which was only identified in 2002. CP112 is composed of two parts:
- Part 1 was developed to address issue SA01a. The main objective of CP112 Part 1 is to allow an early modelling of sense reversals in TCAS-TCAS encounters, when a manoeuvre opposite to the RA sense is detected onboard one aircraft. CP112 Part 1 is, therefore, weakening the conditions to model these sense reversals once a specific set of conditions enabling the detection of opposite reaction to the RA sense is met; and
  - Part 2 was developed to address issue SA01c. The main objective of CP112 Part 2 is to forbid the issuance of reversal RAs when they are likely to induce two altitude crossings. CP112 Part 2 is, therefore, strengthening the conditions to issue a reversal RA if the aircraft are converging in altitude following a crossing RA issuance.

## **OVERVIEW OF THE NEW CHANGE PROPOSAL CP112E**

### **Objective of the SIR project**

- Ex.12. The first objective of the SIR project was to improve the CP112 solution (i.e. developing a new solution, referenced to as CP112E) by addressing both issue SA01b and the two major comments related to CP112:
- CP112 has the potential to improve the current reversal logic in only 50% of the issue SA01a cases. This behaviour is due to the Mode S priority rule included in the CAS logic (i.e. the aircraft with the lower Mode S address is the master aircraft. It controls the coordinated sense selection and is the only one with the ability to initiate a reversal RA. The slave aircraft is only reversing to remain complementary to the new sense decided by the master aircraft); and
  - Some negative aspects have been identified for one particular scenario with one specific encounter class of the US airspace model (i.e. a scenario involving a SA01c-type geometry but with one pilot not following his RAs).
- Ex.13. The second objective of the SIR project was to develop the TCAS investigation final report of the Überlingen mid-air collision.

### **New change proposal CP112E**

- Ex.14. CP112E is, first, invoked for the SA01 geometries.
- Ex.15. For the SA01a/b geometry (i.e. two aircraft vertically close, climbing or descending simultaneously towards the same altitude), the conditions to issue a reversal RA are weakened.
- Ex.16. With TCAS-TCAS encounters, the need to reverse is considered when:
- Own aircraft is detected manoeuvring opposite to its RA. Here, the new reversal logic modelling no more assumes that the own aircraft is following its RA; or
  - The monitoring of the Vertical Miss Distance (VMD) indicates a predicted mid-air collision course in the vertical plane. This VMD criterion is used to circumvent the Mode S priority rule, which prevents a reversal RA issuance onboard the slave aircraft even if the aircraft is detected manoeuvring opposite to its RA.
- Ex.17. With TCAS-unequipped encounters, the VMD monitoring is also used when assessing the need to reverse.
- Ex.18. For the SA01c geometry (i.e. high vertical convergence after crossing RA issuance), the conditions for a sense reversal to be issued are strengthened. Here, sufficient time is given to the CAS logic to observe a compliance with the initial RA and avoid a late and undesired reversal RA issuance.

## **SAFETY AND OPERATIONAL SIMULATION RESULTS**

### **General**

- Ex.19. Numerous simulations have been conducted to both assess the safety benefits brought by CP112E and confirm that no side effects were observed in the overall operational performances of the CAS logic.
- Ex.20. In particular, various scenarios were considered including the CP112E interoperability with version 6.04a and version 7.0. The impact of different pilot behaviours (i.e. aggressive and slow as defined in the ACASA project [ACA1]) was also investigated. Here, the objective was not to demonstrate that CP112E brings significant benefits for slow or aggressive pilots but to check CP112E robustness (i.e. that CP112E does not debate the safety performance of the CAS logic even when faced with non-nominal pilot reactions).

### **Safety encounter models**

- Ex.21. The ACAS simulations were conducted on two different safety encounter models:
- The European ACAS safety encounter model; and
  - The ICAO safety standard encounter model.
- Ex.22. Unlike the European ACAS safety encounter model, the ICAO safety standard encounter model does not represent any operational airspace. However, it offers more stringent conditions to test the reversal logic.
- Ex.23. The risk ratios presented in table 2 and 3 (i.e. the measure of the safety performance of TCAS, which is defined as the NMAC probability with TCAS divided by the NMAC probability without TCAS) were computed for different equipage scenarios as presented in the table 1.

Scenario	Equipage
1	Both aircraft are equipped and follow their RAs
2	Both aircraft are equipped and one does not follow his RAs
3	The intruder is not equipped with TCAS

**Table 1: Scenarios**

Scenario	Version 7.0	Version 7.0+CP112E	Risk ratio reduction
1	1.1%	1.0%	9%
2	11.0%	7.0%	36%
3	9.9%	9.3%	6%

**Table 2: Logic risk ratios with the ICAO safety standard encounter model**

Scenario	Version 7.0	Version 7.0+CP112E	Risk ratio reduction
1	2.3%	2.3%	-
2	19.0%	16.8%	12%
3	12.7%	12.5%	2%

**Table 3: Logic risk ratios with the European ACAS safety encounter model**

- Ex.24. The results presented in Table 2 and Table 3 show some significant improvements whatever the model considered. When considering that CP112E is only focusing on issue SA01 (i.e. on a small number of encounters within both the ICAO safety standard encounter model and the European ACAS safety encounter model), these improvements can be seen as even more significant. Scenario 2 is of particular interest because it provides a measure of the rectification of issue SA01a.
- Ex.25. The trend is less obvious with scenario 1. This is because the risk ratios are already particularly low with version 7.0 and because the risk ratio measure is not accurate enough to reflect the improvements which were actually observed on the cases of concern included in the models.
- Ex.26. Finally, it is important to note that these safety improvements were gained without any trade-off (i.e. no induced NMACs were identified).

**Encounters extracted from the US airspace model**

- Ex.27. An other piece of work has consisted in investigating the CP112E impact on a set of encounters provided by the FAA Technical Centre and for which some negative aspects were observed with the initial CP112 solution and a TCAS-TCAS scenario involving one pilot not following his RAs.
- Ex.28. This set of encounters belongs to the encounter class 8 of the US airspace model. The new solution has again shown its positive contribution. There is no longer a problem as all the provided encounters were satisfactorily solved with CP112E.

### **Actual examples of issue SA01a**

- Ex.29. To further validate the safety performance of CP112E, simulations were also conducted on four actual examples of issue SA01a for which radar data are available:
- Belgian event in July 2001;
  - French event in November 2001;
  - German event in February 2002; and
  - Überlingen collision in July 2002.
- Ex.30. These events were gathered thanks to the EMOTION-7 operational performance monitoring.
- Ex.31. For these actual examples of issue SA01a, CP112E has again shown its potential to improve the CAS reversal logic behaviour.

### **European database of actual encounters**

- Ex.32. The European database is composed of more than 1000 representative encounters extracted from radar data (without TCAS contribution). This database has been used to verify that no side effects were observed when considering the overall operational performance of the CAS logic.
- Ex.33. The analysis performed on this data confirmed that CP112E does not debase the operational performance of the CAS logic.

### **ÜBERLINGEN MID-AIR COLLISION**

- Ex.34. On 1st July 2002, a mid-air collision occurred in the European RVSM (Reduced Vertical Separation Minima) airspace involving a Boeing 757-200 and a Tupolev 154, which were both TCAS II version 7 equipped.
- Ex.35. One task of the SIR project consisted in participating to the investigation of this collision by developing an Überlingen investigation report focusing on ACAS aspects.
- Ex.36. The results of this investigation into the TCAS aspects of the accident remain confidential. However it is clear that:
- From an ACAS standpoint one aircraft went opposite to the RA inducing a complex situation difficult to address;
  - TCAS operated according to its specification but the design purpose of the reversal logic was not achieved (i.e., no reversal RAs were issued); and
  - In this specific scenario, implementation of CP112 or CP112E could have provided safety benefit by permitting the possibility of a reversal RA.



- Ex.37. In addition, a replay of the mid-air collision was developed, using data provided by the BFU. Both the report and the animation were sent to the BFU.

### **CONCLUSION**

- Ex.38. The SA01 operational scenario has been identified in several occasions.
- Ex.39. A mature draft of CP112E to address issue SA01 is now available. The simulations performed with CP112E indicate a significant improvement in the safety performance of the CAS logic when compared with both the current version 7.0 and the initial CP112 solution. This has been observed with various equipage configurations, different pilot behaviours and different safety encounter models.
- Ex.40. All the known anomalies in the CAS reversal logic have been addressed. In particular, sub-issue SA01b is now addressed. With the RTCA SC147 restart, it is anticipated that a close US / Europe cooperation will enable to confirm the efficacy of CP112E.
- Ex.41. It is expected that the EUROCONTROL SIR project will provide the basis for a rapid rectification of the safety issue SA01.

### **RECOMMENDATIONS**

- Ex.42. Airspace authorities should seek to identify occurrences of issue SA01 events and to assess their frequency of occurrence.
- Ex.43. The results obtained with CP112E should be confirmed in the context of the work being progressed within RTCA SC147.
- Ex.44. CP112E should be implemented as soon as possible to permit rectification of issue SA01.

## Table of contents

<b>Executive summary .....</b>	<b>3</b>
<b>Table of contents .....</b>	<b>10</b>
<b>List of figures.....</b>	<b>13</b>
<b>List of tables.....</b>	<b>15</b>
<b>Acronyms .....</b>	<b>16</b>
<b>List of definitions.....</b>	<b>18</b>
<b>1. Introduction.....</b>	<b>20</b>
1.1. Context.....	20
1.2. Scope and objectives .....	20
1.3. Project overview.....	21
1.3.1. Development of a CAS logic modification .....	21
1.3.2. Further contribution to the Überlingen mid-air collision .....	21
1.4. Document overview.....	22
<b>2. Tools and methods.....</b>	<b>23</b>
2.1. Introduction.....	23
2.2. Use of encounter models.....	23
2.2.1. General description of an encounter model.....	23
2.2.2. ICAO safety standard encounter model .....	23
2.2.3. European ACAS Safety encounter model .....	24
2.2.4. NMACs .....	24
2.2.5. Risk ratio .....	25
2.2.6. Pilot behaviour .....	26
2.3. Specific theoretical SA01 encounters databases.....	27
2.4. Actual encounters.....	27
2.5. The OSCAR simulation facilities.....	28
<b>3. Background .....</b>	<b>32</b>
3.1. Issue SA01.....	32
3.1.1. Introduction.....	32
3.1.2. Issue SA01a.....	32
3.1.3. Issue SA01b .....	33
3.1.4. Issue SA01c.....	34
3.2. Actual occurrences of Issue SA01a.....	36
3.2.1. Likelihood of occurrence of issue SA01a .....	36
3.2.2. Actual SA01a event.....	36
3.2.2.1. Introduction .....	36
3.2.2.2. Description of the event.....	37
3.2.2.3. Conclusion .....	40
3.2.3. Überlingen Mid-air Collision .....	40
3.2.3.1. Introduction .....	40
3.2.3.2. Description of the event.....	40
3.2.3.3. Conclusion .....	41
<b>4. Development and presentation of CP112E.....</b>	<b>42</b>

<b>4.1.</b>	<b>Incremental approach in the development of CP112E .....</b>	<b>42</b>
4.1.1.	Introduction .....	42
4.1.2.	Task A: Investigation of the SA01a priority rule issue and solution proposal .....	42
4.1.2.1.	Description of the issue .....	42
4.1.2.2.	Areas of improvement .....	43
4.1.3.	Task B: Investigation of the SA01a/b one-hundred foot box issue and solution proposal .....	44
4.1.3.1.	Description of the issue .....	44
4.1.3.2.	Areas of improvement .....	50
4.1.4.	Task C: Investigation of the SA01a design philosophy issue and solution proposal .....	55
4.1.4.1.	Description of the issue .....	55
4.1.4.2.	Areas of improvement .....	55
4.1.5.	Task D: Investigation for SA01c rectification improvement and solution proposal .....	56
4.1.5.1.	Description of the issue .....	56
4.1.5.2.	Areas of improvement .....	60
<b>4.2.</b>	<b>Description of CP112E .....</b>	<b>61</b>
4.2.1.	Basic principle of CP112E .....	61
4.2.1.1.	General .....	61
4.2.1.2.	Addressing issues SA01a and SA01b .....	61
4.2.1.3.	Addressing issue SA01c .....	62
4.2.2.	Detailed behaviour of CP112E .....	62
4.2.2.1.	Introduction .....	62
4.2.2.2.	Treatment of issues SA01a and SA01b .....	62
4.2.2.3.	Treatment of issue SA01c .....	72
<b>5.</b>	<b>Validation of CP112E .....</b>	<b>75</b>
<b>5.1.</b>	<b>Overview of the validation activity .....</b>	<b>75</b>
5.1.1.	Safety validation on encounter models .....	75
5.1.2.	Safety validation for class 8 of the US airspace model .....	75
5.1.3.	Safety validation on actual encounters .....	75
5.1.4.	Operational validation on actual encounters .....	75
<b>5.2.</b>	<b>Safety validation on encounter models .....</b>	<b>76</b>
5.2.1.	Scenarios simulated .....	76
5.2.2.	Validation on the ICAO Safety standard encounter model .....	79
5.2.2.1.	Simulations with standard pilot models .....	79
5.2.2.2.	Interoperability simulations .....	80
5.2.2.3.	Simulations with slow and aggressive pilots .....	82
5.2.3.	Validation on the European ACAS Safety encounter model .....	84
5.2.3.1.	Simulations with standard pilot models .....	84
5.2.3.2.	Interoperability simulations .....	85
5.2.3.3.	Simulations with slow and aggressive pilots .....	87
<b>5.3.</b>	<b>Safety validation for class 8 of the US airspace model .....</b>	<b>89</b>
5.3.1.	Class 8 encounter description .....	89
5.3.2.	Simulation results with TCAS II logic version 7.0 .....	92
5.3.3.	Simulation results with initial CP112 .....	95
5.3.4.	Simulation results with new CP112E .....	97
5.3.5.	Conclusion .....	99
<b>5.4.</b>	<b>Safety validation on actual encounters .....</b>	<b>99</b>
<b>5.5.</b>	<b>Operational validation on actual encounters .....</b>	<b>104</b>
<b>5.6.</b>	<b>Conclusion on the validation results .....</b>	<b>108</b>
5.6.1.	Safety validation on encounter models .....	108
5.6.2.	Safety validation for class 8 of the US airspace model .....	108
5.6.3.	Safety validation on actual encounters .....	108
5.6.4.	Operational validation on actual encounters .....	108
<b>6.</b>	<b>Work on the Überlingen collision .....</b>	<b>109</b>

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6.1.	Überlingen report.....	109
6.2.	Replay of the mid-air collision .....	109
7.	<i>Conclusion</i> .....	111
7.1.	Issue SA01 rectification .....	111
7.2.	Überlingen mid-air collision.....	112
8.	<i>Recommendations</i> .....	112
	<i>Appendix A: SIR working papers and Deliverables</i> .....	113
	<i>Appendix B: External references</i> .....	114
	<i>Appendix C: Operational performance indicators</i> .....	115
	<i>Appendix D: Background on the reversal logic</i> .....	117
	<i>Appendix E: High level comments on the CP112E pseudocode</i> .....	124
	<i>Appendix F: CP112E</i> .....	143

## List of figures

Figure 1: OSCAR display .....	29
Figure 2: OSCAR symbols .....	30
Figure 3: SA01a geometry .....	33
Figure 4: SA01b geometry .....	34
Figure 5: Issue SA01c geometry .....	35
Figure 6: Issue SA01a - Encounter simulated with TCAS II logic version 7.0 RAs onboard aircraft 2 (Shown in red line).....	38
Figure 7: Issue SA01a - Encounter simulated with TCAS II logic version 7.0 RAs onboard aircraft 1 (Shown in black dotted line).....	39
Figure 8: Überlingen collision - Chain of events.....	41
Figure 9: Vertical separation rule of TCAS II logic version 7.0 for the SA01a geometry – Example with own having a descend RA .....	45
Figure 10: Vertical separation rule of TCAS II logic version 7.0 for the SA01b geometry - Example with own having a descend RA .....	46
Figure 11: Issue SA01a - Encounter without TCAS contribution .....	47
Figure 12: Issue SA01a - Encounter simulated with TCAS II version 7.0 RAs onboard aircraft 1 (Shown in full red line).....	48
Figure 13: Issue SA01a - Encounter simulated with TCAS II version 7.0 RAs onboard aircraft 2 (shown in black dotted line) .....	49
Figure 14: VMD test of TCAS II logic version 7.0 – Encounter without TCAS contribution .....	51
Figure 15: VMD test of TCAS II logic version 7.0 - Encounter simulated with TCAS II version 7.0 RAs onboard aircraft 1 (Shown in full red line) .....	52
Figure 16: Task B – Vertical separations rules for Issue SA01a and SA01b Example with own having a descend RA.....	54
Figure 17: Issue SA01c - Encounter without TCAS contribution .....	57
Figure 18: Issue SA01c - Encounter simulated with TCAS II version 7.0 RAs onboard aircraft 1 (Shown in full red line).....	58
Figure 19: Issue SA01c - Encounter simulated with TCAS II version 7.0 RAs onboard aircraft 2 (Shown in black dotted line) .....	59
Figure 20: Illustration of the VMD test .....	63
Figure 21: Issue SA01b - Encounter without TCAS contribution .....	65
Figure 22: Issue SA01b – Encounter simulated with TCAS II logic version 7.0 RAs onboard aircraft 2 (shown in back dotted line).....	66
Figure 23: Issue SA01b – Encounter simulated with TCAS II logic version 7.0+CP112E - RAs onboard aircraft 2 (shown in back dotted line).....	67
Figure 24: Issue SA01a - Encounter simulated with TCAS II version 7.0 +CP112E - RAs onboard aircraft 1 (Shown in full red line).....	70
Figure 25: Issue SA01a - Encounter simulated with TCAS II version 7.0+CP112E - RAs onboard aircraft 2 (shown in black dotted line).....	71
Figure 26: Issue SA01c - Encounter simulated with TCAS II version 7.0 and without reversal RAs (using CP112E) - RAs onboard aircraft 1 (Shown in black dotted line).....	73
Figure 27: US airspace model class 8 encounter - Encounter without TCAS contribution.....	90
Figure 28: US airspace model class 8 encounter - Encounter simulated with TCAS II version 7.0 RAs onboard aircraft 1 (Shown in full red line) .....	92
Figure 29: US airspace model class 8 encounter - Encounter simulated with TCAS II version 7.0 RAs onboard aircraft 2 (Shown in black dotted line).....	93
Figure 30: US airspace model class 8 encounter - Encounter simulated with TCAS II version 7.0+CP112 RAs onboard aircraft 1 (Shown in full red line).....	95
Figure 31: US airspace model class 8 encounter - Encounter simulated with TCAS II version 7.0+CP112 RAs onboard aircraft 2 (Shown in black dotted line).....	96
Figure 32: US airspace model class 8 encounter - Encounter simulated with TCAS II version 7.0+CP112E RAs onboard aircraft 1 (Shown in full red line).....	97
Figure 33: US airspace model class 8 encounter - Encounter simulated with TCAS II version 7.0+CP112E RAs onboard aircraft 1 (Shown in full red line).....	98

Figure 34: Issue SA01a - Encounter simulated with CP112E - RAs onboard aircraft 2 (Shown in full red line)	100
Figure 35: Issue SA01a - Encounter simulated with CP112E - RAs onboard aircraft 1 (Shown in black dotted line)	101
Figure 36: Issue SA01a - Encounter simulated with CP112E - RAs onboard aircraft 2 (Shown in full red line) – Mode S addresses inverted	102
Figure 37: Issue SA01a - Encounter simulated with CP112E - RAs onboard aircraft 1 (Shown in black dotted line) – Mode S addresses inverted	103
Figure 38: Issue SA01b - Encounter without TCAS contribution	105
Figure 39: Issue SA01b – Encounter simulated with TCAS II logic version 7.0	106
Figure 40: Issue SA01b - Encounter simulated with CP112E	107
Figure 41: Version 7.0 - The intruder is causing the crossing RA	118
Figure 42: Version 7.0 - Crossing encounters - Condition on the vertical separation to reverse	119
Figure 43: Version 7.0 - Crossing encounter – Condition to reverse	119
Figure 44: Version 7.0 - Non crossing encounter – Condition to reverse	121
Figure 45: Version 7.0 - Non crossing encounter - Conditions to reverse when own takes a long time to follow his RA - Unequipped intruder	122
Figure 46: Version 7.0 - Non crossing encounter – Condition to reverse when both aircraft are in the same sense - Unequipped intruder	123
Figure 47: CP112E – Meaning of the time parameters	131
Figure 48: CP112E - VMD condition	136

## List of tables

<i>Table 1: Scenarios .....</i>	<i>6</i>
<i>Table 2: Logic risk ratios with the ICAO safety standard encounter model.....</i>	<i>7</i>
<i>Table 3: Logic risk ratios with the European ACAS safety encounter model.....</i>	<i>7</i>
<i>Table 4: Pilot models.....</i>	<i>26</i>
<i>Table 5: OSCAR labels .....</i>	<i>30</i>
<i>Table 6: Scenarios simulated for each encounter model for the safety validation .....</i>	<i>77</i>
<i>Table 7: ICAO safety standard encounter model - Risk ratios with standard pilots.....</i>	<i>79</i>
<i>Table 8: ICAO safety standard encounter model - Interoperability simulations V7/V7+CP112E .....</i>	<i>80</i>
<i>Table 9: ICAO safety standard encounter model - Interoperability simulations V604a/V7+CP112E .....</i>	<i>81</i>
<i>Table 10: ICAO safety standard encounter model - Risk ratios with slow pilots.....</i>	<i>82</i>
<i>Table 11: ICAO safety standard encounter model - Risk ratios with aggressive pilots.....</i>	<i>83</i>
<i>Table 12: European ACAS Safety encounter model - Risk ratios with standard pilots.....</i>	<i>84</i>
<i>Table 13: European ACAS Safety encounter model - Interoperability simulations V7/V7+CP112E .....</i>	<i>85</i>
<i>Table 14: European ACAS Safety encounter model - Interoperability simulations V604a/V7+CP112E .....</i>	<i>85</i>
<i>Table 15: European ACAS Safety encounter model - Risk ratios with slow pilots .....</i>	<i>87</i>
<i>Table 16: European ACAS Safety encounter model - Risk ratios with aggressive pilots.....</i>	<i>88</i>

## Acronyms

ACAS	Airborne Collision Avoidance System
ACASA	ACAS Analysis
BFU	German Federal Bureau of Aircraft Accidents Investigation
ATC	Air Traffic Control
CAS	Collision Avoidance System
CENA	Centre d'Etudes de la Navigation Aérienne
CPA	Closest Point of Approach
EMOTION-7	European Maintenance Of TCAS II version 7.0
FAA	Federal Aviation Administration
FL	Flight Level
HMD	Horizontal Miss Distance
ICAO	International Civil Aviation Organization
MOPS	Minimum Operational Performance Standards
NM	Nautical Mile
NMAC	Near Mid-Air Collision
OSCAR	Off-line Simulator for Collision Avoidance Resolution
RA	Resolution Advisory
RVSM	Reduced Vertical Separation Minima
SIR	Safety Issue Rectification
Sofréavia	Société Française d'Etudes et Réalisations d'Equipements Aéronautiques
TA	Traffic Advisory
TCAS	Traffic Alert and Collision Avoidance System
UK	United Kingdom
US	United States of America
VMD	Vertical Miss Distance



VSL          Vertical Speed Limit

WP          Work Package

## **List of definitions**

### **CP112**

The Change Proposal, result of the work on issue SA01 of the EMOTION-7 project. This CP aims at addressing issue SA01 discovered by the EMOTION-7 project.

### **CP112E**

The enhanced CP112, result of the work performed in the SIR project and developed to enhance CP112.

### **Double equipage encounter**

Encounter involving two TCAS equipped aircraft.

### **Horizontal Miss Distance (HMD)**

The horizontal separation at the time of closest approach between the two aircraft in an encounter.

### **Near Mid-Air Collision (NMAC)**

An encounter in which horizontal separation is less than 500ft and vertical separation less than 100ft simultaneously. In this report, it is generally taken to be an encounter in which  $hmd < 500ft$  and  $vmd < 100ft$  (i.e. at closest approach).

### **Positive RA**

An RA requesting a climb or descend at 1500ft/mn.

### **Reversal RA**

RA that reverses the sense of the initial RA. For example, an RA requesting the aircraft to climb at 1500fpm, while an initial RA was previously requesting a descent at 1500fpm.

### **Risk Ratio**

The risk of collision in an airspace for a given ACAS equipage scenario divided by the risk of collision in that airspace in the absence of ACAS.

### **Single equipage encounter**

Encounter involving a TCAS equipped aircraft and an aircraft not equipped with TCAS, or equipped with TCAS but in Stand-by or in TA-only mode.

### **Vertical Miss Distance (VMD)**

The vertical separation at the time of closest approach between the two aircraft in an encounter.

## **1. Introduction**

### **1.1. Context**

- 1.1.1. When compared with the previous TCAS II (i.e., version 6.04a), one significant change included in TCAS II version 7.0 is that reversal RAs are now permitted in TCAS-TCAS coordinated encounters.
- 1.1.2. This change was introduced to cope with changing situations where the initial RA sense has clearly become the wrong thing to do, in particular when one of the pilots decides not to follow the RAs.
- 1.1.3. The EMOTION-7 Project set up by the EUROCONTROL ACAS Programme has identified in early 2000 a safety issue, related to the reversal logic of TCAS II logic version 7.0. These areas of improvement were documented in [EMO1] and referenced as issue SA01. A solution called CP112 was proposed within the EMOTION-7 project, to address this issue.
- 1.1.4. Six real occurrences of issue SA01 were found in 2001 and 2002 thanks to the EMOTION-7 monitoring, including the Überlingen mid-air collision. A new occurrence of issue SA01 has even been observed in the French airspace in 2004. Issue SA01 is therefore considered as an operationally realistic and recurrent issue.
- 1.1.5. One major comment made to CP112 was about the fact that due to the Mode S priority rule included in the CAS logic, CP112 has the potential to improve the current reversal logic behaviour in only 50% of the cases (This behaviour is due to the Mode S priority rule included in the CAS logic: the aircraft with the lower Mode S address is the master aircraft. It controls the coordinated sense selection and is the only one with the ability to initiate a reversal RA. The slave aircraft is only reversing to remain complementary to the new sense decided by the master aircraft). It was also observed that CP112 can degrade the performance of TCAS II logic version 7.0 for a specific geometry referenced as US encounter model class 8. In addition, work in the CAS logic area has identified in September 2002 a new issue with the reversal logic, referenced to as issue SA01b.
- 1.1.6. As a result the EUROCONTROL ACAS Programme decided to set up the SIR project, which stands for **S**afety **I**ssue **R**ectification.

### **1.2. Scope and objectives**

- 1.2.1. The SIR project was conducted by Sofréavia with the support of the French CENA.
- 1.2.2. The main objective of the SIR project was to progress on the rectification of issue SA01 extended in scope and to address the major comments related to CP112. The second objective was to develop the TCAS investigation final report of the Überlingen mid-air collision.

- 1.2.3. This work was of paramount importance for the Agency and, in particular, the EUROCONTROL ACAS Programme because of the CAS logic issues highlighted by the 2002 Überlingen mid-air collision investigation, and the need to support the European position (developed during the former EMOTION-7 Project) for a rapid implementation of the issue SA01 rectification in an appropriate timescale.
- 1.2.4. To address the objectives, the SIR project was organised in three main parts:
- Development of a CAS logic modification to improve the behaviour of the reversal logic of TCAS II logic version 7.0, so as to fully address issue SA01; and
  - Further contribution to the EUROCONTROL Überlingen mid-air collision investigation; and
  - Development of this SIR final report. The purpose of this document is to present the work achieved from May 2003 to May 2004 within the SIR project.

### **1.3. *Project overview***

#### **1.3.1. Development of a CAS logic modification**

- 1.3.1.1. The first part of the work consisted in developing the enhanced CP112 to provide rectification for all the issues found in the reversal logic. The work was divided into four tasks, each of them investigating one possible area of improvement for CP112. This work is described in section 4.
- 1.3.1.2. The second part was a validation phase. It consisted in verifying that the final proposed solution does rectify the SA01 issue and that other parts of the CAS logic are not affected by the proposed modification. This phase was supported by numerous safety simulations. Additional simulations were also conducted on some actual events. This work is described in section 5.

#### **1.3.2. Further contribution to the Überlingen mid-air collision**

- 1.3.2.1. A description of the Überlingen mid-air collision is provided, in section 3.2.3.
- 1.3.2.2. The first part of the work consisted in participating to the Überlingen mid-air collision investigation by developing an investigation report focusing on the CAS logic aspects. Section 6 presents this work.
- 1.3.2.3. The second part of the work consisted in developing a replay of the Überlingen mid-air collision so as to have a better description of what has occurred and so as to illustrate the Überlingen investigation report. Section 6 also presents this work.

## **1.4. Document overview**

1.4.1. This report is structured as follows:

- First, the tools and methods used in the SIR project are presented in chapter 2. These tools and methods were used within the development and the validation phase of the enhanced CP112 referenced to as CP112E;
- Chapter 3 presents some general background on issue SA01. It presents issue SA01 as identified in the former EMOTION-7 project and some actual events during which this issue was observed;
- Chapter 4 presents the approach of the SIR team and the main choices made while developing the enhanced change proposal to the CAS logic. It also presents CP112E;
- Chapter 5 presents the results of the validation process of CP112E on two encounter models and on actual encounters;
- Chapter 6 presents the work performed on the Überlingen mid-air collision;
- The appendices present:
  - The list of SIR working papers and Deliverables;
  - The external references;
  - The operational performances indicators used within the validation on actual encounters;
  - Some background on the reversal logic;
  - High level comments on the CP112E pseudocode;
  - The CP112E pseudocode.

## **2. Tools and methods**

### **2.1. *Introduction***

- 2.1.1. This part presents the tools and methods used in the SIR project.
- 2.1.2. These tools and methods were mostly used for the validation phase of CP112E, but also for the development of CP112E.

### **2.2. *Use of encounter models***

#### **2.2.1. General description of an encounter model**

- 2.2.1.1. The work described in this report was performed using encounter models.
- 2.2.1.2. An encounter model consists in a very large set of encounters that are built according to a set of probability tables. These probability tables describe the statistical distribution of parameters which define the trajectories of each aircraft and pair of aircraft (e.g. altitude, approach angle, horizontal manoeuvres, vertical miss-distance, ground speed, etc.).
- 2.2.1.3. Each encounter lasts 50 seconds, and the CPA occurs 40 s after the start of the encounter.
- 2.2.1.4. The encounter models only contain encounters with horizontal separations at CPA less than 500 ft.
- 2.2.1.5. Two different encounter models were used:
  - The ICAO safety standard encounter model; and
  - The European ACAS Safety encounter model.

#### **2.2.2. ICAO safety standard encounter model**

- 2.2.2.1. The ICAO SARPS [SAR] specify a standard encounter model for the calculation of logic risk ratios.
- 2.2.2.2. This model corresponds to an idealised non existent airspace.
- 2.2.2.3. There are two sorts of comments on the ICAO safety standard encounter model [SAR]:
  - Those of technical nature concerning the way the aircraft trajectories are built;
  - Those dealing with the operational realism of the model. Indeed, this model is not representative of any airspace.

- 2.2.2.4. However, this model is interesting when working on the CAS logic as it offers stringent conditions to test it, and especially the reversal logic.

### **2.2.3. European ACAS Safety encounter model**

- 2.2.3.1. A new encounter model was built within the scope of the ACASA project [ACA1]. This encounter model is referred to as the European ACAS Safety encounter model.
- 2.2.3.2. This encounter model was built using French and UK radar data, amounting to about one year of coverage from a single ATC SSR radar [ACA1].
- 2.2.3.3. Statistics were derived from this data, to build the probability tables necessary for the description of the encounter model. The statistics were adapted so as to obtain an operationally realistic mid-air collision rate.
- 2.2.3.4. The comments made to the ICAO safety standard encounter model are addressed by the European ACAS Safety encounter model, as improvements were brought to the way the encounters are built, and as it is representative of a mix between the French and UK airspaces.
- 2.2.3.5. This model is interesting, for the operational realism it brings to simulations when compared to the ICAO safety standard encounter model. The main drawback of this model when compared to the ICAO safety standard encounter model results from the lower, but operationally realistic, number of NMACs it contains. This model offers less stringent conditions to test the reversal part of the CAS logic.

### **2.2.4. NMACs**

- 2.2.4.1. An NMAC is an encounter in which horizontal separation is less than 500 ft and vertical separation is less than 100 ft simultaneously. In this report it is taken to be an encounter in which  $hmd < 500$  ft and  $vmd < 100$  ft (i.e., at CPA).
- 2.2.4.2. The performance of TCAS is assessed on encounter models, counting NMACs rather than collisions. This explains why encounter models only contain encounters with horizontal separations at CPA less than 500 ft.
- 2.2.4.3. One usually distinguishes between unresolved NMACs and induced NMACs:
- An unresolved NMAC occurs when a TCAS-equipped aircraft encounters an intruder with less than 100 ft of vertical separation and a TCAS RA does not increase separation to more than 100 ft.
  - An induced NMAC occurs when a TCAS-equipped aircraft encounters an intruder with more than 100 ft of vertical separation and a TCAS RA decreases the vertical separation to less than 100 ft.
- 2.2.4.4. When developing the CAS logic modification, particular attention was brought to induced NMACs.



### **2.2.5. Risk ratio**

- 2.2.5.1. The effect of ACAS on the risk of collision is usually expressed through a measure referred to as risk ratio.
- 2.2.5.2. A risk ratio expresses the risk of collision with ACAS divided by the risk of collision without ACAS. This is therefore a relative indicator, computed on an encounter model and for NMACS. As a result, the risk ratio is highly dependent on the number of NMACs in the encounter model.
- 2.2.5.3. The risk ratio is computed applying an altimetry error model to the trajectories of the aircraft. The altimetry error model is defined in the ACAS SARPS [SAR]. The way the altimetry error is used supposes that the known trajectories of the aircraft are based on altimetry measurements, which are only approximate, and are thus in error. The altimetry errors are added after the ACAS simulations are complete.
- 2.2.5.4. As a result, an encounter during which the aircraft are vertically separated at CPA by more than 100 ft before the altimetry error is applied, has a chance to actually result in an NMAC once this error is applied. However, the higher the vertical separation at CPA before applying the altimetry error, the lower this chance is. Similarly, an encounter resulting in an NMAC before the altimetry error is applied has a chance not to be anymore an NMAC after the altimetry is applied.
- 2.2.5.5. The number of NMACs used for the computation of the risk ratios are counted after the altimetry error has been added.
- 2.2.5.6. The encounter models, which were used in the SIR project contain several classes of encounters (i.e., encounters are classified according to whether or not the aircraft are transitioning at the beginning and end of the encounter, and whether or not the encounter is crossing.), which are represented according to probabilities tables defined in the specification of these encounter models. The risk ratio is computed for the whole encounter model.
- 2.2.5.7. This approach is therefore different from the other approach, used for example by FAA, which consists in performing simulations for several given classes of encounters, and then performing a mix of the results obtained for each of the classes to obtain the final risk ratios.
- 2.2.5.8. However, the final risk ratio is valid with both methods.
- 2.2.5.9. The risk ratios presented in this report are actually logic risk ratios (i.e., indicator of the CAS logic performance regardless of the TCAS surveillance performances, assumed to be perfect).

## 2.2.6. Pilot behaviour

- 2.2.6.1. In TCAS simulations, pilot responses to RAs are simulated.
- 2.2.6.2. The standard pilot response to a corrective RA is that he reacts within 5 s and applies an acceleration of 0.25 g to achieve the required vertical velocity.
- 2.2.6.3. The logic has been designed for this response and most risk ratios assume this response.
- 2.2.6.4. A study performed in the scope of the ACASA project [ACA1] showed that pilots do not always respond to RAs as standard pilots. Some of them respond to RAs slowly or aggressively. The following table presents the characteristics of these pilots, compared to the standard pilot. These characteristics were obtained within the ACASA project [ACA1], using operational data.

	Slow	Standard	Aggressive	Not responding
Initial corrective RA delay	9s	5s	5s	-
Other RA delay (includes weakening, strengthening, increase and reverse RAs)	2.5s	2.5s	2.5s	-
Standard RA acceleration (includes initial, strengthening and weakening RAs)	0.10g	0.25g	0.25g	-
Increase/Reversal RA acceleration	0.10g	0.35g	0.25g	-
Positive RA rate	500fpm	1500fpm	3700fpm	-
Increase RA rate	500fpm	2500fpm	3700fpm	-
Vertical speed limit	as requested by RAs			-

**Table 4: Pilot models**

- 2.2.6.5. The slow pilot model simulates a slow response to all RAs with an acceleration of 0.10 g instead of 0.25 g or 0.35 g. In addition, this pilot climbs or descends with a vertical rate of 500 fpm instead of 1500 fpm or 2500 fpm. As a result, most RAs have only a poor efficiency with this pilot. Therefore risk ratios obtained with slow pilots are higher than with standard pilots [ACA1].

- 2.2.6.6. With the aggressive pilot model, the pilot follows the initial RAs with a correct acceleration, but with a vertical rate of 3700 fpm, whatever the RA. The reversal and increase RAs are followed slowly, with an acceleration of 0.25 g instead of 0.35 g. As a result, reversal RAs often require this pilot to go from 3700 fpm to -3700 fpm or vice versa, with a slow response.
- 2.2.6.7. With an aggressive pilot model, the initial RAs are more efficient than with the standard pilot model, which is observed through decreased risk ratios when compared with standard pilot models [ACA1]. However, this pilot model results in increased deviations when compared to the standard pilot. The reversal RAs can be inefficient or even dangerous because this pilot follows reversal RAs slowly, from a high vertical rate of 3700 fpm. As a result, the aggressive pilot model behaviour is very efficient with initial RAs, but inefficient for the secondary RAs.
- 2.2.6.8. Other pilots choose not to respond to RAs. They do not follow RAs, and remain on the initial trajectory.
- 2.2.6.9. These four pilots models were used in the simulations performed in the SIR project, because even though the CAS logic modification was tuned with standard reactions, it is useful to have a picture of the way the CAS logic behaves for the non standard pilots. This also enables to highlight the need for correct pilot responses to RAs, especially in reversing situations, which are often debased situations when compared to usual RA situations.

### **2.3. *Specific theoretical SA01 encounters databases***

- 2.3.1. In order to help in the development of CP112E, specific data bases of SA01 encounters were built.
- 2.3.2. The principle was to use known theoretical and actual encounters in which issue SA01 was identified, and to build theoretical encounters close to the initial encounters, but with small differences on some parameters such as vertical rates, ground speeds, altitude, etc.
- 2.3.3. These encounters were built with tools used in the ACASA project to build the European ACAS Safety encounter model [ACA1], so as to modify each parameter slightly.
- 2.3.4. Only the encounters resulting in vertical separations at CPA below 200 ft were kept and analysed.
- 2.3.5. Creating theoretical encounters permitted to see the effect of small changes on a specific given encounter in terms of CAS logic behaviour and to have more encounters corresponding to issue SA01 to work with.

### **2.4. *Actual encounters***

- 2.4.1. Encounter models enable to compute risk ratios, which permit to have a good picture of the safety benefits brought by a CAS logic.

- 2.4.2. However, a risk ratio by itself is not sufficient. When developing a modification to the CAS logic, it is important to check that the CAS logic modification does not have implications on other parts of the logic. For example, a CAS logic modification to the reversal logic, which would also increase the number of RAs, would not be acceptable. This was checked using several operational performance indicators, presented in appendix C.
- 2.4.3. Checking this is done on a set of actual encounters, recorded in the European airspace.
- 2.4.4. This data base of actual encounters is composed of more than 1000 encounters for single equipage simulations, and roughly 400 encounters for double equipage simulations.
- 2.4.5. In addition to these encounters, a few actual SA01 encounters were simulated with the CAS logic modification, to assess the benefits of the CAS logic modification on these actual encounters.

## **2.5. *The OSCAR simulation facilities***

- 2.5.1. The OSCAR test bench is a set of integrated tools to prepare, execute and analyse scenarios of encounters involving TCAS II equipped aircraft. It includes an implementation of the TCAS II version 7.0, of CP112 and of CP112E.
- 2.5.2. For each encounter, the most relevant results of the TCAS II simulations are provided by screen dumps of OSCAR windows. Several types of information are displayed:

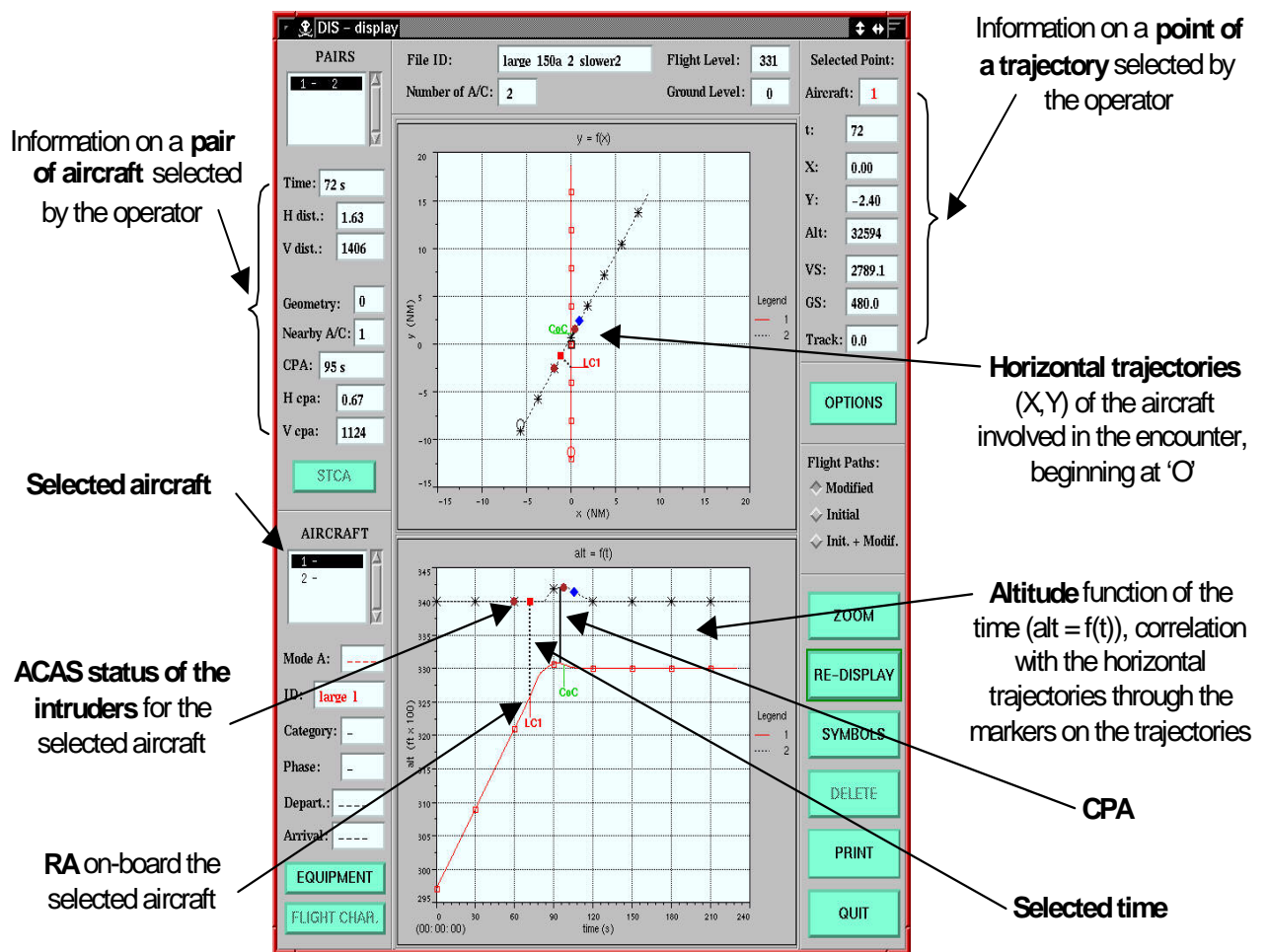


Figure 1: OSCAR display

- 2.5.3. 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 and labels described hereafter:



**Figure 2: OSCAR symbols**

Label	Advisory
CoC	Clear of Conflict
CI	Climb (1500 fpm)
DDes	Don't Descend
LD5 / LD1 / LD2	Limit Descent 500 / 1000 / 2000 fpm
Des	Descend (1500 fpm)
DCI	Don't Climb
LC5 / LC1 / LC2	Limit Climb 500 / 1000 / 2000 fpm
CCI	Crossing Climb (1500 fpm)
RCI	Reverse Climb (1500 fpm)
ICI	Increase Climb (2500 fpm)
MCI	Maintain Climb
CDes	Crossing Descend (-1500 fpm)
RDes	Reverse Descent (-1500 fpm)
IDes	Increase Descent (-2500 fpm)
MDes	Maintain Descent

**Table 5: OSCAR labels**

- 2.5.4. OSCAR permits to perform simulations using the user interface of the test bench. It also permits to launch simulations without using the test bench, with a single UNIX batch job. OSCAR also permits to simulate several encounters in a single file
- 2.5.5. This enables to simulate the CAS logic on an encounter model and to compute a risk ratio in an automated manner with a single UNIX command. The output of this UNIX command is a set of result files containing the results of the TCAS

simulations for each encounter of the encounter model for a given set of TCAS equipage and pilot responses, and an output file containing the risk ratio, statistics about the TAs and RAs, and more generally the operational performance of the CAS logic.

- 2.5.6. These facilities were used for the simulations performed in the scope of the SIR project.

### **3. Background**

#### **3.1. *Issue SA01***

##### **3.1.1. Introduction**

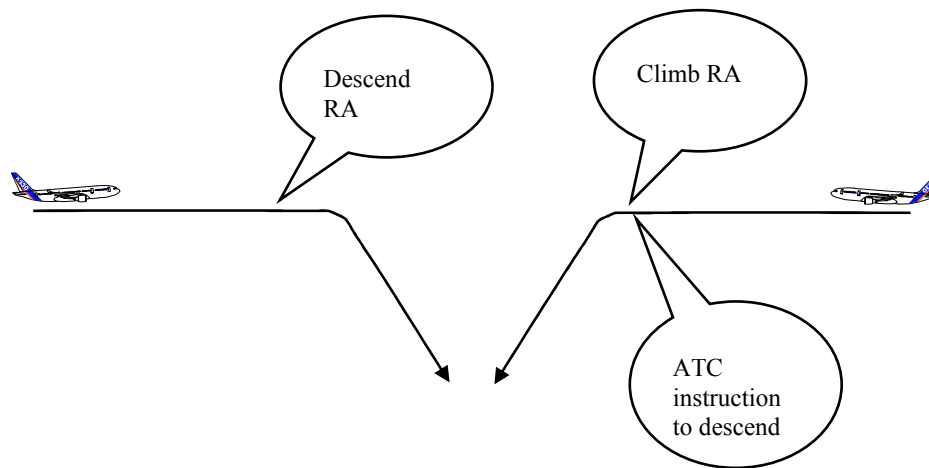
- 3.1.1.1. When compared with the previous TCAS II (i.e., version 6.04a), one significant change included in TCAS II version 7.0 is that reversals RAs are now permitted in TCAS-TCAS coordinated encounters (Appendix D provides a background on the reversal logic).
- 3.1.1.2. This change was introduced to cope with changing situations where the initial RA sense has clearly become the wrong thing to do, in particular when one of the pilots decides not to follow the RAs but manoeuvres contrary instead and thwarts the initial RAs.
- 3.1.1.3. The EMOTION-7 Project has identified in early 2000 some areas of improvements for the reversal logic. These areas of improvement were documented in [EMO1] and referenced as issue SA01.
- 3.1.1.4. Issue SA01 consists in 3 sub-issues, which deal with the reversal logic: Issues SA01a, SA01b and SA01c.
- 3.1.1.5. What follows is a rapid presentation of these 3 sub-issues. For each sub-issue, a general presentation is provided. Then some examples of actual occurrences of issue SA01 are shown.
- 3.1.1.6. A more detailed presentation of each issue is given in part 4.

##### **3.1.2. Issue SA01a**

- 3.1.2.1. An issue for the reversal logic has been identified in early 2000. This issue deals with either the non issuance or the late issuance of reversal RAs in a geometry in which it is necessary to have them triggered early enough. This issue is entitled **Late reversal RAs or no reversal RAs in coordinated encounters**.
- 3.1.2.2. The issue has been identified for an encounter set, which is representative of operationally realistic scenarios: two aircraft are flying at the same FL and are converging in range with a very late ATC instruction inducing an intruder manoeuvre that thwarts the initial RAs.



3.1.2.3. The following figure presents an example of the SA01a geometry.



**Figure 3: SA01a geometry**

3.1.2.4. The EMOTION-7 Project has provided evidences that the SA01a scenario was indeed happening in operational use (e.g., Japanese event January 2001, Belgian event July 2001, French event November 2001, German event February 2002, French Event March 2002, Überlingen collision July 2002).

### **3.1.3. Issue SA01b**

3.1.3.1. In the second half of 2002, the work in the CAS reversal logic area (conducted in parallel with the investigation of the TCAS aspects of the Überlingen collision) has also highlighted the potential for failure to initiate the reversal logic either in single equipage encounter or similarly in double equipage encounter but with one TCAS II either in stand-by mode or in TA-only mode.

3.1.3.2. The geometries involved are comparable to those already described during the investigation of issue SA01a. In particular, one geometry is for two aircraft flying at the same FL and converging in range with a very late ATC instruction inducing an intruder manoeuvre which thwarts the initial RA issued onboard the own aircraft. This scenario was already identified in 1995 [SIC] but with TCAS II logic version 6.04a.

3.1.3.3. This issue is entitled **Late reversal RAs or no reversal RAs in uncoordinated encounters**.

3.1.3.4. The following figure presents an example of the SA01b geometry.

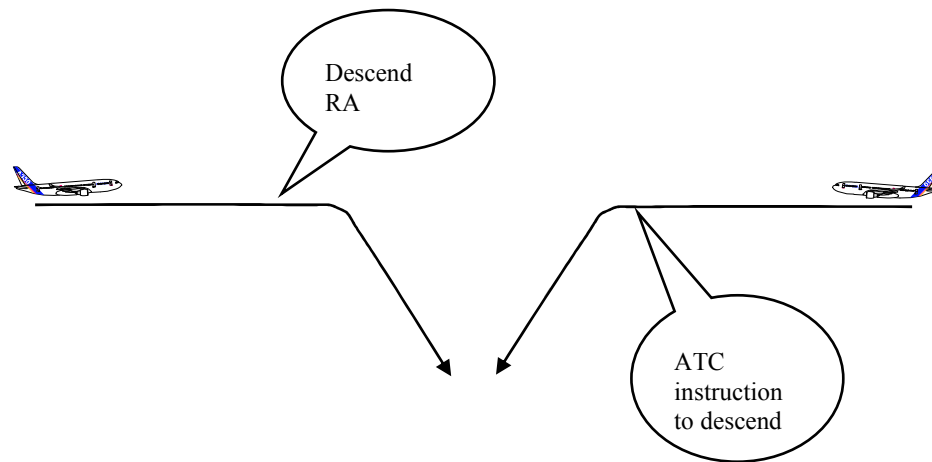
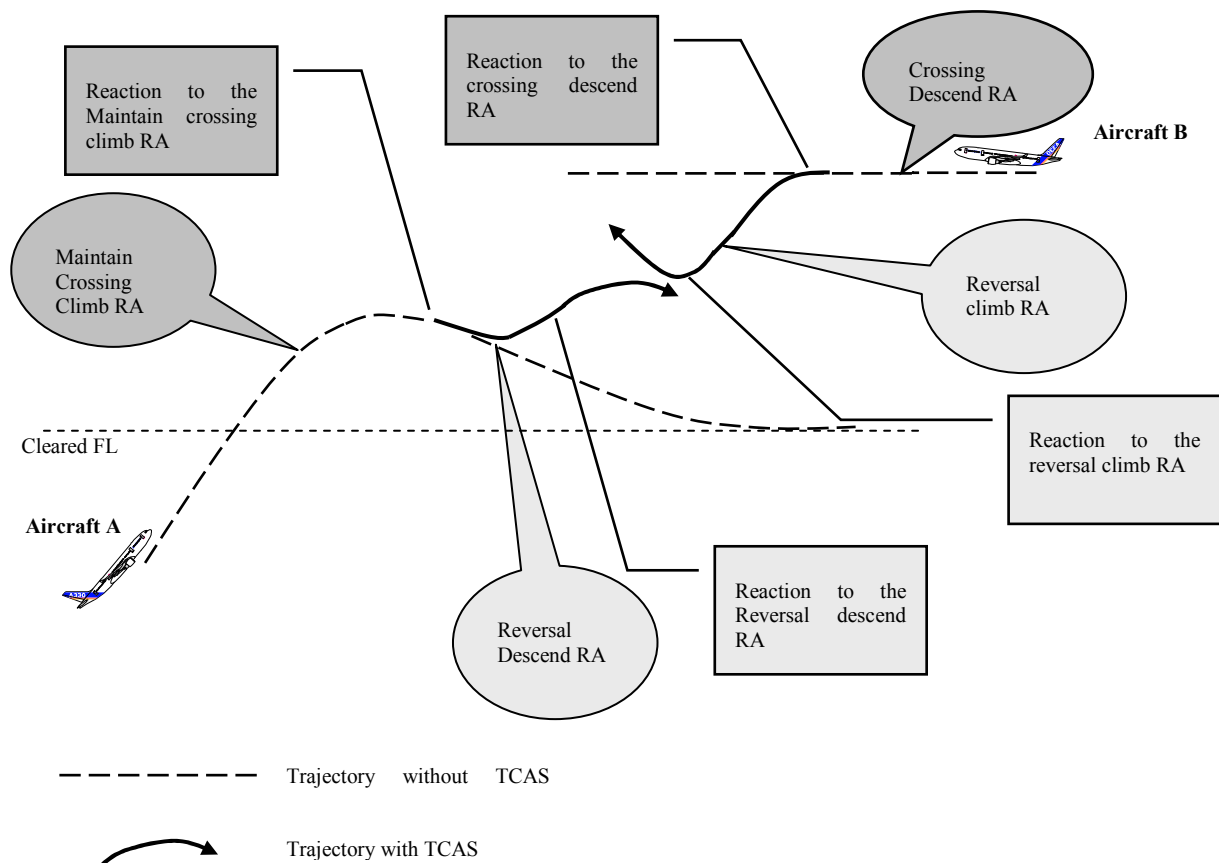


Figure 4: SA01b geometry

### 3.1.4. Issue SA01c

- 3.1.4.1. Another area of improvement for the reversal logic has also been identified in early 2000, and is entitled **Undesirable reversal RAs in coordinated encounters**. This area deals with the undesirable issuance of reversal RAs in coordinated crossing encounters when both pilots follow correctly their RAs. Indeed, in some cases not observed with TCAS II logic version 6.04a, the TCAS II logic version 7.0 contribution may seriously decrease the vertical separation at CPA.
- 3.1.4.2. The issue has been identified in altitude bust scenarios, which are common operationally as it was reported that :
- 500 altitude busts have been detected each year in a major European State; and
  - 21 altitude busts have been reported each month by a major European airline.

3.1.4.3. The following figure presents an example of issue SA01c geometry, during a level-bust.



**Figure 5: SA01c geometry**

- 3.1.4.4. In this geometry, aircraft A, which has busted its cleared flight level receives a maintain crossing climb RA (whereas aircraft B receives a coordinated crossing descent RA).
- 3.1.4.5. However, at the time the Maintain crossing climb RA is triggered, aircraft A is beginning to manoeuvre to descend back to its cleared flight level. Therefore, aircraft A first descends before climbing in response to the RA.
- 3.1.4.6. A reversal descend RA is then triggered, however at this time aircraft A is beginning to manoeuvre to climb so as to comply with the initial Maintain crossing climb RA.
- 3.1.4.7. A few seconds later, aircraft A descends to comply with the reversal descend RA.

### **3.2. Actual occurrences of Issue SA01a**

#### **3.2.1. Likelihood of occurrence of issue SA01a**

- 3.2.1.1. Figures concerning the probability of occurrence of encounters leading to reversal RAs were initially provided in 2000 [EMO2]. Simulations were made on around 600,000 flight hours extracted from French radar data recordings, representing 4 months of recording. It was found that one encounter leading to reversal RAs should be expected every 2 months in the French airspace, corresponding to a probability of  $3.3 \cdot 10^{-6}$  per flight hour. Therefore, **it was considered that such encounters should not be considered as rare events in the European airspace.**
- 3.2.1.2. In addition to the Japanese accident of January 2001, five SA01 events were identified by the EMOTION-7 project monitoring between mid 2001 and mid 2002:
- Event in Belgium in July 2001. **This event is presented in 3.2.2.**
  - Event in France in November 2001;
  - Event in Germany in February 2002 [EMO8];
  - Event in France in March 2002;
  - Überlingen mid-air collision in July 2002, described briefly hereafter.
- 3.2.1.3. If a similar monitoring had been undertaken in other locations, it would likely have permitted to identify occurrences of issue SA01 in these locations, thus confirming that issue SA01 is not airspace dependent.
- 3.2.1.4. Using some of the events found through the EMOTION-7 project monitoring, it was possible to estimate a more accurate probability, that an aircraft experiences issue SA01a in the European airspace. It was computed that this probability is equal to  **$4.7 \cdot 10^{-6}$  per flight hour** [EMO8].
- 3.2.1.5. A new SA01 event was even found in France in February 2004, after the end of EMOTION-7 monitoring. The scenario is comparable to the Überlingen mid-air collision [WP2/17].

#### **3.2.2. Actual SA01a event**

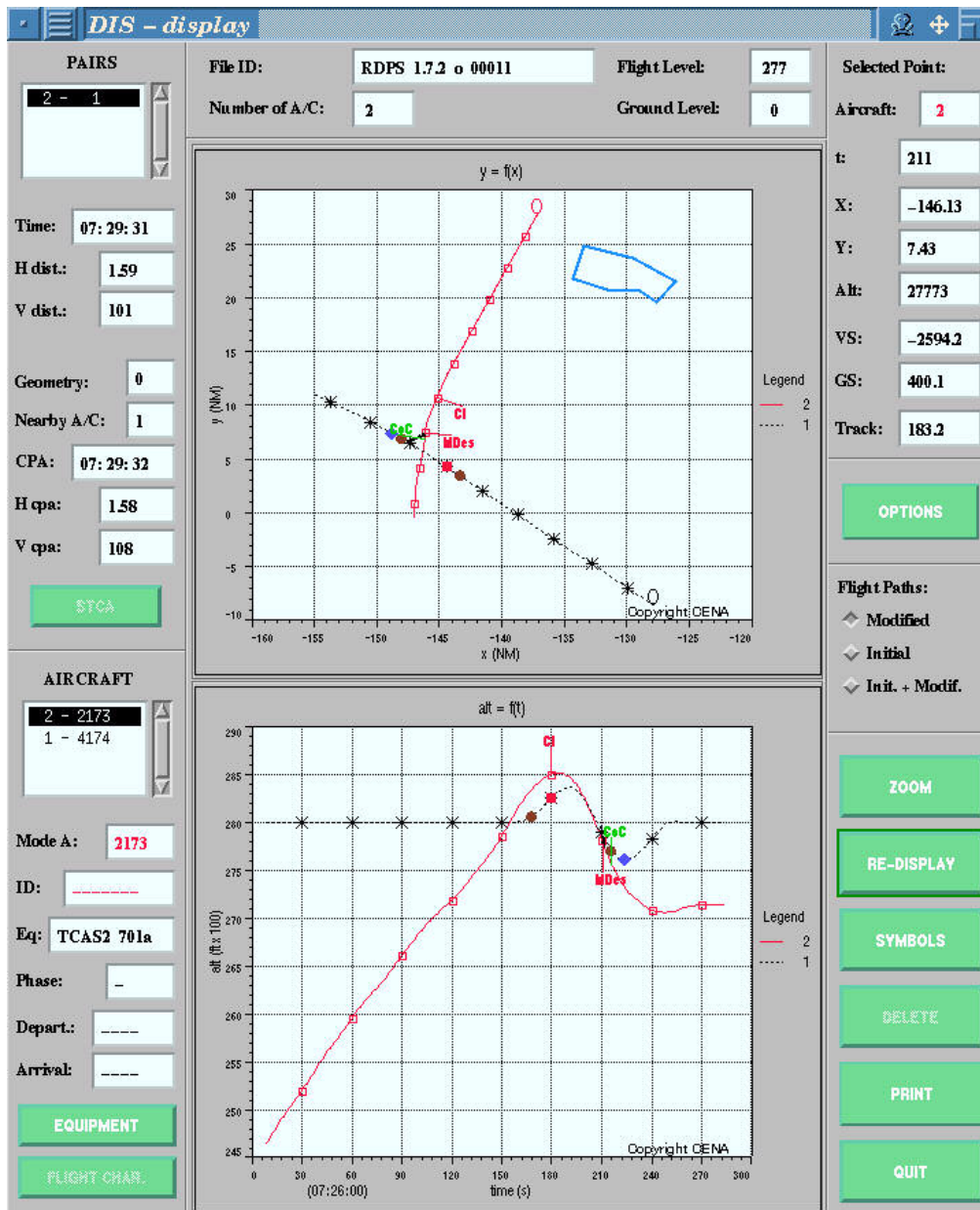
##### **3.2.2.1. Introduction**

- 3.2.2.1.1. This part presents an example of a real SA01 encounter [EMO5], which occurred in July 2001.
- 3.2.2.1.2. This event was identified through the EMOTION-7 monitoring [EMO5]. It involved two aircraft, which experienced issue SA01a, because one pilot did not follow his RAs and manoeuvred contrary to them. The event involved a level aircraft at FL280 (aircraft 1) and an aircraft cleared to climb to FL270 (aircraft 2). Both aircraft were in contact with the same controller.

### **3.2.2.2. Description of the event**

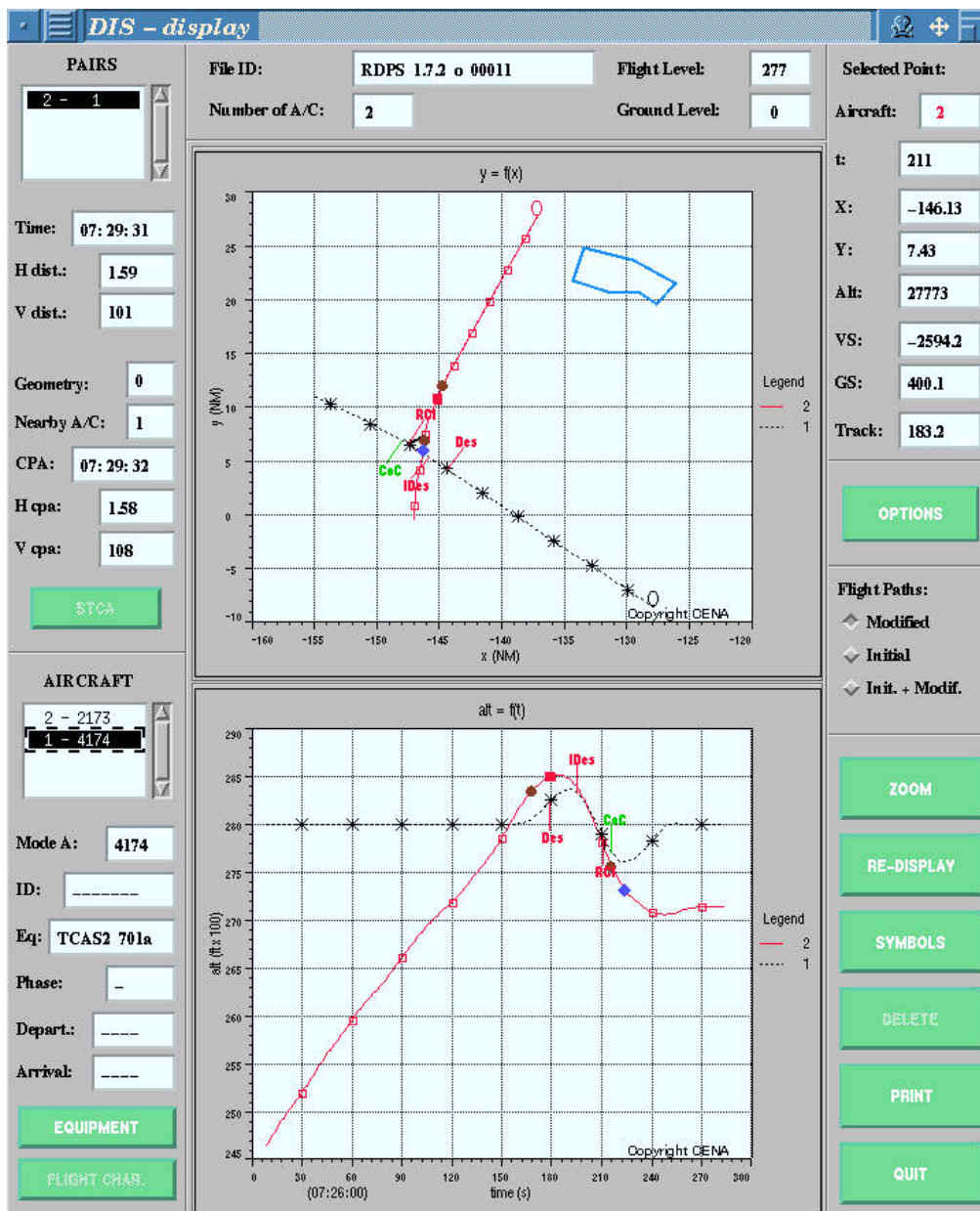
- 3.2.2.2.1. Aircraft 1 reported ATC it was at FL280. Aircraft 2 contacted ATC and was cleared to climb to FL270.
- 3.2.2.2.2. ATC then asked aircraft 2 if it could achieve a rate of climb of at least 2000 fpm if re-cleared to FL290. Aircraft 2 answered that it could not and it was told to wait for further climb. At this stage, aircraft 2 continued its climb to FL290 instead of levelling off at FL270. ATC instructed aircraft 2 to descend immediately to FL270 (aircraft 2 was observed passing FL274 climbing).
- 3.2.2.2.3. ATC instructed aircraft 1 to climb to FL290 and provided a traffic information (aircraft 2 was observed passing FL278 climbing).
- 3.2.2.2.4. But aircraft 2 was still climbing, and ATC instructed it to maintain FL280. Then, ATC requested aircraft 1 and 2 to turn left. Aircraft 1 was also instructed to expedite climb.
- 3.2.2.2.5. Aircraft 1 reported following a descend RA. Aircraft 2 had a climb RA and descended instead of following this RA. ATC instructed aircraft 2 to maintain its level. Aircraft 2 reported having aircraft 1 in sight. Aircraft 1 reported not having aircraft 2 in sight and the end of the TCAS II advisory.

3.2.2.2.6. The following figures show the radar data for this encounter, simulated with TCAS II version 7.0.



**Figure 6: Issue SA01a - Encounter simulated with TCAS II logic version 7.0  
RAs onboard aircraft 2 (Shown in red line)**

**Sequence of RAs:** Cl: Climb RA, MDes: Maintain Descent RA, CoC: Clear of Conflict



**Figure 7: Issue SA01a - Encounter simulated with TCAS II logic version 7.0  
RAs onboard aircraft 1 (Shown in black dotted line)**

**Sequence of RAs:** Des: Descend RA, IDes: Increase Descent RA, RCl: Reversal Climb RA, CoC: Clear of Conflict

3.2.2.2.7. With TCAS II logic version 7.0, reversal RAs are triggered 1 s before CPA, which is too late to be efficient.

3.2.2.2.8. According to the radar data, the vertical separation at CPA is 108 ft.

### **3.2.2.3. Conclusion**

3.2.2.3.1. [EMO9] shows that that **the event timeline would not have been changed with a nil HMD at CPA.**

3.2.2.3.2. In this event, the reversal logic did not perform as expected, as reversal RAs were triggered but were inefficient due to their lateness.

3.2.2.3.3. This encounter was simulated with CP112E. The result is presented in part 5.4.

## **3.2.3. Überlingen Mid-air Collision**

### **3.2.3.1. Introduction**

3.2.3.1.1. On 1st July 2002, a mid-air collision occurred in the European airspace involving a Boeing 757-200, callsign DHX 611, and a Tupolev 154, callsign BTC 2937, which were both TCAS II version 7 equipped.

### **3.2.3.2. Description of the event**

3.2.3.2.1. All the details available in the investigation report can not be shown, because of confidentiality agreements between the SIR team and BFU

3.2.3.2.2. The BTC 2937 and the DHX 611 were level at FL360 on converging tracks.

3.2.3.2.3. At 21:34:49, the BTC 2937 received an ATC instruction to expedite descent to FL350.

3.2.3.2.4. At 21:34:56, the BTC 2937 and the DHX 611 received coordinated RAs. DHX 611 followed his descend RA, whereas BTC 2937 did not follow his climb RA, and rather descended to follow the ATC instruction.

3.2.3.2.5. At 21:35:03, the BTC 2937 received a second ATC instruction to expedite descent to FL350.

3.2.3.2.6. At 21:35:19, the DHX 611 reported a "TCAS Descent" to ATC.

3.2.3.2.7. DHX 611 received an increase RA at 21:35:10.

3.2.3.2.8. BTC 2937 received an increase climb RA at 21:34:24.

3.2.3.2.9. The collision occurred 8 seconds later.



3.2.3.2.10. The following figure summarizes the chain of events.

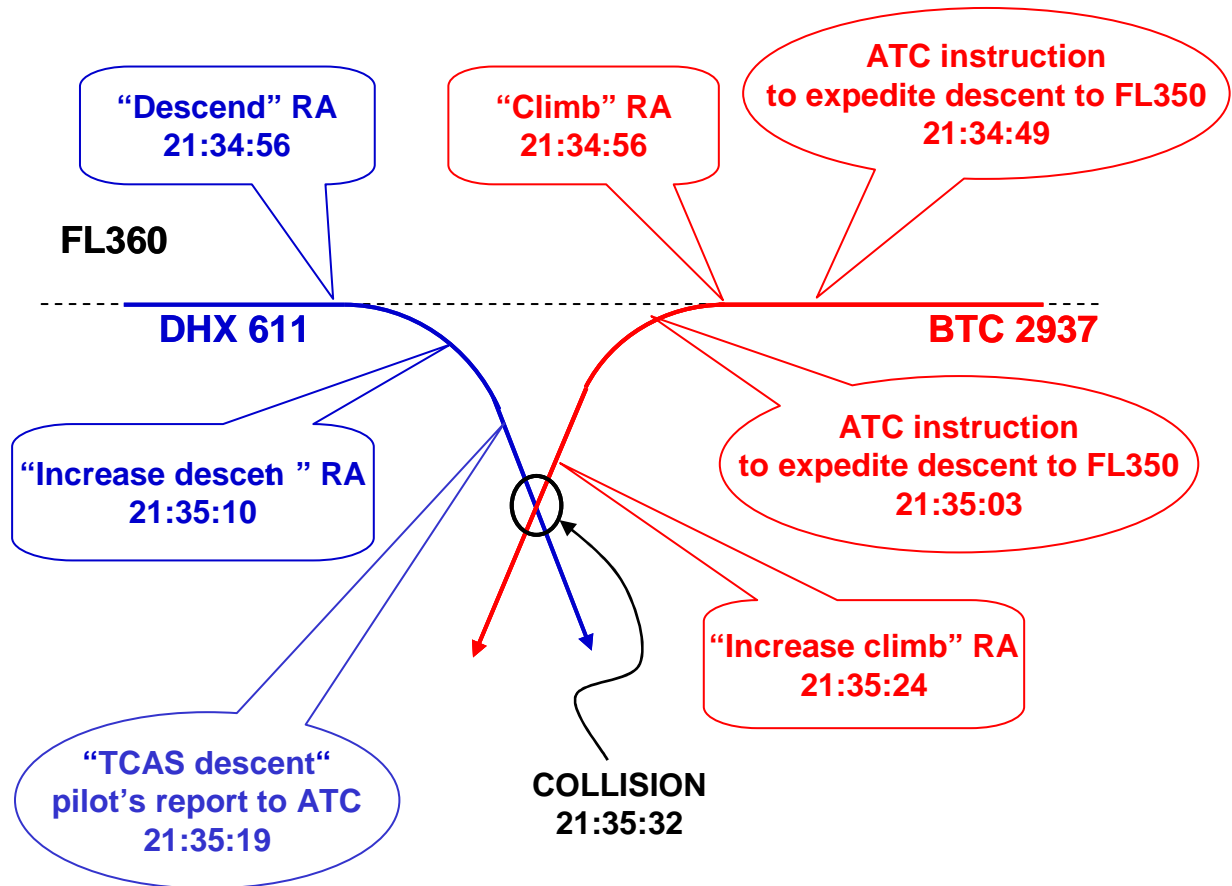


Figure 8: Überlingen collision - Chain of events

### 3.2.3.3. Conclusion

3.2.3.3.1. As a conclusion, this event is another example of the SA01a geometry.

## **4. Development and presentation of CP112E**

### ***4.1. Incremental approach in the development of CP112E***

#### **4.1.1. Introduction**

- 4.1.1.1. For the understanding of this part, it is essential that section 3 was read.
- 4.1.1.2. To expand the CP112 solution, the work has been divided into four tasks, each of them investigating one possible area of improvement for the reversal logic.
- 4.1.1.3. These development tasks are as follows:
  - Task A: Investigation of the SA01a priority rule issue and solution proposal
  - Task B: Investigation of the SA01a/b one-hundred foot box issue and solution proposal
  - Task C: Investigation of the SA01a design philosophy issue and solution proposal
  - Task D: Investigation for SA01c rectification improvement and solution proposal
- 4.1.1.4. Section 4.1 presents these four tasks. For each of them, the issue which had to be addressed is presented. Then, the main choices which were made to solve these issues are presented.
- 4.1.1.5. Section 4.2 presents the principle of CP112E, with examples illustrating its behaviour.

#### **4.1.2. Task A: Investigation of the SA01a priority rule issue and solution proposal**

##### **4.1.2.1. Description of the issue**

- 4.1.2.1.1. In the CAS logic, mode S addresses are used to define priorities for the decision of the sense of the RAs (e.g., decision of which aircraft will climb or descend in case they are converging and level at co-altitude).
- 4.1.2.1.2. In the reversal logic, the aircraft with the lower Mode S address is the master aircraft. It controls the coordinated sense selection and is the only one with the ability to initiate a reversal RA. The slave aircraft is only reversing to remain complementary to the new sense decided by the master aircraft.
- 4.1.2.1.3. This limitation can result in different behaviours of the CAS logic for a given encounter, depending on the order of the mode S addresses. Indeed, during an encounter during which reversal RAs would be necessary, the triggering or not of reversal RAs depends on the order of the mode S addresses, because the aircraft

may have dissymmetrical perceptions of what is occurring (e.g., tracker's uncertainties etc.).

4.1.2.1.4. This limitation can result in some necessary reversal RAs not being triggered because the lower mode S address aircraft does not compute that a reversal RA is necessary (while the higher mode S address aircraft sometimes does, but can not initiate the reversal RA).

4.1.2.1.5. The solution to issue SA01 developed within the EMOTION-7 project and referenced in the RTCA arena as CP112 [EMO3], introduced a mechanism in the reversal logic, which detects that own aircraft is going opposite to the RAs. However, one major comment on CP112 was about the fact that because of the mode S priorities included in TCAS II logic version 7.0, this detection can only lead to the triggering of a reversal RA if the aircraft, which is going opposite to the RAs has the lower mode S address. As a result, CP112 is only efficient in 50% of the encounters.

#### **4.1.2.2. Areas of improvement**

##### **Rationale for the use of the VMD**

4.1.2.2.1. One solution to address this issue would have been to modify or remove the mode S priorities in the reversal logic. This is considered a major change to the CAS logic, and such a change would raise issues when considering interoperability with TCAS II logic version 7.0 and 6.04a, therefore it was decided to seek for another solution.

4.1.2.2.2. The goal of the work performed in task A was to develop this solution. It first aimed at finding a criterion, which would bring more symmetry to the way the reversal logic behaves for the SA01a geometry.

4.1.2.2.3. While analysing some actual SA01a events, the computation of VMDs showed that this criterion was a good mean of detecting a possibly debased situation in the SA01a geometry, onboard both aircraft. Indeed, in these events during which reversal RAs would have been necessary, the VMDs were close and low on board both aircraft.

4.1.2.2.4. Therefore, in order to enhance CP112, it was chosen to use the VMD together with parameters describing the current situation of the two aircraft involved (e.g., altitudes, vertical rates). The use of these parameters permits to solve most SA01a encounters, because the master aircraft can detect that the encounter is evolving as in the SA01a geometry and will likely result in the aircraft being close at CPA, independently of its response to RAs.

##### **Use of the VMD by TCAS II logic version 7.0**

4.1.2.2.5. The VMD parameter is already used in the reversal logic of TCAS II logic version 7.0, in a part dedicated to encounters with unequipped aircraft. This part uses the VMD for encounters in which both aircraft evolve in the same direction.

4.1.2.2.6. This part was likely added to TCAS II logic version 7.0 to cope with SA01b like geometries, while enhancing version 6.04a, as the issue had already been highlighted in 1995 with version 6.04a [SIC]. In this context, potential to use VMD had been previously identified but the approach was not progressed.

#### **Use of the VMD in CP112E**

4.1.2.2.7. It was considered that using VMD was appropriate but with refinements when compared to its use in TCAS II logic version 7.0, so as to apply to both issues SA01a and SA01b, and so as to solve a maximum of problem encounters without generating too many reversal RAs.

4.1.2.2.8. The work in Task A was performed using the detection parameters of TCAS II logic version 7.0, but with refinements, so as to address the limitations caused by the mode S priority rule, but also so as to improve the treatment of issue SA01b:

- Possible uncertainties on the tracking of the intruder are taken into account when computing the VMD; and
- The detection of the need of a reversal RA on the basis of the VMD has to be passed several times, to avoid the triggering of reversal RAs because of a VMD being low only one cycle. The goal of this condition is to avoid the triggering of reversal RAs, which would be undesirable at that time.

4.1.2.2.9. The part of TCAS II logic version 7.0 using the VMD was not modified. A new part specifically dealing with issue SA01a and SA01b was rather added, in order not to take the risk of debasing the performance of the existing in TCAS II logic version 7.0.

### **4.1.3. Task B: Investigation of the SA01a/b one-hundred foot box issue and solution proposal**

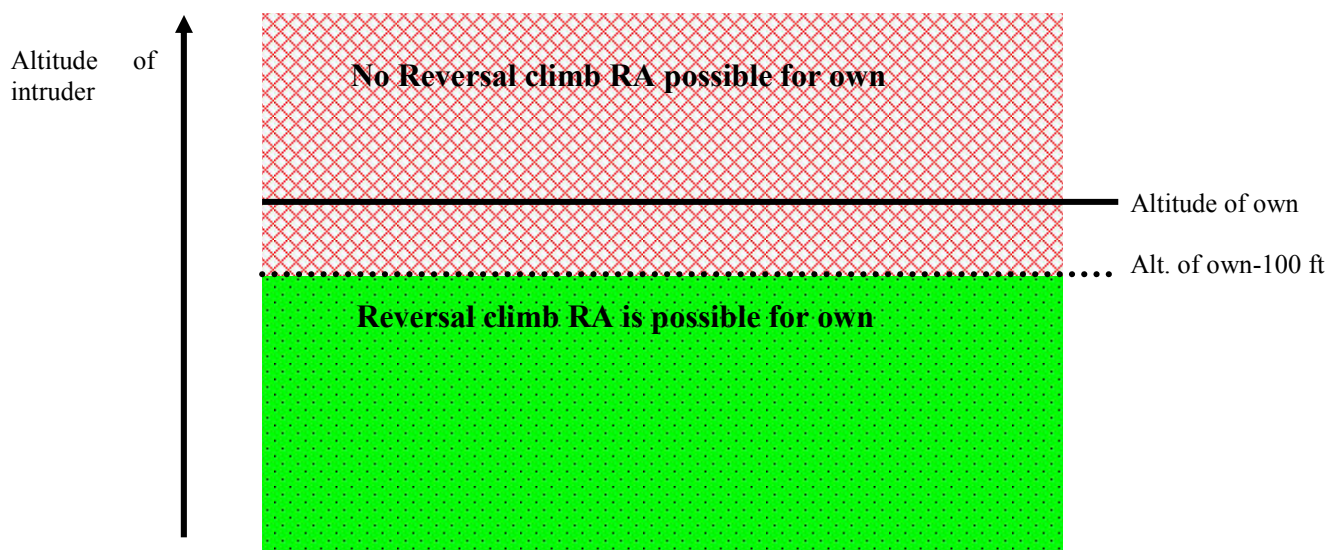
#### **4.1.3.1. Description of the issue**

4.1.3.1.1. In encounters during which one pilot does not follow his RAs or in single equipage encounters, many NMACs would not be solved by the reversal logic because the reversal RAs would happen too late to be efficient. There are even encounters during which the reversal RAs would be triggered after the CPA or not triggered at all. It is obvious that such reversal RAs are useless.

4.1.3.1.2. One reason for this is a limitation of the reversal logic:

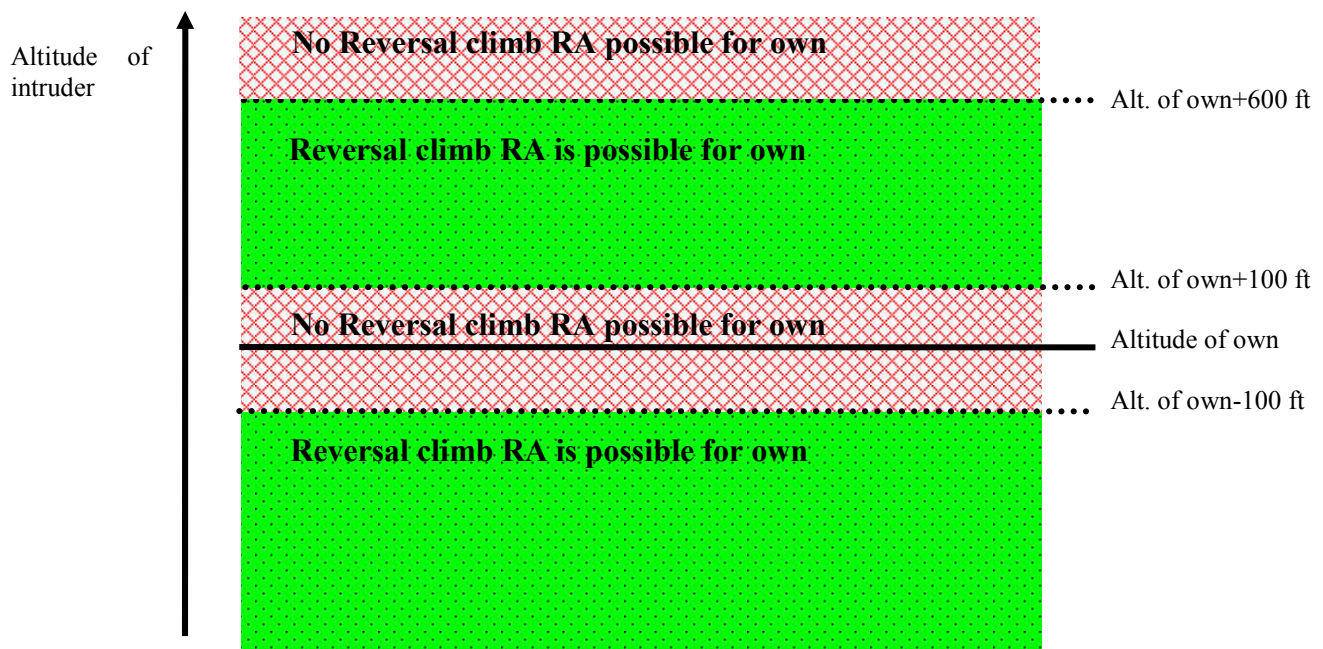
- In single equipage encounters, in the SA01b geometry, the reversal logic only authorizes a reversal RA for aircraft which are separated by more than 100 ft vertically;
- In coordinated encounters, in the SA01a geometry, the reversal logic only authorizes a reversal climb RA if own aircraft is at least 100 ft above the intruder, or a reversal descent RA if own is at least 100 ft below the intruder.

4.1.3.1.3. The following figure illustrates this, in the case of own having a descent RA, in the case of the SA01a geometry.



**Figure 9: Vertical separation rule of TCAS II logic version 7.0 for the SA01a geometry – Example with own having a descend RA**

4.1.3.1.4. The following figure illustrates this, in the case of own having a descent RA, in the case of the SA01b geometry.



**Figure 10: Vertical separation rule of TCAS II logic version 7.0 for the SA01b geometry - Example with own having a descent RA**

- 4.1.3.1.5. In the SA01b geometry, the altitude band around own aircraft, in which the intruder must not be for a reversal RA to be possible, is certainly resulting from an omission from a former change in the reversal logic to cope with the issue detected in 1995 in [SIC]. There is no operational reason for this altitude band.
- 4.1.3.1.6. The following figures show an example of SA01a theoretical encounter, extracted from the ICAO safety standard encounter model illustrating this issue. Figure 11 shows the encounter without TCAS contribution. Aircraft 1 and aircraft 2 are nearly head on at the same altitude. Aircraft 1 starts a descent, possibly following an ATC instruction.

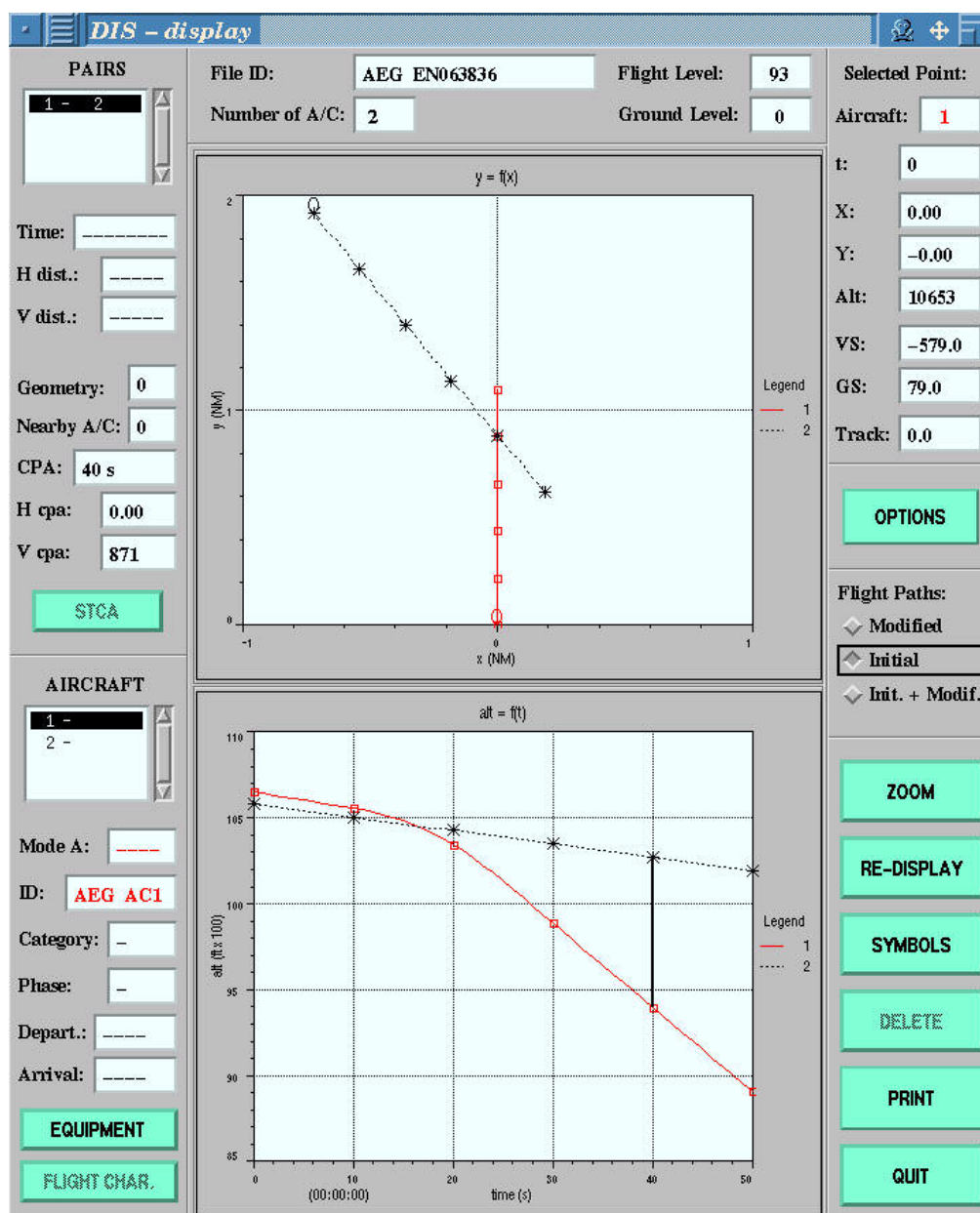
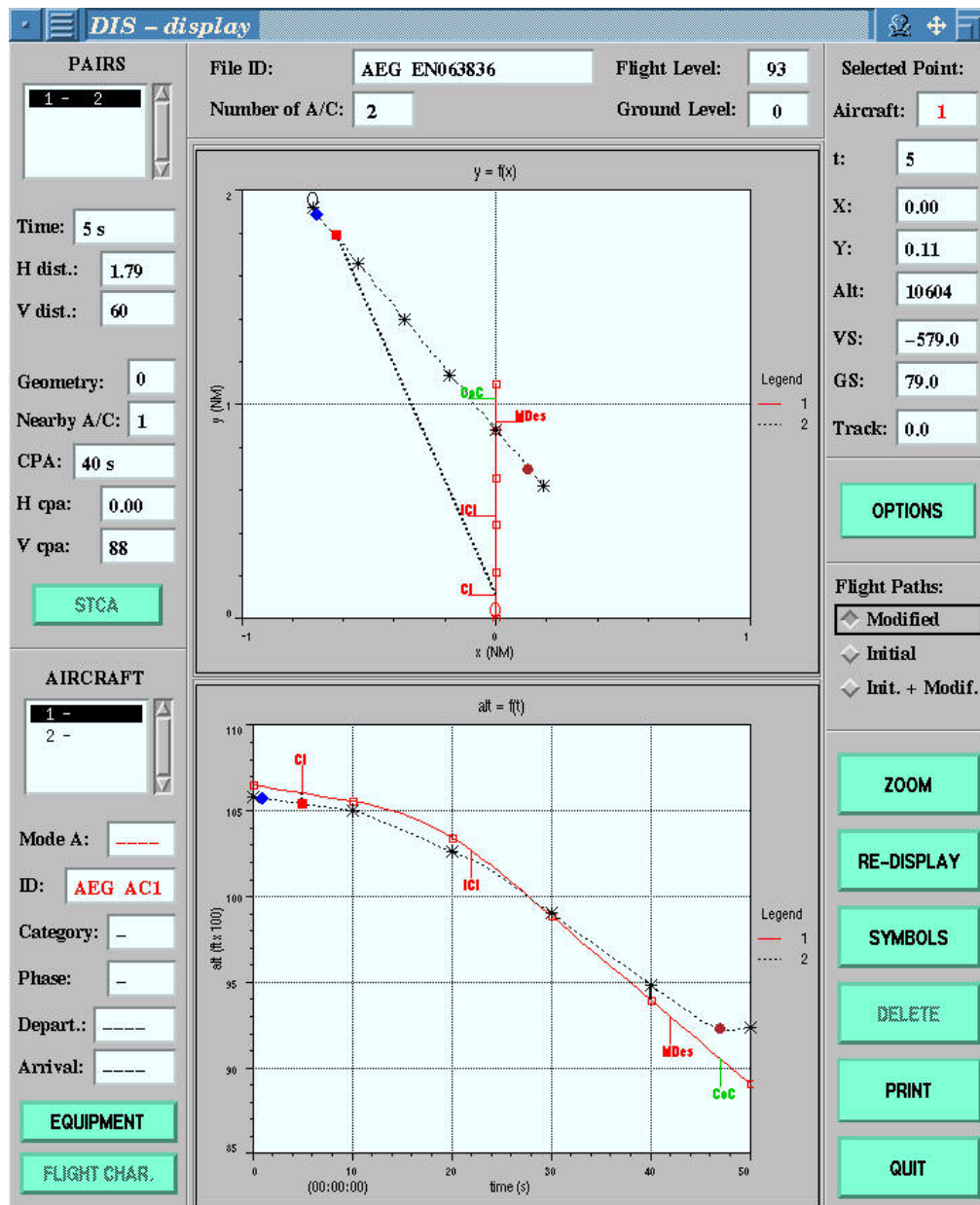


Figure 11: Issue SA01a - Encounter without TCAS contribution

4.1.3.1.7. Figure 12 and Figure 13 show this encounter with TCAS II logic version 7.0 simulated onboard both aircraft. The pilot of aircraft 1 has a climb RA, which he does not follow because he possibly follows the ATC instruction to descend. The pilot of aircraft 2 has a descend RA, which the pilot follows. This results in both aircraft descending.



**Figure 12: Issue SA01a - Encounter simulated with TCAS II version 7.0  
RAs onboard aircraft 1 (Shown in full red line)**

**Sequence of RAs:** Cl: Climb RA, ICl: Increase climb RA, MDes: Maintain Descent RA, CoC: Clear of Conflict



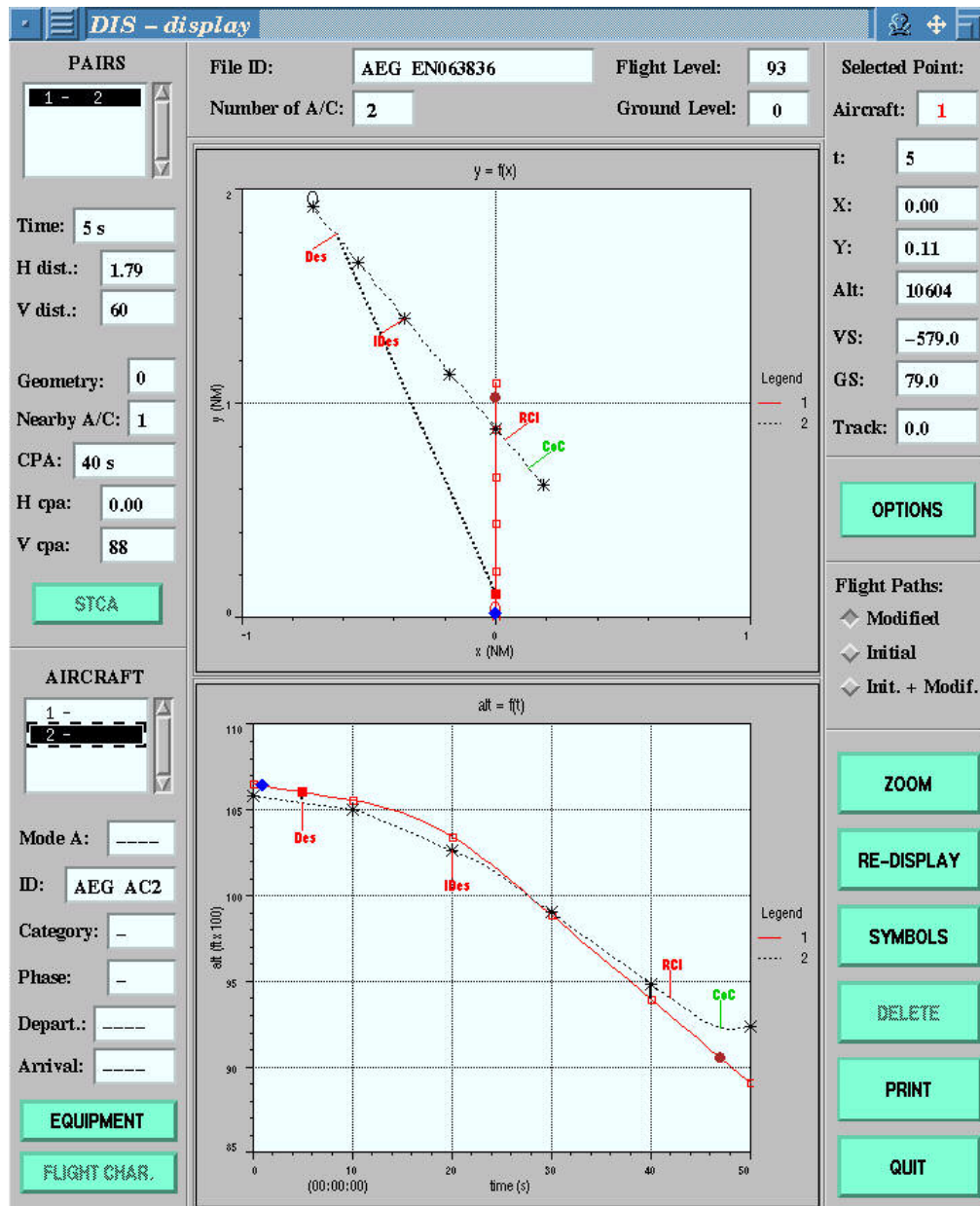


Figure 13: Issue SA01a - Encounter simulated with TCAS II version 7.0  
RAs onboard aircraft 2 (shown in black dotted line)

Sequence of RAs: Des: Descend RA, IDes: Increase Descent RA, RCI: Reversal Climb RA, CoC: Clear of Conflict

4.1.3.1.8. Both aircraft have reversal RAs. However, these RAs are triggered too late to be efficient (i.e., 2 s after CPA) because the vertical separation between the aircraft becomes higher than 100 ft only 2 s after CPA. The resulting vertical separation at CPA is lower than 100 ft. Reversal RAs triggered well before CPA would be beneficial.

4.1.3.1.9. The result of this encounter simulated with CP112E is shown on Figure 24.

#### **4.1.3.2. Areas of improvement**

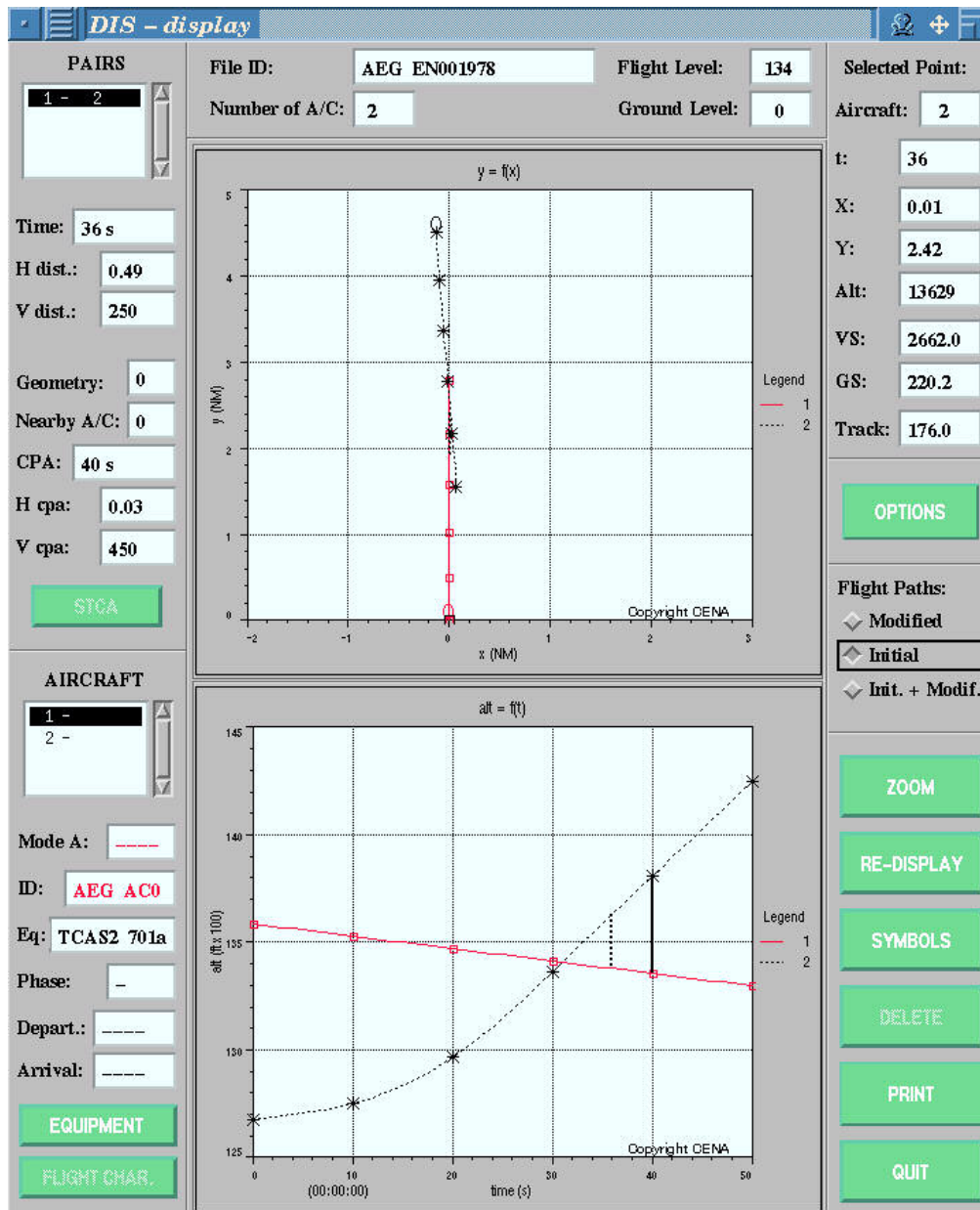
4.1.3.2.1. CP112 already addressed the 100 ft box issue by using rules, which are less restricting than in the reversal logic of TCAS II logic version 7.0 concerning the required vertical separation between the aircraft to trigger a reversal RA.

4.1.3.2.2. The goal of the work performed in task B was to make these rules even less restricting so as to have a better efficiency in solving issue SA01a, and in improving the processing of SA01b.

4.1.3.2.3. The possibility of triggering reversal crossing RA was envisaged, because the part of the reversal logic of TCAS II logic version 7.0 using the VMD parameter already permits such reversal RAs, but for unequipped intruders. What follows is an illustration of the behaviour of this part of the logic.

4.1.3.2.4. The following figure presents an example of the behaviour of TCAS II logic version 7.0, for a single equipage encounter.

4.1.3.2.5. The following figure presents the initial encounter, simulated without ACAS contribution.

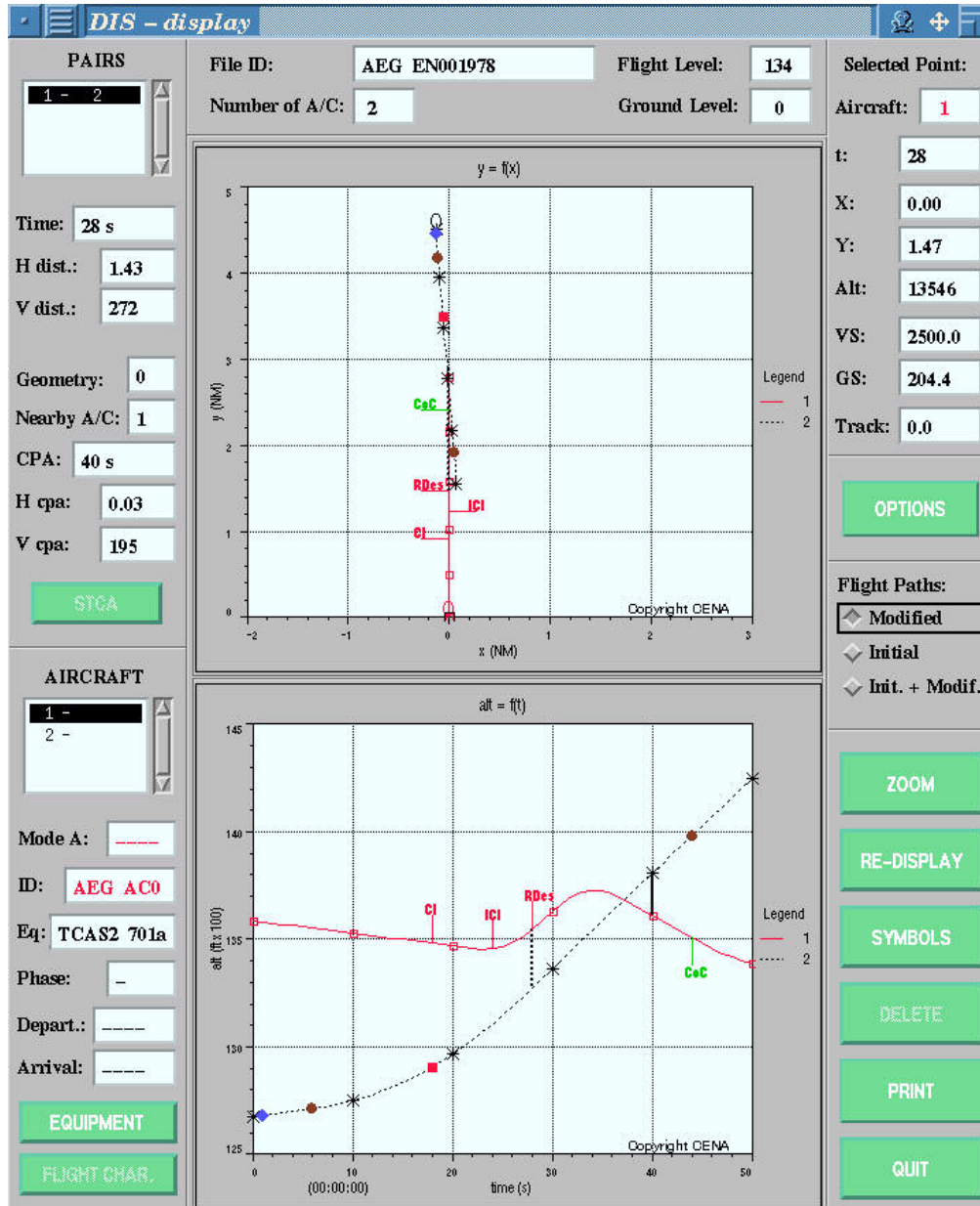


**Figure 14: VMD test of TCAS II logic version 7.0 – Encounter without TCAS contribution**

4.1.3.2.6. In this encounter, aircraft 1 is equipped with TCAS, whereas the intruder is not equipped with TCAS or in TA-only mode.

4.1.3.2.7. Aircraft 1 is level, and the intruder is crossing its flight level, at roughly 2500 fpm.

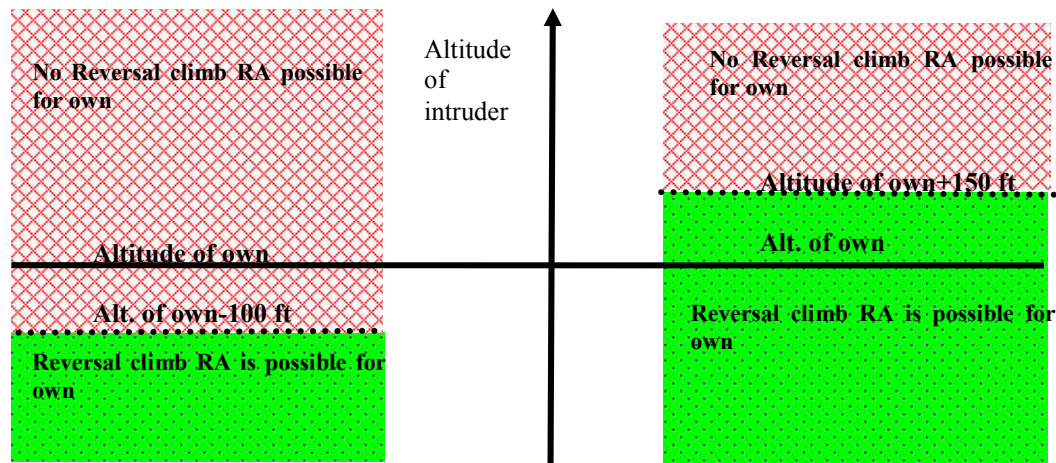
4.1.3.2.8. The following figure present the encounter with TCAS II logic version 7.0 simulated onboard aircraft 1.



**Figure 15: VMD test of TCAS II logic version 7.0  
Encounter simulated with TCAS II version 7.0  
RAs onboard aircraft 1 (Shown in full red line)**

**Sequence of RAs:** Cl: Climb RA, ICl: Increase climb RA, RDes: Reversal Descent RA, CoC: Clear of Conflict

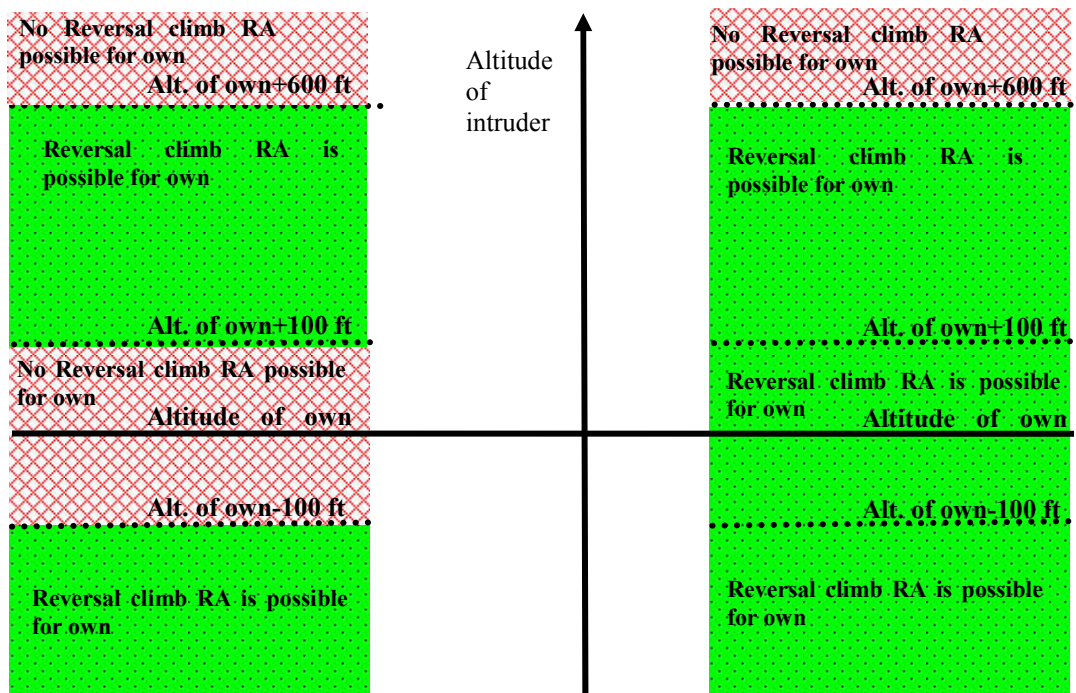
- 4.1.3.2.9. TCAS II logic version 7.0 triggers a climb RA, followed by an increase climb RA. Then a reversal descend RA is triggered, while the intruder is 272 ft below, because the reversal logic predicts that own aircraft will be only 89 ft above the intruder at CPA.
- 4.1.3.2.10. The reversal RA is a reversal “crossing” RA.
- 4.1.3.2.11. This example highlights the fact that a part of TCAS II logic version 7.0 already allows reversal “crossing” RAs.
- 4.1.3.2.12. Indeed TCAS II logic version 7.0 permits reversal “crossing” RAs in single equipage encounters, for aircraft vertically separated from 100 ft by up to 600 ft. In Task B, this maximum vertical separation to authorize reversal “crossing” RAs has been set much lower, because it was considered that reversal “crossing” RAs could be triggered, but only for situations in which the aircraft are already close to NMAC conditions in the vertical plane.
- 4.1.3.2.13. The following figures summarize the differences between version 7.0 and CP112E in that area.



Version 7.0

Version 7.0+CP112E

### Coordinated encounter



Version 7.0

Version 7.0+CP112E

### Non-Coordinated encounter

**Figure 16: Task B – Vertical separations rules for Issue SA01a and SA01b  
Example with own having a descend RA**

#### **4.1.4. Task C: Investigation of the SA01a design philosophy issue and solution proposal**

##### **4.1.4.1. Description of the issue**

- 4.1.4.1.1. The need to proceed with the modification of the reversal modelling was known and confirmed while working on some events corresponding to issue SA01a, for which it was impossible to trigger reversal RAs, even after Tasks A and B were performed.
- 4.1.4.1.2. The reversal logic includes a mechanism called reversal modelling. Before triggering any reversal RA, and after several geometrical tests are passed, the reversal logic goes through this mechanism in order to compute the predicted vertical separations at CPA with the ongoing RA and with the possible reversal RA.
- 4.1.4.1.3. A reversal RA can be triggered if the ongoing RA would not achieve ALIM and if the reversal RA would achieve a vertical separation at CPA higher than 0 ft in the correct sense (i.e., own has to be above the intruder if it has a climb sense RA, or below if it has a descend sense RA).
- 4.1.4.1.4. When computing the predicted vertical separation at CPA with the ongoing RA, the reversal modelling always assumes that own aircraft is following RAs and computes the predicted vertical separations at CPA with this assumption. This can lead to a perception of the situation in favour of the ongoing RA, when own is in fact not following the RAs.
- 4.1.4.1.5. As a result, some necessary reversal RAs are not triggered because of this overestimation of the efficacy of the ongoing RA.

##### **4.1.4.2. Areas of improvement**

- 4.1.4.2.1. The goal of the work performed in task C was to take into account in this modelling the fact that the pilot of own aircraft might not be following the RAs and might be going opposite instead.
- 4.1.4.2.2. The first part of the work consisted in analysing encounters for which the modelling was responsible for the lack of reversal RAs. It enabled to find the parts of this modelling, which had to be addressed.
- 4.1.4.2.3. The method applied consisted in modifying the modelling process, so as to make different computations in case own is detected as not following RAs and going opposite to them.
- 4.1.4.2.4. In case own is not following RAs and is going opposite to them, own is now modelled as maintaining its current vertical rate (i.e., projected linearly with its current vertical rate) rather than following RAs when modelling the benefits of the ongoing RA. The decision to reverse is then taken in case the ongoing RA is modelled as leading to an NMAC.
- 4.1.4.2.5. Otherwise, the algorithm is not changed.

4.1.4.2.6. Manoeuvres opposite to RAs are detected for positive RAs and for don't climb/don't descend RAs. This detection is not made for VSL RAs (i.e., VSL 500, 1000 and 2000), because with such RAs, an aircraft can be descending at 2000 fpm with a climb sense RA. Indeed, it is difficult to find a correct operational criterion to detect a manoeuvre opposite to the RA in this case.

#### **4.1.5. Task D: Investigation for SA01c rectification improvement and solution proposal**

##### **4.1.5.1. Description of the issue**

4.1.5.1.1. Issue SA01c deals with coordinated encounters during which the following criteria are met:

- Both pilots follow their RAs, in a crossing situation;
- The relative altitude rate is high;
- The reversal RAs are generated late, which mean 10 seconds or less before CPA.

4.1.5.1.2. In the SA01c geometry an NMAC occurs, despite the fact that pilots comply with their RAs perfectly.

4.1.5.1.3. The following figures present a theoretical example of such an encounter. Figure 17 shows the encounter without TCAS contribution. Figure 18 and Figure 19 show the encounter with TCAS II logic version 7.0 simulated onboard both aircraft. The pilots of both aircraft follow their RAs.



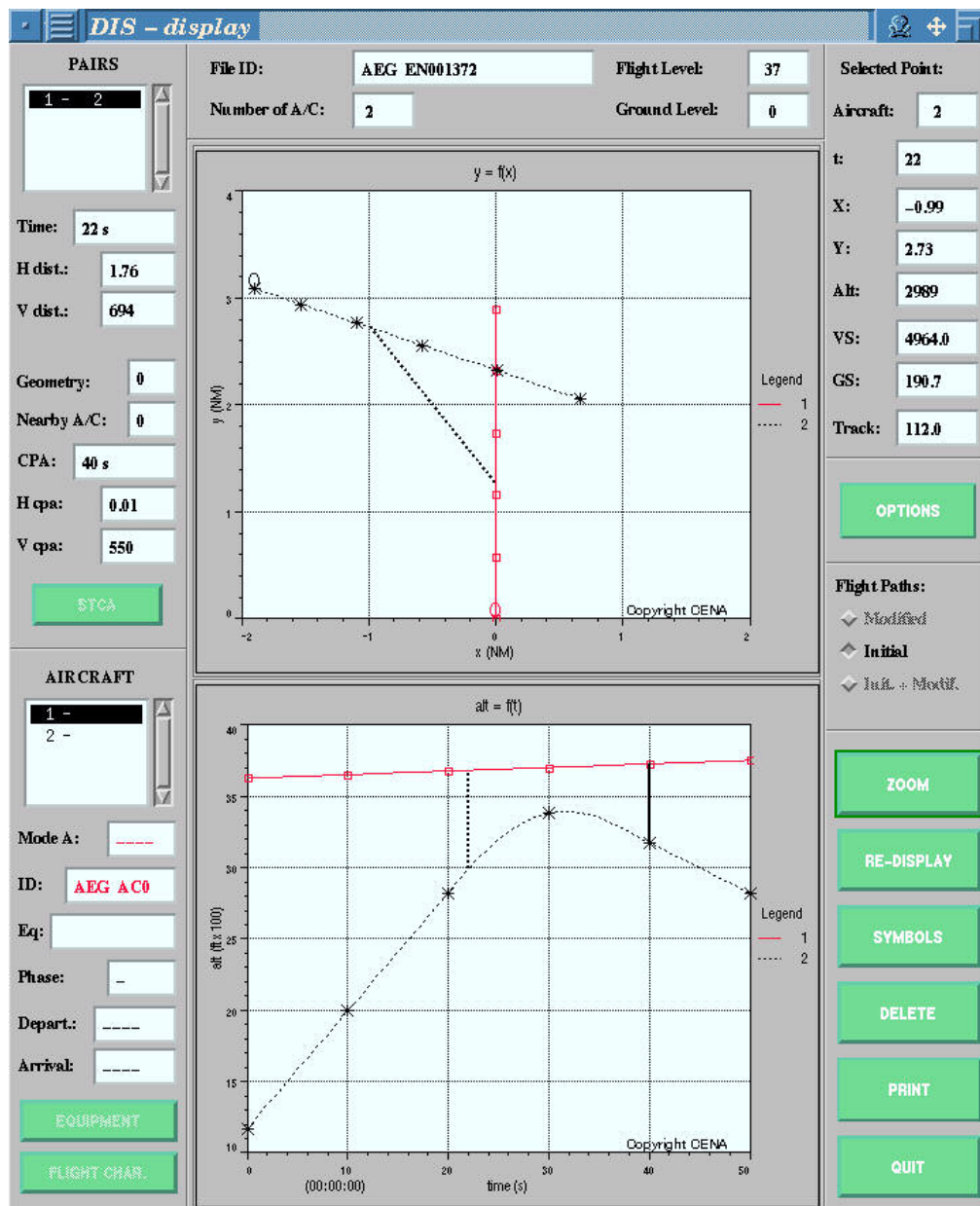
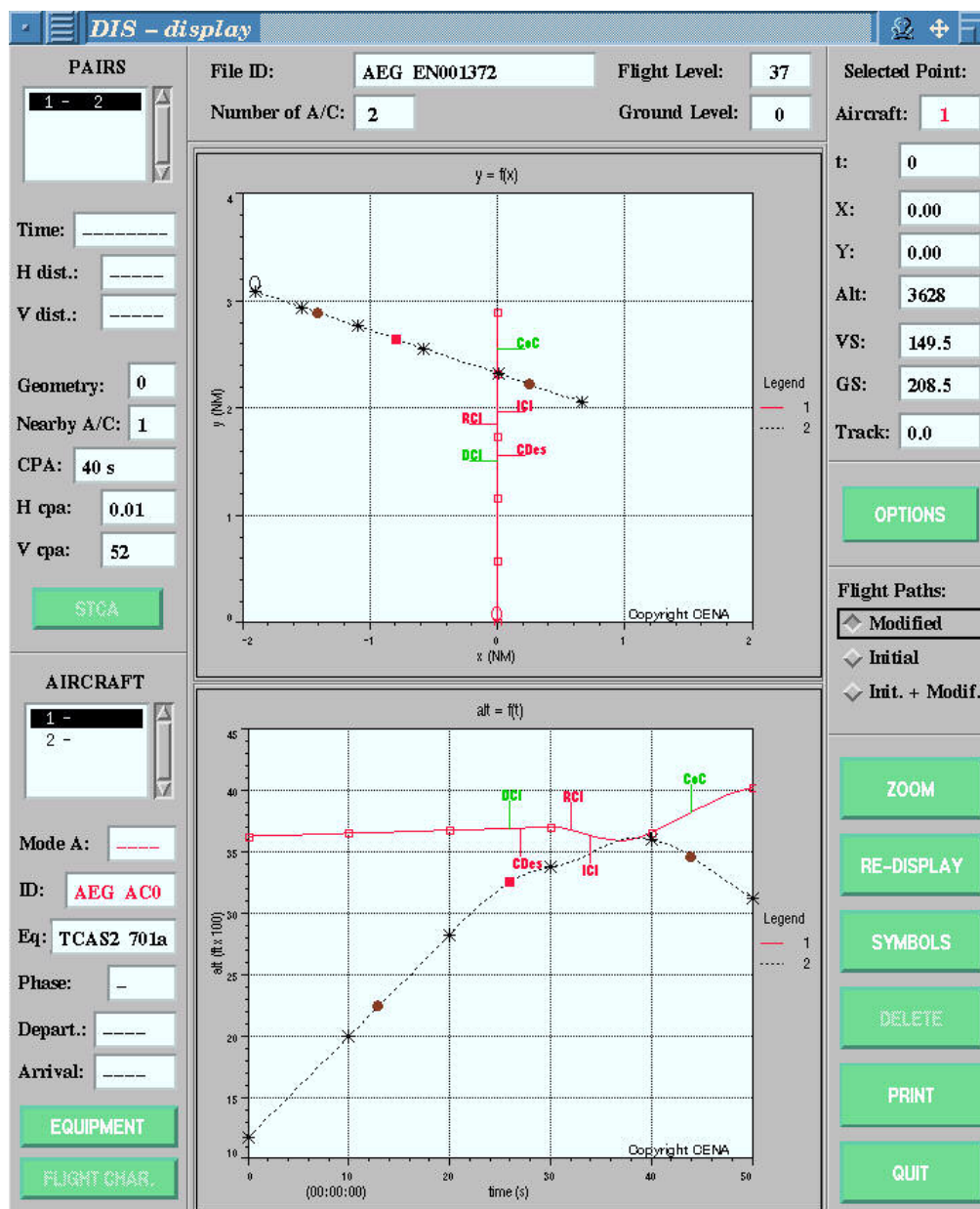


Figure 17: Issue SA01c - Encounter without TCAS contribution

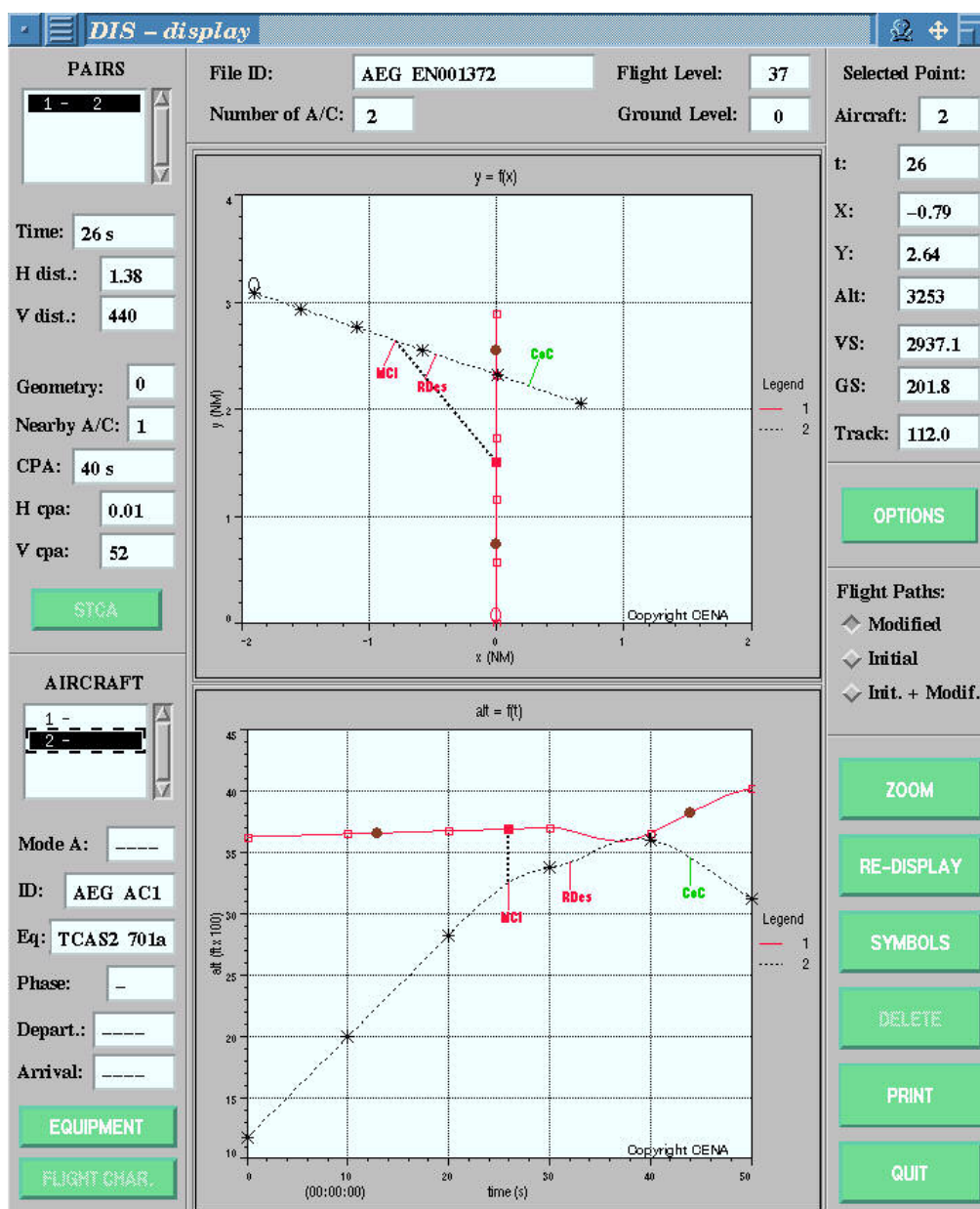
4.1.5.1.4. This encounter is an altitude bust. Aircraft 2 is climbing with a very high vertical rate towards a level aircraft due to an error from the crew or from ATC. The crew suddenly detects the intruder a few hundreds of feet above. As a result it performs a rapid vertical manoeuvre and starts a descend.

4.1.5.1.5. The following figures show the encounter simulated with TCAS II logiversion 7.0.



**Figure 18: Issue SA01c - Encounter simulated with TCAS II version 7.0  
RAs onboard aircraft 1 (Shown in full red line)**

**Sequence of RAs:** DCI: Don't Climb RA, CDes: Crossing Descent RA, RCI: Reversal Climb RA  
ICI: Increase Climb RA, CoC: Clear of Conflict



**Figure 19: Issue SA01c - Encounter simulated with TCAS II version 7.0  
RAs onboard aircraft 2 (Shown in black dotted line)**

Sequence of RAs: MCl: Maintain Climb RA, RDes: Reversal Descent RA  
CoC: Clear of Conflict

4.1.5.1.6. In the encounter shown on Figure 18 and Figure 19, aircraft 1 has a crossing descent RA, and aircraft 2 has a maintain climb RA, which requires him to climb at around 3000 fpm. However, at the time this RA is triggered, aircraft 2 is levelling-off. The vertical rate decreases to around 1500 fpm and a reversal descent RA is triggered. Unfortunately, this reversal RA is triggered while aircraft 2 is beginning to accelerate upwards to comply with the maintain climb RA. This situation results in an NMAC.

4.1.5.1.7. The vertical separation at CPA is less than 100 ft, despite the fact the both pilots comply correctly with their RAs.

4.1.5.1.8. Without any reversal RA, the vertical separation at CPA is over 400 ft.

4.1.5.1.9. It is clear that **reversing in that kind of encounter should be avoided**.

4.1.5.1.10. CP112 already included a part addressing this issue. The need to improve CP112 appeared while observing that it could cancel the triggering of some useful reversal RAs [FAA1 & EMO2].

#### **4.1.5.2. Areas of improvement**

4.1.5.2.1. The goal of the work performed in task D was to improve the features of CP112 to solve SA01c, by using additional parameters permitting a better discrimination between the encounters during which reversal RAs can be triggered and between those during which they must not.

4.1.5.2.2. The start of the work was the observation that in SA01c encounters, the reversal RAs are triggered too close in time to the initial RA and too close in time to CPA.

4.1.5.2.3. On the basis of this observation, a CAS logic modification was developed, and tested on some examples.

4.1.5.2.4. Then, the work was refined by using roughly 60 theoretical encounters, including SA01c encounters and encounters during which reversal RAs should not be cancelled, and by going deeply in the code of the modified CAS logic for each of these encounters cycle by cycle, to find the correct settings and parameters to use.

4.1.5.2.5. As a result of this work, CP112E detects the SA01c geometry and prevents TCAS II logic version 7.0 to trigger a reversal RA when it is likely to be hazardous. In case the reversal RA would be triggered before the crew had time to comply with the initial RA, and would be triggered too late to be efficient, CP112E prevents its triggering.

## **4.2. Description of CP112E**

### **4.2.1. Basic principle of CP112E**

#### **4.2.1.1. General**

4.2.1.1.1. One basic principle of CP112E is to avoid the triggering of reversal RAs while the aircraft did not have time to comply with the initial RAs.

4.2.1.1.2. This choice was made to avoid the triggering of reversal RAs very early in the encounter, because such reversal RAs can be surprising for the crew and because early reversal RAs would be triggered while the crew are manoeuvring to comply with the initial RAs.

4.2.1.1.3. For similar reasons, care is taken for the triggering of reversal RAs just after an increase RA.

#### **4.2.1.2. Addressing issues SA01a and SA01b**

4.2.1.2.1. CP112E aims at detecting that the ongoing encounter is corresponding to the SA01a or SA01b geometry (i.e., two aircraft vertically close, climbing and descending towards the same point), and then possibly triggers a reversal RA if required. The detection that a reversal RA can improve the situation is made using two means, each of them being dedicated to a situation related to the way the pilot complies with the RAs:

- By detecting that the Vertical Miss distance at CPA will likely be low. This parameter is used to circumvent the mode S priority rule, which prevents the triggering of reversal RAs after the detection that own is going opposite to RAs, when own is the slave aircraft. It is also used to fully address issue SA01b. Indeed, the goal of this test is to trigger reversal RAs when the master aircraft is the one, which is following RAs.
- By detecting that own is not following its RAs and is manoeuvring opposite to them for coordinated encounters only. In this case, the reversal modelling performed in the reversal logic takes into account the fact that own is not following RAs. This permits to trigger reversal RAs when the master aircraft is the one, which is not following RAs.

4.2.1.2.2. CP112E first tries to use the VMD criterion. Then, in case this criterion did not detect the need to reverse and in case of a double equipage encounter the CAS logic goes through the part, which tries to detect the lack of response of the pilots.

4.2.1.2.3. The conditions to reverse in case the SA01a or SA01b geometry is detected are weakened when compared with TCAS II logic version 7.0. Indeed, reversal RAs triggered when aircraft are vertically separated by less than 100 ft are now permitted, whereas they are not with TCAS II logic version 7.0.

#### **4.2.1.3. Addressing issue SA01c**

- 4.2.1.3.1. CP112E also detects the SA01c geometry and prevents TCAS II logic version 7.0 to trigger a reversal RA when it is likely to be hazardous. In case the reversal RA would be triggered before the crew had time to comply with the initial RA, and would be triggered too late to be efficient, CP112E prevents its triggering.

#### **4.2.2. Detailed behaviour of CP112E**

##### **4.2.2.1. Introduction**

- 4.2.2.1.1. This part presents the main features of CP112E. More details are available in Appendix E, with the main tasks of CP112E commented.

##### **4.2.2.2. Treatment of issues SA01a and SA01b**

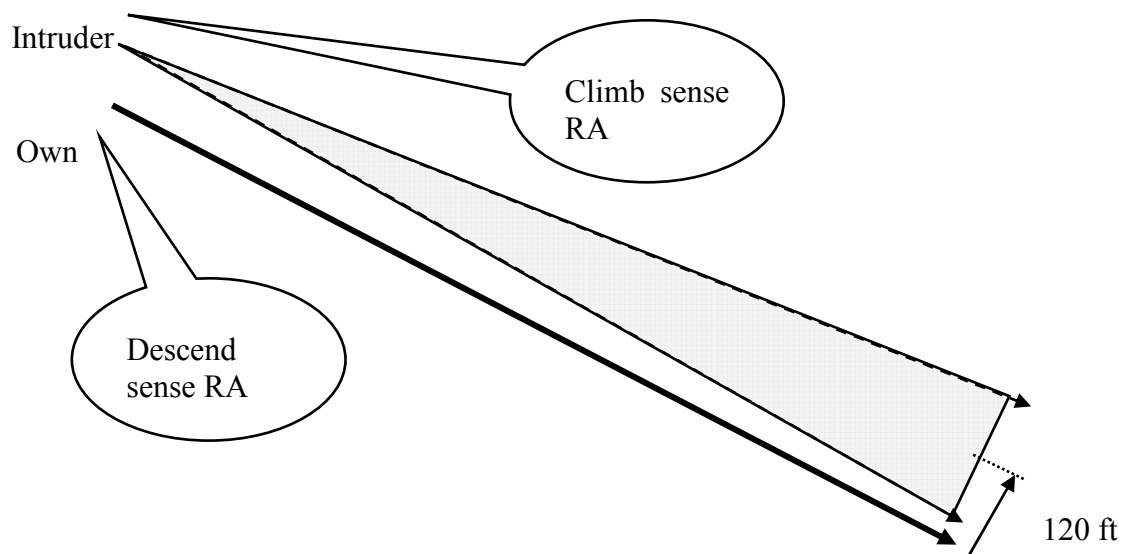
- 4.2.2.2.1. The process RA\_MONITORING is called within the process REVERSAL\_CHECK.
- 4.2.2.2.2. It is called only if at least 4 seconds remain before CPA, because a reversal RA triggered in the last 4 seconds is useless, and only if at least 10 seconds have elapsed since the initial RA, because a reversal RA triggered too early does not give enough time to the crew to comply to the initial RA.

##### **VMD test**

- 4.2.2.2.3. The VMD condition is used to determine if the ongoing situation is likely to lead to an NMAC, especially when own aircraft is the one following RAs in the SA01a case, but also in the SA01b case. In fact, the VMD is compared to a threshold somewhat higher than 100 ft (i.e., 120 ft), because due to uncertainties on the tracked altitudes and vertical rates, the calculated VMD at CPA can remain greater than 100 ft whereas the aircraft are going to be vertically separated by less than 100 ft at CPA.
- 4.2.2.2.4. In addition, the VMD is not computed only using the tracked vertical rate of the intruder, but also the inner and outer rate bounds, which take into account uncertainties on the tracked vertical rate of the intruder. Therefore, the VMD conditions takes into account the fact that the intruder will likely be in an altitude interval at CPA rather than at a given predicted altitude. The VMD condition is passed when the most pessimistic scenario shows that the intruder will likely be too close at CPA (e.g., for own having a descent RA, the intruder will be declared too close at CPA if it is less than 120 ft above at CPA, when using the value of the intruder's tracked vertical rate giving the most pessimistic result in terms of vertical separation at CPA).
- 4.2.2.2.5. Other conditions need to be passed to ensure that the geometry is a SA01a or SA01b geometry. The aircraft have to be vertically separated by less than 600 ft and own and intruder must have tracked vertical rates greater than 1000 fpm or greater than -1000 fpm. In addition, the vertical rates of own and intruder have to be in the same sense. These conditions were chosen so as to be consistent with a part of the

reversal logic which already uses such conditions, in the process CROSS\_THROUGH\_CHECK.

- 4.2.2.2.6. The following figure illustrates these conditions with an example in which own has a descend sense RA, and the intruder a climb sense RA. The predicted trajectory of own is shown with a full bold line. The boundaries of intruder's predicted trajectory are shown with a dotted line. The grey zone represents the zone in which intruder will likely be until CPA, taking into account the uncertainties on its tracked vertical rate.



**Figure 20: Illustration of the VMD test**

- 4.2.2.2.7. This example shows that in the worst case, the intruder will be less than 120 ft above own aircraft at CPA. Therefore, there is a possibility that the encounter will end in an NMAC if the vertical rates remain unchanged and taking into account the uncertainties on the tracked vertical rate of the intruder. Therefore, reversing can be envisaged depending on the vertical separation between the aircraft.
- 4.2.2.2.8. Another condition is related to the time elapsed since the initial RA. Indeed, the time required by own to comply with the vertical rate required by the initial RA, and bounded between 10 s and 15 s is used to determine that enough time has elapsed since the initial RA. If not enough time has elapsed, then the reversal RA will not be triggered. The time required by own to comply with the vertical rate required by the initial RA is bounded downwards by 10 s, so as to avoid early reversal RAs, and upwards by 15 s so as not to trigger the reversal RAs too late even in case of very important vertical rates.

- 4.2.2.2.9. Indeed, one basic principle of CP112E is to avoid the triggering of reversal RAs while the aircraft did not have time to comply with the initial RAs.
- 4.2.2.2.10. Other conditions are related to the vertical separation between the aircraft. If sufficient time remains before CPA (i.e., there is enough time to comply with a reversal RA before CPA with a margin of a few seconds, and at least 10 s remain), reversal RAs which will lead to a crossing of altitude are permitted. Such reversal RAs are not permitted in case CPA is already too close in time, or in case of a slow convergence in the horizontal plane, because in this case, the computation of the time to CPA might not be accurate enough.
- 4.2.2.2.11. Care is taken for the triggering of reversal RAs just after an increase RA, and some restrictions are applied. No reversal RAs is triggered the cycle after an increase RA, to avoid stressing the crew with the triggering of a reversal RA while the aural announcement of a preceding increase RA has just finished or has not finished yet. If the aircraft are already close in time to CPA, a reversal RA will not be triggered in the 5 s following an increase RA. In addition, in the 5 seconds following an increase RA, the maximum vertical separation between the aircraft to trigger reversal crossing RAs is reduced. The reason for these choices is to avoid the triggering of reversal RAs, or to make the triggering more difficult, in a phase during which the aircraft might be accelerating vertically to comply with an increase RA.
- 4.2.2.2.12. The above conditions have to be passed several times for a reversal RA to be declared as a possible solution, so as to avoid the triggering of reversal RAs because of a VMD being low only one cycle. It was chosen to have this test passed at least 2 times in the last 3 cycles for a reversal RA to be a possible solution, in order to be consistent with a part of the reversal logic which already uses such a condition.
- 4.2.2.2.13. When the conditions are passed, a model of the ongoing RA and of the possible reversal RA is performed in the reversal modelling, to determine if the reversal RA will bring benefits to the current situation. For a reversal RA to be possible, the ongoing RA has to achieve less than ALIM at CPA and the reversal RA has to achieve a positive vertical separation at CPA.
- 4.2.2.2.14. The following example illustrates the results obtained using the VMD test. The following encounter is a SA01b encounter, however it is important to notice that this encounter simulated with both aircraft equipped results in the same behaviours and in the same vertical separations, whatever the order of the mode S addresses.



4.2.2.2.15. Figure 21 shows the encounter without TCAS contribution. Aircraft 2 is equipped with TCAS II logi version 7.0, whereas aircraft 1 is unequipped or equipped but in TA-only mode

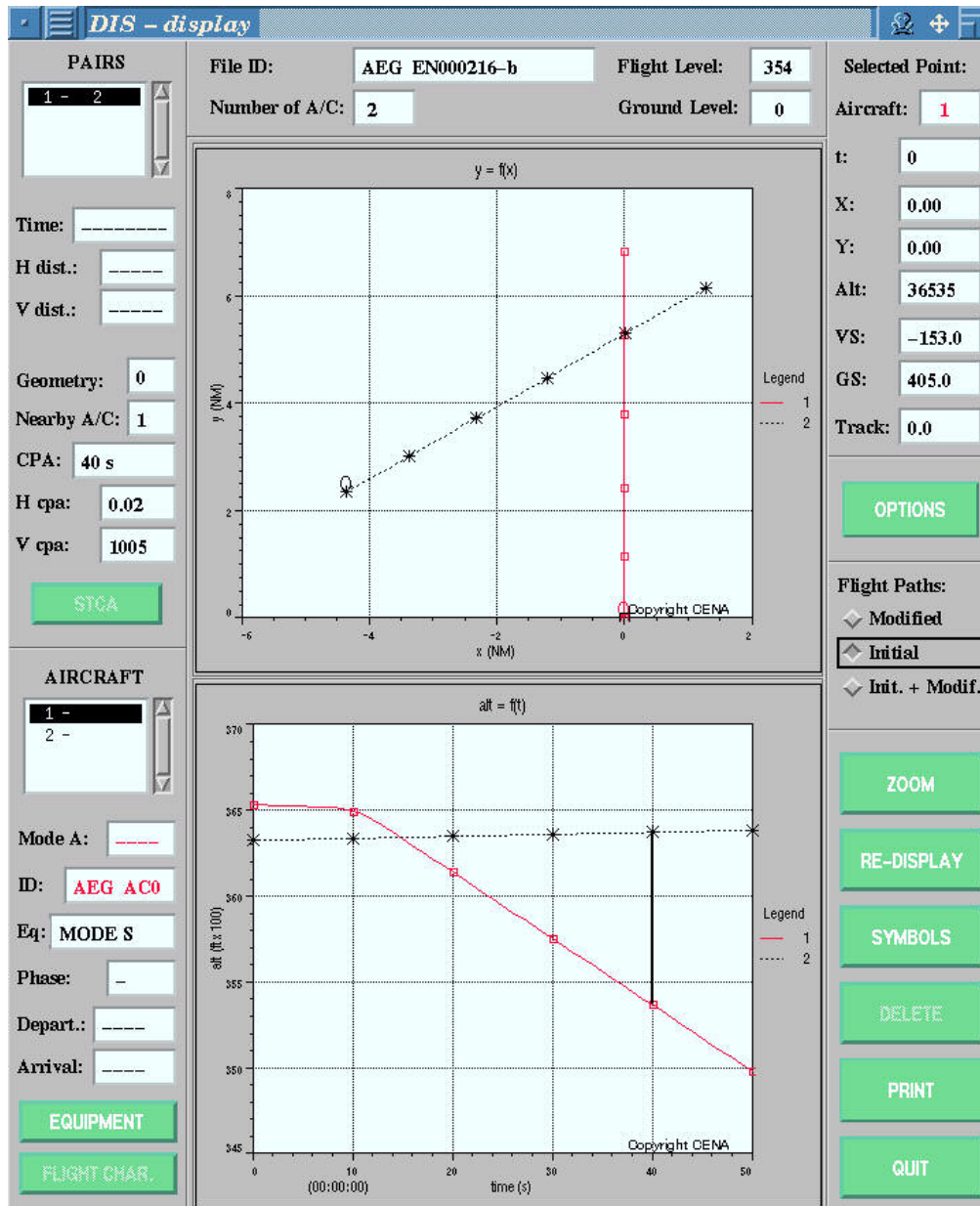
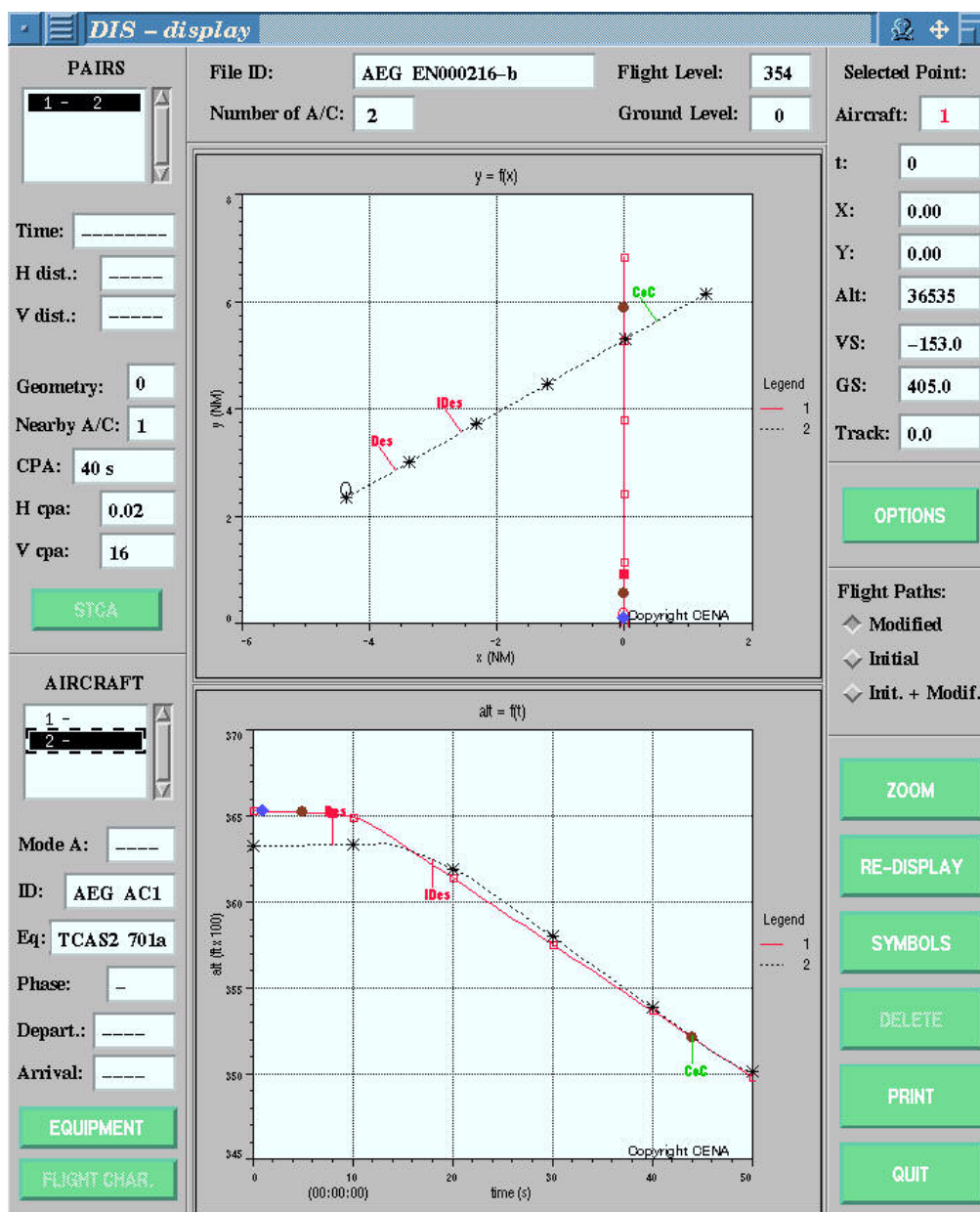


Figure 21: Issue SA01b - Encounter without TCAS contribution

4.2.2.2.16. Aircraft 2 is level at FL363, whereas aircraft 1 is descending from FL365.

4.2.2.2.17. Figure 22 shows the encounter simulated with TCAS II logic version 7.0 onboard aircraft 2.

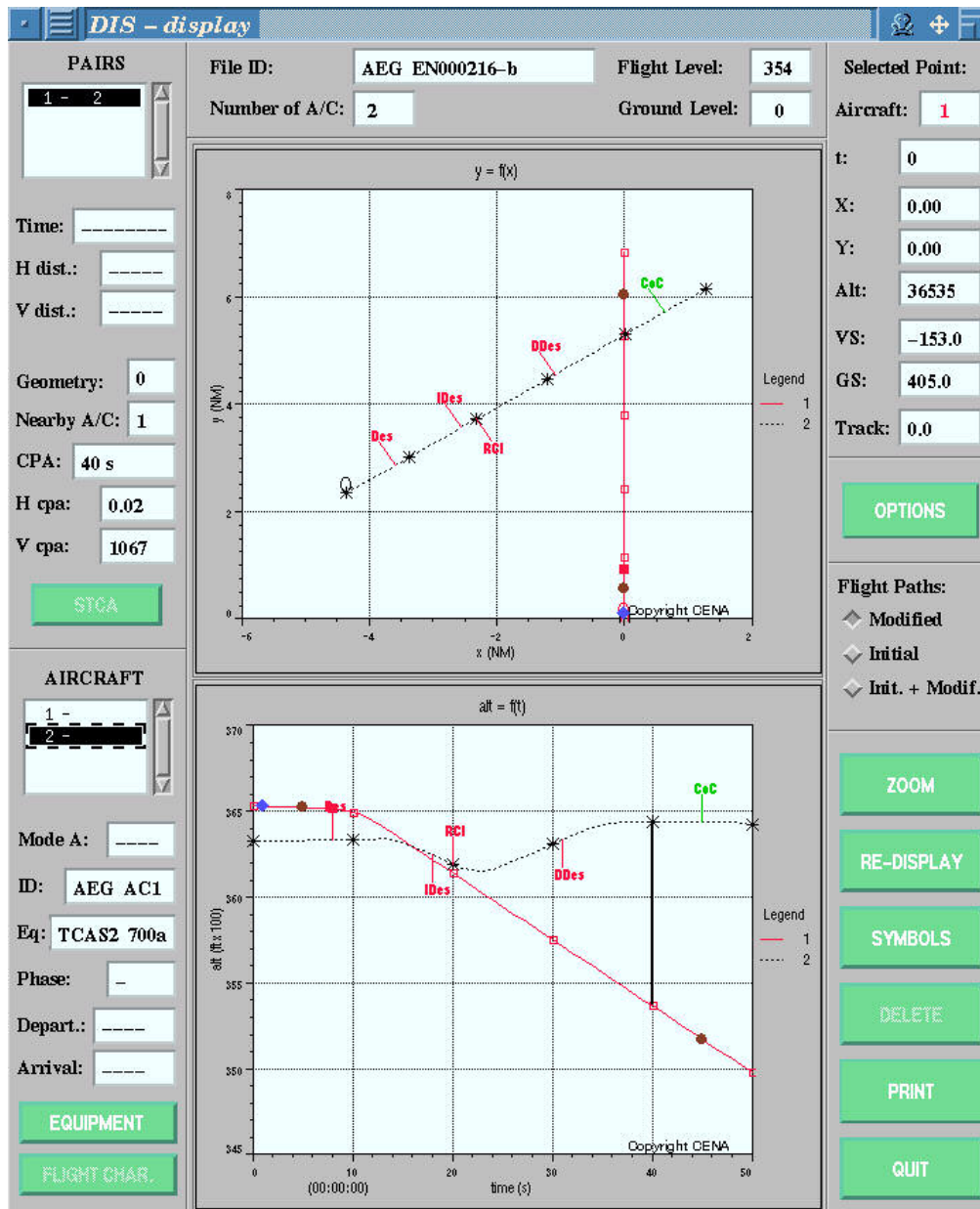


**Figure 22: Issue SA01b – Encounter simulated with TCAS II logic version 7.0  
RAs onboard aircraft 2 (shown in back dotted line)**

**Sequence of RAs:** Des: Descend RA, Ides: Increase descend RA, CoC: Clear of Conflict

4.2.2.2.18. Aircraft 2 receives a descend RA, and then an increase descend RA. No reversal RA is triggered because the aircraft remain vertically separated by less than 100 ft, and there is an NMAC.

4.2.2.2.19. Figure 23 shows the encounter simulated with CP112E.



**Figure 23: Issue SA01b – Encounter simulated with TCAS II logic version 7.0+CP112E - RAs onboard aircraft 2 (shown in back dotted line)**

**Sequence of RAs:** Des: Descend RA, IDes: Increase descend RA, RCI: Reversal Climb RA, CoC: Clear of Conflict

4.2.2.2.20. With CP112E, a reversal climb RA is triggered 20 s before CPA and the vertical separation at CPA is over 1000 ft.

4.2.2.2.21. At the time the reversal RA is considered, the VMD computed by CP112E shows that the master aircraft is projected high above the intruder at CPA.

4.2.2.2.22. Indeed, the computed VMDs were equivalent the preceding cycle. The master aircraft has a descend RA, it is projected to be above the intruder at CPA 2 cycles in a row, therefore a reversal RA is envisaged.

4.2.2.2.23. Then the reversal RA is triggered because the possibility of reversing is validated by the reversal modelling, which computes that the ongoing RA will achieve a low vertical separation at CPA and that the reversal RA will achieve a sufficient vertical separation at CPA.

#### **Detection of own not following RAs and going opposite instead**

4.2.2.2.24. In case the VMD conditions were not passed, and in case of a double equipage encounter, CP112E tries to detect a manoeuvre opposite to the RAs onboard own aircraft. This test is used only when the part of CP112E based on the VMD has not computed that a reversal RA was necessary.

4.2.2.2.25. As for the VMD tests, the time elapsed since the initial RA is used, and no reversal RA is triggered if not enough time has elapsed since the initial RA.

4.2.2.2.26. The intruder has to be evolving in the same sense as own aircraft, with a vertical rate greater than +1000 fpm or greater than -1000 fpm.

4.2.2.2.27. A manoeuvre opposite to the RA onboard own aircraft is possibly detected, based on the vertical rate of own and on the sense of his RA. If own has for example a positive climb sense RA, and is descending at more than 1200 fpm, then it is declared as going opposite to the RAs. If own has for example a don't descend RA, and if it is descending at more than 1500 fpm, then it is also declared as going opposite to his RAs. The threshold used, 1500 fpm, is higher than in the case of positive RAs, because the required vertical rate to comply with a don't climb or don't descent RA is lower (i.e., 0 fpm) than in the case of a positive RA (i.e., 1500 fpm).

4.2.2.2.28. This detection is not made for VSL RAs (i.e., VSL 500, 1000 and 2000), because with such RAs, an aircraft can be descending at 2000 fpm with a climb sense RA. Indeed, it is difficult to find a correct operational criterion to detect a manoeuvre opposite to the RA in this case.

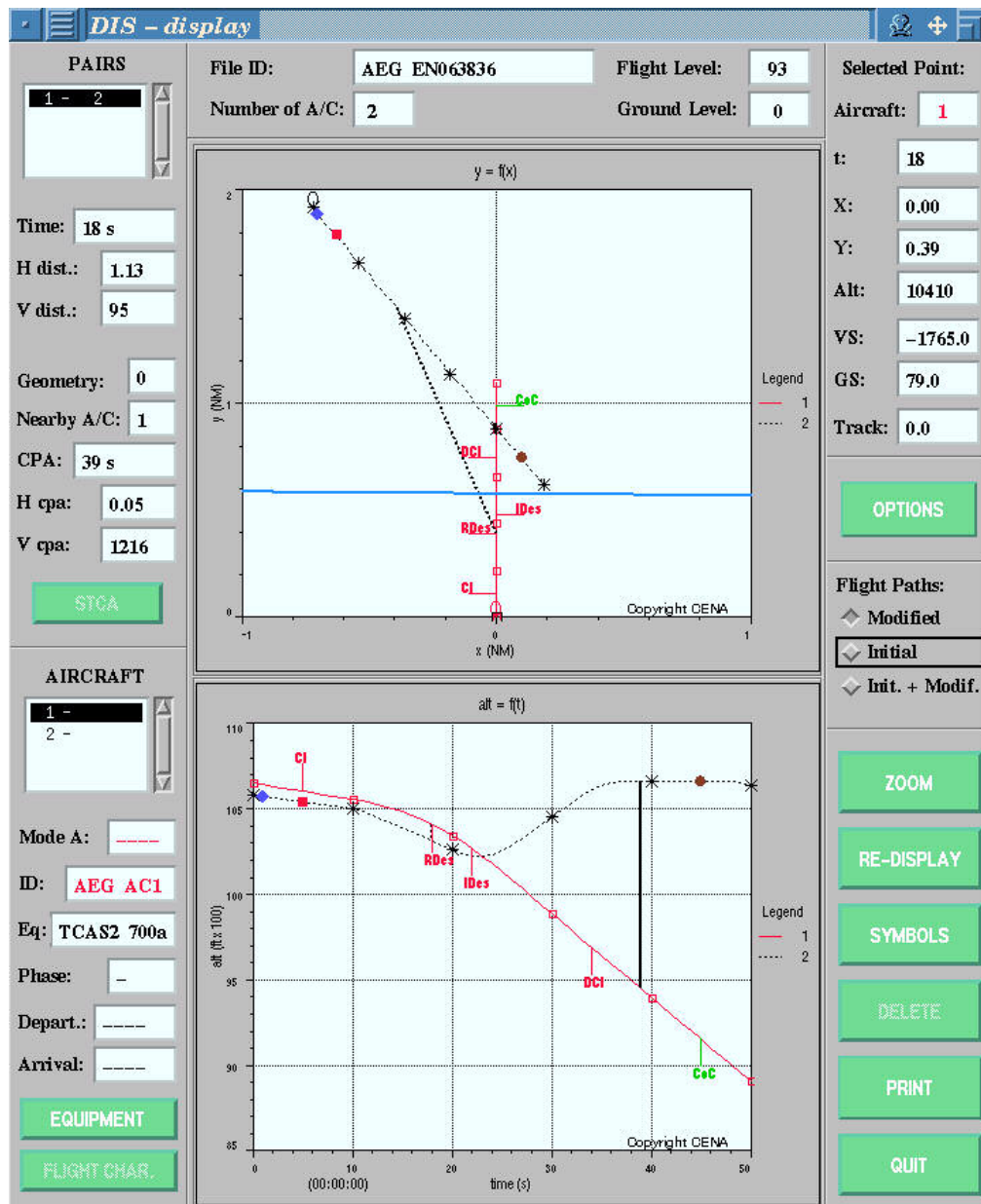
4.2.2.2.29. The conditions are similar in case of descend sense RAs.

4.2.2.2.30. The conditions on the vertical separation between the aircraft are identical to those used in the VMD test (see 4.2.2.2.10).

4.2.2.2.31. When this test is passed, a flag is set to false to indicate that own is not following RAs. This it is then taken into account in the reversal modelling process in which the reversal logic computes a prediction of the ongoing RA and of the possible reversal RA to decide to reverse or not, and own is modelled as not following his RAs.

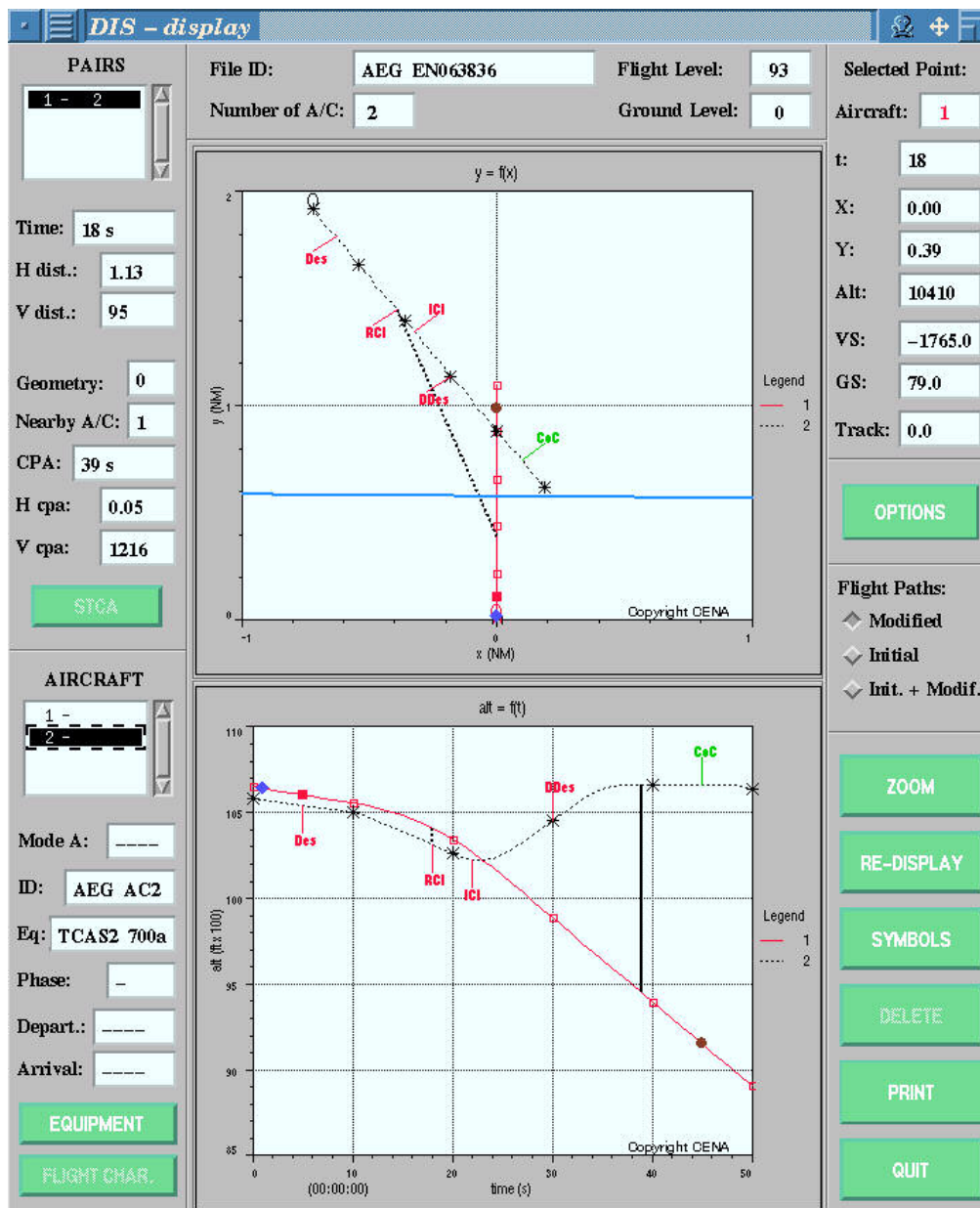
- 4.2.2.2.32. When own is not following his RAs and is going opposite instead, the prediction of the result of the ongoing RA is made assuming own is maintaining its vertical rate, instead of following RAs, and reversing is made possible if this prediction brings the aircraft within 120 ft at CPA. The prediction of the result of the reversal RA is not taken into account when deciding to reverse or not, because the benefit of the reversing manoeuvre results from the manoeuvre of the intruder, which is never modelled in the CAS logic. In addition, when own is not following RAs, the computations of the ongoing RA and of the possible reversal RA would give the same result, as both would model own and the intruder flying with a constant vertical rate equal to their tracked vertical rates.
- 4.2.2.2.33. Contrary to the VMD test, the test of own not following RAs does not need to be passed several times for the reversal RAs to be triggered. Indeed, passing the tests twice for a reversal RA to be triggered when using the VMD was only chosen to avoid the triggering of reversal RAs because of an inaccurate prediction in the VMD only one cycle or because of a transitioning situation during which the VMD becomes suddenly low.

4.2.2.2.34. The following example illustrates the results obtained using this test. This is the same encounter as shown on Figure 11, Figure 12 and Figure 13 but simulated with CP112E onboard the aircraft.



**Figure 24: Issue SA01a - Encounter simulated with TCAS II version 7.0 +CP112E - RAs onboard aircraft 1 (Shown in full red line)**

**Sequence of RAs:** Cl: Climb RA, RDes: Reversal descend RA, Ides: Increase descend RA, DCI: Don't Climb RA, CoC: Clear of Conflict



**Figure 25: Issue SA01a - Encounter simulated with TCAS II version 7.0+CP112E - RAs onboard aircraft 2 (shown in black dotted line)**

**Sequence of RAs:** Des: Descend RA, RCI: Reversal climb RA, ICI: Increase climb RA, DDes: Don't descend Ra, CoC: Clear of Conflict

4.2.2.2.35. With TCAS II logic version 7.0, this encounter ended in NMAC with reversal RAs triggered after CPA. With CP112E, reversal RAs are triggered 22 s before CPA, resulting in a vertical separation at CPA over 1200 ft, thanks to the detection of own aircraft (i.e., aircraft 1) not following its RAs and going opposite.



### **Quality of the tracking**

4.2.2.2.36. While developing CP112E, it was observed that for some encounters, the quality of the vertical tracking could result in some unnecessary reversal RAs being triggered. As a result, some restrictions are applied to the required vertical separation between the aircraft to allow reversal RAs, when the firmness of the tracking of the intruder is not excellent. This mainly results in CP112E being slightly less efficient with intruders reporting their altitude in 100ft quanta than with intruders reporting their altitude in 25 ft quanta, because the tracking with the 25 ft tracker is of better quality.

4.2.2.2.37. These restrictions mostly apply in the last 10 seconds before CPA, because it is in this time interval that the quality of the tracking is the most critical, as reversal RAs triggered less than 10 s to CPA can solve an encounter, but with less margin than reversal RAs triggered earlier. Therefore, the computations made to decide to reverse or not have to be accurate enough.

#### **4.2.2.3. Treatment of issue SA01c**

4.2.2.3.1. The process RA\_CNCL is called within the process REVERSAL\_PROJ\_CHECK and prevents the triggering of reversal RAs in a crossing situation, when:

- Not enough time has elapsed since the initial RA for the pilot to comply with the initial RA. This condition is important to avoid reversal RAs being triggered while the aircraft can still be in a phase in which they are still manoeuvring, which can thwart the prediction made by the reversal logic on the necessity to reverse or not; and
- Not enough time remains until CPA for the reversal RAs to be efficient, or the aircraft are already separated vertically by less than ALIM in the 10 s before CPA. This latter condition offers a protection for aircraft already close vertically.

4.2.2.3.2. The basic principle is that when the aircraft are still accelerating vertically to comply with crossing RAs, and are already close in time to CPA or close vertically, it is preferable to go on with the initial RA, rather than attempting an hazardous reversing manoeuvre.

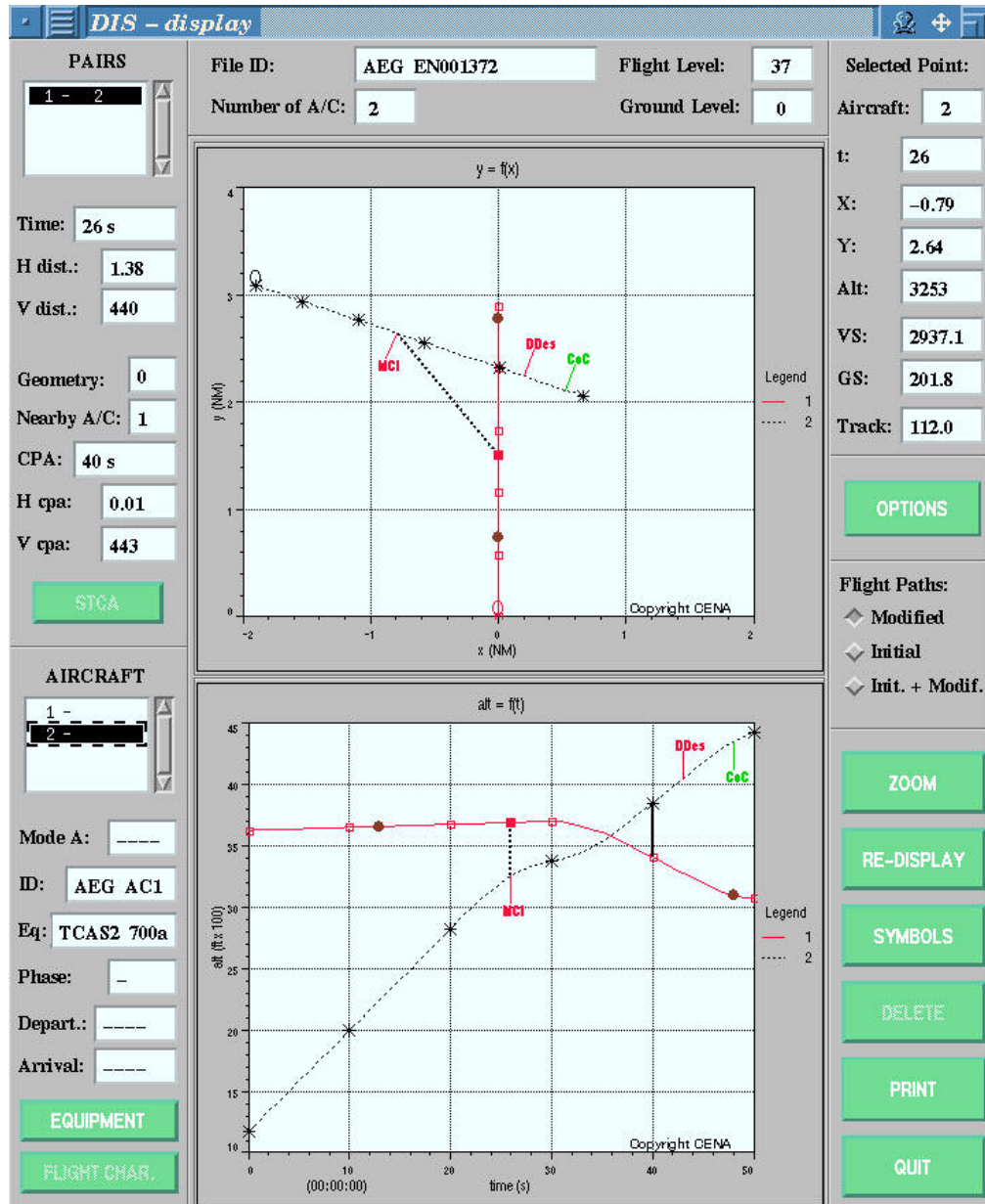
4.2.2.3.3. When only one of these conditions is met, a reversal RA is not cancelled:

- Indeed, a reversal RA triggered early, but with enough time before CPA is not considered potentially dangerous as the aircraft have time to manoeuvre;
- A reversal RA triggered close to CPA, but far in time to the initial RA is also not considered as dangerous, as after the time the initial RAs had time to be followed, the aircraft are considered in a linear phase (i.e., the vertical rates do not change rapidly), during which the prediction made by the reversal logic on the necessity of reversing is considered accurate enough for the reversal RAs to bring benefits (knowing that in the SA01c geometry and with version 7.0, reversal RAs are not triggered in the last 4 seconds before CPA).



4.2.2.3.4. Figure 18 and Figure 19 presented in section 4.1 provide an example of SA01c encounter.

4.2.2.3.5. The following figure shows the same encounter simulated with TCAS II logic version 7.0 and CP112E.



**Figure 26: Issue SA01c - Encounter simulated with TCAS II version 7.0 and without reversal RAs (using CP112E) - RAs onboard aircraft 1 (Shown in black dotted line)**

**Sequence of RAs:** MCI: Maintain Climb RA, CoC: Clear of Conflict

4.2.2.3.6. With CP112E, the vertical separation at CPA is over 400 ft.

4.2.2.3.7. In this example, the reversal RAs cancelled by CP112E are both too close to CPA (i.e., 8 s, whereas more time would be required to comply with reversal RAs) and too close to the initial RA (i.e., 6s, whereas more time should have elapsed). In addition, the aircraft are already separated vertically by less than ALIM and vertically converging.

## **5. Validation of CP112E**

### **5.1. *Overview of the validation activity***

#### **5.1.1. Safety validation on encounter models**

- 5.1.1.1. Two encounter models were used to validate CP112E, by computing a total of 48 risk ratios. The goal of this validation was to assess the performance of CP112E on safety when compared to TCAS II logic version 7.0 and CP112. The results of this validation are presented in section 5.2.

#### **5.1.2. Safety validation for class 8 of the US airspace model**

- 5.1.2.1. Comments had been made on CP112 concerning an encounter class of the US airspace model for which CP112 could induce some additional NMACs, even if overall benefits were observed. Part of the validation consisted in verifying that CP112E addresses this comment. The results of this validation are presented in section 5.3.

#### **5.1.3. Safety validation on actual encounters**

- 5.1.3.1. Simulations were also performed on several actual examples of encounters in which issue SA01 was detected. The goal of this validation was to check that CP112E brings benefits on these encounters. This validation is presented in section 5.4.

#### **5.1.4. Operational validation on actual encounters**

- 5.1.4.1. Simulations were made on an European database of roughly 400 actual encounters for double equipage encounters, and of over 1000 encounters for single equipage encounters. These encounters were extracted from radar data recording. The goal of this validation was to ensure that CP112E does not debase the operational performance of TCAS II logic version 7.0. This validation is presented in section 5.5.

## **5.2.     *Safety validation on encounter models***

### **5.2.1.   Scenarios simulated**

5.2.1.1.   For the validation of CP112E, the simulations were conducted using:

- The ICAO safety standard encounter model.
- The European ACAS Safety encounter model.

5.2.1.2.   Three cases of equipage were simulated:

- Two TCAS version 7.0 equipped aircraft, with:
  - Both pilots following the RAs;
  - One pilot not following the RAs, one pilot following the RAs.
- Only one TCAS V7 equipped aircraft with a pilot following the RAs.

5.2.1.3.   All the scenarios were simulated using both 25 ft altitude reports and 100 ft altitude reports.

5.2.1.4.   Interoperability simulations were also performed. They involve:

- One aircraft with version 7.0 and one aircraft with version 7.0 including CP112E. These simulations were performed on the scenarios involving 2 equipped aircraft;
- One aircraft with version 6.04a and one aircraft with version 7.0 including CP112E. These simulations were performed on the scenarios involving 2 equipped aircraft and the 100 ft tracker.

5.2.1.5.   Simulations were performed using standard pilot models.

5.2.1.6.   Simulations with slow and aggressive pilot models (as defined within the framework of the ACASA project [ACA1]) were also performed to check the robustness of the solution developed for standard reactions. These pilot models were simulated in only one aircraft of each encounter.

5.2.1.7. The following table presents the scenarios simulated for each encounter model.

Configuration		Pilots configuration	CAS logic simulated
100 ft tracker	Both aircraft follow their RAs	Standard vs. standard	V7+CP112E/V7+CP112E
			V7+CP112E/V7
			V7+CP112E/V604a
		Standard vs. slow	V7+CP112E/V7+CP112E
		Standard vs. aggressive	V7+CP112E/V7+CP112E
	One aircraft does not follow its RAs	Non-following vs. standard	V7+CP112E/V7+CP112E
			V7+CP112E/V7
			V7+CP112E/V604a
		Non following vs. slow	V7+CP112E/V7+CP112E
		Non following vs. aggressive	V7+CP112E/V7+CP112E
	The intruder is not equipped with TCAS	Standard vs. unequipped	V7+CP112E
		Slow vs. unequipped aircraft	V7+CP112E
		Aggressive vs. unequipped aircraft	V7+CP112E
25 ft tracker	Both aircraft follow their RAs	Standard vs. standard	V7+CP112E/V7+CP112E
			V7+CP112E/V7
		Standard vs. slow	V7+CP112E/V7+CP112E
		Standard vs. aggressive	V7+CP112E/V7+CP112E
	One aircraft does not follow its RAs	Non-following vs. standard	V7+CP112E/V7+CP112E
			V7+CP112E/V7
		Non following vs. slow	V7+CP112E/V7+CP112E
		Non following vs. aggressive	V7+CP112E/V7+CP112E
	The intruder is not equipped with TCAS	Standard vs. unequipped	V7+CP112E
		Slow vs. unequipped aircraft	V7+CP112E
		Aggressive vs. unequipped aircraft	V7+CP112E

**Table 6: Scenarios simulated for each encounter model for the safety validation**

- 5.2.1.8. The goal of the validation using slow and aggressive pilot models is not to demonstrate that CP112E brings significant benefits when one pilot is slow or aggressive. It is to check that CP112E does not debase safety even when the conditions are not nominal.

## 5.2.2. Validation on the ICAO Safety standard encounter model

### 5.2.2.1. Simulations with standard pilot models

5.2.2.1.1. The following table presents the logic risk ratios computed on the ICAO Safety standard encounter model with TCAS II logic version 7.0, with TCAS II logic version 7.0 including CP112, and with TCAS II logic version 7.0 including CP112E.

Configuration		Version 7.0	Version 7.0+ CP112	Version 7.0+ CP112E
100 ft tracker	Both aircraft follow their RAs	1.0%	1.0%	1.0%
	One aircraft does not follow its RAs	12.0%	10.8%	8.5%
	The intruder is not equipped with TCAS	12.4%	12.4%	11.8%
25 ft tracker	Both aircraft follow their RAs	1.1%	1.0%	1.0%
	One aircraft does not follow its RAs	11.0%	9.8%	7.0%
	The intruder is not equipped with TCAS	9.9%	9.9%	9.3%

**Table 7: ICAO safety standard encounter model - Risk ratios with standard pilots**

5.2.2.1.2. The risk ratios computed with CP112E are significantly reduced when compared with both version 7.0 and version 7.0 including CP112.

5.2.2.1.3. The improvements are especially significant for scenarios involving one pilot not following his RAs, thus illustrating the rectification of issue SA01a (e.g., with the 25 ft tracker with one pilot not following RAs, the risk ratio decreases from 11.0% to 7.0%, representing a relative decrease of 36%).

**5.2.2.1.4. The simulation results based on the ICAO safety standard encounter model show that CP112E brings significant improvements on safety and has no adverse effects on safety, as no additional induced NMACs were observed.**

### 5.2.2.2. Interoperability simulations

5.2.2.2.1. The following table presents the results of simulations performed with one aircraft fitted with version 7.0 and one aircraft fitted with version 7.0 including CP112E.

Configuration		Version 7.0/Version 7.0	Version 7.0/ Version 7.0+CP112E	Version 7.0 +CP112E/ Version 7.0 +CP112E
100 ft tracker	Both aircraft follow their RAs	1.0%	1.0%	1.0%
	One aircraft does not follow its RAs	12.0%	10.1%	8.5%
25 ft tracker	Both aircraft follow their RAs	1.1%	1.1%	1.0%
	One aircraft does not follow its RAs	11.0%	9.0%	7.0%

**Table 8: ICAO safety standard encounter model - Interoperability simulations  
V7/V7+CP112E**

5.2.2.2.2. Even with the interoperability simulations, the risk ratios are significantly decreased when compared with version 7.0.

5.2.2.2.3. As anticipated, the interoperability scenario results in intermediate risk ratios when compared to the Version 7.0/Version 7.0 and the CP112E/CP112E scenarios.

5.2.2.2.4. It is also interesting to notice that the risk ratios obtained with version 7.0 vs. version 7.0+CP112E are lower than those obtained with a full equipage of CP112 (see table 7). This highlights once again the significant improvements brought by CP112E.



5.2.2.2.5. The following table presents the results of simulations performed with one aircraft fitted with version 6.04a and one aircraft fitted with version 7.0 including CP112E.

Configuration		Version 6.04a/ Version 7.0	Version 6.04a/ Version 7.0 +CP112E
100 ft tracker	Both aircraft follow their RAs	1.3%	1.3%
	One aircraft does not follow its RAs	13.6%	12.0%

**Table 9: ICAO safety standard encounter model - Interoperability simulations  
V604a/V7+CP112E**

5.2.2.2.6. In interoperability simulations involving version 6.04a aircraft, and as anticipated, CP112E brings improvements when compared with version 7.0, and does not debase safety.

5.2.2.2.7. The interoperability simulation results based on the ICAO safety standard encounter model show that CP112E brings some improvements and performs well against TCAS II logic version 7.0 and version 6.04a aircraft.

### 5.2.2.3. Simulations with slow and aggressive pilots

5.2.2.3.1. Simulations were performed with slow and aggressive pilot models [ACA1] instead of standard pilot models.

5.2.2.3.2. The following table presents the results of the simulations performed with slow pilot models.

Configuration		Version 7.0	Version 7.0+ CP112E
100 ft tracker	Both aircraft follow their RAs	3.3%	3.3%
	One aircraft does not follow its RAs	40.4%	39.2%
	The intruder is not equipped with TCAS	48.4%	48.4%
25 ft tracker	Both aircraft follow their RAs	3.1%	2.8%
	One aircraft does not follow its RAs	38.4%	37.2%
	The intruder is not equipped with TCAS	44.8%	44.8%

**Table 10: ICAO safety standard encounter model - Risk ratios with slow pilots**

5.2.2.3.3. Improvements are brought by CP112E and especially for scenarios with one pilot not following RAs. This illustrates that even in the case of non nominal pilot responses, CP112E brings improvements to safety.

5.2.2.3.4. In addition, with a slow pilot model CP112E never debases safety.

5.2.2.3.5. The following table presents the results of the simulations performed with aggressive pilot models.

Configuration		Version 7.0	Version 7.0+ CP112E
100 ft tracker	Both aircraft follow their RAs	1.2%	1.2%
	One aircraft does not follow its RAs	6.9%	5.6%
	The intruder is not equipped with TCAS	10.2%	10.2%
25 ft tracker	Both aircraft follow their RAs	1.0%	1.0%
	One aircraft does not follow its RAs	6.8%	5.0%
	The intruder is not equipped with TCAS	8.8%	8.8%

**Table 11: ICAO safety standard encounter model - Risk ratios with aggressive pilots**

5.2.2.3.6. With an aggressive pilot model CP112E improves the results for the scenarios involving one pilot not following RAs and does not debase safety.

5.2.2.3.7. **The simulation results based on the ICAO safety standard encounter model show that CP112E brings some improvements and has a good robustness for non nominal responses.**

### 5.2.3. Validation on the European ACAS Safety encounter model

#### 5.2.3.1. Simulations with standard pilot models

5.2.3.1.1. The following table presents the logic risk ratios computed on the European ACAS Safety encounter model with TCAS II logic version 7.0, with TCAS II logic version 7.0 including CP112, and with TCAS II logic version 7.0 including CP112E.

Configuration		Version 7.0	Version 7.0+CP112	Version 7.0+CP112E
100 ft tracker	Both aircraft follow their RAs	2.7%	2.7%	2.7%
	One aircraft does not follow its RAs	21.0%	20.7%	19.9%
	The intruder is not equipped with TCAS	16.6%	16.6%	16.6%
25 ft tracker	Both aircraft follow their RAs	2.3%	2.3%	2.3%
	One aircraft does not follow its RAs	19.0%	18.2%	16.8%
	The intruder is not equipped with TCAS	12.7%	12.7%	12.5%

**Table 12: European ACAS Safety encounter model - Risk ratios with standard pilots**

5.2.3.1.2. The risk ratios computed with CP112E are reduced when compared with both version 7.0 and version 7.0 including CP112.

5.2.3.1.3. The improvements are especially significant for scenarios involving one pilot not following his RAs, thus illustrating the rectification of issue SA01a (e.g., with the 25 ft tracker with one pilot not following RAs, the risk ratio decreases from 19.0% to 16.8%, representing a relative decrease of 11.5%).

5.2.3.1.4. The European ACAS Safety encounter model has fewer NMACs and reversal RAs than the ICAO Safety standard encounter model. This explains why the improvement brought by CP112E are less significant on the European ACAS Safety encounter model than on the ICAO Safety standard encounter model.

**5.2.3.1.5. The simulation results based on the European ACAS safety encounter model show that CP112E brings significant improvements on safety and has no adverse effects on safety, as no additional induced NMACs were observed.**

### 5.2.3.2. Interoperability simulations

5.2.3.2.1. The following table presents the results of simulations performed with one aircraft fitted with version 7.0 and one aircraft fitted with version 7.0 including CP112E.

Configuration		Version 7.0/Version 7.0	Version 7.0/ Version 7.0+CP112E	Version 7.0 +CP112E/ Version 7.0 +CP112E
100 ft tracker	Both aircraft follow their RAs	2.7%	2.7%	2.7%
	One aircraft does not follow its RAs	21.0%	20.9%	19.9%
25 ft tracker	Both aircraft follow their RAs	2.3%	2.3%	2.3%
	One aircraft does not follow its RAs	19.0%	17.6%	16.8%

**Table 13: European ACAS Safety encounter model - Interoperability simulations V7/V7+CP112E**

5.2.3.2.2. Even with the interoperability simulations, the risk ratios are significantly decreased when compared with version 7.0.

5.2.3.2.3. As anticipated, the interoperability scenario results in intermediate risk ratios when compared to the Version 7.0/Version 7.0 and the CP112E/CP112E scenarios.

5.2.3.2.4. The following table presents the results of simulations performed with one aircraft fitted with version 6.04a and one aircraft fitted with version 7.0 including CP112E.

Configuration		Version 6.04a/ Version 7.0	Version 6.04a/ Version 7.0+CP112E
100 ft tracker	Both aircraft follow their RAs	3.0%	3.0%
	One aircraft does not follow its RAs	22.5%	22.3%

**Table 14: European ACAS Safety encounter model - Interoperability simulations V604a/V7+CP112E**

- 5.2.3.2.5. In interoperability simulations involving version 6.04a aircraft, and as anticipated, CP112E brings improvements when compared with version 7.0, and does not degrade safety.
- 5.2.3.2.6. The interoperability simulation results based on the European ACAS safety encounter model show that CP112E brings some improvements and performs well against TCAS II logic version 7.0 and version 6.04a aircraft.

### 5.2.3.3. Simulations with slow and aggressive pilots

5.2.3.3.1. The same simulations were performed with slow and aggressive pilot models [ACA1] instead of standard pilot models.

5.2.3.3.2. The following table presents the results of the simulations performed with slow pilot models.

Configuration		Version 7.0	Version 7.0+CP112E
100 ft tracker	Both aircraft follow their RAs	4.6%	4.5%
	One aircraft does not follow its RAs	71.6%	71.6%
	The intruder is not equipped with TCAS	72.1%	72.1%
25 ft tracker	Both aircraft follow their RAs	5.7%	5.5%
	One aircraft does not follow its RAs	86.0%	85.7%
	The intruder is not equipped with TCAS	87.0%	86.9%

**Table 15: European ACAS Safety encounter model - Risk ratios with slow pilots**

5.2.3.3.3. Improvements are brought by CP112E and especially for scenarios with one pilot not following RAs. This illustrates that even in the case of non nominal pilot responses, CP112E brings improvements to safety.

5.2.3.3.4. In addition, with a slow pilot model, CP112E never debases safety.

5.2.3.3.5. The following table presents the results of the simulations performed with aggressive pilot models.

Configuration		Version 7.0	Version 7.0+CP112E
100 ft tracker	Both aircraft follow their RAs	2.3%	2.3%
	One aircraft does not follow its RAs	9.9%	10.6%
	The intruder is not equipped with TCAS	13.6%	13.6%
25 ft tracker	Both aircraft follow their RAs	2.3%	2.3%
	One aircraft does not follow its RAs	8.8%	9.0%
	The intruder is not equipped with TCAS	10.3%	10.1%

**Table 16: European ACAS Safety encounter model - Risk ratios with aggressive pilots**

5.2.3.3.6. With an aggressive pilot model, CP112E slightly increases the risk ratios with the scenarios involving one pilot not following RAs. These scenarios involve a pilot who does not follow RAs against an aggressive pilot model (i.e., the aggressive pilot model follows initial RAs strongly with a vertical rate of 3700 fpm instead of 1500 fpm, and then follows reversal RAs slowly with a vertical acceleration of 0.25g instead of 0.35g). **It shows that the slow response to reversal RAs of the aggressive pilot model is difficult to handle in some specific encounters.**

5.2.3.3.7. One can also wonder if the slow response to reversal RAs of the aggressive pilot defined in [ACA1] is operationally realistic.

5.2.3.3.8. This slight increase results from 5 encounters with the 100 ft tracker, and 2 encounters for the 25 ft tracker. The increase is higher with the 100 ft tracker scenario than with the 25 ft tracker scenario. It can be explained by tracker performances in encounters with high vertical rates and rapid manoeuvres.

**5.2.3.3.9. These results highlight that in case of reversal RAs slow response can not be expected to provide significant benefits, and can even be hazardous.**

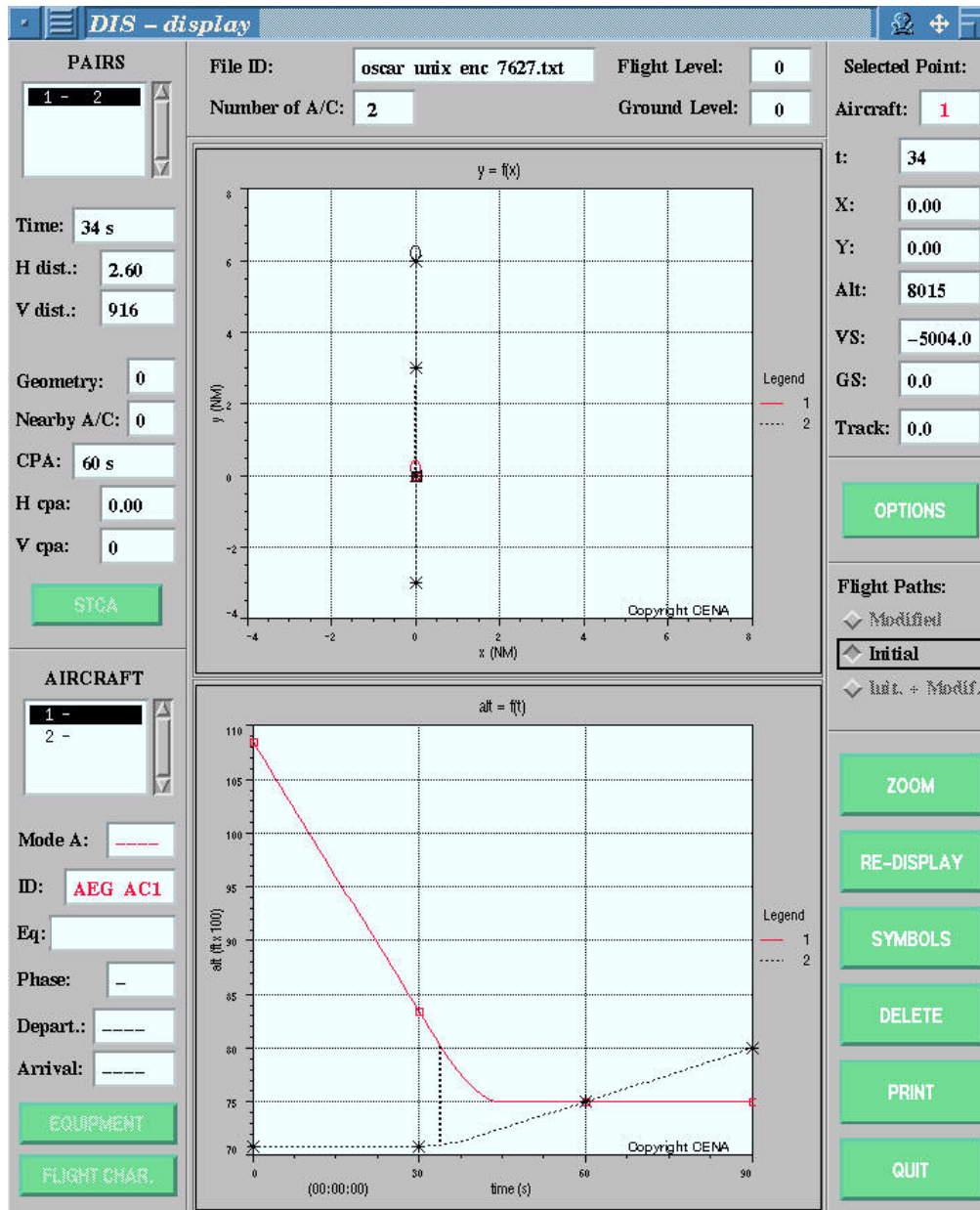


### **5.3.     *Safety validation for class 8 of the US airspace model***

#### **5.3.1.   Class 8 encounter description**

- 5.3.1.1. It was noticed that CP112 can debase the performance of TCAS II logic version 7.0 for a specific geometry, corresponding to class 8 encounters of the US airspace model. The geometry is close to the SA01c geometry but with one aircraft not following his RAs.
- 5.3.1.2. In early 2004, in the scope of the SIR project, a cooperation between the FAA technical centre and the SIR project began. The FAA technical centre sent 6 examples of encounters in which the problem was identified, so that their findings could be replicated by the SIR project.
- 5.3.1.3. These 6 encounters are very similar, therefore only one example is shown in the following. The results for the 5 other encounters are identical to those obtained for this encounter.
- 5.3.1.4. The following shows an example of encounter in which the issue was found by FAA, and reproduced by the SIR team. This encounter is first presented simulated with TCAS II logic version 7.0, then with CP112 and then with CP112E.

5.3.1.5. The following figure shows the encounter without TCAS contribution.



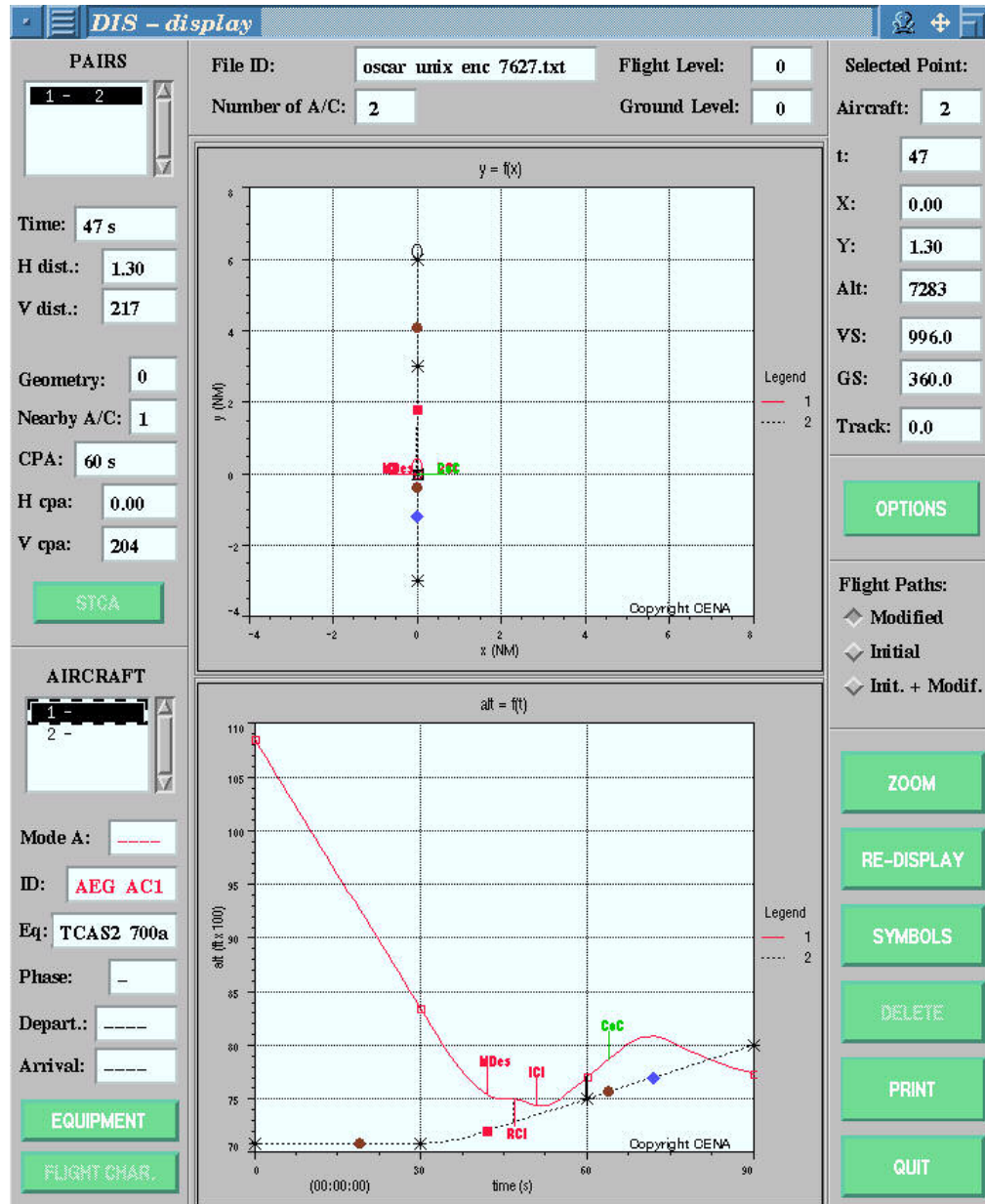
**Figure 27: US airspace model class 8 encounter - Encounter without TCAS contribution**

- 5.3.1.6. In this encounter, aircraft 1 is descending at 5000 fpm and levels-off at FL75, with a zero ground speed. Aircraft 2 is level at FL71, with a ground speed of 360 knots. Thirty seconds after the beginning of the encounter, aircraft 2 starts a climb at 1000 fpm.
- 5.3.1.7. In the simulations reported in this part and in the problem geometry highlighted by FAA [FAA1], aircraft 2 does not follow RAs and receives a climb sense RA, which

is reversed a few seconds after. One can consider that this pilot is following the initial RA nearly correctly (i.e., as the aircraft is climbing at 1000 fpm instead of 1500 fpm), but not the subsequent reversal descent RA. This is a very difficult situation to handle for the CAS logic.

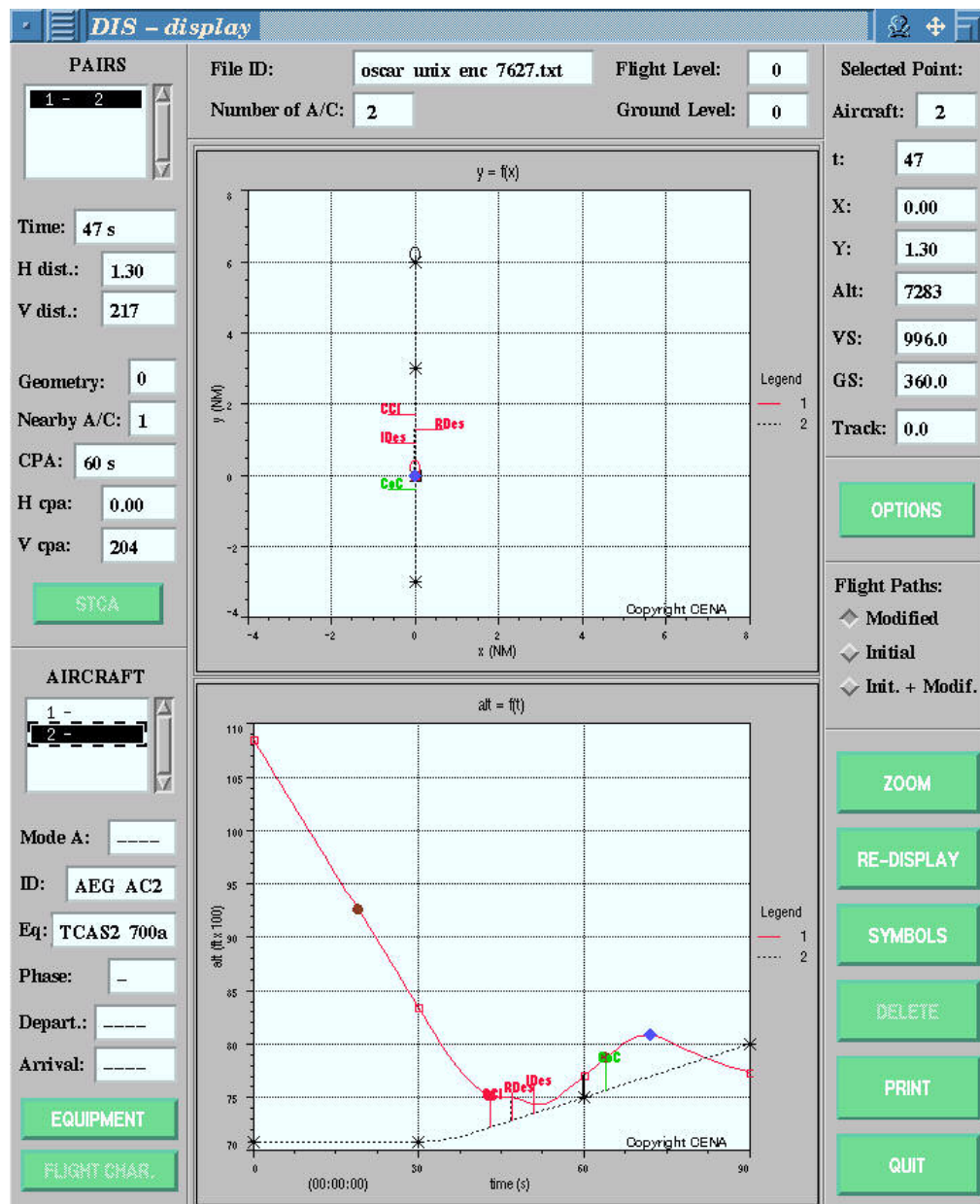
### 5.3.2. Simulation results with TCAS II logic version 7.0

5.3.2.1. The following figures show the encounter simulated with TCAS II logic version 7.0 onboard both aircraft. Aircraft 2 is not following any RA.



**Figure 28: US airspace model class 8 encounter  
Encounter simulated with TCAS II version 7.0  
RAs onboard aircraft 1 (Shown in full red line)**

**Sequence of RAs:** Mdes: Maintain Descent RA, RCI: Reverse climb RA, ICI: Increase climb RA, CoC: Clear of conflict



**Figure 29: US airspace model class 8 encounter**  
**Encounter simulated with TCAS II version 7.0**  
**RAs onboard aircraft 2 (Shown in black dotted line)**

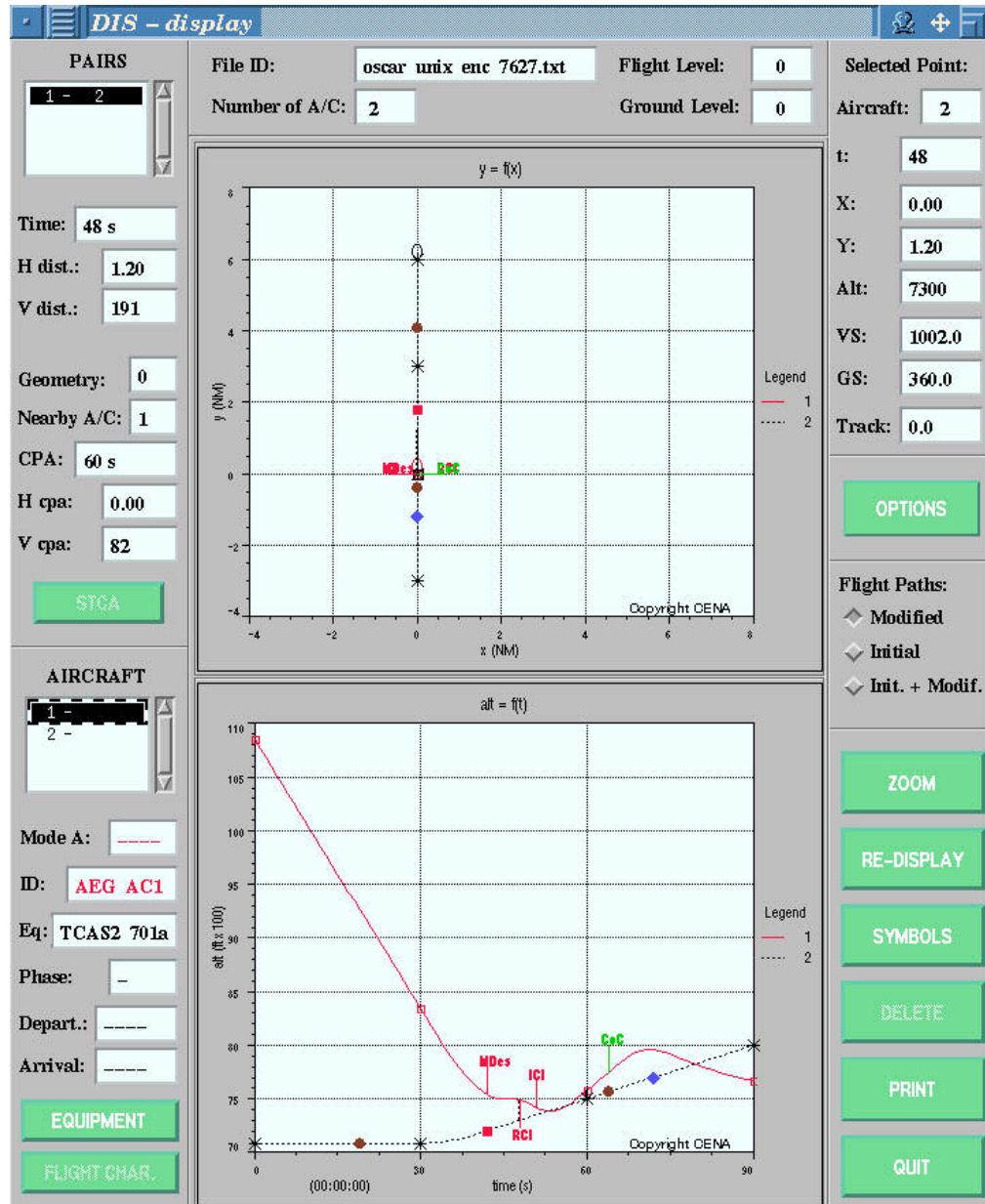
**Sequence of RAs:** CCI: Crossing climb RA, RDes: Reverse descent RA, IDes: Increase descent RA, CoC: Clear of conflict

- 5.3.2.2. This simulation reproduces nearly exactly the behaviour simulated by the FAA technical center on this encounter.
- 5.3.2.3. For this scenario, the resulting vertical separation at CPA is 204 ft. This low vertical separation at CPA is resulting from the fact that aircraft 2 is not following RAs

correctly, and especially the reversal RA. Simulations show that if aircraft 2 follows the reversal RA, the vertical separation at CPA is above 600 ft.

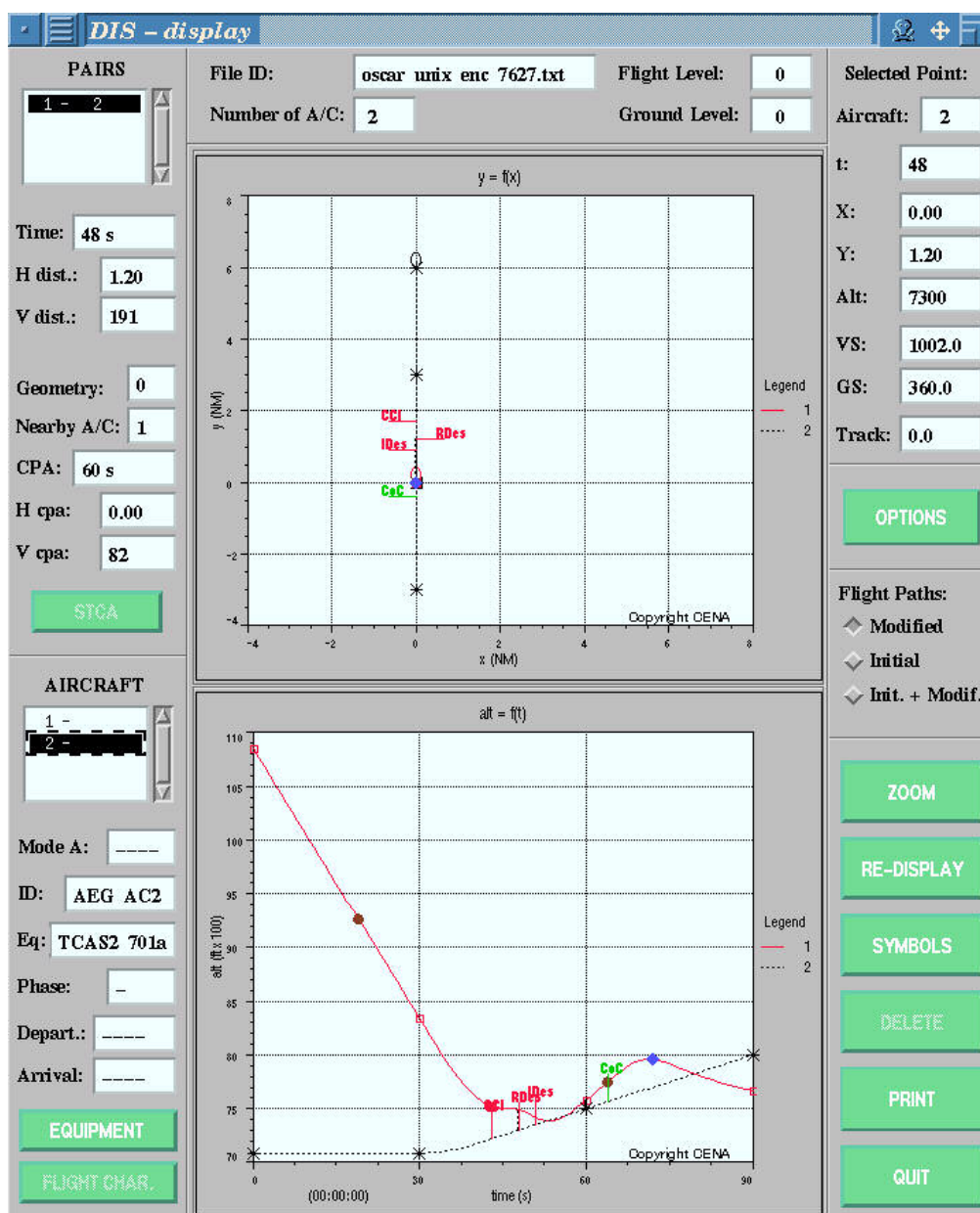
### 5.3.3. Simulation results with initial CP112

5.3.3.1. The following figures show the encounter simulated with TCAS II logic version 7.0 and CP112 onboard both aircraft. Aircraft 2 is not following any RAs.



**Figure 30: US airspace model class 8 encounter  
Encounter simulated with TCAS II version 7.0+CP112  
RAs onboard aircraft 1 (Shown in full red line)**

**Sequence of RAs:** Mdes: Maintain Descent RA, RCI: Reverse climb RA, ICI: Increase climb RA, CoC: Clear of conflict



**Figure 31: US airspace model class 8 encounter  
Encounter simulated with TCAS II version 7.0+CP112  
RAs onboard aircraft 2 (Shown in black dotted line)**

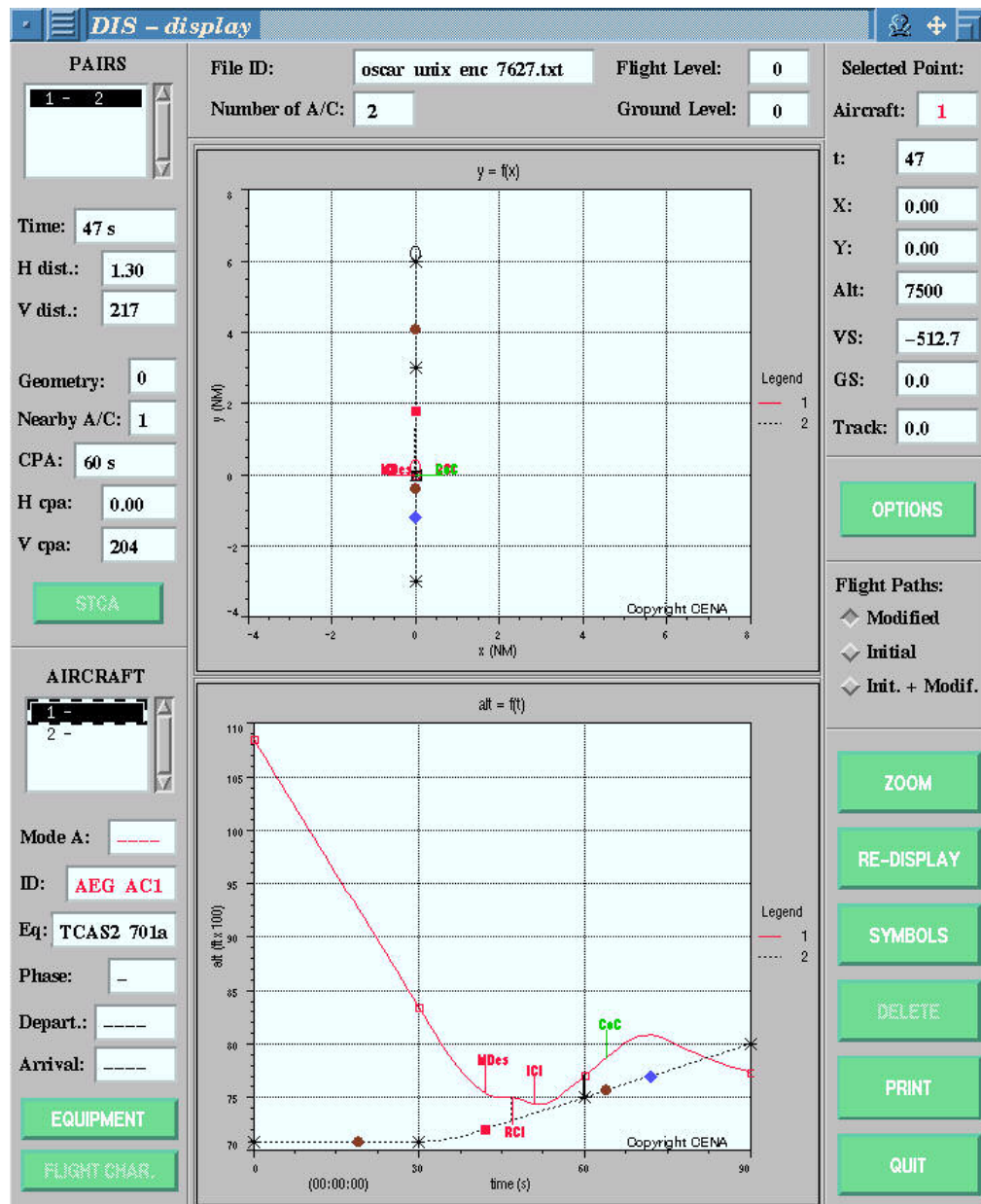
**Sequence of RAs:** CCI: Crossing climb RA, RDes: Reverse descent RA, IDes: Increase descent RA  
CoC: Clear of conflict

- 5.3.3.2. This simulation reproduces nearly exactly the behaviour simulated by the FAA technical center on this encounter with CP112.
- 5.3.3.3. With CP112, the vertical separation at CPA is decreased to 82 ft. Indeed, CP112 is delaying the reversal RA issuance in this specific case.



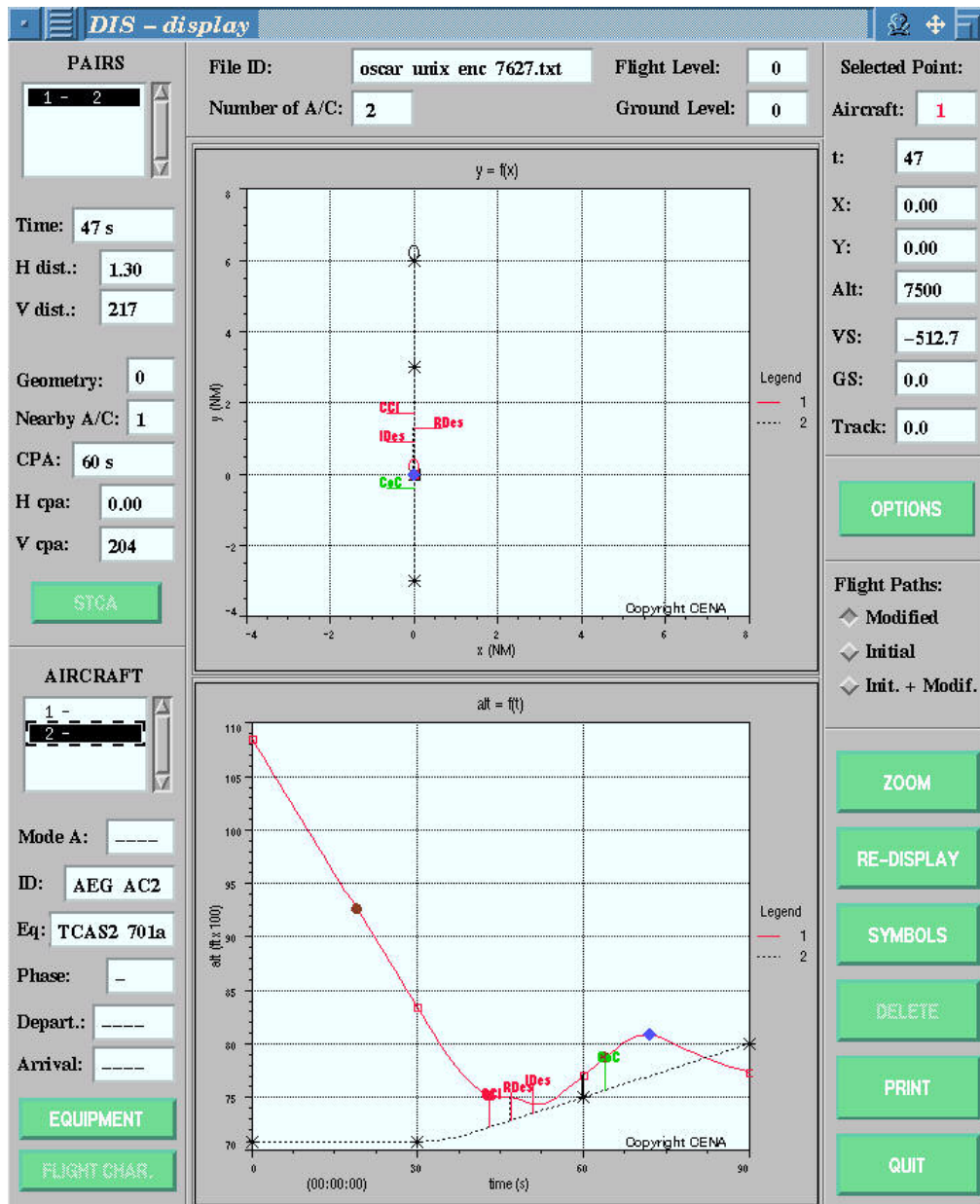
### 5.3.4. Simulation results with new CP112E

- 5.3.4.1. The following figures show the encounter simulated with TCAS II log version 7.0 and CP112E onboard both aircraft. Aircraft 2 is not following any RAs.



**Figure 32: US airspace model class 8 encounter  
Encounter simulated with TCAS II version 7.0+CP112E  
RAs onboard aircraft 1 (Shown in full red line)**

**Sequence of RAs:** Mdes: Maintain Descent RA, RCl: Reverse climb RA, ICl: Increase climb RA, CoC: Clear of conflict



**Figure 33: US airspace model class 8 encounter**  
**Encounter simulated with TCAS II version 7.0+CP112E**  
**RAs onboard aircraft 1 (Shown in full red line)**

**Sequence of RAs:** CCI: Crossing climb RA, RDes: Reverse descent RA, IDes: Increase descent RA, CoC: Clear of conflict

- 5.3.4.2. With CP112E, the result is unchanged when compared with TCAS II logiversion 7.0, and the vertical separation at CPA is 204 ft again. Indeed, CP112E does not delay the reversal RAs.

5.3.4.3. This behaviour was expected, as the new CP112E considers that at the time the reversal RAs are triggered, there is enough time (i.e., 13 s) before CPA for them to provide sufficient vertical separation at CPA.

5.3.4.4. It is important to mention that both FAA technical centre and SIR simulation results are very similar for the V7/V7 scenarios and the V7+CP112/V7+CP112 scenarios.

### **5.3.5. Conclusion**

5.3.5.1. The simulations performed with the OSCAR test bench enabled to confirm the findings of the FAA Technical Centre on a possible issue induced by CP112 for class 8 encounters and with a specific scenario (i.e., one pilot not following his RAs) [SIR/WP2/16/W].

5.3.5.2. However the issue highlighted by FAA on this geometry appears to be strictly defined, as it requires a high vertical rate of the descending aircraft, altitudes below FL100 and crossing RAs [SIR/WP16/W].

5.3.5.3. The simulation results also indicate that, as expected, the issue is not observed when applying the CP112E solution [SIR/WP16/W].

### **5.4. *Safety validation on actual encounters***

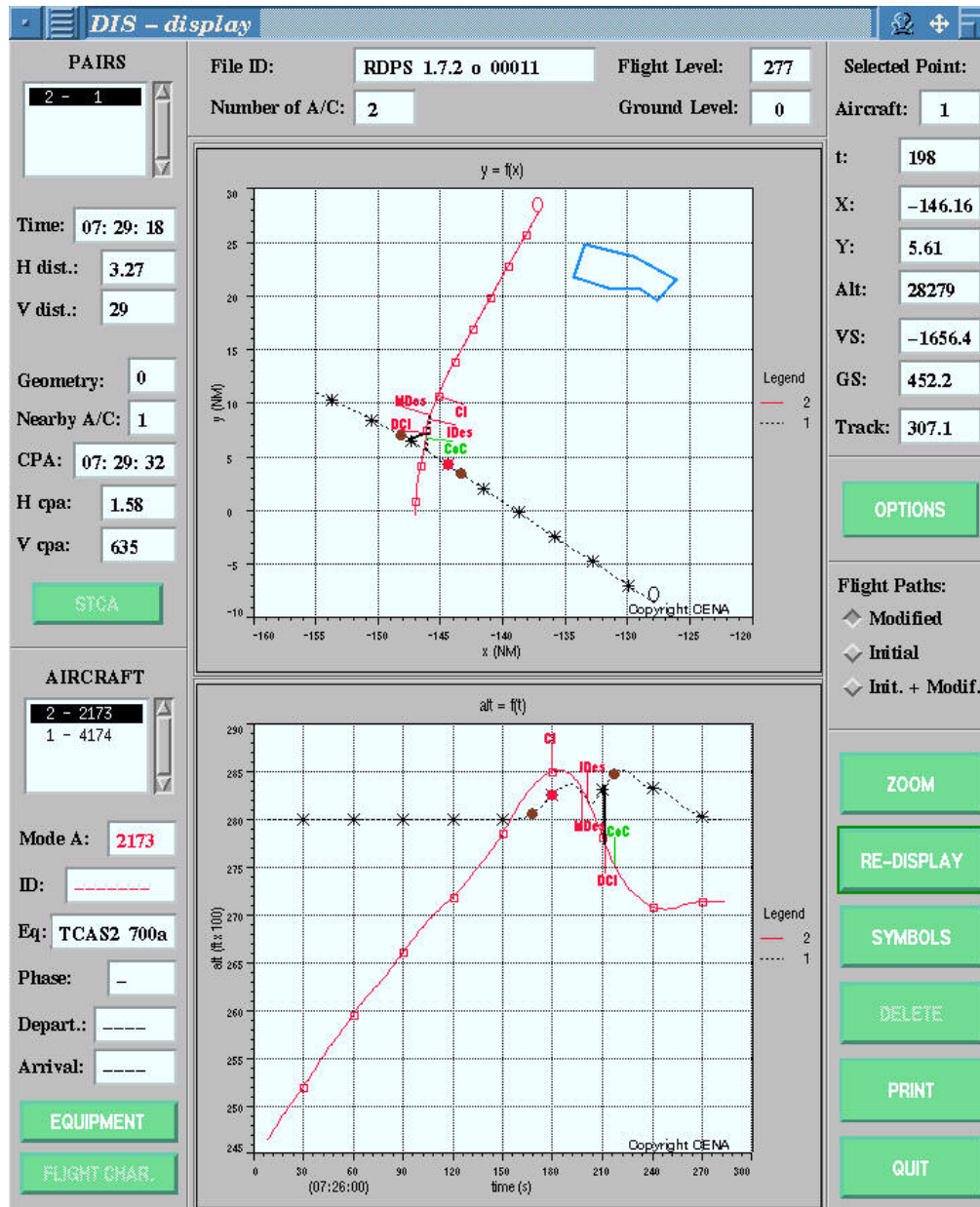
5.4.1.1. Simulations were also performed on 4 examples of recent and actual SA01a encounters [EMO5], including the Überlingen mid-air collision, which occurred in the European Airspace, and during which no or very late reversal RAs were triggered. In these actual encounters, the lack of reversal RA with version 7.0 led to very hazardous situations.

5.4.1.2. As anticipated, with CP112E, reversal RAs are triggered well before CPA (i.e., more than 10 s before CPA).

5.4.1.3. For these actual events, the safety is significantly improved independently of the mode S addresses.

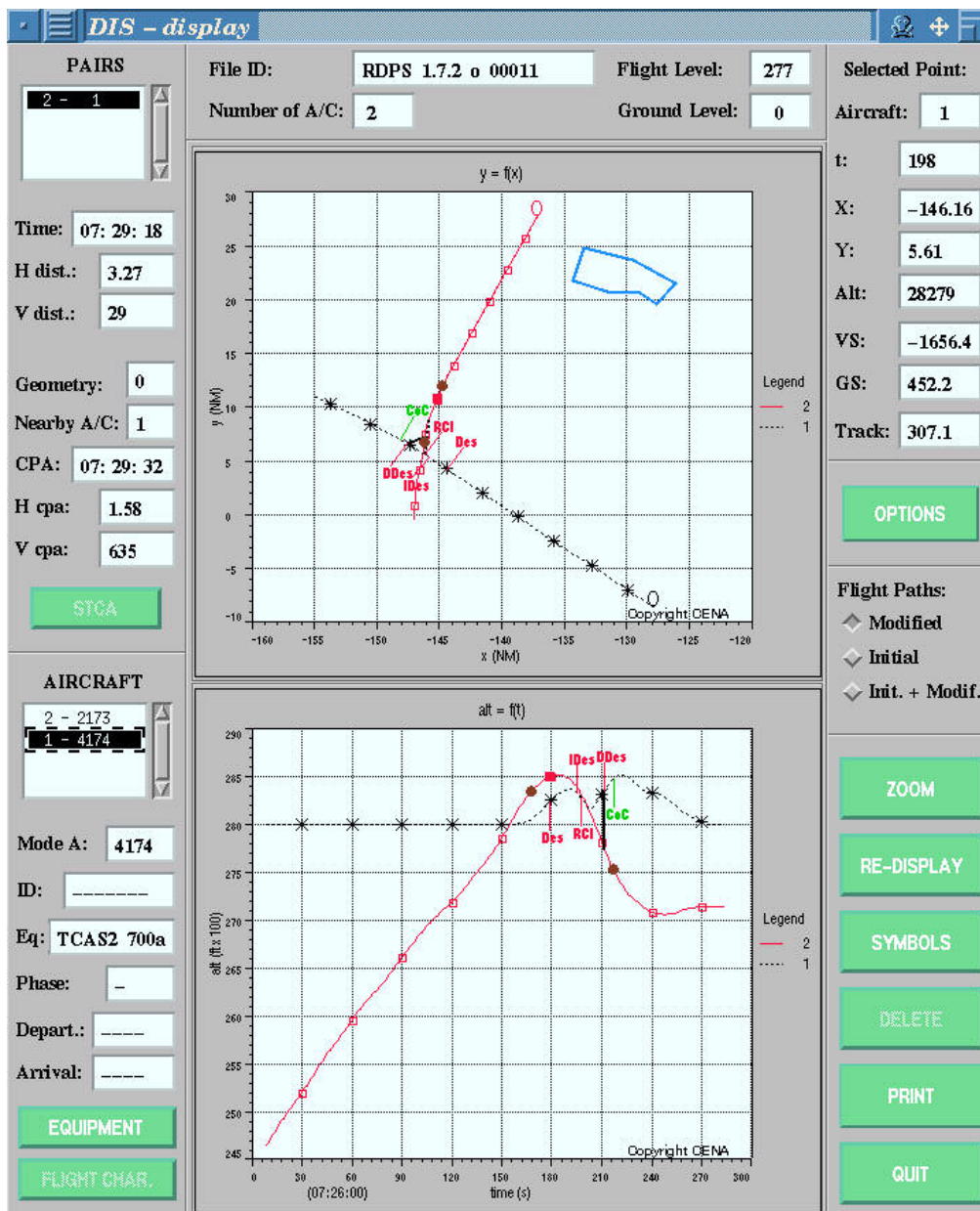
5.4.1.4. The following is an illustration of these improvements on the example shown in section 3.2.2.

5.4.1.5. The following figures show the example of part 3.2.2 (Figure 6 and Figure 7) simulated with CP112E. The aircraft not following RAs is the master aircraft (i.e., aircraft 2).



**Figure 34: Issue SA01a - Encounter simulated with CP112E - RAs onboard aircraft 2 (Shown in full red line)**

**Sequence of RAs:** CI: Climb RA, IDes: Increase Descent RA, MDes: Maintain Descent RA, DCI: Don't Climb RA, CoC: Clear of Conflict



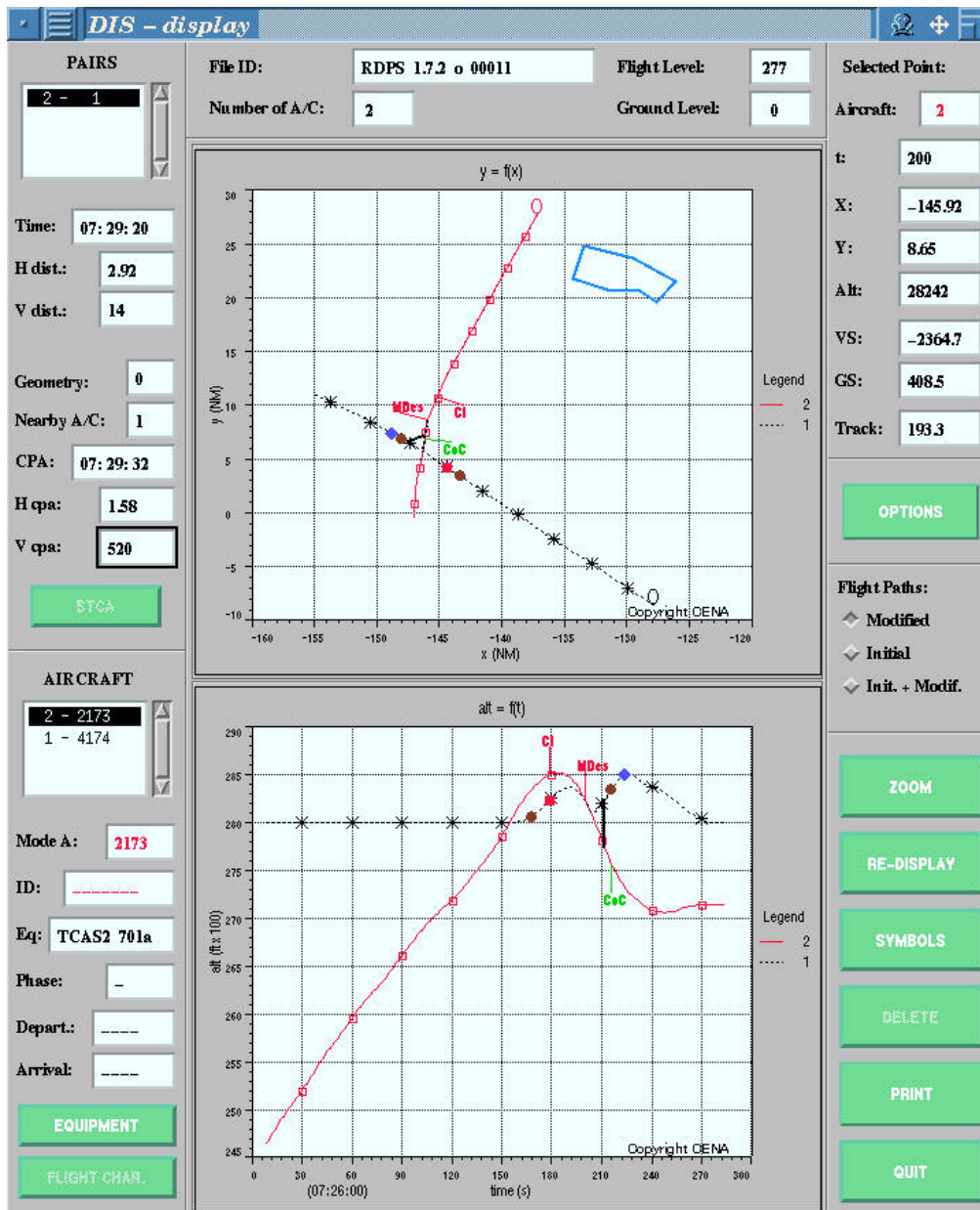
**Figure 35: Issue SA01a - Encounter simulated with CP112E - RAs onboard aircraft 1  
(Shown in black dotted line)**

**Sequence of RAs:** Des: Descend RA, IDes: Increase Descent RA, RCI: Reversal Climb RA, DDes: Don't Descend RA, CoC: Clear of Conflict

- 5.4.1.6. With CP112E, reversal RAs are triggered 14 s before CPA, which is early enough to be efficient. The vertical separation at CPA is 635 ft.

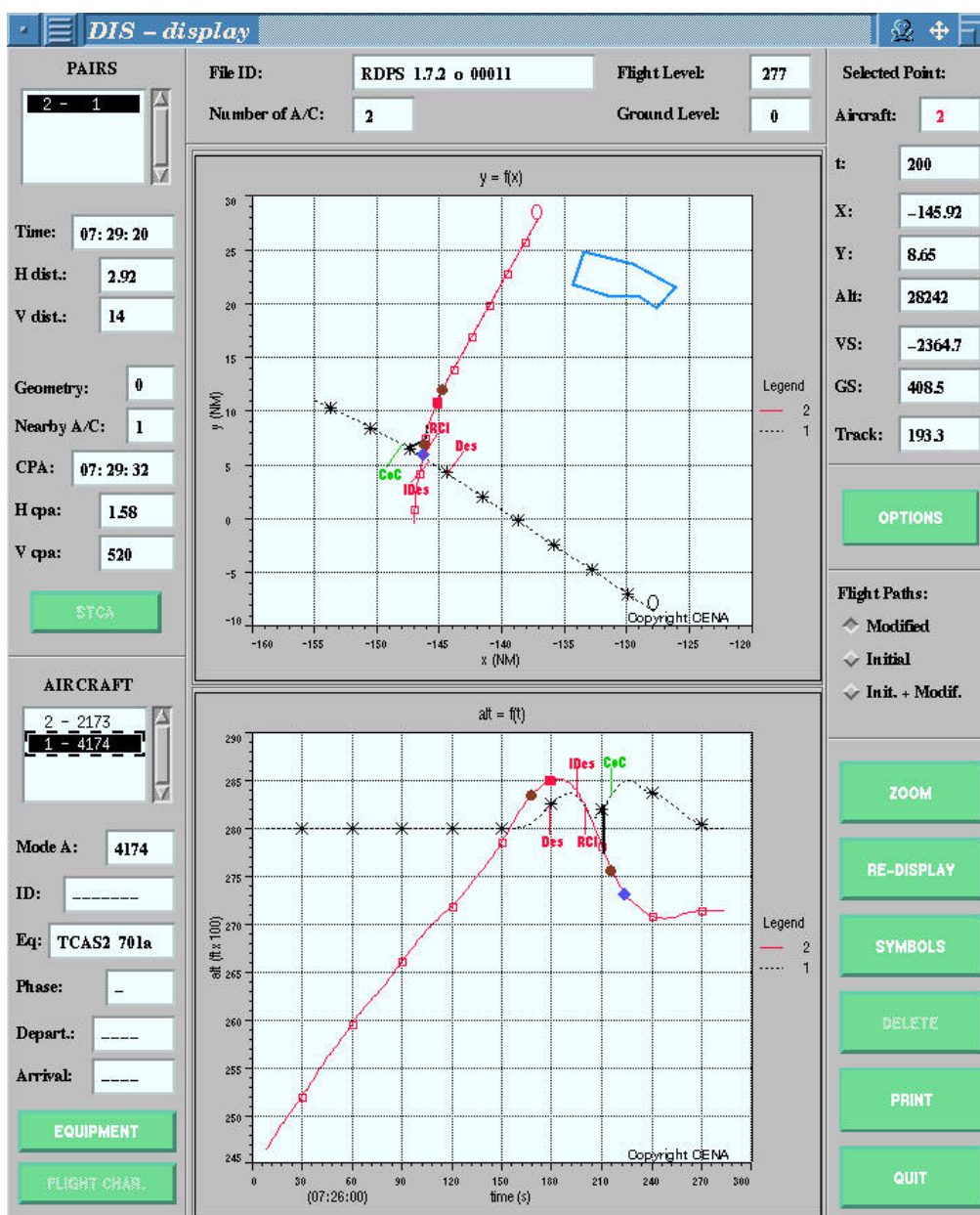


5.4.1.7. The following figures show the same encounter with the Mode S addresses inverted. The aircraft following RAs is now the master aircraft (i.e., aircraft 1).



**Figure 36: Issue SA01a - Encounter simulated with CP112E - RAs onboard aircraft 2 (Shown in full red line) – Mode S addresses inverted**

**Sequence of RAs:** Cl: Climb RA, MDes: Maintain Descent RA, CoC: Clear of Conflict



**Figure 37: Issue SA01a - Encounter simulated with CP112E - RAs onboard aircraft 1 (Shown in black dotted line) – Mode S addresses inverted**

**Sequence of RAs:** Des: Descend RA, IDes: Increase Descent RA, RCI: Reversal Climb RA, CoC: Clear of Conflict

- 5.4.1.8. With CP112E, reversal RAs are triggered 12 s before CPA, which is also early enough to be efficient. The vertical separation at CPA is 520 ft.
- 5.4.1.9. This example illustrates that CP112E permits to trigger reversal RAs, which improve safety whatever the order of the mode S addresses.

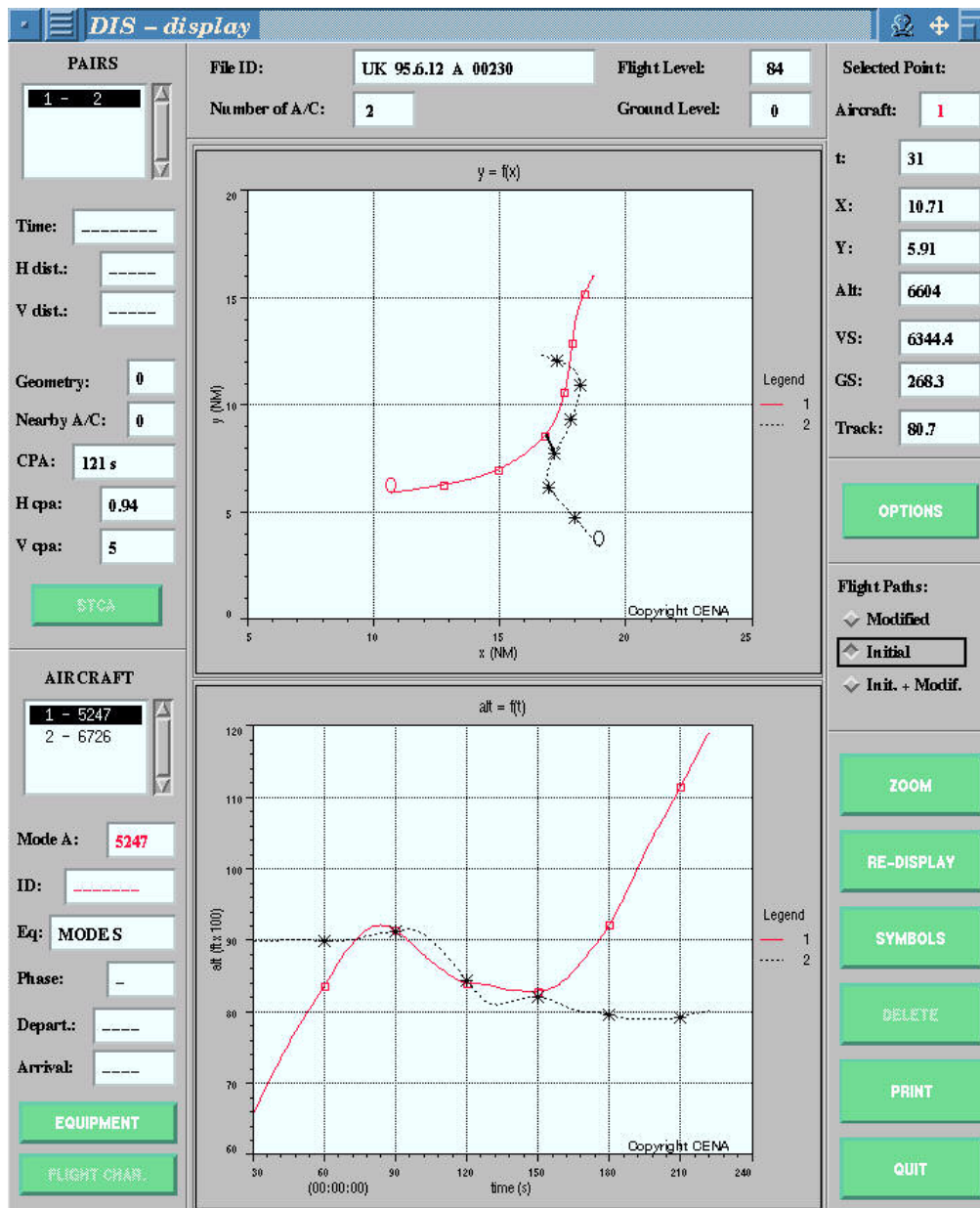
## **5.5. Operational validation on actual encounters**

- 5.5.1.1. Simulations were made on an European database of roughly 400 actual encounters for double equipage encounters, and of over 1000 encounters for single equipage encounters. These encounters were extracted from radar data recording.
- 5.5.1.2. These encounters were simulated with TCAS II logic version 7.0 and version 7.0 including CP112E using the following configurations:
  - Two TCAS V7 equipped aircraft, with:
    - Both pilots following the RAs;
    - One pilot not following the RAs, one pilot following the RAs;
  - Only one TCAS V7 equipped aircraft with a pilot following the RAs.
- 5.5.1.3. All the scenarios were simulated using both 25 ft altitude reports and 100 ft altitude reports.
- 5.5.1.4. The objective of these simulations was to assess if CP112E affects the overall operational performance of the logic (e.g., TA logic, Vertical deviations, etc). The goal was to determine if CP112E is affecting other parts of the CAS logic because a change proposal, which would affect other parts of the CAS logic would be unacceptable.
- 5.5.1.5. Appendix C presents the sets of indicators, which were computed to perform this assessment.
- 5.5.1.6. It has been verified that the rate of strengthening RAs (i.e. increase and reversal RAs) should be extremely close to the one currently observed with version 7.0:
  - 1.0% with both version 7.0 and CP112E for the best case (i.e. with the A1/B1 scenarios); and
  - 3.4% with version 7.0 Vs 3.6% with CP112E for the worse case (i.e. with the A2/B2 scenarios).
- 5.5.1.7. For all the other encounters and indicators, the results are unchanged.
- 5.5.1.8. These results confirm that CP112E does not debase the operational performance of the CAS logic.**



5.5.1.9. The following figures show an example of encounter extracted from the European encounter database. This encounter is a good example of an issue SA01b encounter.

5.5.1.10. The following figure shows the initial encounter, simulated without ACAS contribution.



**Figure 38: Issue SA01b - Encounter without TCAS contribution**

5.5.1.11. In this encounter, aircraft 1 is unequipped with TCAS or in TA-only mode, whereas aircraft 2 is equipped with TCAS.

5.5.1.12. The following figure shows the encounter simulated with TCAS II logic version 7.0 on board aircraft 2.

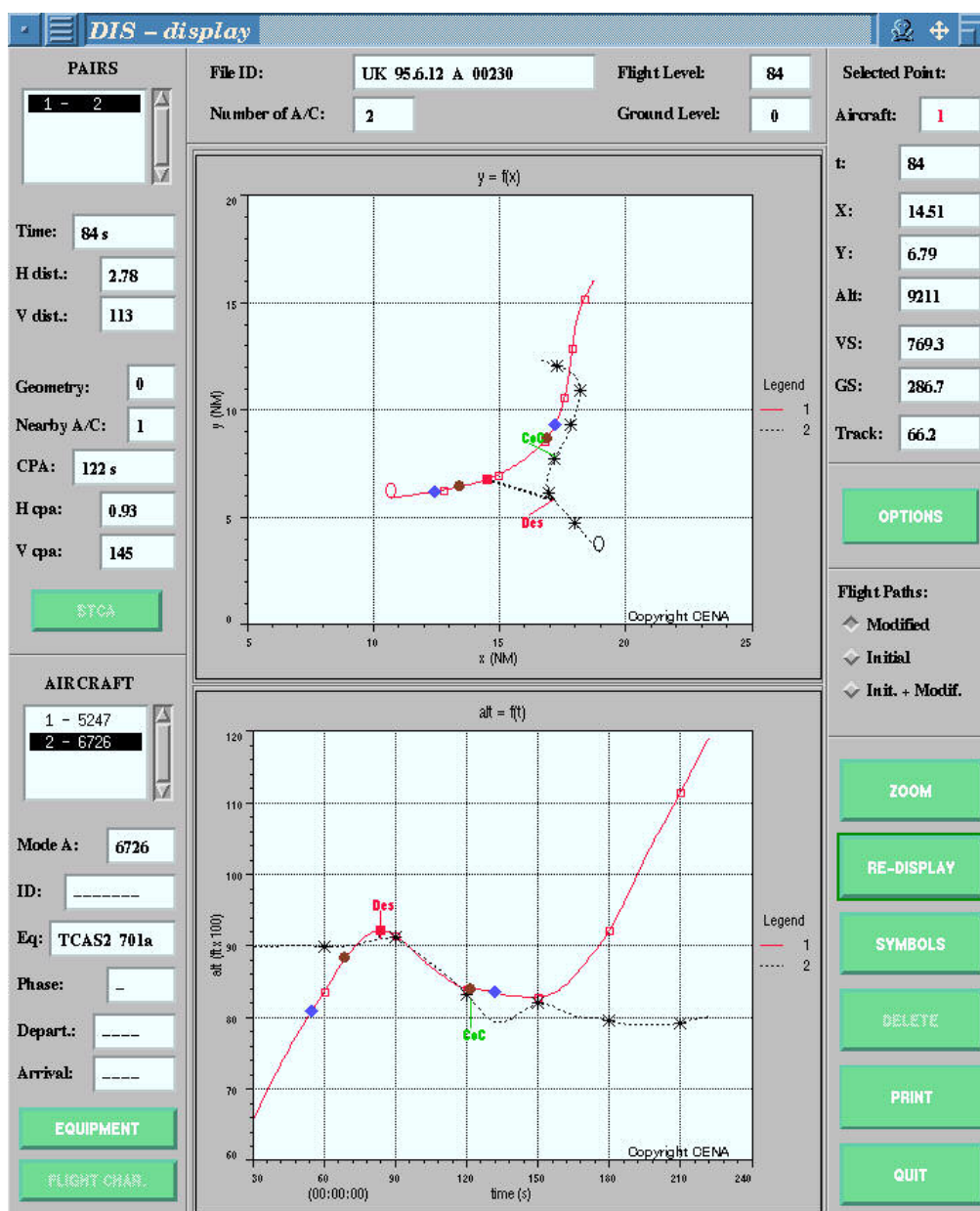


Figure 39: Issue SA01b – Encounter simulated with TCAS II logic version 7.0

Sequence of RAs: Des: Descend RA, CoC: Clear of Conflict

5.5.1.13. With TCAS II logic version 7.0, a descend RA is triggered at  $t=84$  s. Then both aircraft descend for nearly 40 s without any reversal RAs being triggered, because the aircraft remain within 100 ft vertically. The horizontal separation at CPA is 0.93NM, and the vertical separation at CPA is 145 ft. The vertical separation at CPA is over 100 ft because during the very last seconds before CPA, aircraft 1 decreases its descent rate.

5.5.1.14. The following figure shows this encounter simulated with CP112E.

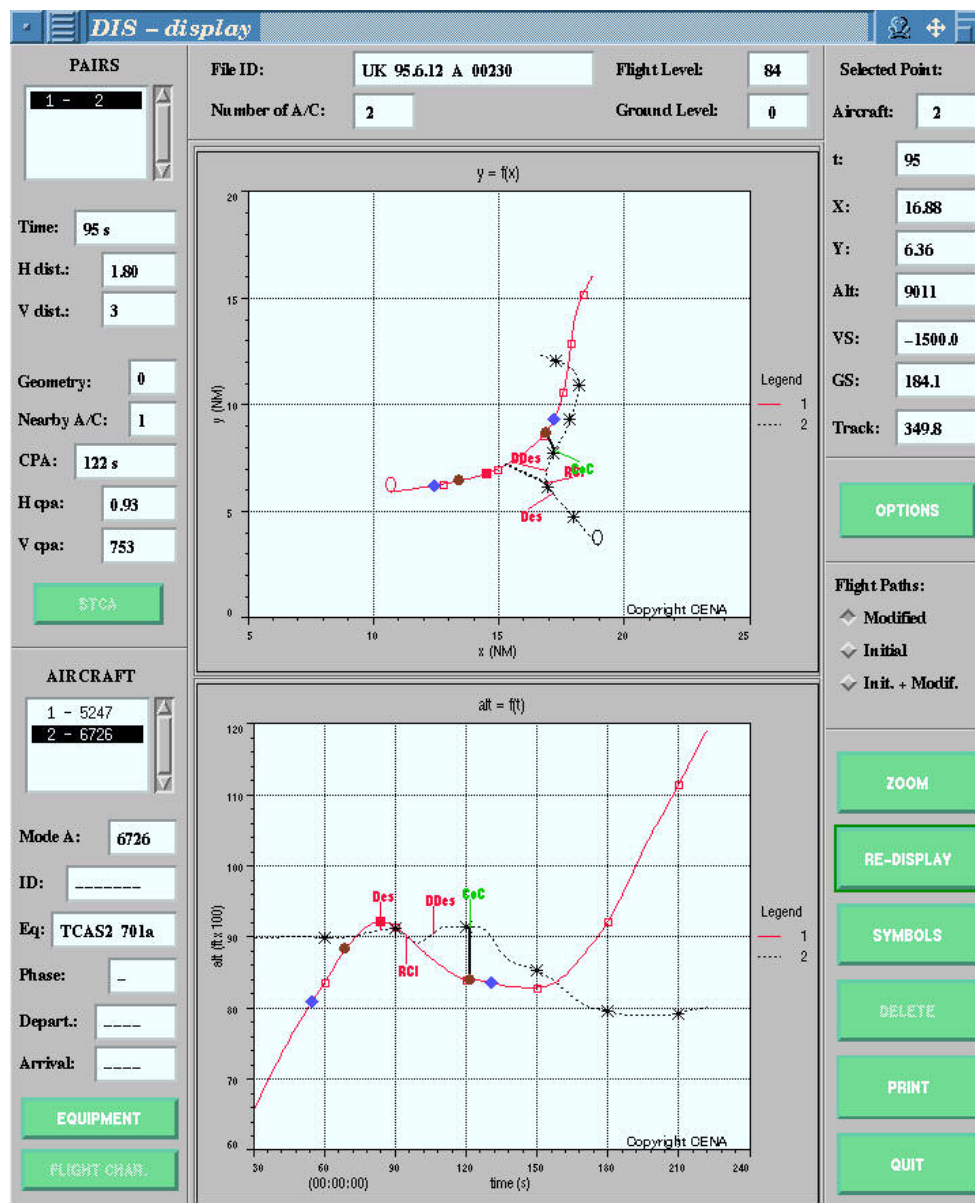


Figure 40: Issue SA01b - Encounter simulated with CP112E

Sequence of RAs: Des: Descend RA, RCl: Reversal climb RA, DDes: Don't Descend RA  
CoC: Clear of Conflict

5.5.1.15. With CP112E, a reversal climb RA is triggered 11 seconds after the initial RA, and 27s before CPA. As a result, the vertical separation at CPA increases to 753 ft.

5.5.1.16. This encounter is an example of issue SA01b encounter, for which CP112E has a positive impact. **CP112E improves safety as the vertical separation at CPA increases from less than 145 ft up to more than 700 ft, with a weakening RA triggered.**

## **5.6. Conclusion on the validation results**

### **5.6.1. Safety validation on encounter models**

- 5.6.1.1. The simulations performed on the ICAO safety standard encounter model and on the European ACAS Safety encounter model using CP112E indicate a significant improvement in the safety performance of the CAS logic when compared with both the current version 7.0 and the initial CP112 solution.
- 5.6.1.2. In addition, CP112E brings some improvements to safety and shows a good robustness even with non nominal pilots.
- 5.6.1.3. Interoperability simulations also show that CP112E performs very well even against TCAS II logic version 7.0 and version 6.04a aircraft and brings improvements to safety.

### **5.6.2. Safety validation for class 8 of the US airspace model**

- 5.6.2.1. CP112E addresses the comments on CP112 concerning the fact that it can debase the performance of TCAS II logic version 7.0 on class 8 encounters of the US airspace model. The class 8 encounters issue of CP112 is no more an issue with CP112E. This was verified through a cooperation with FAA, which sent 6 example encounters of the identified issue.
- 5.6.2.2. The use of the VMD parameter permits to circumvent the mode S priority rule issue. As a result, CP112E is now able to trigger reversal RAs in an encounter, in which reversal RAs are needed, whatever the order of the mode S addresses.

### **5.6.3. Safety validation on actual encounters**

- 5.6.3.1. The simulations performed on four examples of actual encounters on which issue SA01 was identified and for which radar data are available show that CP112E improves safety, with reversal RAs triggered early enough to ensure a sufficient vertical separation at CPA.

### **5.6.4. Operational validation on actual encounters**

- 5.6.4.1. The simulations performed on the data base of actual encounters show that CP112E does not affect the operational performance of TCAS II logic version 7.0, and even improves safety on some encounters.

## 6. Work on the Überlingen collision

### 6.1. *Überlingen report*

- 6.1.1. An important task of the SIR project consisted in further developing the initial report on the ACAS aspects of the Überlingen collision written during the EMOTION-7 project [EMO0].
- 6.1.2. The final report [WP1/06] developed by the EUROCONTROL Überlingen Mid-Air Collision Investigation Team presents the results of the TCAS II analysis of this Überlingen collision. It is a contribution to BFU to aid understanding of the TCAS aspects of the Mid-Air Collision.
- 6.1.3. The objective of the Final Report was to investigate mainly technical but also operational aspects related to TCAS II. In particular, it assesses the safety performances of TCAS II for this accident. The report has been developed so as to be readable by non TCAS experts.
- 6.1.4. The study has focused on the analysis of the actual accident based on three TCAS II simulations, using three different sources of data and two different sophisticated TCAS II analysis tools (i.e., the InCAS tool, and the OSCAR tool). The final report [WP1/06] describes first what happened with a detailed description of the CAS logic behaviour in the alert sequence and then what could have happened if either both flight crews had accurately followed their RAs or if reversal RAs (generated in accordance with CP112) had been triggered by TCAS II and followed by flight crews.
- 6.1.5. The results of this investigation have been passed to the BFU team investigating the accident. In addition, a presentation of the results was given at a constructive meeting at the BFU headquarters which enabled several issues to be elaborated. The results of the investigation into the TCAS aspects of the accident remain confidential. However it is clear that:
  - From an ACAS standpoint one **aircraft went opposite to the RA inducing a complex situation difficult to address**; and
  - TCAS operated according to its specification but **the design purpose of the reversal logic was not achieved (no reversal RAs were issued)**; and
  - In this specific scenario, implementation of **CP112 or CP112E could have provided benefit by permitting the possibility of a reversal RA**.

### 6.2. *Replay of the mid-air collision*

- 6.2.1. During the Überlingen investigation, another task of WP1 consisted in developing the replay of the mid-air collision [WP1/07]. It provides a simultaneous (and as realistic as possible) display of:
  - The controller's view on a radar-like display;

- The flight crews' view on an IVSI, which was the TCAS display installed on the DHX 611 and BTC 2937 aircraft (i.e., the two aircraft involved in the collision);
  - The RTF between the controller and the DHX 611 and BTC 2937 in text format.
- 6.2.2. The replay is focused on the TCAS aspects. Therefore, it begins a few tens of seconds before the first TCAS alerts (i.e. the TAs) and ends at the collision time. In addition, only data relevant to the two involved aircraft is included ( e.g. RT messages with other aircraft are not displayed).
- 6.2.3. For a maximum operational realism, the data used by the replay was as far as possible data provided by BFU, including radar data, the transcript of the RTF, airborne data (i.e. altitude and vertical speed) and the timing of the alert sequence.
- 6.2.4. Three scenarios can be replayed to illustrate what happened and what could have happened:
- “Scenario A: mid-air collision”. This is the replay of the mid-air collision with the display of the actual data provided by BFU.
  - “Scenario B: accurate reactions to RAs”. The data has been modified after the initial RAs to simulate an accurate reaction of both flight crews to their respective RAs.
  - “Scenario C: reversal RAs”. The data has been modified to simulate the triggering of reversal RAs by a modified TCAS II version 7 including CP112 and the accurate reaction of the DHX 611 flight crew to the reversal RA.
- 6.2.5. The replay is not a stand-alone analysis tool of the mid-air collision. Nevertheless, the dynamic replay of the event sequence (including both the RTF and the TCAS alerts) enables a better perception of the situation. It also serves to illustrate dynamically the various results and conclusions provided in the investigation report of the ACAS aspects of the Überlingen collision [WP1/06].
- 6.2.6. As the report, the replay remains confidential.

## 7. Conclusion

### 7.1. *Issue SA01 rectification*

7.1.1. The SA01 operational scenario has been identified in several occasions.

7.1.2. A mature draft of CP112E to address issue SA01 is now available. The simulations performed with CP112E indicate a significant improvement in the safety performance of the CAS logic when compared with both the current version 7.0 and the initial CP112 solution. This has been observed with various equipage configurations, different pilot behaviours and different safety encounter modes:

- Simulations were performed on the ICAO safety standard encounter model and on the European ACAS Safety encounter model, using version 7.0, the initial CP112 and the new CP112E. The results indicate a significant improvement in the safety performance of the CAS logic when compared with both the current version 7.0 and the initial CP112 solution.
- Using these two encounter models, simulations were performed with non nominal pilot pilots. CP112E brings some improvements to safety and shows a good robustness even with these non nominal pilots.
- Interoperability simulations performed on these two encounter models also show that CP112E performs very well even against TCAS II logic version 7.0 and version 6.04a aircraft and brings improvements to safety.
- CP112E addresses the comments on CP112 concerning the fact that it can debase the performance of TCAS II logic version 7.0 on class 8 encounters of the US airspace model. The class 8 encounters issue of CP112 is no more an issue with CP112E. This was verified through a cooperation with FAA, which sent 6 example encounters of the identified issue.
- The use of the VMD parameter permits to circumvent the mode S priority rule issue. As a result CP112E is now able to trigger reversal RAs in encounters, in which reversal RAs are needed whatever the order of the mode S addresses.
- The simulations performed on four examples of actual encounters on which issue SA01 was identified and for which radar data are available show that CP112E improves safety, with reversal RAs triggered early enough to ensure a sufficient vertical separation at CPA.
- The simulations performed on the data base of over 1000 actual encounters show that CP112E does not affect the operational performance of TCAS II logic version 7.0, and even improves safety on some encounters.

7.1.3. All the known anomalies in the CAS reversal logic have been addressed. In particular, sub-issue SA01b is now addressed. With the RTCA SC147 restart, it is anticipated that a close US / Europe cooperation will enable to confirm the efficacy of CP112E.

- 7.1.4. It is expected that the EUROCONTROL SIR project will provide the basis for a rapid rectification of the safety issue SA01.

## **7.2. *Überlingen mid-air collision***

- 7.2.1. The SIR project provided the tool to analysis the Überlingen mid-air collision on the TCAS aspects for BFU, on the behalf of EUROCONTROL.
- 7.2.2. An Überlingen investigation report focusing on TCAS aspects was developed and sent to BFU.
- 7.2.3. From this investigation, it is clear that one aircraft went opposite to the RA inducing a situation difficult to address, and that TCAS operated according to its specification but the design purpose of the reversal logic was not achieved as no reversal RA was triggered. In addition, the investigation has demonstrated that implementing CP112 or CP112E could have provided safety benefits by triggering reversal RAs.
- 7.2.4. A replay of the mid-air collision was also developed, presenting the actual event, the potential benefits of accurate reactions to RAs, and the potential benefits from CP112. It enables to have a better perception of the progress of this event, and serves to illustrate the results and conclusions provided in the investigation report.

## **8. Recommendations**

- 8.1. Airspace authorities should seek to identify occurrences of issue SA01 events and to assess their frequency of occurrence.
- 8.2. The results obtained with CP112E should be confirmed in the context of the work being progressed within RTCA SC147.
- 8.3. CP112E should be implemented as soon a possible to permit rectification of issue SA01.



## Appendix A: SIR working papers and Deliverables

Paper Number	Title	Version	Date	Nature
WP0/01	Project Management Plan	1.1	11 June 2003	Deliverable
WP1/02	Project Management Plan	1.1	13 June 2003	Working document
WP0/03	Notes on the Kick-Off Meeting	1.0	11 June 2003	Working document
WP2/04	Reversal logic of TCAS II version 7.0 – Overview	1.0	02 July 2003	Working Document
WP2/05	WP2 Progress Report #1	1.0	02 July 2003	Working Document
WP1/06	July 1 <sup>st</sup> 2002 Mid-Air Collision – TCAS II Analysis – EUROCONTROL Final Report	2.1	29 July 2003	Deliverable
WP1/07	Animation of the Überlingen Mid-Air Collision	2.1	29 July 2003	Deliverable
WP0/08	Notes on the Progress Meeting #2	1.0	16 July 2003	Working Document
WP2/09	Interim Report – Tasks A & B for CP112 enhancement (SA01 issue rectification)	1.0	26/09/2003	Working Document
WP0/10	Progress report to APSG n°12 (3 & 4 December 2003) on SIR Project	1.0	20/11/2003	Working Document
WP2/11	Interim Report – Tasks A, B & C for CP112 enhancement (SA01 issue rectification)	1.0	08 December 2003	Deliverable
WP2/12	CP112 Enhancement	1.0	10 December 2003	Working Document
WP0/13	Notes on the Progress Meeting n°3	1.0	15 December 2003	Working Document
WP2/14	Interim Report – Tasks A, B, C & D for CP112 enhancement (SA01 issue rectification)	1.0	13-02-04	Working Document
WP2/15	RTCA CP112E – TCAS II change proposal	1.0	28-05-04	Deliverable
WP2/16	Analysis of the set of theoretical encounters sent by FAA	1.0	03-03-04	Working Document
WP2/17	Event of Reims – 18 February 2004	1.0	12-03-04	Working Document
WP0/18	SCRSP WGA paper: Safety Issue SA01 Rectification – Status Report on CP112 Enhancement (CP112)	1.1	01-04-04	Working Document
WP2/19	RTCA SC147: Safety Issue SA01 & Change Proposal CP112 Enhanced	1.1	12-05-04	Working Document
WP1/20	SIR Final Report	1.1	11-06-04	Deliverable
WP0/21	Notes on the Final Progress Meeting n°4	1.0	09-06-04	Working Document

## Appendix B: External references

Reference	Title	Author	Date
EMO0	'July 1st 2002 Mid-Air Collision - TCAS II Analysis – Initial Results' – EMOTION7 version 1.0	EUROCONTROL Überlingen Mid-Air Collision Investigation Team	16 October 2002.
EMO1	Issue analysis report – Issue SA01 – Inappropriate reversal logic initiation in co-ordinated encounters - EMOTION7/WP1/012/D version 1.0	Stéphan Chabert	13 April 2000
EMO2	Issue rectification report – Issue SA01 – Inappropriate reversal logic initiation in co-ordinated encounters - EMOTION7/WP2/024/D version 1.1	Stéphan Chabert	13 October 2000
EMO3	RTCA CP SA01 - EMOTION7/WP2/028/D version 1.1	Thierry Arino & Stéphan Chabert	25 October 2000
EMO4	Study extension – Issue SA01 extension – inappropriate reversal logic initiation in coordinated encounters – EMOTION7/WP2/047/D version 1.0	Stéphan Chabert	21 March 200
EMO5	Analysis of a TCAS II event with late reversal RAs in a coordinated encounter' – EMOTION7/WP3/062/D version 1.0	Eric Vallauri	20 September 2001
EMO6	EMOTION-7 final Report – EMOTION-7/WP5/107D	Stéphan Chabert	24 January 2003
EMO7	Issue SA01 – Status of the EMOTION-7 list of issues – EMOTION7/WP3/094/W version 2.0	Thierry Arino	15 October 2002
EMO8	Issue SA01 –Probability of occurrence of late reversal RAs	Stéphan Chabert	14 June 2002
EMO9	Complementary simulations on the first operational occurrence of issue SA01	Eric Vallauri	29 October 2001
FAA1	FAA William J. Hughes Technical Center final Analysis of EMOTION-7 issue SA01 Working Group A, Langen, Germany	Kathryn Ciaramella	01 October 2002
BFU1	Status report – Factual information' - AX001-1-2/02	BFU	26 August 2002
ACA1	ACASA project – Work Package 1 – Final report on the Safety of ACAS II in Europe – ACASA/WP1.8/210D	CENA/Sofréavia and Qinetiq	March 2002
ACA2	European Encounter Model. Specifications and Probability tables – ACASA/WP1/186D	CENA/Sofréavia and Qinetiq	March 2002
SAR	ICAO 'SARPs' – 'Annex 10, volume IV, Surveillance Radar and Collision Systems	ICAO	1998
SIC	A theoretical example of a collision induced by TCAS II logic – SICASP/WP2/491	Thierry Arino & Francis Casaux	March 1995.

## Appendix C: Operational performance indicators

Three sets of indicators were computed in order to validate CP112E. These indicators are:

- safety related;
- pilot acceptance related;
- compatibility with ATC related.

The set related to safety is composed of:

- the number of RAs without provision of version 7.0 ALIM at CPA 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 with TCAS contribution versus VMD at CPA in 100 ft bins.

The set related to pilot acceptance is composed of:

- 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 2 updates in the sequence;
- the number of TAs ('Traffic Advisory');
- 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.

The set related to compatibility with ATC is composed of:

- the number of RAs;
- the number of RAs only for level-off geometry;
- 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 only for level-off geometry;
- 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.

## Appendix D: Background on the reversal logic

### General principle

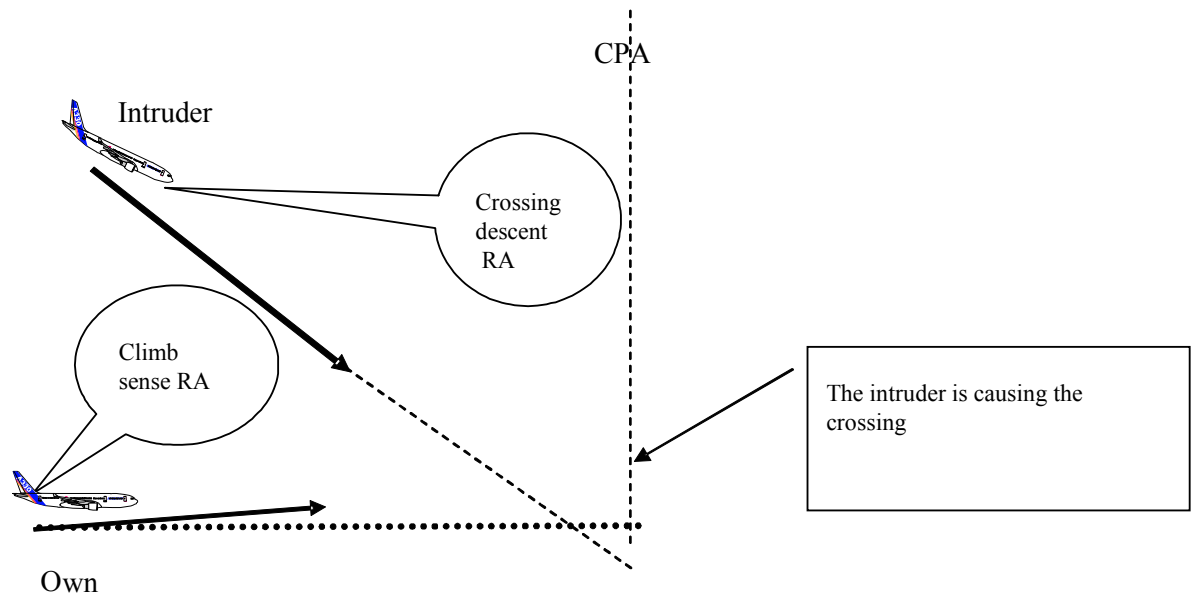
- D.1. The principle of the reversal logic is to monitor, each cycle after the initial RA, that the ongoing RA will provide a sufficient vertical separation at CPA.
- D.2. The reversal logic uses geometrical tests based on the altitudes and vertical rates of the own and intruder aircraft to detect that the ongoing RA is no more efficient, because either own or the intruder thwarted this initial RA. This appendix concentrates on these tests.
- D.3. Once these geometrical tests are passed, the reversal logic compares the efficiency of the ongoing RA with the efficiency of a reversal RA by performing a modelling of both manoeuvres. In case the ongoing RA will not achieve ALIM, and the reversal RA will achieve an acceptable vertical separation at CPA (i.e., a reversal climb RA for own is acceptable if own ends above the intruder at CPA), then the reversal logic triggers the reversal RA.
- D.4. If these tests are passed onboard the aircraft with the lower mode S address, it will trigger a reversal RA. The aircraft with the higher mode S address will reverse only to remain complementary to the new sense decided by the master aircraft.
- D.5. **In the following, the explanations are given assuming that the initial RA of own aircraft is a climb sense RA.** The explanations would be equivalent for a descend sense RA.

### Geometrical test

#### Crossing status of the intruder

- D.6. The way the reversal logic behaves depends on the crossing status of the encounter, as different geometrical tests are used depending on this crossing status.
- D.7. A non-crossing encounter has to meet the geometrical requirements and the modelling requirements only one time to be reversed. A crossing encounter has to meet them at least 2 times in 3 cycles.
- D.8. A crossing encounter is an encounter during which either the intruder or the own aircraft has an RA announced as crossing. A non crossing encounter is an encounter during which the RAs are not crossing onboard own and the intruder.
- D.9. The crossing status is determined as follows.
- D.10. Firstly, and for example, if own has a climb sense RA, the intruder has to be at least 100 ft above for the encounter to be crossing. CPA must also be at least 4 s away.
- D.11. Then, if the RA of own is not positive the intruder is causing the crossing situation.

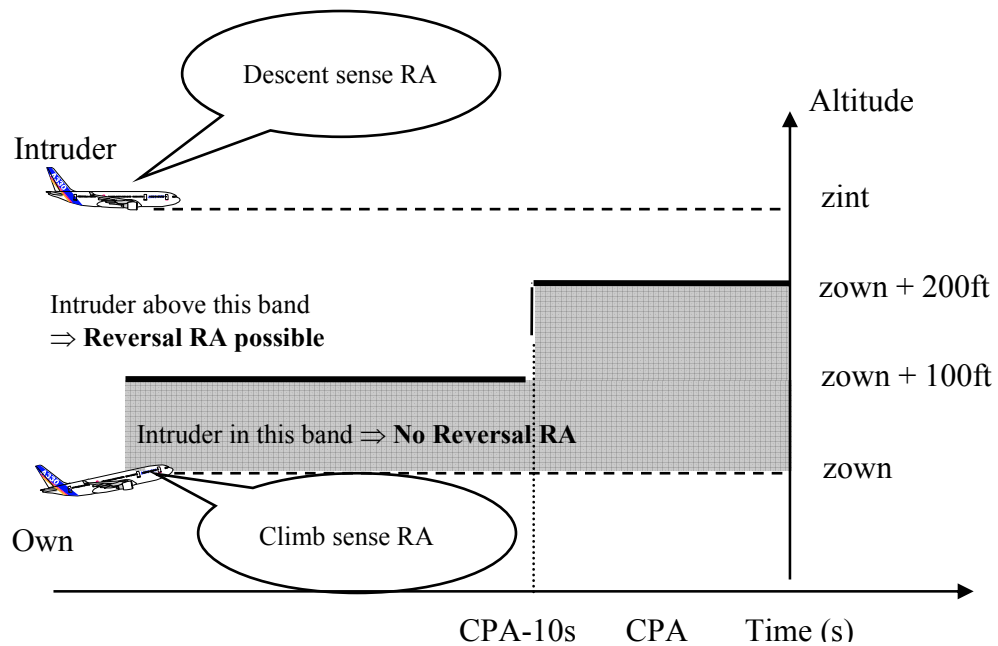
- D.12. If the RA of own is positive, if the intruder is not level and if the projected altitude of intruder at CPA crosses own current altitude, the intruder is causing the crossing. Otherwise own is causing the crossing.



**Figure 41: Version 7.0 - The intruder is causing the crossing RA**

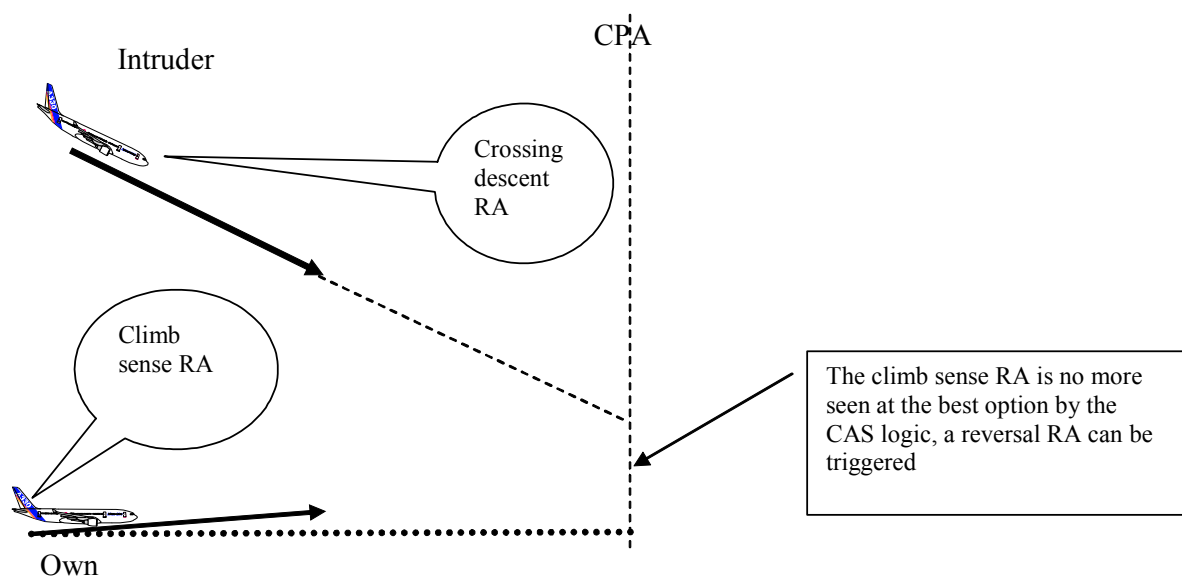
### Geometrical tests for crossing encounters

- D.13. In case of a crossing encounter, a reversal RA will not be triggered when true tau (i.e., the opposite of the range divided by the range rate) becomes lower than 4 s, or when true tau is rising.
- D.14. Then, own aircraft has to be at least 100 ft below the intruder if true tau is higher than 10 s, and 200 ft below in the last 10s.



**Figure 42: Version 7.0 - Crossing encounters - Condition on the vertical separation to reverse**

- D.15. Then, if these conditions are passed, the altitude of own has to be lower than the projected altitude of the intruder at CPA. A typical example of the use of this test is the SA01c geometry.



**Figure 43: Version 7.0 - Crossing encounter – Condition to reverse**

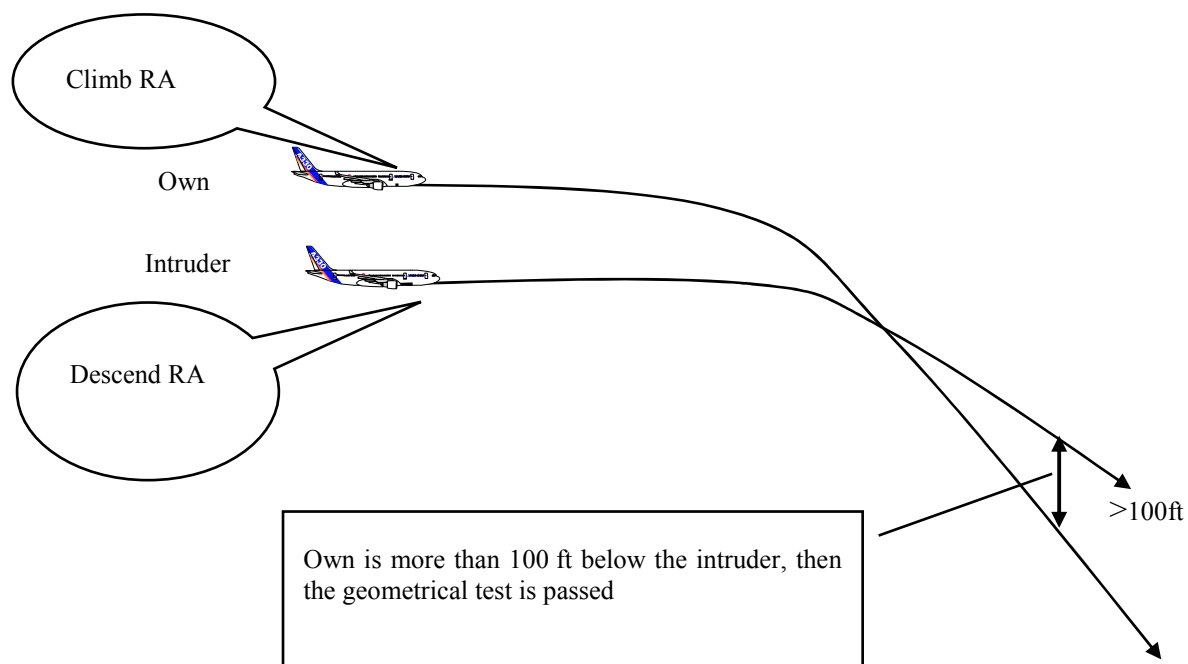
- D.16. Finally in case own is causing the crossing situation, the geometrical test is passed if the reversed sense would achieve a vertical separation at CPA 100 ft better than the current sense. If the intruder is causing the crossing, this condition does not have to be met.



## Geometrical tests for non crossing encounters

### *Equipped/non-equipped intruder*

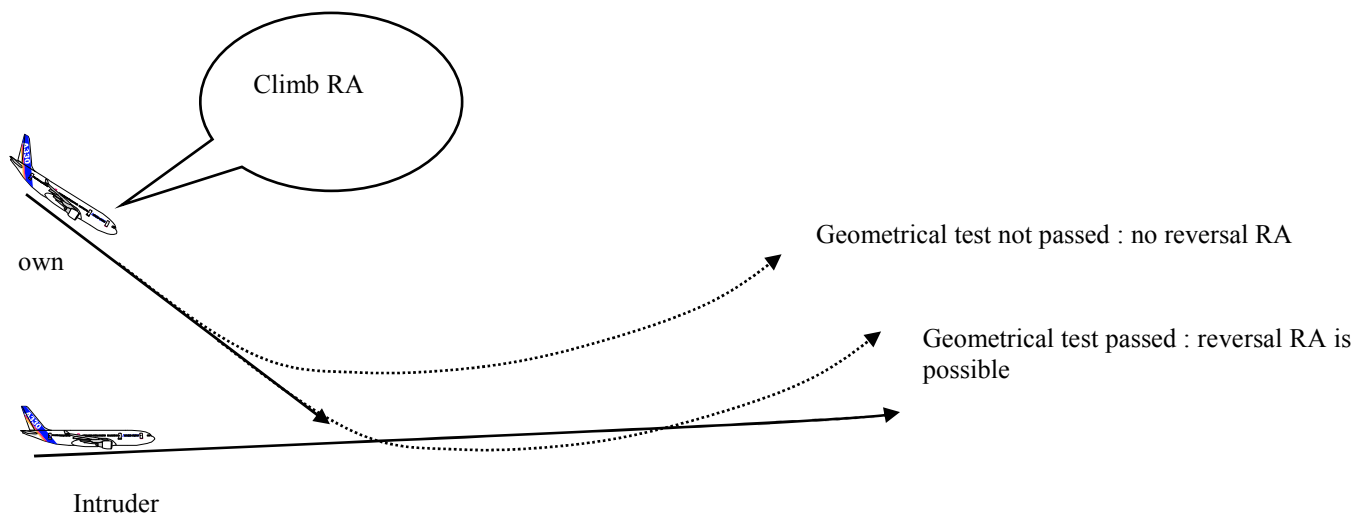
- D.17. When the intruder is either equipped or unequipped, the reversal logic only tests if the intruder is at least 100 ft above own.



**Figure 44: Version 7.0 - Non crossing encounter – Condition to reverse**

### *Unequipped intruder (1)*

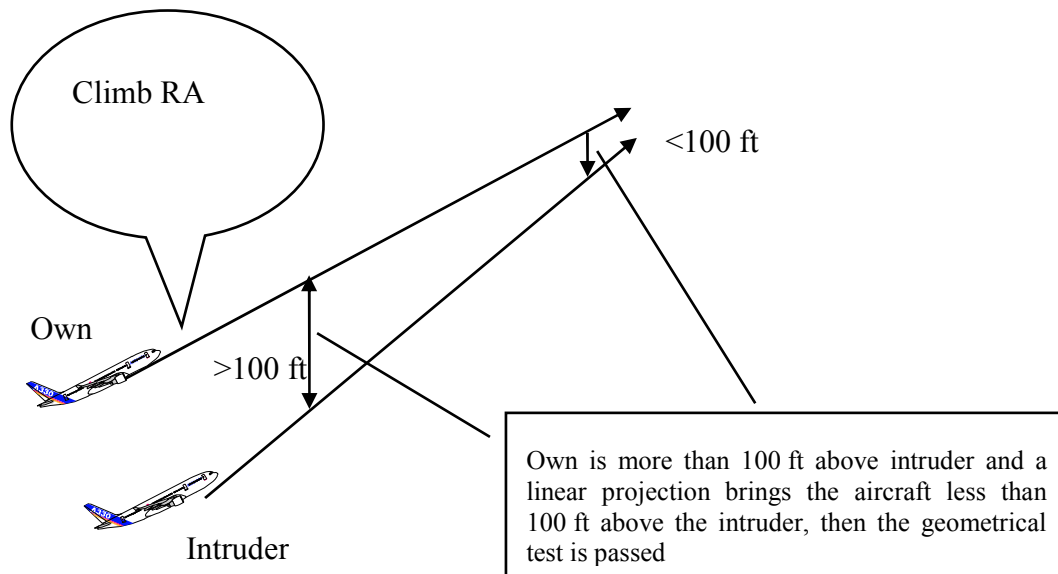
- D.18. When the intruder is less than 100 ft above own and when this intruder is not equipped, the reversal logic tries to detect if own has no more the time to follow its current RA.
- D.19. Own will be declared as late in following the RA only if it is descending with a vertical rate higher than 600 fpm, while it should be climbing to follow its climb RA.
- D.20. The reversal logic tries to avoid 2 altitude crossings. If the reversal logic predicts that the current RA will likely cause 2 altitude crossings, then the geometrical test to reverse is passed. This detection is made using a model of what will happen if own levels-off. If at the time own has levelled off, the trajectories have crossed, than the condition to reverse is met.



**Figure 45: Version 7.0 - Non crossing encounter - Conditions to reverse when own takes a long time to follow his RA - Unequipped intruder**

***Unequipped intruder (2)***

- D.21. In case own and intruder are not level, in the same sense, with own in the sense required by its RA (which has to be a positive vertical RA), if own is at least 100 ft above and not more than 600 ft above intruder, if track firmness is high, then if the separation at CPA is linearly projected to be below 100 ft, then the geometrical test is passed.



**Figure 46: Version 7.0 - Non crossing encounter – Condition to reverse when both aircraft are in the same sense - Unequipped intruder**

- D.22. It is important to notice on the above figure that if own is projected below or more than 100 ft below the intruder at CPA, the geometrical test is also passed. In fact, a climb RA has to bring own above the intruder. A climb RA, which brings own below the intruder is considered as inefficient and can be reversed.

## Coordination

- D.23. The slave aircraft is only reversing to remain complementary to the new sense decided by the master aircraft.

## Appendix E: High level comments on the CP112E pseudocode

- E.1. The goal of this appendix is to describe the 3 main tasks of CP112E in details.

### Process RA\_CNCL

#### Principle

- E.2. This process addresses issue SA01c.
- E.3. This process is called within the process reversal\_proj\_check, when a reversal RA is seen as possible by TCAS II logic version 7.0, in a coordinated encounter involving only two aircraft.
- E.4. When a reversal RA is considered as possible by TCAS II logic version 7.0, RA\_cncl uses the time required to comply with the initial RA, and the time required to comply with a reversal RA so as to determine:
- If the reversal RA will be triggered before the aircraft had time to comply with the initial RA;
  - If the reversal RA has the time to be efficient when considering the time remaining before CPA.
- E.5. The principle of RA\_cncl is to forbid a reversal RA which would be triggered while the aircraft did not even have time to comply with the initial RA, and which would not have time to be efficient before CPA.

#### Details

- E.6. The following details the process RA\_cncl, using the pseudocode.

PROCESS RA\_cncl

IF (ITF.ADOTNE 0)

THEN MY\_TAUUV=-ITF.A/ITF.ADOT;

ELSE MY\_TAUUV=-9999999;

- E.7. These lines compute a tauv like parameter, because the itf.tauv parameter is not recomputed each cycle in the CAS logic. In case the relative tracked vertical rate is nil, the tauv like parameter is set to a fixed arbitrary high value in order to avoid a division by 0.

IF (OWNTENT(7) EQ \$FALSE)

THEN DELTA\_VZ1=MAX(ABS(G.ZDOWN-P.DESRT),ABS(G.ZDMODEL-P.DESRT));

DELTA\_VZ2=MAX(ABS(ITF.ZDINT-P.CLMRT),ABS(TF.INITZDI-P.CLMRT));

ELSE DELTA\_VZ1=MAX(ABS(G.ZDOWN-P.CLMRT),ABS(G.ZDMODEL-P.CLMRT));

DELTA\_VZ2=MAX(ABS(ITF.ZDINT-P.DESRT),ABS(TF.INITZDI-P.DESRT));

T\_NOREV=MAX(DELTA\_VZ1,DELTA\_VZ2)/P.RACCEL+P.QUICKREAC;

- E.8. These lines compute the time T\_NOREV. It represents the time needed for a reversal RA to be efficient from the current situation.
- E.9. It is computed as the difference between the vertical rate of the considered aircraft at a given time and the goal vertical rate, which would be required by a reversal RA, divided by the vertical acceleration in case of a reversal RA, plus 2.5 s.
- E.10. This time takes into account the manoeuvres of own aircraft and of the intruder. For own and the intruder, it is computed using two different vertical rates (one for the current time, another which corresponds to a vertical rate that the aircraft will maybe have time to reach before actually complying with the reversal RA), to take into account the fact that in the SA01c geometry, at the time the reversal RA is going to be triggered, own and/or the intruder may be in an acceleration phase, which will make them change their vertical rates before actually complying with the reversal RA.
- E.11. For own aircraft, the two vertical rates used are G.ZDOWN (tracked vertical rate) and G.ZDMODEL (escape rate to maintain for safe separation), because in the SA01c geometry, one aircraft has time to accelerate to try to reach the vertical rate required by the initial RA before actually complying with the reversal RA. The worst case was considered, therefore G.ZDMODEL was used.
- E.12. For the intruder, these vertical rates are ITF.ZDINT (intruder tracked vertical rate) and TF.INITZDI (intruder tracked vertical rate at the time of the initial RA). TF.INITZDI was used because an equivalent of G.ZDMODEL is not available in the CAS logic for the intruder. G.ZDMODEL was approximated by TF.INITZDI by considering that in the SA01c geometry, in the worst case, the intruder has an initial RA, which is a crossing maintain RA, usually with a high vertical rate, and it has begun to level-off at the time the reversal RA is possible. Therefore, the vertical rate of the intruder at the time of the initial RA can be taken as an approximation of the rate it will maybe try to reach before actually complying with the reversal RA.

- E.13. The resulting time T\_NOREV is computed as the maximum of the four times computed (i.e., 2 times computed for own with G.ZDOWN and G.ZDMODEL and 2 times computed for the intruder with ITF.ZDINT and TF.INITZDI) and is certainly overestimated when compared with the time actually required to reverse, but permits to ensure that any triggered reversal RA will have time to be efficient.

```

IF (((OWNTENT(7) EQ $FALSE AND (TF.INITZO LT TF.INITZI))
OR (OWNTENT(7) EQ $TRUE AND (TF.INITZO GT TF.INITZI)))
AND ((G.TCUR-G.TLASTNEWRA) LT 10 OR G.REV_AVOID GT 0)
AND (ITF.TRTRU LT (T_NOREV+P.QUIKREAC))
AND (MY_TAUUV GT 0 AND MY_TAUUV LT 90))
THEN

```

- E.14. The goal of this test is to ensure that the encounter is a crossing situation, and to avoid the cancellation of some reversal RAs, which would not be hazardous.

- E.15. This test is passed if:

- The encounter is a crossing situation (i.e., own had a climb RA and was below intruder at the time of the initial RA or vice versa); and
- The initial RA is less than 10 s old, or a reversal RA was already cancelled by this procedure. This test was added so as to avoid to cancel reversal RAs triggered more than 10 s after the initial RA, because it was observed that on the available examples of issue SA01c, the problem reversal RAs were triggered in the first ~10 s. In addition, the condition using G.REV\_AVOID ensures that in an encounter for which a reversal RA was not appropriate just before the 10<sup>th</sup> second after the initial RA, the reversal RA would still be cancelled when the time from the initial RA becomes higher than 10 s;
- CPA is closer than T\_NOREV+2.5 seconds. T\_NOREV is the time needed to reverse, for both aircraft. Therefore T\_NOREV+2.5s represents this time plus a margin of 2.5 s. The goal of this test is to ensure that in an encounter during which the aircraft have a time margin to comply with their reversal RAs, the reversal RA will not be cancelled. A short (i.e., 2.5 s) margin was chosen, because in this geometry there is little time before CPA;
- MY\_TAUUV is between 0 and an arbitrary high fixed value. This test was added because in an encounter during which the aircraft are not converging or converging vertically very slowly, it is better to reverse than going on with the ongoing RA. The high fixed value 90 s was set on the basis of events for which this condition was useful, and taking a 30 s margin.

IF (((G.TTOFOLLOW GT (G.TCUR-G.TLASTNEWRA+1)) OR ((G.TCUR-G.TLASTNEWRA) LE P.TV1) OR (G.REV\_AVOID GT 0)) AND ((ABS(ITF.RZ) LT G.ALIM AND ITF.TRTRU LT P.MINRVSTIME) OR ((ITF.TRTRU LT T\_NOREV) AND (MY\_TAUUV LT P.TVTETBL(ITF.LEV)))) AND (ITF.ADOT LT P.ZDTHR))

THEN CLEAR ITF.REVERSE

IF (G.REV\_AVOID EQ 0) THEN  
G.REV\_AVOID=3;

END RA\_cnc;

E.16. Then, the reversal RA is cancelled if:

- Not enough time has elapsed since the initial RA and the pilot likely did not have time to comply with their initial RAs or if a reversal RA was already cancelled. The condition was written G.TTOFOLLOW GT (G.TCUR-G.TLASTNEWRA+1) instead of G.TTOFOLLOW GT (G.TCUR-G.TLASTNEWRA) because testing on the available examples have shown better performance. The time G.TTOFOLLOW is computed as the difference between the vertical rate of own 5 s after the initial RA (i.e., delay time to begin to comply with the RA) and the vertical rate G.ZDMODEL, divided by 0.25g and plus 5 seconds; and
- The aircraft are vertically separated by less than ALIM and CPA is close in time, or CPA is closer (in time) than T\_NOREV and the aircraft are converging fast enough. The condition using ALIM was added, because it was considered that triggering reversal RAs in a crossing situation for aircraft, which did not even had the time to comply with the initial RAs, and which are already close vertically and close in time to CPA, could be hazardous. In this situation, going on with the initial RA appears as a better solution; and
- The aircraft are converging vertically.

E.17. The condition using G.REV\_AVOID was added for the same reason as described above.

E.18. When a reversal RA is cancelled, G.REV\_AVOID is set to 3, so that the time conditions to the initial RA are still verified the cycles following the cycle during which a reversal RA is cancelled.

## RA\_monitoring

### Principle

- E.19. This process is called within reversal\_check.
- E.20. It computes several parameters needed in the process take\_decision.

### Details

PROCESS RA\_monitoring

$T\_TOFOLLOW = \min(\max(10, G.TTOFOLLOW), 15);$

- E.21. G.TTOFOLLOW is the time to comply with the vertical rate required by the initial RA. It is computed as the difference between the vertical rate 5 s after the initial RA (i.e., delay time to begin to comply with the RA) and the vertical rate G.ZDMODEL, divided by 0.25g and plus 5 seconds.
- E.22. The time needed to comply with the vertical rate required by the initial RA is not used directly. It is bounded between 2 values (i.e., 10 s and 15 s), in order:
- To let the crew a minimum time before triggering a reversal RA. The value of 10 s was chosen in order to be consistent with other parts of CP112E (i.e., RA\_cncl), and because testing on the encounter models often showed that reversing in the ~10 s first seconds could be too early. Indeed, the goal of CP112E is to trigger a reversal RA to solve a situation during which one aircraft is not following RAs. Allowing reversal RAs too early would result in some unnecessary reversal RAs being triggered. In addition, 10 s corresponds to the time needed for an aircraft at 1000 fpm (i.e., not level), to comply with an RA requiring a vertical rate of 1500 fpm in the opposite sense assuming a 5 s delay, therefore it appears as an acceptable minimum time. The last reason for choosing 10 s is that for most of the time thresholds used within CP112E, a value equal to a multiple of 2.5 s was chosen, therefore the value of 10 s was appropriate.
  - Not to wait too long before triggering a reversal RA, because a reversal RA triggered too late would be inefficient. The value of 15 s was chosen, because it lets time to the aircraft, even in encounters with high vertical rates, to achieve a manoeuvre, which will bring it to an acceptable escape vertical rate (For example, in 15 s, a standard pilot has time to level-off from 4800 fpm to 0 fpm assuming a 5 s delay). Therefore 15 s is sufficient for most encounters.

IF (ITF.EQP EQ \$TCAS)



THEN  
T\_RZ=MAX(ABS(G.ZDOWN)/P.RACCEL,ABS(ITF.ZDINT)/P.RACCEL)  
+P.QUIKREAC;

ELSE IF (ITF.EQP NE \$TCAS) THEN  
T\_RZ=ABS(G.ZDOWN)/P.RACCEL+P.QUIKREAC;

E.23. These lines compute a simplified time to comply with the vertical rate required by the reversal RA. This time is used to avoid reversal RAs, which would be triggered too late to be efficient (i.e., too close to CPA).

E.24. When the intruder is equipped with TCAS, this time also takes into account its manoeuvre because this aircraft will also receive a reversal RA.

E.25. It was computed, assuming that even if the aircraft only level-off after a reversal RA, this will be beneficial. Therefore, it was computed as a time to go from the current vertical rate to zero, rather than the vertical rate required by the reversal RA (i.e., +/-1500fpm).

Z=G.ZOWN+G.ZDOWN\*MIN(P.TVPETBL(ITF.LEV),ITF.TRTRU);

E.26. This line predicts the altitude of own at CPA, as computed in other parts of the CAS logic.

ZI= ITF.ZINT+(ITF.ZDINT)\*MIN(P.TVPETBL(ITF.LEV),ITF.TRTRU);

ZI\_IN=ITF.ZINT+(ITF.ZDINR)\*MIN (P.TVPETBL(ITF.LEV),ITF.TRTRU);

ZI\_OUT=ITF.ZINT+(ITF.ZDOUTR)\*MIN(P.TVPETBL(ITF.LEV),ITF.TRTRU);

E.27. These lines compute the altitude of the intruder at CPA. The values itf.zdinr and itf.zdoutr (i.e., respectively slacker and steeper bound of rate uncertainty) are also used, to take into account the uncertainty on the tracked vertical rate of the intruder in the decision to reverse or not on the basis of a vertical miss distance.

E.28. As a result, the decision to reverse is not made assuming that the intruder will be at a given position at CPA, but assuming that intruder will be in an altitude interval at CPA.

E.29. The use of these uncertainties was made necessary because of the differences sometimes observed between the tracked vertical rates and the actual vertical rates for some encounters (above 1000 fpm of error for some high vertical rates encounters). These differences can be explained by the fact that in the SA01a/b geometry, the aircraft are often performing rapid manoeuvres, which the vertical tracker has difficulties to cope with.

E.30. To give an example, even an error of 500 fpm on the vertical rate of the intruder, represents an error of 125 ft on the VMD 15 s before CPA. As in the SA01a/b geometry, one can sometimes not obtain a vertical separation better than a few

hundreds of feet, even an uncertainty of 500 fpm can have a dramatic impact on the performance of the reversal logic.

DELTA\_Z\_CPA=Z-ZI;

DELTA\_Z\_MIN=MIN(Z-ZI\_OUT,Z ZI,Z-ZI\_IN);

DELTA\_Z\_MAX=MAX(Z-ZI\_OUT,Z-ZI,Z-ZI\_IN);

- E.31. These lines compute 3 signed VMDs. DELTA\_Z\_CPA is the usual VMD, computes using the tracked vertical rates. DELTA\_Z\_MIN and DELTA\_Z\_MAX are the minimum and the maximum of the VMDs computed taking into account uncertainties.

IF (ITF.EQP EQ \$TCAS)

THEN

IF (ABS(G.ZDOWN) GT 3\*P.ILEV AND ABS(ITF.ZDINT) GT 3\*P.ILEV)  
THEN FACT\_MULT=1.5;

DELTA\_T\_RZ=3.0;

ELSE IF (ABS(G.ZDOWN) GT 2\*P.ILEV AND ABS(ITF.ZDINT) GT 2\*P.ILEV) THEN

FACT\_MULT=1.25;

DELTA\_T\_RZ=3.0;

ELSE IF (ABS(G.ZDOWN) GT 1.5\*P.ILEV AND ABS(ITF.ZDINT) GT 1.5\*P.ILEV)

THEN FACT\_MULT=1.1;

DELTA\_T\_RZ=3.0;

ELSE FACT\_MULT=1.0;

DELTA\_T\_RZ=P.TV1;

ELSE FACT\_MULT=1.0;

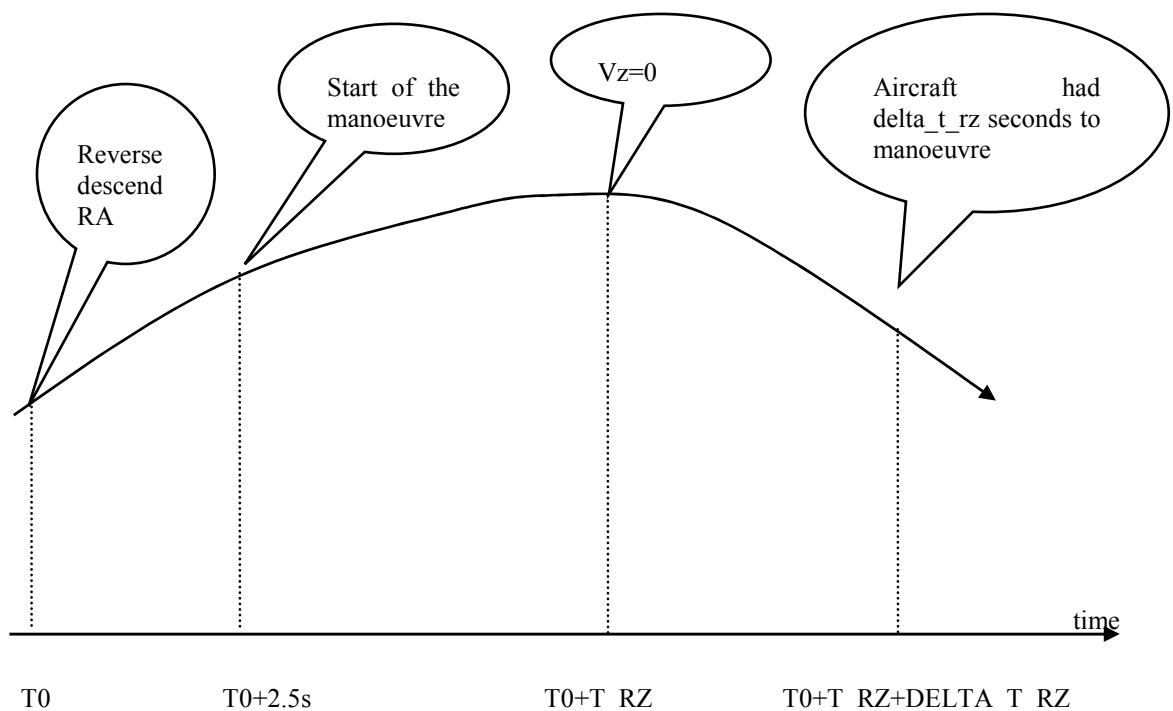
DELTA\_T\_RZ=P.TV1;

- E.32. These lines are used to compute the maximum difference of altitude between the aircraft to allow a reversal “crossing” RA.

- E.33. This computation uses 2 parameters:

- **FACT\_MULT**: this parameter is the factor applied to **P.CROSSTHR** (i.e., 100 ft), to determine this altitude difference;
- **DELTA\_T\_RZ**: is a time margin used to ensure that there is enough time for the aircraft to manoeuvre before CPA.

E.34. The following figure illustrates the way the computation is made and the meaning of the parameters **T\_RZ** and **DELTA\_T\_RZ**, for an aircraft climbing and complying with a reversal descend RA.



**Figure 47: CP112E – Meaning of the time parameters**

- E.35. As mentioned above, **T\_RZ** is the time for both aircraft to level-off, if the encounter is coordinated, or for the equipped aircraft to level-off in a single-equipage encounter.
- E.36. The parameter **FACT\_MULT** is set assuming that one aircraft will at least level-off because of the reversal RA. Even if this aircraft only remains level, a vertical separation will be gained by the other aircraft continuing its climb or descent. The faster the vertical rates, the faster the vertical separation will be gained. Therefore, the higher the vertical rates, the higher **FACT\_MULT** is set. The maximum value of **FACT\_MULT** was chosen on the basis of some encounters, for which a reversal “crossing” RA was necessary, and which are considered as the worst possible situations (e.g., CDG event 22 November 2001), which can be solved with reversal RAs. This led to the choices of maximum altitude differences of:
- 150 ft for vertical rates over 3000 fpm;

- 125 ft for vertical rates over 2000 fpm;
- 110 ft for vertical rates over 1500 fpm;
- 100 ft otherwise;

E.37. The principle for choosing the values of DELTA\_T\_RZ was identical. Only 2 different values were chosen for simplicity.

IF ((G.TCUR-ITF.TCMD) LE P.TV1 AND G.ANYINCREASE EQ \$TRUE)  
THEN FACT\_MULT=FACT\_MULT/4;

E.38. It was considered that triggering a reversal RA too close in time to an increase RA could be hazardous. Firstly a crew, which would receive an increase RA followed by a reversal RA in the opposite sense would be seriously stressed by the repetition of contradictory alerts. Therefore one can assume that this crew would maybe not comply with the reversal RA correctly.

E.39. The reason for this choice is to avoid the triggering of reversal RAs, or to make the triggering more difficult, in a phase during which the aircraft might be accelerating vertically to comply with an increase RA.

E.40. An aircraft at 1500 fpm, which receives an increase RA, will reach 2500 fpm 4 s after the reception of the increase RA. Therefore, in the 5 s following an increase RA, a restriction is applied to the parameter FACT\_MULT. A factor of 1/4 is applied, so as to still allow reversal crossing RAs, but with lower authorized vertical separations, so as to minimize risks: only aircraft nearly at co-altitude will receive reversal RAs leading to a crossing of altitude. The choice of still allowing reversal RAs was made observing that just forbidding reversal crossing RAs in the 5 seconds following an increase RA was very restrictive, especially for encounters in which the aircraft are nearly at co-altitude.

E.41. The choice of the 1/4 restriction was made observing that, taking into account the tracking uncertainties, aircraft tracked at less than ~25 ft vertically can be considered at co-altitude. As in the case of no increase RA being triggered the vertical separation threshold to authorize a reversal crossing RA is close to 100 ft, it was decided to bring it close to 25 ft with a 1/4 factor.

IF ((ITF.TRTRU GE (T\_RZ+DELTA\_T\_RZ)) AND (ITF.RD LT -5\*P.RDTHR)  
AND (ITF.TRTRU GT P.MINRVSTIME))

THEN THRES\_RZ=-FACT\_MULT\*P.CROSSTHR;

ELSE IF ((ITF.TRTRU GE (T\_RZ+DELTA\_T\_RZ)) AND (ITF.RD LT -5\*P.RDTHR))

THEN THRES\_RZ=-FACT\_MULT\*P.CROSSTHR\*0.25;

ELSE THRES\_RZ=0;

E.42. THRES\_RZ represents the vertical separation between the aircraft to authorize a reversal crossing RA.

E.43. The following rules are used:

- A reversal “crossing” RA, for aircraft vertically separated by a maximum of fact\_mult\*100 ft, will be triggered if more than the maximum of T\_rz+delta\_t\_rz and 10 s remains before CPA;
- A reversal “crossing” RA, for aircraft vertically separated by a maximum of ¼\*fact\_mult\*100 ft, will be triggered if more than T\_rz+delta\_t\_rz remain before CPA. This second rule was used to allow the triggering of reversal RAs leading to crossing of altitudes for aircraft vertically separated by only a few feet, with an easier time constraint. As the vertical distance between the aircraft is smaller, the time constraint is made easier to be passed, by removing the 10 s protection. The ¼ factor was chosen so as to be consistent with other restrictions applied in RA\_monitoring to vertical separations to authorize reversal “crossing” RAs, and for which a ¼ factor was chosen.

E.44. These two rules do not apply if the encounter is a slow horizontal convergence encounter, because in such encounters, the computation of the time remaining before CPA can be erroneous. For such encounters, reversal RAs leading to crossing of altitudes are not authorized. The range rate ITF.RD is compared to -5\*P.RDTHR (i.e., 50 ft/s). This threshold was set according to encounters during which it appeared that the parameter ITF.TRTRU was not precise enough. Indeed, it was initially chosen to use a comparison of the range between the aircraft and DMOD, however this criterion was filtering too many reversal RAs at high altitudes. Therefore, a range rate was preferred.

IF (ITF.TRTRU LE P.MINRVSTIME AND ITF.IFIRM LT P.MINFIRM) THEN  
THRES\_RZ=THRES\_RZ+P.CROSSTHR;

ELSE IF (ITF.TRTRU LE P.MINRVSTIME AND ITF.IFIRM EQ P.MINFIRM)  
THEN THRES\_RZ=THRES\_RZ+P.CROSSTHR/2;

E.45. These lines take into account possible low firmness on the vertical tracking. In case the firmness is low, the threshold THRES\_RZ is set higher, in the 10 last seconds before CPA, because it is in this time interval that the reversal RAs can be the most hazardous if triggered on the basis of altitudes and vertical rates, which are inaccurate, because little time remains before CPA.

- E.46. This means for examples, that if own has a climb RA and in the last 10 s before CPA, and in case of a firmness equal to 3 (i.e., excellent firmness), it will be authorized to reverse if the intruder is tracked above. In case the firmness is equal to 2, the intruder will have to be tracked at least 50 ft above. In case the firmness is equal to 1 or 0, the intruder will have to be tracked at least 100 ft above.
- E.47. The value of the restriction was chosen on the basis of several encounters, for which it was observed that the quality of the tracking was poor because of very rapid manoeuvres, and which could lead to unnecessary reversal RAs. The restrictions were chosen so as to try to cope with such encounters, using values close to values already existing in the CAS logic (i.e., using P.CROSSTHR). They were chosen below 100 ft so as not to debase the performance of CP112E too much.

CALL Take\_decision

IN(DELTA\_Z\_MIN,DELTA\_Z\_MAX,DELTA\_Z\_CPA,T\_TOFOLLOW,THRES\_RZ,T\_RZ);

END RA\_monitoring;

## Take\_decision

### Principle

- E.48. This process uses the parameters computed within RA\_monitoring to choose if a reversal RA is an adequate solution.
- E.49. The first part uses the vertical miss distances and parameters such as vertical rates and altitudes, to decide if a reversal RA is adequate in the SA01a or SA01b geometry. The conditions to reverse have to be passed 2 times in the last three cycles for the reversal RA to be triggered. This part is dedicated to SA01a and SA01b encounters, and is intended to cope with the case of own following RAs.
- E.50. In case the first part did not trigger a reversal RA, the second part aims at detecting a manoeuvre opposite to the RAs onboard own aircraft, and in case it succeeds, goes into the reversal modelling taking it into account. This part is dedicated to SA01a encounters, in case own is the one not following the RAs.

### Details

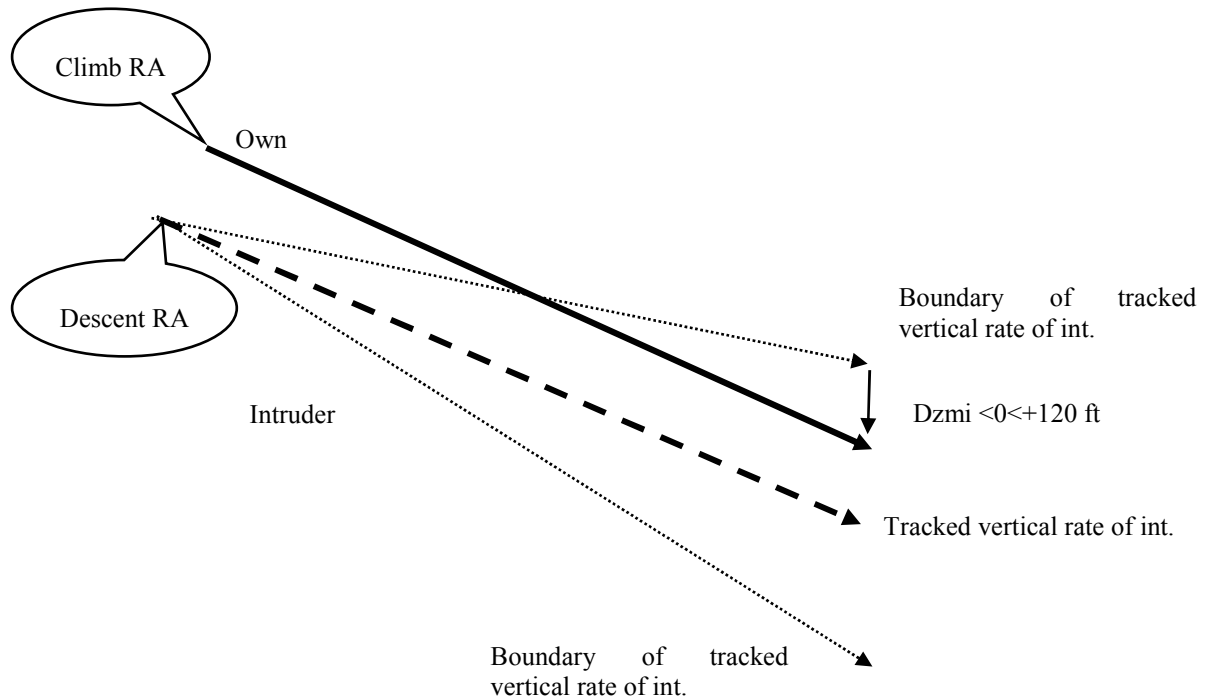
PROCESS Take\_decision

IN (dzmi,dzma,dzc,tfollow,thresrz,trz)

IF ((OWNTENT(7) EQ \$FALSE AND (dzmi LT 1.2\*P.CROSSTHR)) OR (OWNTENT(7) EQ \$TRUE AND (dzma GT-1.2\*P.CROSSTHR)))

- E.51. This line applies the VMD condition to determine if a reversal RA is required.
- E.52. dzmi and dzma are the minimum and maximum values of the predicted VMDs at CPA computed using the tracked vertical rates and the tracked vertical rates with uncertainties. Dzmi and dzma are equal to the parameters DELTA\_Z\_MIN and DELTA\_Z\_MAX of RA\_monitoring.
- E.53. Dzmi and dzma are compared to 120 ft, instead of 100 ft, because it can happen that during an encounter, the VMD is never seen below 100 ft but rather little higher than 100 ft, whereas the encounter ends in NMAC. The value of 120 ft was chosen on the basis of some events, during which the VMDs were never less than 100 ft, but for which reversing was necessary. In addition, it must be pointed out that 20 ft represents an error of 80 fpm 15 s before CPA on the relative vertical rate of the aircraft, therefore such an error on the computation of VMD is not infrequent.
- E.54. The following figure illustrates this condition in case of own having a climb RA. The predicted trajectory of own as seen by the CAS logic is presented in full bold line. The predicted trajectory of the intruder as seen by the CAS logic is presented in dotted bold line. The predicted trajectories of the intruder taking into account the uncertainties on the vertical rates are shown in thin dotted line. The minimum value of the predicted VMDs at CPA is negative on this example, therefore, the condition

is passed, as it is lower than +120 ft. Indeed on this example, taking into account the uncertainties, it is not unlikely that with the ongoing RA, which is a climb RA, own aircraft will be below the intruder at CPA. Therefore, the VMD condition is passed.



**Figure 48: CP112E- VMD condition**

AND (ABS(ITF.RZ) LT P.MAXALTDIFF)

E.55. This condition tests that the aircraft are vertically close. The value P.MAXALTDIFF used is the one already used in the process CROSS\_THROUGH\_CHECK.

AND (G.ZDOWN\*ITF.ZDINT GT 0)

E.56. This line tests if both aircraft evolve in the same sense. This condition is essential in testing that the aircraft are in a SA01a or SA01b like geometry.

AND (ABS(ITF.ZDOWN) GT P.ILEV)  
AND (ABS(ITF.ZDINT) GT P.ILEV)

E.57. These 2 lines test if both aircraft are not level.



AND ((G.TCUR-G.TLASTNEWRA) GE tfollow)

- E.58. This line tests if enough time has elapsed since the initial RA. Otherwise, it is considered that the crew did not have the time to comply with the vertical rate required by the initial RA, therefore it is too early in the encounter to envisage a reversal RA.

AND ((ITF.TRTRU GT trz) OR ((G.TCUR-ITF.TCMD) GT P.TV1 AND G.ANYINCREASE EQ \$TRUE) OR (G.ANYINCREASE EQ \$FALSE))

- E.59. If enough time remains before CPA (i.e., pilot has time to level-off before CPA) or if no increase RA was triggered, then this condition is passed. Otherwise, if an increase RA was triggered in the past 5 s, the condition is not passed and no reversal RA will be triggered.
- E.60. The basic idea is to avoid, when too close in time to CPA, to trigger any reversal RA in a phase during which the aircraft is accelerating vertically, because this can thwart the predictions made by the reversal logic.
- E.61. This test is important to avoid the triggering of reversal RAs close in time of increase RAs, and especially when CPA is already close. This condition was added to cope with some encounters during which the triggering of a reversal RA, close to CPA, and close to an increase RA, could lead to NMACs. Indeed a crew, which would receive an increase RA followed by a reversal RA would be seriously stressed by the repetition of contradictory alerts. Therefore one can assume that this crew would maybe not comply with the reversal RA as a standard pilot. As the aircraft are already close, it appears to be safer to go on with the increase RA, which can solve the debased situation, rather than triggering a reversal RA.
- E.62. The reason for this choice is that CP112E tries to avoid the triggering of reversal RAs, or makes the triggering more difficult, in a phase during which the aircraft might be accelerating vertically to comply with an increase RA.
- E.63. An aircraft at 1500 fpm, which receives an increase RA, will reach 2500 fpm 4 s after the reception of the increase RA. Therefore, in the 5 s following an increase RA, it was considered that the triggering of a reversal RA is dangerous.

AND ((ITF.EQP EQ \$TCAS AND ((OWNTENT(7) EQ \$FALSE AND ITF.RZ LE -thresrz) OR (OWNTENT(7) EQ \$TRUE AND ITF.RZ GE thresrz))) OR (ITF.EQP NE \$TCAS AND ((OWNTENT(7) EQ \$FALSE AND ITF.RZ LE -thresrz) OR (OWNTENT(7) EQ \$TRUE AND ITF.RZ GE thresrz)) AND (G.ZDOWN.G.ZDMODEL GT 0))) THEN

- E.64. This tests applies the vertical distance limitations, using the THRES\_RZ parameter computed in the process RA\_monitoring.

- E.65. The last condition expressed as G.ZDOWN.G.ZDMODEL GT 0 is used for single equipage encounters, to ensure that own aircraft is in the sense required by the ongoing RA before reversing.

ITF.CPT\_REV=ITF.CPT\_REV+1;

- E.66. This line counts the number of times the VMD conditions were passed. A reversal RA will only be possible if this counter reaches 3, 5 or 7. The way the counter ITF.CPT\_REV is used was copied on the counter ITF.VALREVS already used in the reversal logic (see the pseudocode of procedure REVERSAL\_CHECK of CP112E for further information on this counter and on the counter ITF.CPT\_REV).

IF (((G.TCUR-ITF.TCMD) GT 1 AND G.ANYINCREASE EQ \$TRUE) OR  
(G.ANYINCREASE EQ \$FALSE)) THEN

- E.67. This part ensures that a reversal RA will not be triggered in the cycle following an increase RA. This would be a very disturbing situation for the crew, and it is not sure that the aural would be understood well by the crew.

IF (ITF.CPT\_REV EQ 3 OR ITF.CPT\_REV EQ 5 OR  
ITF.CPT\_REV EQ 7)  
THEN  
ITF.REVERSE=TRUE;  
PERFORM Reversal\_modeling;

- E.68. This part ensures that a reversal RA will only be triggered if the VMD conditions were passed at least 2 times in the last 3 cycles.

### Note concerning the process REVERSAL\_CHECK:

A modification was made to the process REVERSAL\_CHECK so as to permit this. In this procedure, the part of TCAS II logic version 7.0 written:

IF (ITF.EQP EQ \$TCAS AND ((G.IDOWN GT ITF.IDINT) OR ((ITF.VALREVS NE  
3, 5, or 7) AND (ITF.INT\_CROSS EQ \$TRUE OR ITF.OWN\_CROSS EQ  
\$TRUE))))  
THEN CLEAR ITF.REVERSE;

had to be modified.

Indeed, in version 7.0, in case the encounter is crossing, the conditions to reverse have to be passed 2 times in the last 3 cycles for the reversal RA to be triggered, thanks to the line presented above. This line was changed in CP112E to

IF (ITF.EQP EQ \$TCAS AND ((G.IDOWN GT ITF.IDINT) OR ((ITF.VALREVS NE  
3, 5, or 7) AND (ITF.CPT\_REV NE  
3, 5, or 7) AND (G.OWN\_FOLLOW EQ \$TRUE) AND (ITF.INT\_CROSS EQ  
\$TRUE OR ITF.OWN\_CROSS EQ \$TRUE))))  
THEN CLEAR ITF.REVERSE;

It was necessary to change this test in CP112E so that in case it was detected that own is not following RAs (G.OWN\_FOLLOW set to false), or in case the VMD test passed at least 2 times (ITF.CPT\_REV set to 3, 5 or 7), a cycle is not lost because the encounter is crossing.

- E.69. The following of the process take\_decision tries to detect a manoeuvre opposite to the RA onboard own aircraft.

IF (((G.TCUR-ITF.TCMD) GT 1 AND G.ANYINCREASE EQ \$TRUE) OR  
(G.ANYINCREASE EQ \$FALSE)) THEN

- E.70. This part ensures that a reversal RA will not be triggered in the cycle following an increase RA. This would be a very disturbing situation for the crew, and it is not sure that the aural would be understood well by the crew.

IF (ITF.REVERSE EQ \$FALSE AND (((OWNTENT(7) EQ \$FALSE) AND (dzc LT  
G.ALIM/2)) OR ((OWNTENT(7) EQ \$TRUE) AND (dzc GT -G.ALIM/2)))) THEN

- E.71. This condition aims at avoiding to trigger a reversal RA when it is likely that the vertical miss distance at CPA will be higher than ALIM/2. The objective is not to go in the following when it is not useful to.

IF (ITF.EQP EQ \$TCAS)  
AND (((ITF.TRTRU GT trz) OR (((G.TCUR-ITF.TCMD) GT P.TV1) AND  
G.ANYINCREASE EQ \$TRUE) OR (G.ANYINCREASE EQ \$FALSE)))

- E.72. This condition has already been explained above.

AND  
(((OWNTENT(5) EQ \$FALSE AND OWNTENT(6) EQ \$FALSE)

- E.73. This line tests if the ongoing RA is positive.

AND (((G.TCUR-G.TLASTNEWRA) GE tfollow) AND (G.TPOSRA EQ  
G.TLASTNEWRA)) OR (((G.TCUR-G.TPOSRA) GT P.TV1) AND ((G.TCUR-  
G.TLASTNEWRA) GE tfollow) AND (G.TPOSRA GT G.TLASTNEWRA)))

- E.74. The goal of this condition is to test if enough time has elapsed since the initial RA.

- E.75. If the initial RA was a positive RA, this is tested comparing the time elapsed since the initial RA with the time required to comply with the vertical rate required by the initial RA tfollow.

- E.76. If the first positive RA was a subsequent RA, then the time elapsed since the initial RA is compared to the time required to comply with the vertical rate required by the initial RA to follow, and the time since the positive RA has to be greater than 5 s. This threshold was fixed to 5 s, because a compromise was required, as a higher threshold would delay the triggering of some reversal RAs by a too important amount.
- E.77. If the above conditions are passed, then it is considered that the pilot had enough time to comply with the initial RA. Therefore the detection of a manoeuvre opposite to the RA is possible.

AND ((G.ZDOWN LT -1.2\*P.ILEV AND ITF.ZDINT LT -P.ILEV  
AND (OWNTENT(7) EQ \$FALSE)) OR (G.ZDOWN GT 1.2\*P.ILEV AND ITF.ZDINT  
GT P.ILEV AND (OWNTENT(7) EQ \$TRUE))))  
OR

- E.78. This condition tests if own aircraft is going opposite to the RAs, and if the intruder is also evolving in the same direction. If own has a climb RA and is descending at more than 1200 fpm, or if own has a descent RA and is climbing at more than 1200 fpm then it is assumed that it is going opposite to the RAs. The value 1200 fpm was chosen rather than 1000 fpm to cope with uncertainties on the tracked vertical rate of own, for some encounters. These uncertainties could lead to the detection of lack of manoeuvres in situations in which it was not necessary to. In addition, the value was not set higher so as not to fail in detecting lacks of manoeuvres in encounters in which it is necessary to.

((OWNTENT(5) EQ \$TRUE AND OWNTENT(6) EQ \$FALSE)

This line tests if the ongoing RA is a don't climb or don't descend RA. VSL (i.e., VSL 500 fpm, 1000 fpm or 2000 fpm) RAs are not treated, as explained in the report, because it was judged impossible to find an operational criterion to detect an opposite manoeuvre to a VSL RA.

AND  
((G.TCUR-G.TLASTNEWRA) GE tfollow)

- E.79. This line tests if enough time has elapsed since the initial RA, by comparing the time elapsed since the initial RA to the time required to comply with the vertical rate required by the initial RA to follow.

AND  
((G.ZDOWN LT -1.5\*P.ILEV AND ITF.ZDINT LT -P.ILEV AND  
(OWNTENT(7) EQ \$FALSE)) OR (G.ZDOWN GT 1.5\*P.ILEV AND ITF.ZDINT GT  
P.ILEV AND (OWNTENT(7) EQ \$TRUE))))

- E.80. This condition tests if own aircraft is going opposite to the RAs, and if the intruder is also evolving in the same direction. If own has a climb sense RA and is descending at more than 1500 fpm, or if own has a descent sense RA and is

climbing at more than 1500 fpm then it is assumed that it is going opposite to the RAs. The value 1500 fpm was chosen because a don't climb or don't descend RA does not require a vertical rate as high as with a positive RA.

THEN

IF (ITF.TRTRU GT P.MINRVSTIME AND ITF.IFIRM LT P.MINFIRM) THEN  
THRES\_RZ=THRES\_RZ+P.CROSSTHR/2;

ELSE IF (ITF.TRTRU GT P.MINRVSTIME AND ITF.IFIRM EQ P.MINFIRM)  
THEN THRES\_RZ=THRES\_RZ+P.CROSSTHR/4;

E.81. These twolines are meant to increase the threshold THRES\_RZ in case the firmness of the tracking is not excellent, before the 10 last seconds before CPA. This was done because in the case of a detection of a manoeuvre opposite to the RA, the reversal RA does not wait 2 positive detections to be triggered. As a result a protection against poor vertical tracking was necessary.

E.82. Testing showed that such protection was mainly necessary close to CPA (i.e., in the 10 last seconds), because far from CPA crews have time to manoeuvre. Therefore the thresholds applied are lower than in RA\_monitoring, and such conditions are not applied in the part of take\_decision using VMD, because the need for it was not observed while testing CP112E, and because doing it has an impact on the safety benefits brought by CP112E because of the need of two positive detections to reverse. In addition, this part has already a protection, as the conditions to reverse have to be passed at least twice for a reversal RA to be triggered.

IF ((ITF.RZ LE -thresrz AND OWNTENT(7) EQ \$FALSE) OR (ITF.RZ GE thresrz AND OWNTENT(7) EQ \$TRUE))

THEN

ITF.REVERSE=TRUE;

G.OWN\_FOLLOW=FALSE;

E.83. This line sets the flag G.OWN\_FOLLOW to false, indicating that own is not following RAs. This flag is used within in the process reversal\_modeling, called hereafter.

PERFORM Reversal\_modeling;

ZI25=ITF.ZINT+2.5\*ITF.ZDINT;

ZO25=G.ZOWN+2.5\*G.ZDOWN;

IF (ITF.REVERSE EQ \$TRUE) THEN

IF (ITF.ADOT LT -P.OLEV OR ABS(ITF.RZ) GT P.CROSSTHR/4) THEN

IF (((OWNTENT(7) EQ \$FALSE AND (ITF.RZ LT 0) AND (ZO25 GT ZI25)) OR (OWNTENT(7) EQ \$TRUE AND (ITF.RZ GT 0) AND (ZO25 LT ZI25))) AND (ITF.TRTRU LE 1.25\*P.MINRVSTIME)) THEN

ITF.REVERSE=FALSE;

- E.84. This part was added to cope with some geometries in which a reversal RA can be hazardous, despite the fact that all the above conditions are passed.
- E.85. This geometry is for an aircraft having time to cross the altitude of the intruder before actually following the reversal RA (in the 2.5 s reaction time, before actually manoeuvring), close in time to CPA. This closeness to CPA was measured comparing ITF.TRTRU to 12.5 s, because it was observed that reversal RAs up to 11 s before CPA could lead to this issue, on the different encounter models used in the development of CP112E.
- E.86. These lines test if with the current vertical rates, the altitudes of own and intruder projected a few seconds after the current time will cross. If yes, the reversal RA is not issued, because it is likely to be hazardous. The time to project the altitudes was chosen as 2.5 s, which is the reaction time for reversal RAs.
- E.87. This condition is not used for aircraft very close vertically (i.e., vertical separation less than 25 ft), and with a slow convergence, so as to avoid the cancellation of some necessary reversal RAs.

END Take\_decision;

## Appendix F: CP112E

DATE: 28 / 05 / 04 No.: CP112E

TCAS II Version: DO-185A (v7) X Other (Specify) \_\_\_\_\_

MOPS Function Area: Surveillance \_\_\_\_\_ Display Req'ts \_\_\_\_\_ CRS \_\_\_\_\_

CAS Pseudocode X Test Suites \_\_\_\_\_ Other \_\_\_\_\_

Priority: URGENT X Necessary \_\_\_\_\_ Optional \_\_\_\_\_

CP Type: ERROR \_\_\_\_\_ Enhancement X Evaluation Request \_\_\_\_\_

Editorial (Logic) \_\_\_\_\_ Editorial (Text) \_\_\_\_\_

### Description of Problem/Issue:

When compared with the previous TCAS II version 6.04a, one significant change included in TCAS II version 7.0 is the sense reversals that are now permitted in TCAS-TCAS encounters. This change was introduced to cope with changing situations where the original sense has clearly become the wrong thing to do, in particular when one of the pilots decides not to follow RAs.

Within the EMOTION7 Project, three areas of improvements have been identified for this change on the CAS logic area. These areas of improvement were referenced as issue SA01a, issue SA01b and issue SA01c.

#### Issue SA01a

An area of improvement for the reversal logic of TCAS II logic version 7.0 has been identified in early 2000. It deals with the late issuance of reversal RAs in a geometry in which it is necessary to have them triggered well before.

The issue has been identified for an encounter set, which is representative of operationally realistic scenarios: two aircraft are flying at the same FL and are converging in range with a very late ATC instruction inducing an intruder manoeuvre that thwarts the initial RAs.

The EMOTION7 Project has provided evidences that the SA01a scenario was indeed happening in operational use (e.g., Japanese event January 2001, Belgian

event July 2001, French event November 2001, German event February 2002, French Event March 2002, Überlingen collision July 2002)

### **Issue SA01b**

The potential for failure to initiate the reversal logic has also been identified either in single equipage encounters or similarly in double equipage encounters but with one TCAS II either in stand-by mode or in TA-only mode.

The geometry involved is comparable to the one already described for issue SA01a.

### **Issue SA01c**

Another area of improvement for the reversal logic has also been identified in early 2000. This area deals with the undesirable issuance of reversal RAs in coordinated crossing encounters when both pilots follow correctly their RAs. Indeed, in some cases not observed with TCAS II version 6.04a, the TCAS version 7.0 contribution is decreasing the vertical separation at CPA.

The issue has been identified for an encounter set that is representative of operationally realistic scenarios (i.e., altitude bust).



**See documentation:**

- EMOTION7/WP-1/012/D Version 1.0 - Issue analysis report - Issue SA01 - Inappropriate reversal logic initiation in co-ordinated encounters – Stéphane Chabert - 13/04/2000
- EMOTION7/WP-2/024/D Version 1.1 - Issue rectification report - Issue SA01 - Inappropriate reversal logic initiation in co-ordinated encounters – Stéphane Chabert - 13/10/2000
- EMOTION7/WP2/047/D Version 1.0 - Study extension – Issue SA01 extension – Inappropriate reversal logic initiation in coordinated encounters — Stéphane Chabert - 21/03/2001.
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- EMOTION7/WP3/074W Version 1.0 – Complementary simulations on the first operational occurrence of issue SA01 – Eric Vallauri – 29/10/01
- EMOTION7/WP3/091D Version 1.1 – Issue SA01 – Probability of occurrence of late reversal RAs– Stéphane Chabert – 14/06/02
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- SIR/WP1/06D Version 2.1 - July 1st 2002 Mid-Air Collision – TCAS II Analysis – EUROCONTROL Final Report - 29-07-03
- SIR/WP1/07D Version 2.1 - Animation of the Bodensee Mid-Air Collision - 29-07-03
- SIR/WP2/09/W Version 1.0 – Interim Report Tasks A and B for the CP112 enhancement (Issue SA01 rectification) – Stéphane Chabert – 26/09/2003
- SIR/WP2/11/D Version 1.1 – Interim Report - Tasks A, B and C for the CP112 enhancement (Issue SA01 rectification) - Stéphane Chabert – 18/12/2003
- SIR/WP2/14/D Version 1.0 – Interim Report - Tasks A, B, C and D for the CP112 enhancement (Issue SA01 rectification) - Stéphane Chabert - 10/02/2004
- SIR/WP3/20D Version 1.0 – SIR final report – Stéphane Chabert – June 2004

**Proposed Resolution:**

CP112E is introducing changes to TCAS II logic version 7.0 in order to address issues SA01a, SA01b and SA01c.

**Treatment of issues SA01a and SA01b**

CP112E aims at detecting that the ongoing encounter is corresponding to the SA01a or SA01b geometry (i.e., two aircraft vertically close, climbing and descending

towards the same point), and then possibly triggers a reversal RA if required. The detection is made using 2 means:

- By detecting that own is not following its RAs, and is manoeuvring opposite to it. In this case, the modelling performed in the reversal logic takes into account the fact that own is not following RAs;
- By using the Vertical Miss distance at CPA. This parameter is used to circumvent the mode S priority rule, which prevents the triggering of reversal RAs after the detection that own is going opposite to RAs, when own is the slave aircraft.

In addition, the conditions to reverse in case the SA01a or SA01b geometry is detected are weakened when compared with TCAS II logic version 7.0.

### **Treatment of issue SA01c**

CP112E detects the SA01c geometry and prevents TCAS II logic version 7.0 to trigger a reversal RA when it is likely to be hazardous. In case the reversal RA would be triggered before the crew had time to comply with the initial RA, and would be triggered too late to be efficient, CP112E prevents its triggering.

**Requester:**      Stéphan Chabert

**Organization:**      Eurocontrol/Sofreavia/CENA

**DISPOSITION OF CHANGE PROPOSAL (Per RWG):**

**DATE OF DISPOSITION**      \_\_\_\_ / \_\_\_\_ / \_\_\_\_

**Rejected**      \_\_\_\_      **Deferred**      \_\_\_\_      **[Review Date:**      \_\_\_\_ / \_\_\_\_ / \_\_\_\_ **]**

**Accepted**      \_\_\_\_      **Modified**      \_\_\_\_      **Withdrawn**      \_\_\_\_

**DISPOSITION OF CHANGE:**

**On Hold**      \_\_\_\_      **Designing**      \_\_\_\_      **Testing**      \_\_\_\_      **Done**      \_\_\_\_      **[Date:**      \_\_\_\_ / \_\_\_\_ / \_\_\_\_ **]**

**Final Approval of Changes:**

**Signature:**      \_\_\_\_\_

**Date:**      \_\_\_\_ / \_\_\_\_ / \_\_\_\_

## Table of Contents

TASK RESOLUTION;	150
PROCESS New_threat_file_entry;	154
PROCESS Process_new_or_continuing_threat;	158
PROCESS Reversal_check;	162
PROCESS Reversal_proj_check;	167
PROCESS Reversal_modeling;	171
PROCESS RA_cncl;	175
PROCESS RA_monitoring;	177
PROCESS Take_decision;	179
New Variables	183

## High level Pseudocode

## BEFORE

### TASK RESOLUTION;

IN (WL entry);

Set up pointers to ITF and TF using Working List pointer entry;

REPEAT WHILE (in coordination lock state);

<Loop while waiting for coordination lock state to end. Performance

Monitor should recognize when TCAS has been locked for more than

P.UNLOCK seconds and take appropriate action.>

ENDREPEAT;

SET G.COLOCK using uninterruptible test and set instruction;

Save lock time;

IF (threat status= 'terminate')

THEN PERFORM Update\_threat\_file\_own; <delete TF entry if no threat intent>

CALL DELETE\_RESOLUTION\_ADVISORY <remove RA unless needed for>

IN (pointer to RA to delete);

<other threat>

CLEAR flags for reversal/increase logic;

Set range-range rate product counter to zero;

ELSEIF (status='new')

THEN indicate vertical Resolution Advisory about to be chosen;

PERFORM New\_threat\_file\_entry;

PERFORM Select\_sense;

Save time of latest RA due to new threat;

OTHERWISE save previous cycle's advisory; <status='continuing'>

IF (status is 'new' or 'continuing')

THEN PERFORM Process\_new\_or\_continuing\_threat;

CALL COORDINATION\_UNLOCK; <Section 3>

END RESOLUTION;

## High level Pseudocode

## AFTER

### TASK RESOLUTION;

IN (WL entry);

Set up pointers to ITF and TF using Working List pointer entry;

REPEAT WHILE (in coordination lock state);

<Loop while waiting for coordination lock state to end. Performance

Monitor should recognize when TCAS has been locked for more than

P.UNLOCK seconds and take appropriate action.>

ENDREPEAT;

SET G.COLOCK using uninterruptible test and set instruction;

Save lock time;

IF (threat status= 'terminate')

THEN PERFORM Update\_threat\_file\_own; <delete TF entry if no threat intent>

CALL DELETE\_RESOLUTION\_ADVISORY <remove RA unless needed for>

IN (pointer to RA to delete);

<other threat>

CLEAR flags for reversal/increase logic;

Set range-range rate product counter to zero;

ELSEIF (status='new')

THEN indicate vertical Resolution Advisory about to be chosen;

PERFORM New\_threat\_file\_entry;

PERFORM Select\_sense;

Save time of latest RA due to new threat;

Save altitudes and vertical rates of own and intruder;

Initialize flag to avoid triggering of a reversal RA in an encounter after a reversal RA was forbidden;

OTHERWISE save previous cycle's advisory; <status='continuing'>

IF (status is 'new' or 'continuing')

THEN PERFORM Process\_new\_or\_continuing\_threat;

CALL COORDINATION\_UNLOCK; <Section 3>

END RESOLUTION;

## Low level Pseudocode

## BEFORE

### TASK RESOLUTION;

IN (WL entry);

Pointer to ITF = WL.IPTR, pointer to TF= ITF.TPTR;

REPEAT WHILE (G.COLOCK EQ \$TRUE);

<Loop while waiting for coordination lock state to end. Performance  
Monitor should recognize when TCAS has been locked for more than  
P.TUNLOCK seconds and take appropriate action.>

ENDREPEAT;

SET G.COLOCK using uninterruptible test and set instruction;

G.TCLOCK = REALTIME.TCLOCK;

IF (WL.STATUS EQ \$TERM)

THEN PERFORM Update\_threat\_file\_own;

CALL DELETE\_RESOLUTION\_ADVISORY

IN (OLDPOI);

CLEAR ITF.REVERSE, ITF.INCREASE, ITF.REV\_RA;

ITF.RRD\_COUNT = 0;

ELSEIF (WL.STATUS EQ \$NEW)

THEN CLEAR All bits in OWNTENT;

SET OWNTENT(4);

PERFORM New\_threat\_file\_entry;

PERFORM Select\_sense;

G.TLASTNEWRA = G.TCUR;

OTHERWISE OWNTENT = TF.PERMTENT;

IF (WL.STATUS EQ \$NEW OR WL.STATUS EQ \$CONT)

THEN PERFORM Process\_new\_or\_continuing\_threat;

CALL COORDINATION\_UNLOCK; <Section 3>

END RESOLUTION;

## Low level Pseudocode

## AFTER

### TASK RESOLUTION;

IN (WL entry);

Pointer to ITF = WL.IPTR, pointer to TF= ITF.TPTR;

REPEAT WHILE (G.COLOCK EQ \$TRUE);

<Loop while waiting for coordination lock state to end. Performance Monitor should recognize when TCAS has been locked for more than P.TUNLOCK seconds and take appropriate action.>

ENDREPEAT;

SET G.COLOCK using uninterruptible test and set instruction;

G.TCLOCK = REALTIME.TCLOCK;

IF (WL.STATUS EQ \$TERM)

THEN PERFORM Update\_threat\_file\_own;

CALL DELETE\_RESOLUTION\_ADVISORY

IN (OLDPOI);

CLEAR ITF.REVERSE, ITF.INCREASE, ITF.REV\_RA;

ITF.RRD\_COUNT = 0;

ELSEIF (WL.STATUS EQ \$NEW)

THEN CLEAR All bits in OWNTENT;

SET OWNTENT(4);

PERFORM New\_threat\_file\_entry;

PERFORM Select\_sense;

G.TLASTNEWRA = G.TCUR;

TF.INITZDI=ITF.ZDINT;

TF.INITZDO=G.ZDOWN;

TF.INITZI=ITF.ZINT;

TF.INITZO=G.ZOWN;

G.REV\_AVOID=0;

OTHERWISE OWNTENT = TF.PERMTENT;

IF (WL.STATUS EQ \$NEW OR WL.STATUS EQ \$CONT)

THEN PERFORM Process\_new\_or\_continuing\_threat;

CALL COORDINATION\_UNLOCK; <Section 3>

END RESOLUTION;



## High level Pseudocode

## BEFORE

PROCESS New\_threat\_file\_entry;

<This process initializes existing or creates new threat file entry>

IF (intruder is Mode S-equipped)

THEN Search for threat file entry with same discrete address;

IF (matching entry not found)

THEN create new threat file entry;

        Save threat's Mode S ID, if any, in TF entry;

        Clear RA and intent indices;

        Set threat intent refresh timer to initial negative value;

        <indicates no intent received>

        Clear advisory bit string;

        <cleared bit 4 indicates no advisory present>

Save TF back pointer to ITF;

Indicate new threat for display;

Initialize the tiebreaker reversal flag;

Initialize the reversal modeling validity counter;

Initialize the geometric reversal flag;

Set own RA change timer to current time;

Save TF pointer in ITF;

END New\_threat\_file\_entry;

## High level Pseudocode

## AFTER

PROCESS New\_threat\_file\_entry;

<This process initializes existing or creates new threat file entry>

IF (intruder is Mode S-equipped)

THEN Search for threat file entry with same discrete address;

IF (matching entry not found)

THEN create new threat file entry;

        Save threat's Mode S ID, if any, in TF entry;

        Clear RA and intent indices;

        Set threat intent refresh timer to initial negative value;

        <indicates no intent received>

        Clear advisory bit string;

        <cleared bit 4 indicates no advisory present>

Save TF back pointer to ITF;

Indicate new threat for display;

Initialize the tiebreaker reversal flag;

Initialize the reversal modeling validity counter;

Initialize SA01 reversal flag;

Initialize the geometric reversal flag;

Set own RA change timer to current time;

Save TF pointer in ITF;

END New\_threat\_file\_entry;

## Low level Pseudocode

## BEFORE

PROCESS New\_threat\_file\_entry;

```
CLEAR SUCCESS;  
IF (ITF.EQP NE $ATCRBS)  
  THEN REPEAT WHILE (more entries in TF AND SUCCESS EQ $FALSE)  
    IF (ITF.IDINT EQ TF.ID)  
      THEN SET SUCCESS;  
      ELSE select next TF entry;  
    ENDREPEAT;  
IF (SUCCESS EQ $FALSE)  
  THEN create new TF entry;  
    TF.ID=ITF.IDINT;  
    TF.POOWRAR, TF.POTHRAR(1),TF.POTHRAR(2)=0;  
    TF.TTHLRMC=P.INIT;  
    CLEAR All bits in TF.PERMTENT;  
    TF.IPTR=ITF.IROW;  
    SET TF.NEW;  
    CLEAR ITF.TIEBREAKER_REVERSAL;  
    ITF.VALREVS=0;  
    CLEAR ITF.REV_GEOM;  
    ITF.TCMD=G.TCUR;  
    ITF.TPTR=address of TF entry;
```

END New\_threat\_file\_entry;

## Low level Pseudocode

## AFTER

PROCESS New\_threat\_file\_entry;

CLEAR SUCCESS;

IF (ITF.EQP NE \$ATCRBS)

THEN REPEAT WHILE (more entries in TF AND SUCCESS EQ \$FALSE)

IF (ITF.IDINT EQ TF.ID)

THEN SET SUCCESS;

ELSE select next TF entry;

ENDREPEAT;

IF (SUCCESS EQ \$FALSE)

THEN create new TF entry;

TF.ID=ITF.IDINT;

TF.POOWRAR, TF.POTHRAR(1),TF.POTHRAR(2)=0;

TF.TTHLRMC=P.INIT;

CLEAR All bits in TF.PERMTENT;

TF.IPTR=ITF.IROW;

SET TF.NEW;

CLEAR ITF.TIEBREAKER\_REVERSAL;

ITF.VALREVS=0;

ITF.CPT\_REV=0;

CLEAR ITF.REV\_GEOM;

ITF.TCMD=G.TCUR;

ITF.TPTR=address of TF entry;

END New\_threat\_file\_entry;

## High level Pseudocode

## BEFORE

PROCESS Process\_new\_or\_continuing\_threat;

IF (status is 'continuing' AND threat is established)

THEN PERFORM Reversal\_check;

PERFORM Select\_advisory;

IF (multiple threats this cycle)

THEN IF (own's advisory this cycle against current threat is not same as previous cycle)

THEN save own's advisory this cycle against current threat;

ELSE PERFORM Update\_threat\_file\_own;

CALL RESOLUTION\_UPDATE

IN (advisory to delete, advisory to add);

IF (status is 'continuing' AND threat is established)

THEN PERFORM increase\_check;

END Process\_new\_or\_continuing\_threat

## High level Pseudocode

## AFTER

PROCESS Process\_new\_or\_continuing\_threat;

IF (5 seconds have elapsed since the initial RA against the threat)  
    THEN PERFORM compute time to follow initial RA;  
ELSE IF (less than 5 seconds have elapsed since initial RA against this threat)  
    THEN Set the computed time to follow initial RA to 0;

IF (status is 'continuing' AND threat is established)  
    THEN PERFORM Reversal\_check;  
PERFORM Select\_advisory;  
IF (multiple threats this cycle)  
    THEN IF (own's advisory this cycle against current threat is not same as previous cycle)  
        THEN save own's advisory this cycle against current threat;  
    ELSE PERFORM Update\_threat\_file\_own;  
        CALL RESOLUTION\_UPDATE  
        IN (advisory to delete, advisory to add);  
IF (status is 'continuing' AND threat is established)  
    THEN PERFORM increase\_check;

END Process\_new\_or\_continuing\_threat

## Low level Pseudocode

## BEFORE

### TASK Process\_new\_or\_continuing\_threat;

```
IF (WL.STATUS EQ $CONT AND ITF.KHIT EQ 3)
    THEN PERFORM Reversal_check;
PERFORM Select_advisory;
IF (G.MACFLG EQ $TRUE)
    THEN IF (OWNTENT NE ITF.TPTR->TF.PERMTENT)
        THEN ITF.TPTR->TF.PERMTENT = OWNTENT;
    ELSE PERFORM Update_threat_file_own;
        Save current TF Pointer;
        CALL RESOLUTION_UPDATE
            IN (OLDPOI,OPTR);
        Restore current TF pointer;
IF (WL.STATUS EQ $CONT AND ITF.KHIT EQ 3)
    THEN PERFORM Increase_check;

END Process_new_or_continuing_threat;
```

## Low level Pseudocode

## AFTER

### PROCESS Process\_new\_or\_continuing\_threat;

```
IF (G.TCUR EQ G.TLASTNEWRA+P.TV1)
    THEN G.TTOFOLLOW=ABS(G.ZDOWN-G.ZDMODEL)/P.VACCEL+P.TV1;
    ELSE IF (G.TCUR LT G.TLASTNEWRA+P.TV1)
        THEN G.TTOFOLLOW=0;

IF (WL.STATUS EQ $CONT AND ITF.KHIT EQ 3)
    THEN PERFORM Reversal_check;
PERFORM Select_advisory;
IF (G.MACFLG EQ $TRUE)
    THEN IF (OWNTENT NE ITF.TPTR->TF.PERMTENT)
        THEN ITF.TPTR->TF.PERMTENT = OWNTENT;
    ELSE PERFORM Update_threat_file_own;
        Save current TF Pointer;
        CALL RESOLUTION_UPDATE
            IN (OLDPOI,OPTR);
        Restore current TF pointer;
IF (WL.STATUS EQ $CONT AND ITF.KHIT EQ 3)
    THEN PERFORM Increase_check;

END Process_new_or_continuing_threat;
```



## High level Pseudocode

## BEFORE

### PROCESS Reversal\_check;

```
CLEAR flag to consider an increase rate RA;
IF (no reversal has been issued)
    THEN IF (current RA is crossing)
        THEN IF (P.MIN_RI_TIME sec. or more remain AND range TAU did not start
            rising when the threat was more than P.NAFRANGE miles away)
            THEN calculate int's proj. alt. at CPA using ITF.ZDINT;
            PERFORM Reversal_proj_check;
            IF (reversal not selected AND time to CPA is not sufficient for
                reversal against threat which may be close in altitude AND
                intruder is not TCAS-equipped)
                THEN SET flag to consider increase rate RA;
            ELSE PERFORM Cross_through_check;
IF (past validity sequence is '100', '101', '110', or '111')
    THEN remove the leading '1'; <Subtract '100'>
        <No need to remove leading '0' if past validity sequence is '000', '001', '010', or '011'>
    Left shift sequence 1 bit; <Multiply by 2>
    <New sequence is '000', '010', '100', or '110'>
IF (reversal flag set this cycle)
    THEN add '1' to new sequence;
        <Sequence becomes '001', '011', '101', or '111'>
    <If reversal flag not set this cycle, sequence remains '000', '010', '100', or '110'>
    IF (intruder is TCAS-equipped AND ((own Mode S ID is higher) OR ((past validity
        sequence is not '011', '101', or '111') AND (current RA is crossing))))
        THEN CLEAR reversal flag;
    ELSE IF (intruder is TCAS-equipped OR only 1 threat has been declared)
        THEN SET geometric reversal flag;
        Reset validity counter to zero;
        Select new sense;
        PERFORM Set_up_for_advisory;
        CLEAR increase flag in ITF;
        Initialize increase rate RA counter;
IF (intruder is TCAS-equipped)
    THEN IF (own Mode S ID is higher)
        THEN IF (threat has selected same sense as own)
            THEN PERFORM Form_complement; <Reverse own sense>
                Indicate that previous intent must be cancelled;
                <Using reversal indication flag>
                PERFORM Set_up_for_advisory;

IF (a reversal has been selected)
    THEN indicate that a reversal RA is currently in effect;
        CLEAR indication of a forced level-off against the threat;

END Reversal_check;
```

## High level Pseudocode

## AFTER

### PROCESS Reversal\_check;

```
IF (A reversal RA has previously been forbidden by the process Ra_cnc1)
    THEN decrease by 1 the flag to avoid triggering of a reversal RA in an encounter after a reversal RA
        was forbidden
SET flag that indicates that own is following his RA to true;
CLEAR flag to consider an increase rate RA;
IF (no reversal has been issued)
    THEN IF (current RA is crossing)
        THEN IF (P.MIN_RI_TIME sec. or more remain AND range TAU did not start
            rising when the threat was more than P.NAFRANGE miles away)
            THEN calculate int's proj. alt. at CPA using ITF.ZDINT;
            PERFORM Reversal_proj_check;
            IF (reversal not selected AND time to CPA is not sufficient for
                reversal against threat which may be close in altitude AND
                intruder is not TCAS-equipped)
                THEN SET flag to consider increase rate RA;
            ELSE PERFORM Cross_through_check;
        IF (past validity sequence for SA01 validity counter is '100', '101', '110', or '111')
            THEN remove the leading '1'; <Subtract '100'>
            Left shift sequence 1 bit; <Multiply by 2>
            IF (a reversal was not selected AND only 1 threat has been declared AND
                P.MIN_RI_TIME sec. or more remain AND initial RA against this threat is more than 10
                seconds old)
                THEN PERFORM RA_monitoring;
        IF (past validity sequence is '100', '101', '110', or '111')
            THEN remove the leading '1'; <Subtract '100'>
            <No need to remove leading '0' if past validity sequence is '000', '001', '010', or '011'>
            Left shift sequence 1 bit; <Multiply by 2>
            <New sequence is '000', '010', '100', or '110'>
        IF (reversal flag set this cycle)
            THEN add '1' to new sequence;
            <Sequence becomes '001', '011', '101', or '111'>
        <If reversal flag not set this cycle, sequence remains '000', '010', '100', or '110'>
        IF (intruder is TCAS-equipped AND ((own Mode S ID is higher) OR ((past validity
            sequence is not '011', '101', or '111') AND (past validity
            sequence for SA01 reversal flag is not '011', '101', or '111') AND (own is following his
            RA) AND (current RA is crossing))))
            THEN CLEAR reversal flag
        ELSE IF (intruder is TCAS-equipped OR only 1 threat has been declared)
            THEN SET geometric reversal flag;
            Reset validity counter to zero;
            Reset SA01 validity counter to zero;
            Select new sense;
            PERFORM Set_up_for_advisory;
            CLEAR increase flag in ITF;
            Initialize increase rate RA counter;
        IF (intruder is TCAS-equipped)
            THEN IF (own Mode S ID is higher)
                THEN IF (threat has selected same sense as own)
                    THEN PERFORM Form_complement; <Reverse own sense>
                    Indicate that previous intent must be cancelled;
                    <Using reversal indication flag>
                    PERFORM Set_up_for_advisory;
        IF (a reversal has been selected)
            THEN indicate that a reversal RA is currently in effect;
```

CLEAR indication of a forced level-off against the threat;

END Reversal\_check;

## Low level Pseudocode

## BEFORE

### PROCESS Reversal\_check;

```
CLEAR CONSIDER_INCREASE;  
IF (ITF.REV_GEOM EQ $FALSE)  
  THEN IF (ITF.INT_CROSS EQ $TRUE OR ITF.OWN_CROSS EQ $TRUE)  
    THEN IF (ITF.TRTRU GT P.MIN_RI_TIME AND ITF.TAURISE LT  
      P.TAURISE_THR)  
      THEN PROJ_ZINT = ITF.ZINT + (ITF.ZDINT *  
        MIN(P.TVPETBL(ITF.LEV),ITF.TRTRU));  
      PERFORM Reversal_proj_check;  
      IF (ITF.REVERSE EQ $FALSE AND ITF.TRTRU LE  
        P.MINRVSTIME AND ITF.EQP NE $TCAS)  
        THEN SET CONSIDER_INCREASE;  
    ELSE PERFORM Cross_through_check;  
  
IF (ITF.VALREVS GT 3)  
  THEN ITF.VALREVS = ITF.VALREVS - 4;  
ITF.VALREVS = 2 * ITF.VALREVS;  
IF (ITF.REVERSE EQ $TRUE)  
  THEN ITF.VALREVS = ITF.VALREVS + 1;  
  IF (ITF.EQP EQ $TCAS AND ((G.IDOWN GT ITF.IDINT) OR ((ITF.VALREVS NE  
    3, 5, or 7) AND (ITF.INT_CROSS EQ $TRUE OR ITF.OWN_CROSS EQ  
    $TRUE))))  
    THEN CLEAR ITF.REVERSE;  
  ELSE IF (ITF.EQP EQ $TCAS OR G.MACFLG EQ $FALSE)  
    THEN SET ITF.REV_GEOM;  
    ITF.VALREVS = 0;  
    OWNTENT(7) = NEW_SENSE;  
    PERFORM Set_up_for_advisory;  
    CLEAR ITF.INCREASE;  
    ITF.INCTEST = 0;  
  
IF (ITF.EQP EQ $TCAS)  
  THEN IF (G.IDOWN GT ITF.IDINT)  
    THEN IF ((TF.POTHRAR(1) EQ 1 AND OWNTENT(7) EQ $TRUE) OR  
      (TF.POTHRAR(1) EQ 2 AND OWNTENT(7) EQ $FALSE))  
      THEN PERFORM Form_complement;  
      SET ITF.TIEBREAKER_REVERSAL;  
      SET ITF.REVERSE;  
      PERFORM Set_up_for_advisory;  
  
IF (ITF.REVERSE EQ $TRUE)  
  THEN SET ITF.REV_RA;  
  CLEAR TF.TTLO;  
END Reversal_check;
```

## Low level Pseudocode

## AFTER

### PROCESS Reversal\_check;

```

    IF (G.REV_AVOID GT 0)
        THEN G.REV_AVOID=G.REV_AVOID-1;
    SET G.OWN_FOLLOW;
    CLEAR CONSIDER_INCREASE;
    IF (ITF.REV_GEOM EQ $FALSE)
        THEN IF (ITF.INT_CROSS EQ $TRUE OR ITF.OWN_CROSS EQ $TRUE)
            THEN IF (ITF.TRTRU GT P.MIN_RI_TIME AND ITF.TAURISE LT
                P.TAURISE_THR)
                THEN PROJ_ZINT = ITF.ZINT + (ITF.ZDINT *
                    MIN(P.TVPETBL(ITF.LEV),ITF.TRTRU));
                PERFORM Reversal_proj_check;
                IF (ITF.REVERSE EQ $FALSE AND ITF.TRTRU LE
                    P.MINRVSTIME AND ITF.EQP NE $TCAS)
                    THEN SET CONSIDER_INCREASE;
            ELSE PERFORM Cross_through_check;
        IF (ITF.CPT_REV GT 3)
            THEN ITF.CPT_REV = ITF.VALREVS - 4;
            ITF.CPT_REV = 2 * ITF.CPT_REV;
            IF (ITF.REVERSE EQ $FALSE AND G.MACFLG EQ $FALSE AND ITF.TRTRU GT
                P.MIN_RI_TIME AND (G.TCUR-G.TLASTNEWRA) GE 10)
                THEN PERFORM RA_monitoring;

    IF (ITF.VALREVS GT 3)
        THEN ITF.VALREVS = ITF.VALREVS - 4;
    ITF.VALREVS = 2 * ITF.VALREVS;
    IF (ITF.REVERSE EQ $TRUE)
        THEN ITF.VALREVS = ITF.VALREVS + 1;
        IF (ITF.EQP EQ $TCAS AND ((G.IDOWN GT ITF.IDINT) OR ((ITF.VALREVS NE
            3, 5, or 7) AND (ITF.CPT_REV NE
            3, 5, or 7) AND (G.OWN_FOLLOW EQ $TRUE) AND (ITF.INT_CROSS EQ
            $TRUE OR ITF.OWN_CROSS EQ $TRUE))))
            THEN CLEAR ITF.REVERSE;
        ELSE IF (ITF.EQP EQ $TCAS OR G.MACFLG EQ $FALSE)
            THEN SET ITF.REV_GEOM;
            ITF.VALREVS = 0;
            ITF.CPT_REV=0;
            OWNTENT(7) = NEW_SENSE;
            PERFORM Set_up_for_advisory;
            CLEAR ITF.INCREASE;
            ITF.INCTEST = 0;

    IF (ITF.EQP EQ $TCAS)
        THEN IF (G.IDOWN GT ITF.IDINT)
            THEN IF ((TF.POTHRAR(1) EQ 1 AND OWNTENT(7) EQ $TRUE) OR
                (TF.POTHRAR(1) EQ 2 AND OWNTENT(7) EQ $FALSE))
                THEN PERFORM Form_complement;
                SET ITF.TIEBREAKER_REVERSAL;
                SET ITF.REVERSE;
                PERFORM Set_up_for_advisory;

    IF (ITF.REVERSE EQ $TRUE)
        THEN SET ITF.REV_RA;
        CLEAR TF.TTLO;
END Reversal_check;

```

## High level Pseudocode

## BEFORE

### PROCESS Reversal\_proj\_check;

```
IF (own and intruder have not yet crossed altitudes AND
    (either they are separated by at least P.AVEVALT ft OR
    (at least P.MINRVSTIME seconds remain to CPA AND they are separated by
    at least P.CROSSTHR ft)))
    THEN IF (intruder causing altitude crossing RA)
        THEN IF (int's proj.alt. at CPA passed own's alt. in RA direction)
            THEN SET ITF reversal flag;
        ELSE IF (own aircraft is causing altitude crossing RA)
            THEN IF (intruder is now projected to cross through own's altitude
                AND intruder is not level)
                THEN CLEAR own causing crossing flags;
                SET intruder causing crossing flag;
            ELSE IF (not multi-aircraft situation)
                <Prevent unnecessary reversals in multi-A/C conflicts>
                THEN CALL MODEL_MANEUVERS
                    IN (ITF entry)
                    OUT (predicted separation for climb,
                        predicted separation for descend);
            IF (pred. sep for clm is better than des)
                THEN IF (prev.sense was des. AND clm
                    100' better than des.)
                    THEN SET ITF reversal flag;
                ELSE IF (prev. sense was clm. AND
                    des 100' better than clm)
                    THEN SET ITF reversal flag;
        IF (a reversal needs to be considered)
            THEN PERFORM Reversal_modeling;
END Reversal_proj_check;
```

## High level Pseudocode

## AFTER

### PROCESS Reversal\_proj\_check;

IF (own and intruder have not yet crossed altitudes AND  
(either they are separated by at least P.AVEVALT ft OR  
(at least P.MINRVSTIME seconds remain to CPA AND they are separated by  
at least P.CROSSTHR ft)))

THEN IF (intruder causing altitude crossing RA)

THEN IF (int's proj.alt. at CPA passed own's alt. in RA direction)

THEN SET ITF reversal flag;

ELSE IF (own aircraft is causing altitude crossing RA)

THEN IF (intruder is now projected to cross through own's altitude  
AND intruder is not level)

THEN CLEAR own causing crossing flags;

SET intruder causing crossing flag;

ELSE IF (not multi-aircraft situation)

<Prevent unnecessary reversals in multi-A/C conflicts>

THEN CALL MODEL\_MANEUVERS

IN (ITF entry)

OUT (predicted separation for climb,  
predicted separation for descend);

IF (pred. sep for clm is better than des)

THEN IF (prev.sense was des.AND clm  
100' better than des.)

THEN SET ITF reversal flag;

ELSE IF (prev. sense was clm. AND  
des 100' better than clm)

THEN SET ITF reversal flag;

IF (only 1 threat has been declared AND a reversal has been selected AND intruder is  
equipped with TCAS) THEN

PERFORM Ra\_cncl;

IF (a reversal needs to be considered)

THEN PERFORM Reversal\_modeling;

END Reversal\_proj\_check;

## Low level Pseudocode

## BEFORE

### PROCESS Reversal\_proj\_check;

```
IF ((OWNTENT(7) EQ $FALSE AND ITF.RZ LE -P.AVEVALT) OR (OWNTENT(7)
  EQ $TRUE AND ITF.RZ GE P.AVEVALT) OR (ITF.TRTRU GT P.MINRVSTIME
  AND ((OWNTENT(7) EQ $FALSE AND ITF.RZ LE -P.CROSSTHR) OR
  (OWNTENT(7) EQ $TRUE AND ITF.RZ GE P.CROSSTHR))))
  THEN IF (ITF.INT_CROSS EQ $TRUE)
    THEN IF ((OWNTENT(7) EQ $FALSE AND G.ZOWN LT PROJ_ZINT) OR
      (OWNTENT(7) EQ $TRUE AND G.ZOWN GT PROJ_ZINT))
      THEN SET ITF.REVERSE;
    ELSE IF (ITF.OWN_CROSS EQ $TRUE)
      THEN IF (((OWNTENT(7) EQ $FALSE AND G.ZOWN GT PROJ_ZINT)
        OR (OWNTENT(7) EQ $TRUE AND G.ZOWN LT PROJ_ZINT))
        AND ABS(ITF.ZDINT) GE P.OLEV)
        THEN CLEAR ITF.OWN_CROSS; SET ITF.INT_CROSS;
        ELSE IF (G.MACFLG EQ $FALSE)
          THEN CALL MODEL_MANEUVERS
            IN ( ITF entry)
            OUT (ZMPCLM,ZMPDES);
          IF (ZMPCLM GT ZMPDES)
            THEN IF (OWNTENT(7) EQ $TRUE AND
              ZMPCLM GT (ZMPDES+
                P.NOZCROSS))
              THEN SET ITF.REVERSE;
            ELSE IF (OWNTENT(7) EQ $FALSE
              AND ZMPDES GT (ZMPCLM+
                P.NOZCROSS))
              THEN SET ITF.REVERSE;
          IF (ITF.REVERSE EQ $TRUE)
            THEN PERFORM Reversal_modeling;
  END Reversal_proj_check;
```



## Low level Pseudocode

## AFTER

### PROCESS Reversal\_proj\_check;

```

IF ((OWNTENT(7) EQ $FALSE AND ITF.RZ LE -P.AVEVALT) OR (OWNTENT(7)
  EQ $TRUE AND ITF.RZ GE P.AVEVALT) OR (ITF.TRTRU GT P.MINRVSTIME
  AND ((OWNTENT(7) EQ $FALSE AND ITF.RZ LE -P.CROSSTHR) OR
  (OWNTENT(7) EQ $TRUE AND ITF.RZ GE P.CROSSTHR))))
  THEN IF (ITF.INT_CROSS EQ $TRUE)
    THEN IF ((OWNTENT(7) EQ $FALSE AND G.ZOWN LT PROJ_ZINT) OR
      (OWNTENT(7) EQ $TRUE AND G.ZOWN GT PROJ_ZINT))
      THEN SET ITF.REVERSE;
    ELSE IF (ITF.OWN_CROSS EQ $TRUE)
      THEN IF (((OWNTENT(7) EQ $FALSE AND G.ZOWN GT PROJ_ZINT)
        OR (OWNTENT(7) EQ $TRUE AND G.ZOWN LT PROJ_ZINT))
        AND ABS(ITF.ZDINT) GE P.OLEV)
        THEN CLEAR ITF.OWN_CROSS; SET ITF.INT_CROSS;
        ELSE IF (G.MACFLG EQ $FALSE)
          THEN CALL MODEL_MANEUVERS
            IN ( ITF entry)
            OUT (ZMPCLM,ZMPDES);
          IF (ZMPCLM GT ZMPDES)
            THEN IF (OWNTENT(7) EQ $TRUE AND
              ZMPCLM GT (ZMPDES+
                P.NOZCROSS))
              THEN SET ITF.REVERSE;
            ELSE IF (OWNTENT(7) EQ $FALSE
              AND ZMPDES GT (ZMPCLM+
                P.NOZCROSS))
              THEN SET ITF.REVERSE;
          IF (G.MACFLG EQ $FALSE AND ITF.REVERSE EQ $TRUE AND ITF.EQP EQ $TCAS)
            THEN PERFORM Ra_cncl;
          IF (ITF.REVERSE EQ $TRUE)
            THEN PERFORM Reversal_modeling;
END Reversal_proj_check;

```

## High level Pseudocode

## BEFORE

### PROCESS Reversal\_modeling;

SET own altitude and own rate to own tracked altitude and own tracked rate;

IF (current RA is positive)

THEN model response to current RA;

        <model maximum displayable rate for climb if current rate exceeds maximum displayable rate or  
        minimum displayable rate for descent if current rate is less than minimum displayable rate>

IF (tracked response lags modeled response in RA direction AND time since RA less than a  
parameter time AND own's rate has not changed by more than P.MODEL\_ZD since the RA was first issued)

THEN set own altitude and own rate to modeled altitude and rate for use in reversal\_modeling;

        Model separation achieved by continuing current RA;

SET delay time to greater of pilot delay time remaining for last advisory against a new threat, and the pilot quick  
reaction time;

IF (considering a reversal from a descend RA to a climb RA)

THEN SET own goal rate to greater of own tracked rate (or maximum displayable rate, whichever is less)  
and nominal climb rate;

ELSE IF (own too close to ground to descend)

THEN SET own goal rate to zero;

ELSE SET own goal rate to lesser of own tracked rate (or maximum displayable rate, whichever is  
greater) and nominal descent rate;

IF (intruder causing crossing OR intruder level and own crossing from above OR intruder rate and own modeled  
rate are opposite in sign)

THEN use outer rate bound to model intruder;

ELSE use inner rate bound to model intruder;

CALL MODEL\_SEP

IN (delay, goal rate, own altitude, own rate, acceleration response, sense after reversal, intruder altitude,  
    modeled intruder rate, ITF entry);

OUT (predicted separation for sense reversal);

IF (predicted separation for sense reversal is not positive OR modeled separation achieved by continuing current  
RA GE G.ALIM)

THEN CLEAR reversal flag in ITF;

END Reversal modeling;

## High level Pseudocode

## AFTER

### PROCESS Reversal\_modeling;

SET own altitude and own rate to own tracked altitude and own tracked rate;

IF (current RA is positive OR own does not follow his RAs)

THEN model response to current RA;

        <model maximum displayable rate for climb if current rate exceeds maximum displayable rate or minimum displayable rate for descent if current rate is less than minimum displayable rate>

IF (tracked response lags modeled response in RA direction AND time since RA less than a parameter time AND own's rate has not changed by more than P.MODEL\_ZD since the RA was first issued)

THEN SET own altitude and own rate to modeled altitude and rate for use in reversal\_modeling;

IF (Own is following ongoing RA)

THEN Model separation achieved by continuing current RA;

ELSE Model separation achieved assuming current RA not followed;

SET delay time to greater of pilot delay time remaining for last advisory against a new threat, and the pilot quick reaction time;

IF (considering a reversal from a descend RA to a climb RA)

THEN SET own goal rate to greater of own tracked rate (or maximum displayable rate, whichever is less) and nominal climb rate;

ELSE IF (own too close to ground to descend)

THEN SET own goal rate to zero;

ELSE SET own goal rate to lesser of own tracked rate (or maximum displayable rate, whichever is greater) and nominal descent rate;

IF (Own is following ongoing RA AND SA01 reversal flag is equal to zero)

THEN IF (intruder causing crossing OR intruder level and own crossing from above OR intruder rate and own modeled rate are opposite in sign)

THEN use outer rate bound to model intruder;

ELSE use inner rate bound to model intruder;

ELSE use intruder's tracked vertical rate to model intruder;

IF (Own is following ongoing RA)

THEN CALL MODEL\_SEP

IN (delay, goal rate, own altitude, own rate, acceleration response, sense after reversal, intruder altitude, modeled intruder rate, ITF entry);

OUT (predicted separation for sense reversal);

ELSE SET predicted separation for sense reversal to zero;

IF ((Own is following ongoing RA AND (predicted separation for sense reversal is not positive OR modeled separation achieved by continuing current RA greater than G.ALIM)) OR (Own is not following ongoing RA AND modeled separation achieved by continuing current RA greater than 1.2\*P.CROSSTHR))

THEN CLEAR reversal flag in ITF;

END Reversal modeling;

## Low level Pseudocode

## BEFORE

### PROCESS Reversal\_modeling;

```

NOMINAL_SEP=0;
Z=G.ZOWN;
ZD=G.ZDOWN;
IF (OWNTENT(5,6) EQ '00')
    THEN DELAY = MAX(P.TV1-(G.TCUR-G.TPOSRA),0);
    IF (OWNTENT(7) EQ $FALSE)
        THEN ZDGOAL = MAX(MIN(G.ZDOWN,P.MAXDRATE), P.CLMRT);
        ELSE ZDGOAL = MIN(MAX(G.ZDOWN,P.MINDRATE), P.DESRT);
    CALL PROJECT_VERTICAL_GIVEN_ZDGOAL
    IN ((G.TCUR-G.TPOSRA), G.ZTV, G.ZDTV, ZDGOAL,P.TV1, P.VACCEL)
    OUT (ZPROJ, ZDPROJ)
    IF (((OWNTENT(7) EQ $FALSE AND ZPROJ GT G.ZOWN
        AND (G.ZDOWN GE G.ZDTV-P.MODEL_ZD)) OR
        (OWNTENT(7) EQ $TRUE AND ZPROJ LT G.ZOWN
        AND (G.ZDOWN LE G.ZDTV+P.MODEL_ZD)))
        AND G.TCUR - G.TPOSRA LT P.MODEL_T)
        THEN Z = ZPROJ;
        ZD= ZDPROJ;
    CALL MODEL_SEP
    IN (DELAY, ZDGOAL, Z, ZD, P.VACCEL, OWNTENT(7), ITF.ZINT, ITF.ZDINT, ITF
    entry)
    OUT (NOMINAL_SEP);
IF (OWNTENT(7) EQ $TRUE)
    THEN NEW_SENSE= $FALSE;
    ELSE NEW_SENSE= $TRUE;
DELAY = MAX(P.TV1-(G.TCUR-G.TLASTNEWRA),P.QUICKREAC);

IF (NEW_SENSE EQ $FALSE)
    THEN ZDGOAL=MAX(P.CLMRT,MIN(G.ZDOWN,P.MAXDRATE));
    ELSE IF (G.NODESCENT EQ $TRUE)
        THEN ZDGOAL=0;
        ELSE ZDGOAL = MIN(P.DESRT, MAX(G.ZDOWN,P.MINDRATE));

IF ((ITF.INT_CROSS EQ $TRUE) OR (ITF.ZDINT EQ 0 AND ITF.RZ GT 0) OR
    (ITF.ZDINT*G.ZDMODEL LT 0))
    THEN MZDINT=ITF.ZDOUTR;
    ELSE MZDINT=ITF.ZDINR;

CALL MODEL_SEP
    IN (DELAY, ZDGOAL, Z, ZD, P.RACCEL, NEW_SENSE, ITF.ZINT, MZDINT, ITF entry)
    OUT (ZMP);
IF (ZMP LE 0 OR NOMINAL_SEP GE G.ALIM)
    THEN CLEAR ITF.REVERSE;
END Reversal_modeling;

```

## Low level Pseudocode

## AFTER

### PROCESS Reversal\_modeling;

```

NOMINAL_SEP=0;
Z=G.ZOWN;
ZD=G.ZDOWN;
IF (OWNTENT(5,6) EQ '00' OR G.OWN_FOLLOW EQ FALSE)
    THEN
        IF (OWNTENT(5,6) EQ '00') THEN DELAY = MAX(P.TV1-(G.TCUR-G.TPOSRA),0);
        ELSE DELAY = 0;
        IF (OWNTENT(7) EQ $FALSE)
            THEN ZDGOAL = MAX(MIN(G.ZDOWN,P.MAXDRATE), P.CLMRT);
            ELSE ZDGOAL = MIN(MAX(G.ZDOWN,P.MINDRATE), P.DESRT);
        CALL PROJECT_VERTICAL_GIVEN_ZDGOAL
            IN ((G.TCUR-G.TPOSRA), G.ZTV, G.ZDTV, ZDGOAL,P.TV1, P.VACCEL)
            OUT (ZPROJ, ZDPROJ)
        IF (((OWNTENT(7) EQ $FALSE AND ZPROJ GT G.ZOWN
            AND (G.ZDOWN GE G.ZDTV-P.MODEL_ZD)) OR
            (OWNTENT(7) EQ $TRUE AND ZPROJ LT G.ZOWN
            AND (G.ZDOWN LE G.ZDTV+P.MODEL_ZD)))
            AND G.TCUR - G.TPOSRA LT P.MODEL_T)
            THEN Z = ZPROJ;
            ZD= ZDPROJ;
        IF (G.OWN_FOLLOW EQ $TRUE)
            THEN CALL MODEL_SEP
                IN (DELAY, ZDGOAL, Z, ZD, P.VACCEL, OWNTENT(7), ITF.ZINT, ITF.ZDINT,
                    ITF entry)
                OUT (NOMINAL_SEP);
            ELSE CALL MODEL_SEP
                IN (0, ZD, Z, ZD, P.VACCEL, OWNTENT(7), ITF.ZINT, ITF.ZDINT, ITF entry)
                OUT (NOMINAL_SEP);

IF (OWNTENT(7) EQ $TRUE)
    THEN NEW_SENSE= $FALSE;
    ELSE NEW_SENSE= $TRUE;
DELAY = MAX(P.TV1-(G.TCUR-G.TLASTNEWRA),P.QUIKREAC);

IF (NEW_SENSE EQ $FALSE)
    THEN ZDGOAL=MAX(P.CLMRT,MIN(G.ZDOWN,P.MAXDRATE));
    ELSE IF (G.NODESCENT EQ $TRUE)
        THEN ZDGOAL=0;
        ELSE ZDGOAL = MIN(P.DESRT, MAX(G.ZDOWN,P.MINDRATE));
IF (G.OWN_FOLLOW EQ $TRUE AND ITF.CPT_REV EQ 0)
    THEN IF ((ITF.INT_CROSS EQ $TRUE) OR (ITF.ZDINT EQ 0 AND ITF.RZ GT 0) OR
        (ITF.ZDINT*G.ZDMODEL LT 0))
        THEN MZDINT=ITF.ZDOUTR;
        ELSE MZDINT=ITF.ZDINR;
    ELSE MZDINT=ITF.ZDINT;

IF (G.OWN_FOLLOW EQ $TRUE)
    THEN CALL MODEL_SEP
        IN (DELAY, ZDGOAL, Z, ZD, P.RACCEL, NEW_SENSE, ITF.ZINT, MZDINT, ITF entry)
        OUT (ZMP);
    ELSE ZMP=0;

IF ((G.OWN_FOLLOW EQ $TRUE AND (ZMP LE 0 OR NOMINAL_SEP GE G.ALIM)) OR
    (G.OWN_FOLLOW EQ $FALSE AND NOMINAL_SEP GT 1.2*P.CROSSTHR))
    THEN CLEAR ITF.REVERSE;

```

END Reversal\_modeling;

## High level Pseudocode

NEW

**PROCESS RA\_cnc1;**

**IF** (ITF.ADOT is not nil)

**THEN** compute MY\_TAUUV using ITF.ADOT;

**ELSE SET** MY\_TAUUV with a specified high value;

Compute the time T\_NOREV, which is the time before CPA during which 1 does not want a reversal RA;

**IF** (Initial RAs make the aircraft cross in altitude)

**AND** ((Less than 10 seconds have elapsed since initial RA) **OR** (A Reversal RA was already forbidden in the past 3 seconds))

**AND** (Less than (T\_NOREV+P.QUICKREAC) seconds remain)

**AND** (MY\_TAUUV is between 0 and a specified high value)

**THEN**

**IF** (((Not enough time has elapsed since initial RA, which implies pilots did not have time to comply)

**OR** (Reversal RA was already forbidden in the past 3 seconds)) **AND** ((vertical separation is lower than ALIM and less than 10 s remain before CPA) **OR** ((Less than T\_NOREV seconds remain)

**AND** (MY\_TAUUV lower than altitude tau limit))) **AND** (aircraft are not diverging vertically))

**THEN SET** ITF.REVERSE to false;

**IF** (A reversal RA has not been forbidden already)

**THEN Set** G.REV\_AVOID to 3;

**END RA\_cnc1;**

## Low level Pseudocode

NEW

**PROCESS RA\_cncl;**

**IF** (ITF.ADOT NE 0)

THEN MY\_TAUV=-ITF.A/ITF.ADOT;

ELSE MY\_TAUV=-9999999;

**IF** (OWNTENT(7) EQ \$FALSE)

THEN DELTA\_VZ1=MAX(ABS(G.ZDOWN-P.DESRT),ABS(G.ZDMODEL-P.DESRT));

DELTA\_VZ2=MAX(ABS(ITF.ZDINT-P.CLMRT),ABS(TF.INITZDI-P.CLMRT));

ELSE DELTA\_VZ1=MAX(ABS(G.ZDOWN-P.CLMRT),ABS(G.ZDMODEL-P.CLMRT));

DELTA\_VZ2=MAX(ABS(ITF.ZDINT-P.DESRT),ABS(TF.INITZDI-P.DESRT));

T\_NOREV=MAX(DELTA\_VZ1,DELTA\_VZ2)/P.RACCEL+P.QUIKREAC;

**IF** (((OWNTENT(7) EQ \$FALSE AND (TF.INITZO LT TF.INITZI))

OR (OWNTENT(7) EQ \$TRUE AND (TF.INITZO GT TF.INITZI)))

AND ((G.TCUR-G.TLASTNEWRA) LT 10 OR G.REV\_AVOID GT 0)

AND (ITF.TRTRU LT (T\_NOREV+P.QUIKREAC))

AND (MY\_TAUV GT 0 AND MY\_TAUV LT 90))

THEN

IF (((G.TTOFOLLOW GT (G.TCUR-G.TLASTNEWRA+1)) OR ((G.TCUR-G.TLASTNEWRA) LE

P.TV1) OR (G.REV\_AVOID GT 0)) AND ((ABS(ITF.RZ) LT G.ALIM AND

ITF.TRTRU LT P.MINRVSTIME) OR ((ITF.TRTRU LT T\_NOREV) AND (MY\_TAUV LT

P.TVTETBL(ITF.LEV)))) AND (ITF.ADOT LT P.ZDTHR))

THEN CLEAR ITF.REVERSE

IF (G.REV\_AVOID EQ 0)

THEN G.REV\_AVOID=3;

**END** RA\_cncl;



## High level Pseudocode

NEW

### PROCESS RA\_monitoring;

SET T\_TOFOLLOW as the bounded value of G.TTOFOLLOW between 10 and 15 seconds;

IF (intruder is TCAS-equipped)

THEN compute time to comply with a reversal RA taking into account own and intruder;

ELSE IF (intruder is not TCAS-equipped)

THEN compute time to comply with a reversal RA taking into account own only;

Compute projected altitude of own at CPA using the current vertical rate;

Compute maximum, minimum and tracked projected altitudes of intruder at CPA using the current vertical rate of intruder, and intruder's vertical rate limits;

Compute the maximum, minimum and tracked projected vertical CPAs;

SET values of FACT\_MULT and DELTA\_T\_RZ according to current vertical rate of own and intruder;

If (an increase RA was triggered less than 5 seconds ago)

THEN use a reduced value for FACT\_MULT;

IF (((T\_RZ+DELTA\_T\_RZ) seconds remain) AND (convergence is not slow) AND (at least 10 seconds remain)) THEN SET THRES\_RZ to -FACT\_MULT\*P.CROSSTHR;

ELSE IF (((T\_RZ+DELTA\_T\_RZ) seconds remain) AND (convergence is not slow)) THEN set

        THRES\_RZ to -FACT\_MULT\*P.CROSSTHR\*0.25;

ELSE set THRES\_RZ to 0;

IF firmness is not good AND CPA close

THEN use increased values of THRES\_RZ;

CALL Take\_decision

IN (DELTA\_Z\_MIN,DELTA\_Z\_MAX,DELTA\_Z\_CPA,T\_TOFOLLOW,THRES\_RZ,T\_RZ);

END RA\_monitoring;

## Low level Pseudocode

NEW

### PROCESS RA\_monitoring;

T\_TOFOLLOW=MIN(MAX(10,G.TTOFOLLOW),15);

IF (ITF.EQP EQ \$TCAS)

THEN T\_RZ=MAX(ABS(G.ZDOWN)/P.RACCEL,ABS(ITF.ZDINT)/P.RACCEL)+P.QUICKREAC;  
ELSE IF (ITF.EQP NE \$TCAS) THEN T\_RZ=ABS(G.ZDOWN)/P.RACCEL+P.QUICKREAC;

Z=G.ZOWN+G.ZDOWN\*MIN(P.TVPETBL(ITF.LEV),ITF.TRTRU);

ZI= ITF.ZINT+(ITF.ZDINT)\*MIN(P.TVPETBL(ITF.LEV),ITF.TRTRU);

ZI\_IN=ITF.ZINT+(ITF.ZDINR)\*MIN (P.TVPETBL(ITF.LEV),ITF.TRTRU);

ZI\_OUT=ITF.ZINT+(ITF.ZDOUTR)\*MIN(P.TVPETBL(ITF.LEV),ITF.TRTRU);

DELTA\_Z\_CPA=Z-ZI;

DELTA\_Z\_MIN=MIN(Z-ZI\_OUT,Z-ZI,Z-ZI\_IN);

DELTA\_Z\_MAX=MAX(Z-ZI\_OUT,Z-ZI,Z-ZI\_IN);

IF (ITF.EQP EQ \$TCAS)

THEN

IF (ABS(G.ZDOWN) GT 3\*P.ILEV AND ABS (ITF.ZDINT) GT 3\*P.ILEV)

THEN FACT\_MULT=1.5;

DELTA\_T\_RZ=3.0;

ELSE IF (ABS(G.ZDOWN) GT 2\*P.ILEV AND ABS (ITF.ZDINT) GT 2\*P.ILEV)

THEN FACT\_MULT=1.25;

DELTA\_T\_RZ=3.0;

ELSE IF (ABS(G.ZDOWN) GT 1.5\*P.ILEV AND ABS (ITF.ZDINT) GT 1.5\*P.ILEV)

THEN FACT\_MULT=1.1;

DELTA\_T\_RZ=3.0;

ELSE FACT\_MULT=1.0;

DELTA\_T\_RZ=5.0;

ELSE FACT\_MULT=1.0;

DELTA\_T\_RZ=5.0;

IF ((G.TCUR-ITF.TCMD) LE P.TV1 AND G.ANYINCREASE EQ \$TRUE)

THEN

FACT\_MULT=FACT\_MULT/4;

IF ((ITF.TRTRU GE (T\_RZ+DELTA\_T\_RZ)) AND (ITF.RD LT -5\*P.RDTHR) AND (ITF.TRTRU GT P.MINRVSTIME))

THEN THRES\_RZ=-FACT\_MULT\*P.CROSSTHR;

ELSE IF ((ITF.TRTRU GE (T\_RZ+DELTA\_T\_RZ)) AND (ITF.RD LT -5\*P.RDTHR))

THEN THRES\_RZ=-FACT\_MULT\*P.CROSSTHR\*0.25;

ELSE THRES\_RZ=0;

IF (ITF.TRTRU LE P.MINRVSTIME AND ITF.IFIRM LT P.MINFIRM)

THEN THRES\_RZ=THRES\_RZ+P.CROSSTHR;

ELSE IF (ITF.TRTRU LE P.MINRVSTIME AND ITF.IFIRM EQ P.MINFIRM)

THEN THRES\_RZ=THRES\_RZ+P.CROSSTHR/2;

CALL Take\_decision

IN (DELTA\_Z\_MIN, DELTA\_Z\_MAX, DELTA\_Z\_CPA, T\_TOFOLLOW, THRES\_RZ, T\_RZ);

END RA\_monitoring;

## High level Pseudocode

NEW

### PROCESS Take\_decision;

IN (dzmi,dzma,dzc,tfollow,thresrz,trz)

IF ((Current RA is climb sense AND (Own is projected not high enough at CPA above the intruder)) OR (Current RA is descent sense AND (Own is projected not low enough below the intruder)))  
AND (The aircraft are vertically separated by less than P.MAXALTDIFF)  
AND (Current tracked vertical rates show the aircraft in the same sense)  
AND (Own is not level)  
AND (Intruder is not level)  
AND (More than tfollow seconds have elapsed since initial RA)  
AND ((trz seconds remain) OR (An increase RA was triggered more than P.TV1 seconds ago for this threat) OR (No increase RA was triggered for this threat))  
AND ((Intruder aircraft is TCAS-equipped AND ((Current RA is climb sense AND ITF.RZ lower than -thresrz) OR (Current RA is descent sense AND ITF.RZ greater than thresrz))) OR (Intruder is not TCAS-equipped AND ((Current RA is climb sense AND ITF.RZ lower than -thresrz) OR (Current RA is descent sense AND ITF.RZ greater than thresrz))) AND Own is in the sense required by the RA)) THEN

Increase ITF.CPT\_REV by 1;

IF (An increase RA was triggered but not the last cycle OR no increase RA was triggered) THEN

IF (ITF.CPT\_REV is equal to 3, 5 or 7)

THEN

SET ITF.REVERSE to TRUE;

PERFORM Reversal\_modeling;

IF (An increase RA was triggered but not the last cycle OR no increase RA was triggered) THEN

IF (ITF.REVERSE is set to \$FALSE AND (Projected vertical distance at CPA is less than ALIM/2)) THEN

IF (Intruder is TCAS-equipped)

AND (((trz seconds remain) OR (An increase RA was triggered more than 5 seconds ago for this threat) OR (No increase RA was triggered for this threat))

AND

((Current RA is positive vertical)

AND (((tfollow seconds have elapsed since initial RA) AND (Initial RA is positive)) OR ((At least

P.TV1 seconds have elapsed since positive RA) AND (tfollow seconds have elapsed since initial RA) AND (Positive RA was triggered after initial RA)))

AND ((Own and intruder are descending at more than a specified vertical rate AND (Current RA is climb sense)) OR (Own and intruder are climbing at more than a specified vertical rate AND (Current RA is descent sense))))

OR

((Current RA is negative vertical)

AND

(tfollow seconds have elapsed since initial RA)

AND

((Own and intruder are descending at more than a specified vertical rate AND (Current RA is climb sense)) OR (Own and intruder are climbing at more than a specified vertical rate AND (Current RA is descent sense))))

THEN

IF firmness is not good AND CPA far, use increased values of THRES\_RZ;

IF ITF.RZ lower than -thresrz AND current RA is climb sense OR ITF.RZ is greater than thresrz AND current RA is descent sense

SET ITF.REVERSE to TRUE;

Clear G.OWN\_FOLLOW;

PERFORM Reversal\_modeling;

Compute altitudes of own and intruder 2.5 seconds after the current time, using current vertical rates;

IF (ITF.REVERSE is set to \$TRUE) THEN

```
IF (the aircraft are converging vertically OR the aircraft are separated by more than a specified amount vertically) THEN  
    IF (((Current RA is climb sense AND (Own is below intruder) AND (Own will cross intruder's altitude in the next 2.5 seconds)) OR (Current RA is descent sense AND (Own is above) AND (Own will cross intruder's altitude in the next 2.5 seconds))) AND (Less than 12.5 seconds remain))  
        THEN CLEAR ITF.REVERSE;  
END Take_decision;
```

## Low level Pseudocode

NEW

### PROCESS Take\_decision;

IN (dzmi,dzma,dzc,tfollow,thresrz,trz)

```

IF ((OWNTENT(7) EQ $FALSE AND (dzmi LT 1.2*P.CROSSTHR)) OR (OWNTENT(7) EQ $TRUE
AND (dzma GT -1.2*P.CROSSTHR)))
AND (ABS(ITF.RZ) LT P.MAXALTDIFF)
AND (G.ZDOWN*ITF.ZDINT GT 0)
AND (ABS(G.ZDOWN) GT P.ILEV)
AND (ABS(ITF.ZDINT) GT P.ILEV)
AND ((G.TCUR-G.TLASTNEWRA) GE tfollow)
AND ((ITF.TRTRU GT trz) OR ((G.TCUR-ITF.TCMD) GT P.TV1 AND G.ANYINCREASE EQ
$TRUE) OR (G.ANYINCREASE EQ $FALSE))
AND ((ITF.EQP EQ $TCAS AND ((OWNTENT(7) EQ $FALSE AND ITF.RZ LE -thresrz) OR
(OWNTENT(7) EQ $TRUE AND ITF.RZ GE thresrz))) OR (ITF.EQP NE $TCAS AND ((OWNTENT(7)
EQ $FALSE AND ITF.RZ LE -thresrz) OR (OWNTENT(7) EQ $TRUE AND ITF.RZ GE thresrz)) AND
(G.ZDOWN*G.ZDMODEL GT 0)))
THEN
    ITF.CPT_REV=ITF.CPT_REV+1;
    IF (((G.TCUR-ITF.TCMD) GT 1 AND G.ANYINCREASE EQ $TRUE) OR (G.ANYINCREASE EQ
    $FALSE))
        THEN
            IF (ITF.CPT_REV EQ 3 OR ITF.CPT_REV EQ 5 OR ITF.CPT_REV EQ 7)
                THEN
                    SET ITF.REVERSE;
                    PERFORM Reversal_modeling;

IF (((G.TCUR-ITF.TCMD) GT 1 AND G.ANYINCREASE EQ $TRUE) OR (G.ANYINCREASE EQ
$FALSE))
THEN
    IF (ITF.REVERSE EQ $FALSE AND (((OWNTENT(7) EQ $FALSE) AND (dzc LT G.ALIM/2)) OR
    ((OWNTENT(7) EQ $TRUE) AND (dzc GT -G.ALIM/2))))
        THEN
            IF (ITF.EQP EQ $TCAS)
                AND (((ITF.TRTRU GT trz) OR ((G.TCUR-ITF.TCMD) GT P.TV1) AND
                G.ANYINCREASE EQ $TRUE) OR (G.ANYINCREASE EQ $FALSE))
                AND (((OWNTENT(5) EQ $FALSE AND OWNTENT(6) EQ $FALSE)
                AND (((G.TCUR-G.TLASTNEWRA) GE tfollow) AND (G.TPOSRA EQ G.TLASTNEWRA))
                OR (((G.TCUR-G.TPOSRA) GT P.TV1) AND ((G.TCUR-G.TLASTNEWRA) GE tfollow) AND
                (G.TPOSRA GT G.TLASTNEWRA)))
                AND ((G.ZDOWN LT -1.2*P.ILEV AND ITF.ZDINT LT -P.ILEV AND (OWNTENT(7) EQ
                $FALSE)) OR (G.ZDOWN GT 1.2*P.ILEV AND ITF.ZDINT GT P.ILEV AND (OWNTENT(7)
                EQ $TRUE))))
                OR
                ((OWNTENT(5) EQ $TRUE AND OWNTENT(6) EQ $FALSE)
                AND ((G.TCUR-G.TLASTNEWRA) GE tfollow)
                AND
                ((G.ZDOWN LT -1.5*P.ILEV AND ITF.ZDINT LT -P.ILEV AND (OWNTENT(7) EQ $FALSE))
                OR (G.ZDOWN GT 1.5*P.ILEV AND ITF.ZDINT GT P.ILEV AND (OWNTENT(7) EQ
                $TRUE))))))
                THEN
                    IF (ITF.TRTRU GT P.MINRVSTIME AND ITF.IFIRM LT P.MINFIRM)
                        THEN THRES_RZ=THRES_RZ+P.CROSSTHR/2;
                        ELSE IF (ITF.TRTRU GT P.MINRVSTIME AND ITF.IFIRM EQ P.MINFIRM)
                            THEN THRES_RZ=THRES_RZ+P.CROSSTHR/4;

```

```
IF ((ITF.RZ LE -thresrz AND OWNTENT(7) EQ $FALSE) OR (ITF.RZ GE thresrz
AND OWNTENT(7) EQ $TRUE))
THEN
    SET ITF.REVERSE;
    CLEAR G.OWN_FOLLOW;
    PERFORM Reversal_modeling;

ZI25=ITF.ZINT+2.5*ITF.ZDINT;
ZO25=G.ZOWN+2.5*G.ZDOWN;
IF (ITF.REVERSE EQ $TRUE) THEN
    IF (ITF.ADOT LT -P.OLEV OR ABS(ITF.RZ) GT P.CROSSTHR/4) THEN
        IF (((OWNTENT(7) EQ $FALSE AND (ITF.RZ LT 0) AND (ZO25 GT ZI25)) OR (OWNTENT(7)
EQ $TRUE AND (ITF.RZ GT 0) AND (ZO25 LT ZI25))) AND (ITF.TRTRU LE
1.25*P.MINRVSTIME))
        THEN
            CLEAR ITF.REVERSE;
END Take_decision;
```

## NEW VARIABLES

### STRUCTURE RESVAR

<\*\*\*RESOLUTION LOCAL VARIABLES\*\*\*>

<u>GROUP</u> Ra_cnc1	<variables needed for Ra_cnc1 only>
<u>FLT</u> MY_TAU	<recomputed tau>
<u>FLT</u> T_NOREV	<time during which no reversal should be triggered>
<u>FLT</u> DELTA_VZ1	<temporary variable 1 for the calculation of T_NOREV>
<u>FLT</u> DELTA_VZ2	<temporary variable 2 for the calculation of T_NOREV>
<u>GROUP</u> RA_monitoring	<variables needed for RA_monitoring only>
<u>FLT</u> THRES_RZ	<altitude threshold>
<u>FLT</u> T_RZ	<time threshold for reversal RA leading to altitude crossing>
<u>FLT</u> DELTA_Z_CPA	<CPA>
<u>FLT</u> DELTA_Z_MIN	<Minimum CPA>
<u>FLT</u> DELTA_Z_MAX	<Maximum CPA>
<u>FLT</u> T_TO FOLLOW	<Bounded time to follow initial RA>
<u>FLT</u> DELTA_T_RZ	<Delta time threshold to add to t_rz>
<u>FLT</u> FACT_MULT	<Multiplying factor>
<u>FLT</u> ZI_IN	<Intruder's altitude computed with ITF.ZDINR>
<u>FLT</u> ZI_OUT	<Intruder's altitude computed with ITF.ZDOUTR>
<u>GROUP</u> Take_decision	<variables needed for Take_decision only>
<u>FLT</u> ZI25	<projected altitude of int 2.5s after current time>
<u>FLT</u> ZO25	<projected altitude of own 2.5s after current time>

<\*\*\*GLOBAL VARIABLES\*\*\*>

STRUCTURE G

GROUP reversal

BIT OWN\_FOLLOW <Indication of own following RAs or not>

FLT TTOFOLLOW <time to follow RA>

INT REV\_AVOID <Indication of reversal RA forbidden>

STRUCTURE TF

GROUP level\_off

FLT INITZI <Intruder's altitude at time of initial RA>

FLT INITZO <Own's altitude at time of initial RA>

STRUCTURE ITF

GROUP reversal

INT CPT\_REV <SA01 reversal flag>

\*\*\* END OF DOCUMENT \*\*\*