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Lincoln Laboratory Evaluation of TCAS II Logic Version 7 – Volume I

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16. Abstract

This report documents the Lincoln Laboratory evaluation of the Traffic Alert and Collision Avoidance System II (TCAS II) logic version 7. TCAS II is an airborne collision avoidance system required since 30 December 1993 by the FAA on all air carrier aircraft with more than 30 passenger seats operating in the U. S. airspace. Version 7 is a major revision to the TCAS II logic consisting of more than 300 separately defined changes affecting all major TCAS areas (surveillance, CAS logic and displays/aurals).

Lincoln Laboratory evaluated the logic by examining approximately two million simulated pairwise TCAS-TCAS encounters, derived from actual tracks recorded in U. S. airspace. The main goals of the evaluation were: (1) to study the performance of the new TCAS-TCAS coordinated reversal logic; (2) to detect and explain any areas of poor performance; (3) to examine the performance of the version 7 logic for the 30 Representative NMACs identified during the 6.04a logic evaluation; and (4) to understand the limitations of the logic by analyzing every version 7 NMAC. Five Lincoln Laboratory analysis programs written for previous logic evaluation work were updated and new software was written to aid in the evaluation of TCAS-TCAS sense reversals.

There were four phases of the evaluation corresponding to the above goals. For each phase the report gives an overview of the evaluation approach taken and a description of the results. An overall summary and perspective on the evolution of the TCAS II logic are given at the end of the report.

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EXECUTIVE SUMMARY

This report documents the Lincoln Laboratory evaluation of the Traffic Alert and Collision Avoidance System II (TCAS II) logic version 7.

BACKGROUND

TCAS II is an airborne collision avoidance system required since December 1993 by the Federal Aviation Administration (FAA) on all air carrier aircraft with more than 30 seats operating in the United States airspace. The FAA mandated the current TCAS II logic version 6.04a by December 1994 in order to correct a potential safety problem in earlier versions of the TCAS II logic. Version 7, also known as Change 7, is a major revision to the 6.04a logic. It provides enhancements to all major TCAS areas (surveillance, Collision Avoidance System (CAS) logic, and displays/aurals) and is essentially equivalent to the Airborne Collision Avoidance System II (ACAS II), the international version that has been mandated world-wide.

Historically, Lincoln Laboratory has been responsible for the surveillance area of TCAS. In addition, however, Lincoln Laboratory has been involved in the testing of the MITRE-developed "CAS logic," the logic that provides for threat declaration and resolution. Lincoln Laboratory has previously worked in collaboration with the William J. Hughes Technical Center (WJHTC), formerly known as the FAA Technical Center (FAATC), to assess CAS logic performance. Based on past success, both organizations were tasked to evaluate the Change 7 CAS logic. This report covers only the Lincoln Laboratory evaluation.

This work was made necessary by the difficulties of designing and validating improvements to the TCAS logic. The logic itself is complicated and can behave quite differently from encounter to encounter. In many cases a fix that resolves problems with a particular type of encounter will result in poorer performance in other types of encounters. Complicating this situation is the fact that there are some encounters that a CAS should not be expected to resolve (e.g. encounters in which the intruder maneuvers sharply in a way that is contrary to the CAS advisory).

It is literally possible to define an uncountable number of different encounter parameter sets, each of which has the potential of revealing different aspects of CAS logic performance. Because of the huge number of possible encounter scenarios, it is impossible to test all possible encounter scenarios. Thus, a carefully designed set of procedures is required to sample the encounter space, characterize the types of performance problems that exist, and ensure that proposed design improvements are beneficial in a universal sense. This report describes the set of procedures and associated software that were developed and exercised to support development of TCAS Change 7 logic.

METHODOLOGY

The data analyzed by Lincoln Laboratory were generated by the WJHTC simulation program known as the Fast Time Encounter Generator (FTEG). Approximately two million simulated pairwise encounters were produced by the WJHTC. The aircraft parameters (e.g., planned vertical separation at closest point of approach, vertical speed, and acceleration rates) used in these encounters were designed to include and extend somewhat beyond the typical values seen

in the airspace. The aircraft maneuvers were timed to generate worst case situations for TCAS in order to be able to test the performance limits of the system.

During previous logic evaluation work, Lincoln Laboratory developed five analysis programs. These five programs were modified to operate with the Change 7 simulated encounter data. A new set of programs was designed to help in the analysis of TCAS–TCAS reversed sense encounters. All of the analysis programs are described in the report and sample results are given. The performance metric used in all of the analysis programs is the vertical separation between the two simulation aircraft at closest point of approach (CPA). Encounters were categorized as unacceptable if the vertical separation at CPA was 100 feet or less, defined as a near mid-air collision (NMAC). During the logic analysis TCAS encounters were compared to the "planned encounter," i.e., what would have happened if TCAS were not present. This planned encounter gives a reference point for determining if TCAS failed to resolve an existing NMAC, or if TCAS induced (caused) an NMAC.

During the 6.04A logic evaluation Lincoln Laboratory identified 639 TCAS-TCAS simulated encounters in which both pilots responded properly and yet the encounter resulted in an NMAC. These 639 encounters were grouped into 30 distinct categories based on encounter geometry and resolution advisory generated. A "representative NMAC" was chosen from each of the 30 categories. These representative NMACs were studied as a part of the Change 7 logic evaluation.

The evaluation of the Change 7 logic began with an interim release of Change 7. This allowed a "dry run" to modify our existing analysis programs so they would work with the revised simulation data formats, and time to design and implement those programs specific to the Change 7 logic evaluation. The evaluation began in earnest with Version 7 Mod 10 and finished with Version 7 Mod 11, as described below.

EVALUATION GOALS

The analysis of the Change 7 CAS logic was designed to answer four questions. First, "did the new Change 7 reversal logic perform properly"? Second, "are there any new areas of concern with the Change 7 logic"? Third, "does the Change 7 logic improve the performance of TCAS II in the 30 Representative NMAC encounters identified in the 6.04a logic evaluation"? And finally, "what are the performance limits of the Change 7 logic"?

RESULTS

During the Version 7 Mod 10 evaluation process using the programs designed to study TCAS–TCAS reversals, Lincoln Laboratory very quickly identified the presence of multiple TCAS–TCAS sense reversals most of which ended in an NMAC. Upon further study, the performance of even single reversals was questionable. At this point, further analysis of Version 7 Mod 10 was suspended while the TCAS community researched the cause of the poor reversal performance and searched for possible solutions. The result of this process was a new version of the Change 7 logic (Version 7 Mod 11). The new logic has a limit of one TCAS–TCAS reversal per encounter and some other improvements to the reversal logic. This new logic also shows significant improvement in TCAS–TCAS reversals performance when both pilots followed their TCAS commands.

The following results refer to the Version 7 Mod 11 logic. To answer the first question "did the new Change 7 reversal logic perform properly" programs were written to specifically examine reversed RAs. For this logic version there are no multiple sense reversals in TCAS–TCAS or TCAS–unequipped encounters. The sense reversals that do occur with the Version 7 Mod 11 logic are effective i.e., they are more likely to result in larger vertical separations than with Version 6.04a.

One of the most compelling reasons for allowing TCAS–TCAS reversals was to protect a pilot that is following a TCAS command against a pilot that is not responding (either ignoring or maneuvering contrary) to a command. A set of simulated encounter data from WJHTC, in which one pilot in each encounter did not respond to the TCAS Resolution Advisory (RA), was analyzed to assess the logic's performance in these scenarios. The results for the non-responding pilot encounters with TCAS–TCAS reversals were very good. In the encounters most representative of real airspace (planned non-crossing) the new logic greatly reduced the number of induced NMACs.

To answer the second question "are there any new areas of concern with the Change 7 logic" an overall evaluation of the logic was performed using the remaining five Lincoln Laboratory analysis tools. Overall the results were good. NMAC counts were tabulated by encounter class (collections of pairwise aircraft encounters related by geometry, aircraft vertical rates and accelerations, see Section 1.1) and logic version. In every case the Change 7 100-foot and Change 7 25-foot logic had either fewer NMACs than 6.04a, or in a few cases the same number of NMACs as 6.04a. Change 7 reduced the overall number of crossing RAs observed, compared to 6.04a. Of the crossing RAs that remain with Change 7 a smaller percent result in NMACs, compared to the percent of crossing RAs that lead to NMACs for 6.04a.

Third, for the Representative NMAC encounters from the 6.04a logic evaluation, Change 7 with the improved 100-foot tracker resolved 28 out of the 30 encounters. The Change 7 logic with the new 25-foot tracker resolved 27 out of the 30 encounters. This represents a significant improvement over the 6.04a logic's inability to resolve any of the 30 encounters.

Fourth, to understand the limits of the Change 7 logic, every NMAC generated by either the Change 7 100-foot or Change 7 25-foot logic was plotted. These hundreds of plots were divided into groups of similar geometry and failure mechanism. There were three groups where the Change 7 logic failed to resolve a situation that would have been an NMAC without TCAS (unresolved NMACs). There were fourteen groups where Change 7 caused an NMAC where there was originally 250 feet or more of vertical separation (induced NMACs). Remembering that the WJHTC simulation is designed to stress the limits of the logic, these groups of failures were studied to determine if they were likely to occur in the airspace. In addition there are some types of encounters that TCAS cannot reasonably be expected to resolve (for example, a high rate climb by the intruder aircraft 20 seconds prior to closest point of approach). All of the seventeen groups of failures fell into the "unlikely to occur" or "impossible to fix" categories.

ACKNOWLEDGMENTS

The Lincoln Laboratory Change 7 logic evaluation was a team effort and the author would like to thank all of the people involved. Ann Drumm, TCAS project leader at Lincoln Laboratory, provided guidance and tremendous insight into the TCAS logic. The author also thanks Katharine Krozel of Lincoln Laboratory who helped edit this report.

The data used in the evaluation were provided by the WJHTC, with Tom Choyce heading a group consisting of Kathryn Ciaramella and J. Stuart Searight. WJHTC provided copies of their simulation software to Lincoln Laboratory so that a duplicate simulation facility could be set up at Lincoln Laboratory.

Lawrence Nivert of the TCAS Program Office was responsible for overseeing this work. He is the glue that keeps the TCAS team together and the rudder that keeps us from going off course.

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1. INTRODUCTION

1.1 BACKGROUND

The Traffic Alert and Collision Avoidance System (TCAS) is an airborne collision avoidance system, required since 30 December 1993 by the FAA on all air carrier aircraft with more than 30 passenger seats operating in U.S. airspace. TCAS works by actively interrogating other nearby transponder-equipped aircraft and tracking the transponder replies. For each aircraft, TCAS computes a tau value, or time to closest approach. When this value drops below a specified threshold, typically 25-30 seconds, TCAS issues a vertical command, or resolution advisory, to the pilot.

There are two levels of TCAS. TCAS II is described above and is the only level discussed in this report. TCAS I is intended for aircraft with 10-30 seats and has lesser capability; i.e., TCAS I displays only traffic advisories (position information) to the pilot, not resolution advisories.

In order to make the operation of TCAS more compatible with the existing air traffic control system as well as to correct a potential safety problem with unnecessary crossing resolution advisories, all TCAS-equipped aircraft were required to install a new logic version, known as version 6.04a, by 30 December 1994.

Since the introduction of version 6.04a, work has continued in both the national and international standards communities to monitor TCAS operation and propose changes that would either enhance current performance or correct problems found. The result of this work is TCAS version 7 (or "Change 7"), a substantial revision of 6.04a, consisting of more than 300 separately defined changes affecting all major TCAS areas. ACAS II, the internationally-defined collision avoidance system that has been mandated world-wide, is essentially equivalent to TCAS Change 7.

One of the key differences between versions 6.04a and 7 is that in TCAS–TCAS coordinated encounters, the Change 7 logic allows a TCAS to reverse its coordinated Resolution Advisory (RA) sense if the encounter geometry indicates that the situation is being degraded. With version 6.04a, once the coordination had taken place, no reversals were permitted. Because Lincoln Laboratory had been responsible for development of the TCAS–TCAS coordination logic, Lincoln Laboratory was asked to take an active role in testing MITRE's TCAS–TCAS geometric reversal logic. Lincoln Laboratory had previously teamed with the FAA's William J. Hughes Technical Center (WJHTC) to perform an overall evaluation of the 6.04a CAS logic. Now Lincoln Laboratory undertook a similar evaluation of the Change 7 CAS logic, with particular attention to the new TCAS–TCAS reversal logic. The Lincoln Laboratory evaluation is the subject of this report.

1.1.1 Logic Versions

The original logic mandated in 1993 was referred to as version 6.02. Version 6.04, a non-mandated version, was made available in late 1992 and was implemented by a few of the airlines in order to make the TCAS logic more compatible with the air traffic control system. Version 6.04 reduced the number of nuisance advisories primarily by reducing the protection volume about the TCAS aircraft and by raising the altitude threshold above which advisories would be issued.

Shortly after the introduction of version 6.04, a potential safety problem known as the "Seattle encounter" was discovered in both versions 6.02 and 6.04. Version 6.04a was developed to fix this problem. Version 6.04a was mandated in all TCAS installations by 30 December 1994.

Change 7 is a major revision to the 6.04a logic, and has been in development since 1994. Modifications to the logic were made in response to change requests (CRFs) and trouble reports (PTRs) submitted by the TCAS community. Among the changes were upgrades to the vertical tracker logic. The 100-foot vertical tracker was improved over the tracker used in 6.04a. A new tracker using 25-foot intruder altimetry data was implemented. These two different trackers give rise to two different Change 7 logic versions studied.

The RA display deferral logic was eliminated for Change 7. Also, the ability for TCAS to reverse sense against a TCAS equipped threat was added. Previously sense reversals were only allowed during the coordination process or against unequipped intruders. In addition to the changes mentioned above, a horizontal miss distance filter was implemented to reduce the number of RAs posted when there is adequate horizontal separation. Also, the multi-aircraft logic was redesigned. Lincoln Laboratory did not study these two enhancements to the logic because the simulation data from WJHTC did not provide horizontal position information or multi-aircraft encounters.

In the Change 7 logic evaluation described in this report, three logic versions are examined - 6.04a, Change 7 using the 100-foot vertical tracker (Change 7-100), and Change 7 using the 25-foot vertical tracker (Change 7-25). This was due to the fact that all three versions will be operated simultaneously in the airspace for some period of time, and it is necessary to examine the interactions between versions.

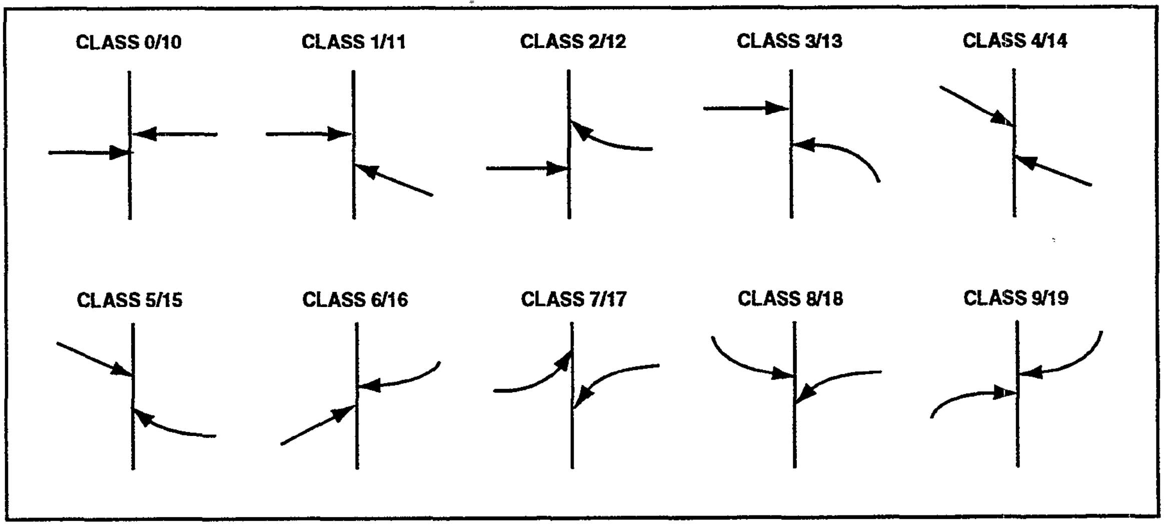
During the Change 7 logic evaluation there were many iterations of the Change 7 logic. In this report there are references to Interim Release 10 Mod 1, Version 7 Mod 10, and Version 7 Mod 11. Interim Release 10 Mod 1 was the first release of the Change 7 logic with TCAS–TCAS reversals that was examined in depth at Lincoln Laboratory. Version 7 Mod 10 is the Change 7 logic that was approved by SC-147 in May 1997. Version 7 Mod 11 is a revision of the logic designed to improve the TCAS–TCAS reversals performance. Version 7 Mod 11 was accepted by SC-147 in November 1997 and was then included in the international standards for ACAS II.

1.1.2 TCAS Development and Testing

During the development of TCAS, MITRE has been responsible for development of the CAS logic, i.e., the algorithms that perform threat detection and maneuver selection. Lincoln Laboratory has been responsible for development of the surveillance logic, i.e., the algorithms for maintaining surveillance on other aircraft, and the coordination logic, i.e., the algorithms that ensure complimentary maneuvers between two aircraft in an encounter. It is the CAS logic that is the subject of this evaluation.

Testing of the CAS logic is done by means of software simulation of large numbers of aircraft encounters. As the principal developer of the CAS logic, MITRE has been responsible for the majority of the CAS logic testing, especially as it relates to assessing the operational impact and safety of different logic versions. WJHTC became involved in the CAS logic testing in order to provide an independent check of performance and to provide an assessment of the strengths and weaknesses of the logic. In 1991, Lincoln Laboratory was tasked to work with WJHTC to help organize and analyze the large amount of data produced by the WJHTC simulation. The Lincoln Laboratory analysis tools proved to be an excellent predictor of logic problems and have been used to evaluate several versions of the CAS logic.

The WJHTC's TCAS simulation program, referred to as the Fast Time Encounter Generator (or FTEG) was described in detail in ATC-240, Section 2. All encounters run through this simulation belong to one of twenty encounter classes based on, but not limited to aircraft tracks recorded at ARTS sites throughout the United States before TCAS was available. These encounter classes are shown in Figure 1-1. The higher numbered classes (10-19) contain encounters where the aircraft do not cross in altitude. The lower numbered classes (0-9) contain encounters where the two aircraft cross in altitude. In Figure 1-1, class 0 appears to be two level aircraft, however there can be vertical rates of up to 400 fpm in class 0.



(Line segments with arrows represent aircraft vertical profiles.)

Figure 1-1. Encounter classes. (0-9 planned crossing, 10-19 planned non-crossing)

The WJHTC provided Lincoln Laboratory with their simulation source code, simulation input files, and two forms of output files. The first form of output file, known as the Encounter Recorded Data (ERD), contains a condensed description of each encounter run in the simulation. The second form of output file, known as the Lincoln Laboratory Parameter file (LLP) is derived from the ERD files and contains a very short record for each encounter that resulted in an NMAC.

In the Change 7 evaluation, because of the large number of encounters defined, there were two separate FTEG data collection/analysis efforts. See Appendix B for a breakdown of the numbers of encounters run in each table. The two tables below show the combinations of logic version and pilot response used in each of the two efforts. An x in a cell means that particular equipage/response combination was run. For example, in Table 1-1, an x in the 6.04a row and Mode C column means that some number of encounters were run in which aircraft 1 was equipped with TCAS version 6.04a and aircraft 2 was Mode C-equipped. For all encounters in Table 1-1, both TCAS pilots responded properly to the TCAS advisory. The full Lincoln Laboratory analysis (as described in Sections 2 and 4 of this report) was performed on the Table 1-1 dataset.

Table 1-1. Version 6.04a, Change 7-100, Change 7-25 Pilot Responding

	Aircraft 2			
Aircraft 1	Mode C	6.04a	C7-100	C7-25
Mode C		x	x	x
6.04a	x	x	x	x
C7-100	x	x	x	x
C7-25	x	x	x	x

In Table 1-2, there were encounters in which one pilot did not respond to (ignored) the TCAS advisory, indicated as PNR (pilot non-responding) in the output. Due to time constraints the WJHTC decided to collect only the Change 7-25 non-responding data. These data were examined to determine if the TCAS–TCAS reversals improved the protection against a non-responding pilot.

Table 1-2. Version 6.04a, Change 7/25 Pilot Responding/Pilot Not Responding (PNR)

	Aircraft 2				
Aircraft 1	Mode C	6.04a	C7-25	6.04a PNR	C7-25 PNR
Mode C		x	x		
6.04a	x	x	x	x	x
C7-25	x	x	x	x	x
6.04a PNR		x	x		
C7-25 PNR		x	x		

1.2 GOALS OF THE CHANGE 7 EVALUATION

There were four goals of the Change 7 evaluation:

1. Study the performance of the new TCAS–TCAS reversal logic. In particular, look for instances of multiple reversals and cases in which the reversal results degraded aircraft separation.

2. Do a general evaluation of the Change 7 logic, using all of the Lincoln Laboratory analysis tools, to detect and explain any "areas of concern." This effort primarily checks for areas in which the Change 7 performance is worse than the baseline 6.04a performance.

3. Examine the performance of the Change 7 logic for the 30 Representative NMACs identified during the 6.04a logic evaluation. Determine if the expected improvements occurred.

4. Analyze every Change 7 NMAC produced by the simulation in order to understand the performance limits of the Change 7 logic. For those NMACs deemed likely to occur in the real airspace, discuss possible courses of action to improve the CAS performance.

1.3 ORGANIZATION OF THIS REPORT

Section 1 provides background on TCAS development and testing, including descriptions of the current CAS logic version 6.04a and the proposed new logic known as TCAS II Change 7. It also describes the major goals of the Change 7 evaluation effort.

Section 2 describes the seven programs developed by Lincoln Laboratory to analyze the simulation outputs. The operation of each program is explained, and sample outputs are given.

Section 3 describes the analysis of the TCAS–TCAS reversals during the evolution of the Change 7 logic.

Section 4 describes the general evaluation effort.

Section 5 discusses the outcome of running the 30 6.04a Representative NMACs with the Change 7 logic.

Section 6 describes the Representative NMAC encounters produced by the Change 7 logic.

Section 7 gives a summary of the Change 7 logic and a historical perspective of the performance of versions 6.02, 6.04, 6.04a, and Change 7.

2. ANALYSIS TOOLS

A block diagram showing the WJHTC simulation facility and the Lincoln Laboratory analysis tools is given in Figure 2-1. There are seven main analysis programs, described in the subsections below. Main inputs to the analysis programs are the WJHTC Encounter Recorded Data (ERD) files. Lincoln Laboratory maintains a duplicate copy of the WJHTC simulation. Second-by-second data outputs from Lincoln Laboratory's simulation are used to generate plots of individual encounters.

The performance metric used in all of the analysis programs is the vertical separation between the two aircraft at point of closest approach. In general, encounters are either acceptable or not acceptable depending upon whether or not the encounter results in an NMAC, or near mid-air collision, defined as a vertical separation of ≤ 100 feet at point of closest approach. (Horizontal separation for an NMAC is defined to be ≤ 0.1 nmi). Because TCAS does not attempt to affect horizontal separation, the evaluation of TCAS logic performance usually assumes that a worst case (zero) horizontal separation will occur. Thus, avoidance of an NMAC depends entirely on achieving sufficient vertical separation.)

A key element in the measurement of performance is the "planned encounter," i.e., an encounter as it would have unfolded if TCAS were not present. The "planned" performance of each geometry used by the simulation (i.e., the vertical separation at closest approach) is determined by running the simulation with a TCAS non-responding aircraft in an encounter with a Mode C aircraft. This planned performance is compared to the performance of various TCAS equipages to determine if TCAS failed to resolve an existing NMAC or induced an NMAC where none had previously existed. Note that according to international guidelines, for every 100 existing NMACs, the goal is for TCAS to be able to resolve 90 NMACs without inducing more than 2 NMACs. Thus, it is accepted that TCAS will not be able to resolve all NMACs, but there is a very low tolerance for inducing NMACs.

Referring to Figure 2-1, there are seven analysis programs. The two Reversal Analysis Programs were developed specifically for the Change 7 logic evaluation. These programs are described in detail in Section 2.1. Four other programs (Hot-Spot Program, Performance Statistics Program, NMAC Characterization Program, and NMAC Analysis Program) were carried over from the 6.04a logic analysis and were described in detail in Project Report ATC-240, Section 3. The Matrix Generator program was carried over from the 6.04a logic analysis, but WJHTC changed the number and definition of some of the tables, so this program will be described in detail in Section 2.2 of this report.

A significant question which needed to be addressed in the Change 7 logic was the performance of the TCAS–TCAS reversal logic. Because of this the Reversal Analysis Programs were the first programs run. Using the Reversal Analysis Programs we were able to quickly detect the presence of multiple reversals, and also the presence of large numbers of reversed encounters that were not NMACs, but experienced significant loss of vertical separation.

The Matrix Generator Program was the next program run and provides a means for very quickly and clearly understanding CAS logic performance (in terms of NMACs) as a function of encounter class (classes 0-19) and equipage pair (6.04a vs. 6.04a, 6.04a vs. Change 7-100, etc.). In cases where a detailed analysis is not required or possible, this single program can provide extremely useful overview performance information, both in absolute terms and in relative terms between the different logic versions.

The Hot-Spot Program combines related cells from two of the Matrix Generator Program tables and produces condensed tables. These tables identify "hot-spots" or areas of poor performance in a given version of the TCAS logic. These hot-spots are then examined in more detail, first by the NMAC Characterization Program and then by the NMAC Analysis Program. The NMAC Characterization Program identifies particular parameters (vertical rate, acceleration, etc.) or combinations of parameters associated with the hot-spots. The NMAC Analysis Program scans through the encounter data for each of the hot-spots, providing a summary of key encounter elements, e.g., the sequence of advisories for each aircraft, timing delays in the issuing of advisories, etc.

Finally, the Performance Statistics Program is run on all of the input data. This program provides statistics on the frequency and performance of altitude crossing advisories.

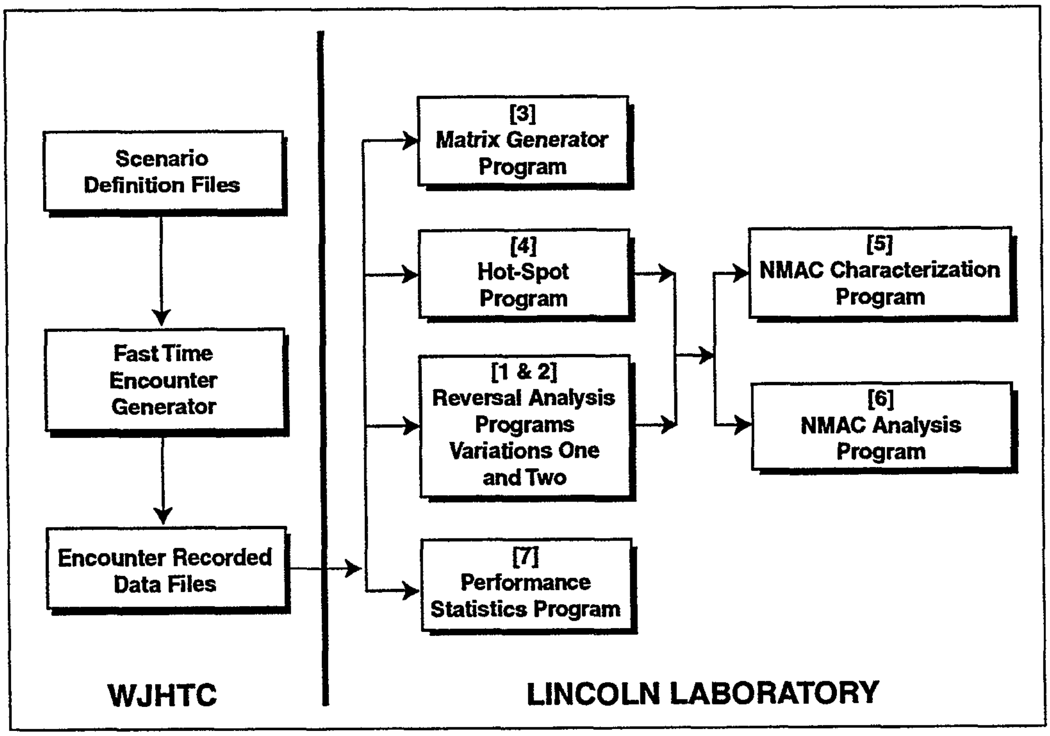


Figure 2-1. Lincoln Laboratory Analysis Programs.

2.1 REVERSAL PROGRAMS

TCAS–TCAS geometric reversals are an important new feature in the Change 7 logic. New software was developed at Lincoln Laboratory to study the behavior of TCAS–TCAS geometric reversals. The purpose of the Reversal Analysis Program is to provide statistics on the frequency and effectiveness of reversed Resolution Advisories (RAs). There are two variations of the Reversal Analysis Program. The first variation shows statistics for reversed RAs based on the presence or absence of NMACs as well as the number of sense reversals observed. The second variation evaluates all encounters with RAs, both reversed and non-reversed, and generates counts of separation gains and separation losses.

2.1.1 Multiple Reversals

The first program variation tabulates information by equipage pair for TCAS-unequipped and TCAS–TCAS reversed encounters. The initial focus of the program was to look for "fast" reversals, i.e., those occurring within three seconds of the initial RA, and multiple sense reversals. Figure 2-2 shows a sample output from Reversals Analysis Program variation one for class 13, Version 7 Mod 11. Results for the full twenty classes are given in Appendix C.

As shown in Figure 2-2, for each equipage there are fifteen statistics computed:

1. the percentage of encounters that produced RAs;
2. the percentage of encounters that produced NMACs;
3. the percentage of NMACs that were induced;
4. the percentage of encounters that had reversals;
5. the percentage of RAs that had reversals;
6. the percentage of reversals that occurred within three seconds of the initial RA;
7. the percentage of reversals that were single reversals;
8. the percentage of single reversals that were NMACs;
9. the percentage of single reversal NMACs that were induced;
10. the percentage of reversals that were double reversals;
11. the percentage of double reversals that were NMACs;
12. the percentage of double reversal NMACs that were induced;
13. the percentage of reversals that had at least three reversals;
14. the percentage of triple (plus) reversals that were NMACs;
15. the percentage of triple (plus) reversal NMACs that were induced.

Remember that class 13 is defined as a non-crossing class (i.e., the aircraft do not plan to cross in altitude), and this is a very common encounter type in the airspace (the fourth highest weight out of all twenty classes). Note that in Figure 2-2, all of the reversal entries in the 6.04a only column are zeros, as TCAS–TCAS geometric reversals were not allowed in version 6.04a. From Figure 2-2 we also observe that C7-100 and C7-25 have more than eight percent of their RAs reversing sense. For C7-100 1.42% of the reversed RAs had NMACs, but C7-25 had no reversed RAs with NMACs. Also note that the last six rows in Figure 2-2 and in all tables found in Appendix C are zero. This will be discussed in depth later in Section 3.

2.1.2 Separation Differences

The second program variation provides an alternative to the NMAC performance criteria by defining a new measure, the separation difference. The separation difference is defined as the absolute value of the achieved separation (with TCAS involved) minus the absolute value of the planned separation (i.e., what would have occurred without TCAS). As an example, for a planned separation of -500 feet (aircraft 1 500 feet below aircraft 2) and an achieved separation of 400 feet (aircraft 1 400 feet above aircraft 2) we get a separation difference of 400 - 500 or -100 feet; a loss of 100 feet in vertical separation. This value is computed for every encounter that had an RA. Two sets of four tables are generated; the first set is for non-reversed RAs and the second set is for reversed RAs.

MITRE encounter classes: 3,13 Date processed: 8/21/97
Based on FAA Technical Center data of: AUGUST 1997
Total Encounters: 93312
Total incorrectly labeled RAs : 0
Class 13 Planned = NON-CROSSING

Percent	6.04A Mode C	C7-100 Mode C	C7-25 Mode C	6.04A only	C7-100 6.04A	C7-25 6.04A	C7-100 only	C7-25 only	C7-25 C7-100
RAs/ runs	59.29	59.17	58.33	62.06	62.52	60.01	62.50	60.15	61.29
NMACs/ runs	0.76	0.37	0.22	0.10	0.05	0.02	0.07	0.00	0.04
Induced/ NMACS	96.77	100.00	100.00	100.00	100.00	100.00	100.00	0.00	100.00
Reversals/ runs	6.89	7.87	9.39	0.00	2.66	2.86	5.17	5.34	5.23
Reversals/ RAs	11.62	13.30	16.09	0.00	4.25	4.76	8.27	8.88	8.54
Fast Rev./ Reversals	38.43	39.25	43.34	0.00	29.95	32.19	33.65	36.24	35.13
1 Rev. / Reversals	100.00	100.00	100.00	0.00	100.00	100.00	100.00	100.00	100.00
NMACS/ 1 Rev.	0.00	0.00	0.00	0.00	0.92	0.43	1.42	0.00	0.70
Ind. NMAC/ NMACs	0.00	0.00	0.00	0.00	100.00	100.00	100.00	0.00	100.00
2 Rev. / Reversals	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMACS/ 2 Rev.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ind. NMAC/ NMACs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3+ Rev. / Reversals	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMACS/ 3+ Rev.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ind. NMAC/ NMACs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

* NMACs and average alt. sep. at CPA are based on simulation truth

Figure 2-2. Sample Reversal Analysis Program Variation One Output – Version 7 Mod 11.

Each set contains four tables, showing the number of: (1) planned crossing encounters showing separation gains, (2) planned crossing encounters showing separation losses, (3) planned non-crossing encounters showing separation gains, and (4) planned non-crossing encounters showing separation losses. Each individual table shows the separation gain or loss grouped in 250 foot bins for each of the possible planned separations. Results for the full twenty classes are given in Appendix D. The separation difference results for classes 3,13 are shown in Figure 2-3. For Figure 2-3, the first four tables describe the behavior of non-reversed RAs; notice that the "gains" tables are well populated and the "losses" tables are almost all zero entries. The next four tables describe the behavior of reversed RAs for Version 7 Mod 11; here we see mostly gains and a few losses that are small in magnitude.

2.2 MATRIX GENERATOR PROGRAM

The purpose of the Matrix Generator Program is to provide an easy-to-read summary of the number of NMACs as a function of encounter class and equipage pair and to provide a description of key parameters associated with those NMACs. In particular, the Matrix Generator Program reads ERD files and generates two sets of outputs: NMAC tables and NMAC parameter files. The Matrix Generator Program is unique among the seven Lincoln Laboratory analysis programs in that it was coded at WJHTC based on Lincoln Laboratory specifications. The other six analysis programs were produced solely by Lincoln Laboratory.

2.2.1 NMAC Tables

There are eight NMAC tables, or matrix tables, for each encounter class. The Matrix Generator Program generates these tables according to the scheme shown in Figure 2-4. First, the TCAS encounters for each class are divided into two groups: those whose corresponding planned encounter resulted in an NMAC and those whose corresponding planned encounter did not result in an NMAC. From the first group (planned NMACs), the program then looks at the vertical separations produced when the aircraft in the encounters are equipped with TCAS. The encounters are then divided into three subgroups:

A: neither aircraft had a resolution advisory (RA), but an NMAC resulted (TCAS had a missed detection);

B: at least one aircraft had an RA, but still an NMAC resulted (TCAS couldn't resolve the original bad situation);

C: at least one aircraft had an RA, but there was no NMAC (TCAS resolved the original bad situation).

From the second group (planned non-NMACs), the program then looks at the vertical separations produced when the aircraft in the encounters are equipped with TCAS. The encounters are then divided into four subgroups:

D: neither aircraft had an RA, and there was no NMAC (TCAS correctly did not perceive there to be a problem);

E: at least one aircraft had an RA, and there was an NMAC (TCAS induced an NMAC);

F: at least one aircraft had an RA, there was no NMAC, but there was a loss in vertical separation.

G: at least one aircraft had an RA, there was no NMAC, and there was increased vertical separation.

From the seven subgroups, eight tables are formed:

Table 1 = subgroup A (unresolved NMACs with no RA, i.e., missed detections)

Table 2 = subgroup B (unresolved NMACs with at least one RA)

Table 3 = Table 1 + Table 2 = total number of unresolved NMACs.

Table 4 = subgroup E (induced NMACs)

Table 5 = subgroup F (reduced separation non-NMACs)

Table 6 = subgroup G (increased separation non-NMACs)

Table 7 = subgroup A + subgroup D (encounters without an RA)

Table 8 = subgroup C (number of RAs resolving NMACs)

Tables are labeled based on the encounter class and table number, e.g., Table 1.4 corresponds to class 1, induced NMACs. Generally, out of the five tables, tables 3 and 4, unresolved NMACs and induced NMACs, are used most frequently.

A sample table, Table 19.4, is shown in Figure 2-5. Note that the table header refers to "simulation truth." The declaration of an NMAC uses the simulation's altitude inputs to the CAS logic, not the CAS tracked altitudes. Since simulation truth is the same for both aircraft the Matrix Generator Program generates the NMAC tables with the results of the FTEG simulation from only one aircraft point of view.

As shown in Figure 2-5, the number of planned TCAS–TCAS encounters is twice the number of planned TCAS-Mode C encounters. There are more TCAS–TCAS encounters because the Mode S ID is varied to test the CAS air-to-air coordination logic. If both aircraft select the same sense RA, the low ID aircraft prevails and the high ID aircraft must reverse sense. This is called a coordination reversal. Thus each geometry is run first with aircraft 1 having the low Mode S ID and then with aircraft 2 having the low Mode S ID.

A full set of 160 NMAC tables (20 classes, 8 tables per class) is given in Appendix E.

2.2.2 Parameter Files

The parameter files provide a quick summary of parameter values for each of the NMAC encounters. Each line in a parameter file corresponds to one encounter. Since there is too much data to print each line on a single page, the lines have been broken up into three parts. Appendix F contains a complete description of the parameters in all three parts, as well as a sample parameter file printout for encounter classes 7/17.

SEP. DIFF. = ABS(ACH. SEP.) - ABS(PLAN SEP.) DATASET 1 CLASSES 313 CH7 VS CH7 ONLY
PLANNED CROSSING 14784 ENCOUNTERS PLANNED NON-CROSSING 16320 ENCOUNTERS
-----NON REVERSED RAs -- GAINS : 15169 LOSSES : 10 NO CHANGE : 3598

PLANNED = CROSSING RA COUNT = 9628 NMAC COUNT = 0

GAINS PLAN SEP	NO GAIN	>0..250	>250..500	>500..750	>750..1000	> 1000
0 FT	0	0	170	1987	401	304
250 FT	0	210	2448	372	262	196
500 FT	2306	632	48	78	24	16
750 FT	106	48	14	2	0	0
1000 FT	0	0	0	0	0	0

LOSSES PLAN SEP		>0..250	>250..500	>500..750	>750..1000	> 1000
0 FT		0	0	0	0	0
250 FT		0	0	0	0	0
500 FT		0	0	0	0	0
750 FT		4	0	0	0	0
1000 FT		0	0	0	0	0

PLANNED = NON-CROSSING RA COUNT = 9149 NMAC COUNT = 0

GAINS PLAN SEP	NO GAIN	>0..250	>250..500	>500..750	>750..1000	> 1000
0 FT	0	0	52	428	32	0
250 FT	0	37	1585	762	308	46
500 FT	898	1055	870	490	181	54
750 FT	146	626	491	226	88	0
1000 FT	142	239	299	84	4	0

LOSSES PLAN SEP		>0..250	>250..500	>500..750	>750..1000	> 1000
0 FT		0	0	0	0	0
250 FT		6	0	0	0	0
500 FT		0	0	0	0	0
750 FT		0	0	0	0	0
1000 FT		0	0	0	0	0

-----REVERSED RAs - GAINS : 897 LOSSES : 41 NO CHANGE : 0

PLANNED = CROSSING RA COUNT = 82 NMAC COUNT = 0

GAINS PLAN SEP	NO GAIN	>0..250	>250..500	>500..750	>750..1000	> 1000
0 FT	0	0	0	70	12	0
250 FT	0	0	0	0	0	0
500 FT	0	0	0	0	0	0
750 FT	0	0	0	0	0	0
1000 FT	0	0	0	0	0	0

LOSSES PLAN SEP		>0..250	>250..500	>500..750	>750..1000	> 1000
0 FT		0	0	0	0	0
250 FT		0	0	0	0	0
500 FT		0	0	0	0	0
750 FT		0	0	0	0	0
1000 FT		0	0	0	0	0

PLANNED = NON-CROSSING RA COUNT = 856 NMAC COUNT = 6

GAINS PLAN SEP	NO GAIN	>0..250	>250..500	>500..750	>750..1000	> 1000
0 FT	0	0	0	0	0	0
250 FT	0	123	458	68	0	0
500 FT	0	104	62	0	0	0
750 FT	0	0	0	0	0	0
1000 FT	0	0	0	0	0	0

LOSSES PLAN SEP		>0..250	>250..500	>500..750	>750..1000	> 1000
0 FT		0	0	0	0	0
250 FT		31	0	0	0	0
500 FT		10	0	0	0	0
750 FT		0	0	0	0	0
1000 FT		0	0	0	0	0

Figure 2-3. Sample Reversal Analysis Program Variation Two Output.

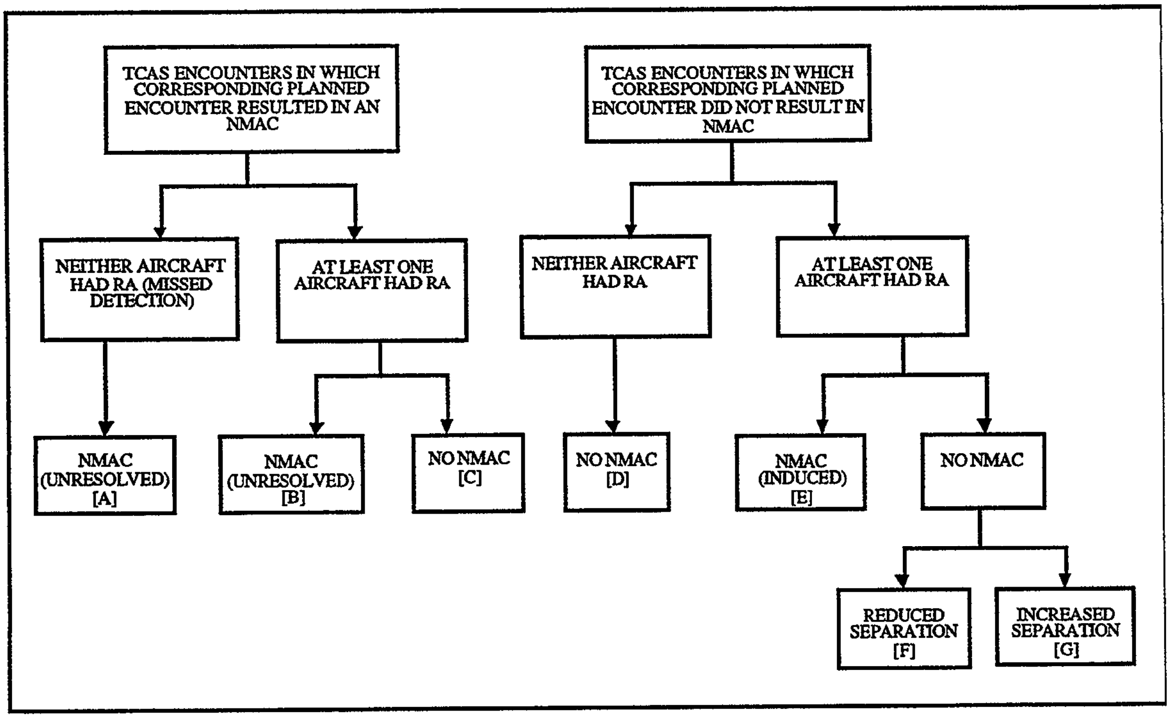


Table x.1	Number of unresolved NMACs with neither aircraft having an RA (missed detections) [A]
Table x.2	Number of unresolved NMACs with at least one aircraft having an RA [B]
Table x.3	Total number of unresolved NMACs [A+B]
Table x.4	Number of induced NMACs [E]
Table x.5	Number of non-NMAC RAs with reduced separation [F]
Table x.6	Number of non-NMAC RAs with increased separation [G]
Table x.7	Number of encounters without an RA [A+D]
Table x.8	Number of RAs resolving NMACs [C]

x = encounter class

Figure 2-4. Scheme for Generating NMAC Tables.

2.3 HOT-SPOT PROGRAM

The purpose of the Hot-Spot Program is to check for areas of concern, defined as matrix table cells for which logic versions Change 7-100 or Change 7-25 have more NMACs than version 6.04a. These areas of concern are known as "hot-spots".

The outputs of the Hot-Spot Program are a compressed form of the NMAC tables called summary NMAC tables. The summary NMAC tables have the same table numbers as the NMAC tables from which they are derived, but there are only two summary NMAC tables per encounter class (tables x.3 and x.4, i.e., unresolved and induced NMACs), instead of eight, as in the original NMAC tables. In addition, the numbers in the summary NMAC tables are not raw counts, but rather percentages (percentage of NMAC encounters out of the total number of encounters run) to allow for easy recognition of hot-spots.

```
MITRE encounter Class: 19   "planned = NON CROSSING" Date processed 8/25/97
Based on FAA Technical Center data of: AUG 1997
All Responding V6.04A vs V7 V&V Baseline Modl; 100 & 25-foot trackers
Failure: CPA <= 100.0 ft based on simulation truth

                              Table 19.4
                         Number of induced Failures
                        (based on simulation truth)
Normalizing Number = number of planned encounters not resulting in failure
Normalizing number for Mode C cells:     3702
Normalizing number for TCAS-TCAS cells:  7404
```

Aircraft 1 \ Aircraft 2	Non-TCAS	V6.04a	Ch7/100	Ch7/25	-
Non-TCAS	--	115	48	30	--
V6.04a	35	36	18	21	--
Ch7/100	22	24	13	10	--
Ch7/25	8	5	9	3	--
	--	--	--	--	--

Figure 2-5. Sample NMAC Table.

Table 19.4 - Percent of induced failures

	6.04A only	Ch7-100 ft only	Ch7-25 ft only	6.04A/ Ch7-100	6.04A/ Ch7-25	Ch7-25/ Ch7-100
TCAS-TCAS	0.486	0.176	0.041	0.284	0.176	0.128
One Mode C	2.026	0.945	0.513	-----	-----	-----

Figure 2-6. Sample Summary NMAC Table.

The technique for computing the summary NMAC tables is described in ATC-240, Section 3.2.1. Figure 2-6 shows a sample summary NMAC table, summary NMAC Table 19.4. Summary NMAC tables are produced by combining the cells from NMAC Table 19.4, shown in Figure 2-5.

In the summary NMAC tables hot-spots are indicated by double asterisks (**) followed by double greater than signs (>>). This indicates that the Change 7 performance was worse than 6.04a and at least two percent of the encounters run were NMACs. Table cells with only double asterisks indicate an increase in NMACs compared to 6.04a, but an insignificant number of NMACs (less than two percent of encounters run).

Summary NMAC tables for the full 20 classes are given in Appendix G.

2.4 NMAC CHARACTERIZATION PROGRAM

The purpose of the NMAC Characterization Program is to identify particular parameters (vertical rates, accelerations, etc.) or combinations of parameters associated with groups of NMACs. These programs were developed during previous logic evaluations and are described in detail in ATC-240, Section 3.3.

There are two variations of the NMAC Characterization Program. The first variation (NMACs as a function of parameter values) looks at the NMACs occurring in a particular matrix cell and determines the frequency of certain parameters or parameter combinations. For example, consider class 19. As shown in Table 2-1 (taken from Appendix A), there are eight parameters in class 19.

Table 2-1. Class 19 Parameter Variations

Parameter	Range	Step Size	No. of Steps
altitude separation @ CPA	-1000, 1000 ft	250	9
vertical rate 1	1000, 5000 fpm	2000	3
vertical rate 2	-5000, 5000 fpm	20000	6
vertical acceleration 1	-15, -.05	.1	2
vertical acceleration 2*	.05, .35	.1	4
time of acceleration 1	25 sec		1
time of acceleration 2	20, 30 sec	5	3
Altitude of AC1 at CPA	3700, 7500 ft	3800	2

*Sign of acceleration is opposite sign of vertical rate

Now look at Table 19.4 (Figure 2-5) and at a particular cell (3,3) in that table, i.e., Class 19, induced NMACs, versions C7-100/C7-100. The table shows that there were 13 NMACs in that cell.

Figure 2-7 shows an output from the first NMAC Characterization Program corresponding to that same cell. Note that the headings on the top right of the table correspond to the eight parameters in Table 2-1 above. For each of the eight parameters (plus a ninth - Mode S ID), the output shows the frequency with which particular parameter values occurred in the 13 NMACs.

PROGRAM LLPRFU - Frequency (COUNT) of Multiple Valued Parameters; (--) are excluded parameters. Tue, 30 Sep 1997

CLASS	TBL	ROW	COL	AC1 EQ	AC2 EQ	AC1 RES	AC2 RES	Com Nmb	Nmb Com	Parameter Comb.Code	COUNT	HI ID	CPA. SEP	AC1 RATE	AC2 RATE	AC1 ACC	AC2 ACC	AC1 TIM	AC2 TIM
19	4	3	3	71	71	1	1	1	1	100000000 (	3)	2	--	--	--	--	--	--	--
19	4	3	3	71	71	1	1	1	1	100000000 (	10)	1	--	--	--	--	--	--	--
19	4	3	3	71	71	1	1	2	1	010000000 (	2)	--	-250.00	--	--	--	--	--	--
19	4	3	3	71	71	1	1	2	1	010000000 (	11)	--	-500.00	--	--	--	--	--	--
19	4	3	3	71	71	1	1	4	1	001000000 (	2)	--	--	1000.0	--	--	--	--	--
19	4	3	3	71	71	1	1	4	1	001000000 (	11)	--	--	5000.0	--	--	--	--	--
19	4	3	3	71	71	1	1	8	1	000100000 (	2)	--	--	--	-3000.0	--	--	--	--
19	4	3	3	71	71	1	1	8	1	000100000 (	11)	--	--	--	-5000.0	--	--	--	--
19	4	3	3	71	71	1	1	16	1	000010000 (	2)	--	--	--	--	-0.05	--	--	--
19	4	3	3	71	71	1	1	16	1	000010000 (	11)	--	--	--	--	-0.15	--	--	--
19	4	3	3	71	71	1	1	32	1	000001000 (	3)	--	--	--	--	--	0.35	--	--
19	4	3	3	71	71	1	1	32	1	000001000 (	4)	--	--	--	--	--	0.25	--	--
19	4	3	3	71	71	1	1	32	1	000001000 (	6)	--	--	--	--	--	0.15	--	--
19	4	3	3	71	71	1	1	128	1	000000010 (	6)	--	--	--	--	--	--	--	-25.0
19	4	3	3	71	71	1	1	128	1	000000010 (	7)	--	--	--	--	--	--	--	-20.0
19	4	3	3	71	71	1	1	256	1	000000001 (	6)	--	--	--	--	--	--	--	--
19	4	3	3	71	71	1	1	256	1	000000001 (	7)	--	--	--	--	--	--	--	--

Figure 2-7. Table 19.4 Cell (3,3) NMACs as a Function of Parameter Values.

For example, looking at the column labeled "count," we see that of the 13 NMACs, there were 3 in which aircraft 2 had the higher Mode S ID and 10 in which aircraft 1 had the higher Mode S ID. Likewise, moving down the column, we see that 2 of the NMACs had a planned separation of -250 feet, and 11 had a planned separation of -500 feet. This type of output shows quickly whether any parameter value was especially troublesome.

Appendix H lists NMACs as a function of parameter values for all classes, Tables x.3 and x.4 (i.e., unresolved and induced NMACs). The column heading 65 represents 6.04a/6.04a, the column heading 71 represents C7-100/C7-100, and the column heading 75 represents C7-25/C7-25.

The second variation (NMACs as a function of logic version) looks at the NMACs occurring in a particular matrix table and determines which NMACs are common to which versions of the logic. For example, in Table 19.4 (Figure 2-5), the 6.04a/6.04a cell shows 36 NMACs, while the C7-100/C7-100 cell shows 13 NMACs. This program allows us to answer questions such as, "Are the 13 C7-100/C7-100 NMACs a subset of the 36 6.04a/6.04a NMACs? Did the Change 7 logic introduce new NMACs not present in the 6.04a logic?"

Appendix I lists NMACs as a function of logic version for all classes, tables x.3 and x.4 (i.e., unresolved and induced NMACs). There are three sets of tables reporting NMACs as a function of logic version. The first set compares 6.04a/6.04a vs. C7-100/C7-100. The next set compares 6.04a/6.04a vs. C7-25/C7-25. The final set compares C7-100/C7-100 vs. C7-25/C7-25.

2.5 NMAC ANALYSIS PROGRAM

The purpose of the NMAC Analysis Program is to understand why an NMAC occurred for one particular TCAS equipage pair and not another, e.g., why a Change 7/Change7 encounter had an NMAC, but a 6.04a/6.04a encounter did not. The program output is a set of encounter summaries, giving key information about the motion of both aircraft, the CAS logic thresholds in use, the specific event that triggered the RA, the sequence of RAs, and the presence of reversed RAs. Appendix J contains a summary of CAS thresholds, layers, and sensitivity levels for reference.

The NMAC Analysis Program was developed during the 6.04a logic evaluation and is described in detail in ATC-240, Section 3.4. For the Change 7 analysis, three sets of encounter summaries were printed together, allowing quick comparison of the differences between logic versions 6.04a, C7-100, and C7-25. In addition, because most of the analysis for Change 7 centered on reversed RAs, any sequence of RAs containing a sense reversal is preceded by "** REV **" in the encounter summaries. A sample set of three encounter summaries is shown in Figure 2-8 with a description of the fields in Figure 2-9. In Figure 2-9, the term RA final condition means that this is the final test that was passed in the CAS logic Range and Altitude tests before the RA was issued. Possible values for RA final condition are range tau (TAUR,) vertical tau (TAUV), relative altitude between the two aircraft (RELZ), and projected vertical miss distance (PVMD). Also in Figure 2-9, ALIM is the vertical separation that the CAS logic is intending to achieve.

```
1541    6.04A RH VS 6.04A RL    18    -144.58    CROSSING_ENCOUNTER

SL =  5  ZTHR =  600.0   TAUR =  25.0   TAUV =  25.0   ALIM = 350.0

 750.0 (-5000.0,0.0)  (0.0,-3000.0)  0.15  -0.05  -25.0  -25.0   3700.0

A/C1:         1165122 TA TIME :19 |TAUR | POTRA @34   (6FT) | DES   @45

[XRA] | IDES  @47
A/C2:         1265022 TA TIME :19 |TAUR | DDES  @43   [XRA] | CL    @47


1541    C7 100 FT RH VS C7 100 FT RL    18       2.12   CROSSING_ENCOUNTER

SL =  5  ZTHR =  600.0   TAUR =  25.0   TAUV =  25.0   ALIM = 300.0

 750.0 (-5000.0,0.0)  (0.0,-3000.0)  0.15  -0.05  -25.0  -25.0   3700.0

A/C1:** REV **1171133 TA TIME :19 |TAUR | POTRA @34   | POTRA @40   | DES
@44   [XRA] | CL  @54

A/C2:** REV **1271033 TA TIME :19 |TAUR | POTRA @34   (LVW) | POTRA @40

       (LVW) | POTRA @42  | DDES  @43   [XRA] | CL    @46     | DES   @53


1541    C7 25 FT RH VS C7 25 FT RL    18   1373.09   NON_CROSSING_ENCOUNTER

SL =  5  ZTHR =  600.0   TAUR =  25.0   TAUV =  25.0   ALIM = 300.0

 750.0 (-5000.0,0.0)  (0.0,-3000.0)  0.15  -0.05  -25.0  -25.0   3700.0

A/C1:         1175144 TA TIME :19 |TAUR | CL    @34   [NXRA]| DDES  @46


A/C2:         1275044 TA TIME :19 |TAUR | DES   @34   [NXRA]| IDES  @41   |
DCL   @51
```

Figure 2-8. Sample Encounter Summary.

```
                         ENCOUNTER SUMMARY FIELD DESCRIPTIONS
Reit#   AC1 Respond    AC2 Respond Class  Achieved
        High Id          Low ID           Separation
1541      6.04A RH VS 6.04A RL      18    -144.58  CROSSING_ENCOUNTER

Sensitivity   Vertical RA        Alarm Times         Vertical Separation
Level         Threshold        Range    Vertical     goal for CAS logic
SL =  5       ZTHR=600.0       TAUR=25. TAUV=25.0      ALIM=350.0

This row shows the values from the planned encounter:
Planned        AC1         AC2              Accel.    Accel. Time  AC1 Alt
Sep.        (beg rate, end rate)          AC1     AC2   AC1  AC2    at CPA
750.0     (-5000.0,0.0) (0.0,-3000.0)    0.15  -0.05   -25.0 -25.0 3700.0

simulation          RA final          delay
mode               condition
A/C1:    1165122 TA TIME :19 |TAUR | POTRA @34 (6FT)

First         CROSSING   Next RA
RA @time        RA         @ time
| DES    @45      [XRA] | IDES  @47

simulation            RA final   First   CROSSING Next RA
mode                 condition  RA @time    RA     @ time

A/C2:     1265022 TA TIME :19 |TAUR | DDES @43 [XRA] | CL @47

Reit = reiteration number an identifying number for a particular combination of
parameter values. The reit number and class uniquely identify an encounter.
```

Climb Sense RA Acronyms		Descend Sense RA Acronyms	
ACRONYM	RA	ACRONYM	RA
LD2	Limit descent to 2000 fpm	LC2	Limit climb to 2000 fpm
LD1	Limit descent to 1000 fpm	LC1	Limit climb to 1000 fpm
LD5	Limit descent to 500 fpm	LC5	Limit climb to 500 fpm
DDES	Don't descend	DCL	Don't climb
CL	Climb	DES	Descend
ICL	Increase climb	IDES	Increase descend

Figure 2-9. Encounter Summary Field Descriptions.

A brief look at the encounter summaries in Figure 2-8, (referring to the field descriptions in Figure 2-9) illustrates the kinds of information quickly provided. First, by looking the first line of each summary, one can tell immediately that version 6.04a did not have an NMAC (achieved separation = -144.58 feet), C7-100 had an NMAC (achieved separation = 2.12 feet), and C7-25 did not have an NMAC (achieved separation = 1373.09 feet). Also, by looking at the third field in the first line this encounter is in class 18, meaning the aircraft did not intend to cross in altitude. From the last field in the first line one can tell that for 6.04a and C7-100 this is a crossing encounter, but for C7-25, this is a non-crossing encounter.

Using the fifth line in the version 6.04a summary we observe that AC2 issued an RA ("don't descend" at time 43 seconds (17 seconds prior to CPA) followed by another RA ("climb") at time 47 seconds. Looking at the fourth line of the version 6.04a summary we see that AC1 issued an

RA ("descend") at time 45 seconds which was strengthened to "increase descend" at time 47 seconds. These RAs caused the aircraft to cross in altitude.

For this same encounter with C7-100 the initial RAs were similar to 6.04a: AC2 issued an RA ("don't descend") at time 43 seconds, then another RA ("climb") at time 46 seconds, and AC1 issued an RA ("descend") at time 44 seconds. These RAs would also cause the aircraft to cross in altitude. The difference shown by the C7-100 logic is that AC2 reversed the sense of its RA ("descend") at time 53 seconds, which forced AC1 to reverse to a "climb" at time 54 seconds, causing the NMAC. In contrast, the C7-25 logic issued RAs much earlier, and was able to choose non-crossing commands: AC1 issued an RA ("climb") at time 34 seconds, AC2 issued an RA ("descend") at time 34 seconds resulting in more than adequate separation.

To aid in the interpretation of the encounter summaries, encounter plots were also produced. A shell program was written to automatically operate the Lincoln Laboratory version of the FTEG simulation. For a specified encounter, the shell program made calls to FTEG and produced encounter plots as well as intermediate files used to generate the encounter summaries.

Figure 2-10 shows the output of the basic version of the shell program. Here, second-by-second position information is plotted for the C7-100 encounter described in Figure 2-9. AC1 is shown starting from the left side of the page with AC1 time along the bottom of the plot. AC2 is shown starting from the right side of the page with AC2 time along the top of the plot. The RAs issued are superimposed on the aircraft position. As you can see from the plot, AC2 was level and had just begun to descend when the "climb" RA was issued, i.e., the RA was opposite to the intended direction of the aircraft. AC1 was descending and had just begun to level off when the "descend" RA was issued. Rather than issue an increase, the RAs were reversed six seconds prior to CPA causing the NMAC.

The encounter summaries and encounter plots were used throughout the numerous iterations of the Change 7 analysis effort to quickly understand the essence of the encounters.

2.6 PERFORMANCE STATISTICS PROGRAM

The purpose of the Performance Statistics Program is to provide statistics on the frequency and effectiveness of altitude crossing advisories. The Performance Statistics Program was developed during the 6.04a logic evaluation and is described in detail in ATC-240, Section 3.5.

Figure 2-11 shows a sample output from the Performance Statistics Program for class 19. For each TCAS equipage, there are eight statistics computed:

1. the percentage of encounters that produced RAs;
2. the percentage of RAs that were crossing RAs;
3. the percentage of encounters that produced crossing RAs;
4. the percentage of crossing RAs that resulted in NMACs;
5. the percentage of NMACs that were crossing RAs;
6. the percentage of encounters that resulted in NMACs;

7. the average warning time in seconds (time of CPA minus time of RA);

8. the average altitude separation at CPA in feet.

Remember that class 19 is defined as a non-crossing class (i.e., the aircraft do not plan to cross in altitude), but as shown in the second row, for version 6.04a nearly 24% of the RAs issued were crossing RAs. Note also that in the fifth row, for all of the equipage pairs, 100% of the NMACs were crossing RAs.

Performance Statistics for the full 20 classes are given in Appendix K.

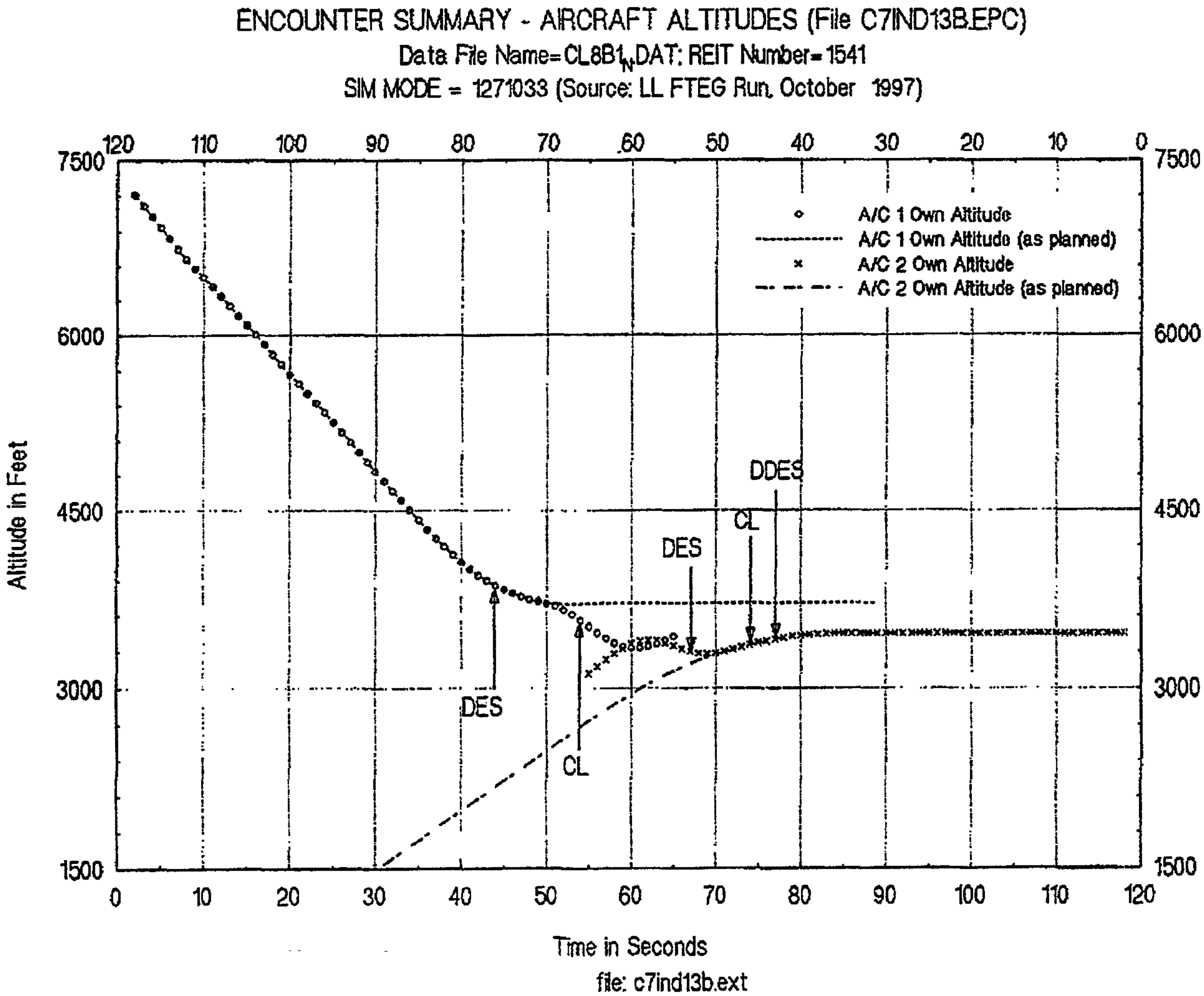


Figure 2-10. Encounter Summary – Aircraft Altitudes. Data file name = CL8B1_N.DAT, REIT Number = 1541, Sim Mode = 1271033.

MITRE encounter classes: 9,19 Date processed: 8/25/97
Based on FAA Technical Center data of: AUGUST 1997
Total TCAS-TCAS runs for single point of view : 139927
Total incorrectly labeled RAs : 41

Class 19 TCAS-TCAS Both Responding

	6.04A only	Ch7-100 ft only	Ch7-25 ft only	6.04A/ Ch7-100	6.04A/ Ch7-25	Ch7-25/ Ch7-100
RAs/ runs (%)	74.29	74.15	73.00	74.08	72.13	73.31
Crossing RAs/ RAs (%)	23.59	18.82	18.71	21.12	20.62	18.78
Crossing RAs/ runs (%)	17.52	13.96	13.66	15.64	14.87	13.77
Cr. RA NMACs/ cross RAs (%)	2.51	1.17	0.28	1.68	1.10	0.87
Cr. RA NMACs/ NMACs* (%)	100.00	100.00	100.00	100.00	100.00	100.00
NMACs*/ runs (%)	0.44	0.16	0.04	0.26	0.16	0.12
Avg warning time** (sec)	20.71	21.36	21.23	21.43	21.43	21.39
Avg alt sep at CPA* (ft)	979.75	981.31	969.19	986.51	985.32	975.20

* NMACs and average alt. sep. at CPA are based on simulation truth
** Average warning time includes negative times (i.e., RA occurs after CPA)

Figure 2-11. Performance Statistics Program, Class 19.

3. TCAS – TCAS REVERSALS

3.1 BACKGROUND

Change 7 of TCAS II is a significant redesign of the CAS logic. Among the new features of Change 7 is the ability of TCAS to reverse sense against a TCAS-equipped intruder. Earlier versions of TCAS allowed TCAS to reverse sense against unequipped intruders only. The assumption had been that TCAS pilots would follow their RAs and that TCAS–TCAS reversals would not be necessary. The assumption of pilot compliance with all the RAs turned out to be untrue. For Change 7 the TCAS community considered that the ability to reverse sense would provide some protection against a non-responding intruder, i.e., when the pilot ignored an RA or maneuvered contrary to the RA. Because sense reversals represent a major operational change to the system it was important to show that the sense reversals provided a measurable benefit.

Lincoln Laboratory emphasized the investigation of the implementation of TCAS–TCAS reversals, specifically multiple sense reversals and rapid reversals within a few seconds of the initial RA. The emphasis on multiple reversals came from the fact that once TCAS–TCAS geometric reversals were permitted, there was no mechanism in place to prevent aircraft in certain geometries from continually reversing sense. The emphasis on the rapid reversals came from the fact that Change 7 eliminated the 3-second display deferral (see Section 3.2 below). If large numbers of rapid reversals were seen in the test results, then re-introduction of the display deferral might have been considered and/or pilot training added.

Also, Lincoln Laboratory considered it important to assess the performance of reversals in general, i.e., did they increase or decrease vertical separation. The Reversal Analysis Program, Variation One was designed to address the multiple reversal and fast reversal issues. The Reversal Analysis Program, Variation Two deals more with overall performance of reversed RA encounters.

3.2 FAST REVERSALS

Previous versions of TCAS logic could defer the display of an RA against a TCAS equipped threat for up to three seconds to ensure that the air to air coordination between the two aircraft was complete. This delay was considered necessary because there is a chance that both aircraft could select the same sense, and then one of the aircraft would have to reverse sense to ensure a compatible solution. However, during the 3-second delay, the geometry of the encounter could change significantly and the deferred RA might no longer be the best solution to the conflict. Analysis at MITRE indicated that the probability of both aircraft selecting the same sense command at the same instant is negligible, so the display deferral was removed. This introduced the possibility that a pilot could see an RA followed immediately by a reversed RA. This is referred to as a "fast reversal."

In the first release of the logic studied by Lincoln Laboratory fast reversals were not observed because there was a 10-second delay after the initial RA selection before a reversal could be considered. The 10-second delay included five seconds for the pilot response delay and another five seconds for tracker lag. However, because results with the first release of the logic were quite poor, later releases eliminated the 10-second delay and fast reversals were observed. Some classes had as many as fifty percent of the reversals occurring within three seconds of the initial

RA. The presence of fast reversals was coupled with significantly better overall reversal performance. The presence of fast reversals in the simulated data was brought to the attention of the Operations Working Group of SC-147; they felt fast reversals could be handled with pilot training. The consensus of the TCAS community was that fast reversals were acceptable, given the good performance in terms of NMAC reduction.

3.3 MULTIPLE REVERSALS

Figure 3-1 shows the Reversal Analysis Program Variation One output for Version 7 Interim Release 10 Mod 1 (V7IR10-mod1) for Class 7. Using the summary results from the Reversal Analysis Program Variation One, encounters were identified in which both aircraft reversed RA sense repeatedly until they ran out of time, finally ending with an induced NMAC. Notice in Figure 3-1, there is an encounter that reversed sense three times. Several of the multiple sense reversal encounters were plotted; the most extreme example identified by the data in Figure 3-1 is shown in Figure 3-2. In Figure 3-2, the encounter had AC1 with 6.04a high Mode S ID, and AC2 with Change 7-25 low Mode S ID. When AC2 reversed, the higher-address 6.04a aircraft had to reverse also.

While the TCAS community assessed the acceptability of multiple sense reversals, the study of reversed encounters continued at Lincoln Laboratory. The Reversal Analysis Program Variation One was expanded to produce a single record containing encounter parameters for every reversed encounter, not just those with NMACs. These data files were merged over all twenty classes then sorted by planned separation. For each planned separation (0 ft, +/- 250 ft, +/-500 ft, +/- 750 ft, and +/- 1000 ft) the achieved separation was tabulated as shown in Table 3-1. In Table 3-1 the achieved separation columns contain tallies of encounters with achieved separation from 0 ft to 250 ft; 0 ft to -250 ft, 0 ft to 500 ft, 0 ft to -500 ft, and so on. Note that the 0 ft to 500 ft column includes the encounters in the 0 ft to 250 ft column.

Looking at Table 3-1 in the 500-foot planned separation row there were 846 reversed encounters with 109 encounters having multiple sense reversals. In this same row, there were 258 NMACs with 10 NMACs occurring in encounters with multiple sense reversals. For this row we observe that 503 (326 + 177) encounters out of 846 ended with less than the planned separation. In addition we observe that 408 (280 + 128) encounters out of 846 ended with less than half of the planned separation. Table 3-1 showed clearly that most encounters with reversed RAs even those that did not result in NMACs lost vertical separation. These results were presented at the November 1996 TCAS program review. At that time, it was decided that the Change 7 reversal logic required further work.

MITRE encounter classes: 7,17 Date processed: 11/13/96
Based on FAA Technical Center data of: SEPT 96
Total Change7 runs : 181358
Total incorrectly labeled RAs : 82

Class 7 Planned = CROSSING Both Responding

	7IR10-100 ATCRBS	7IR10-100 6.04A	7IR10-100 only	7IR10-25 ATCRBS	7IR10-25 6.04A	7IR10-25 only	7IR10-25 7IR10-100
RAs/ runs (%)	99.58	99.18	99.01	99.40	99.26	99.13	99.01
Total NMACs/ runs (%)	9.23	1.92	1.60	6.74	1.17	0.83	1.04
Induced / NMACS (%)	73.24	97.70	100.00	76.34	100.00	100.00	100.00
Reversals/ runs (%)	5.38	0.22	0.67	6.00	0.10	0.34	0.46
Reversals/ RAs (%)	5.40	0.23	0.68	6.03	0.11	0.35	0.47
Fast Reverse/ Reversals (%)	2.53	1.79	72.62	0.67	3.85	76.74	74.78
1 Reversal/ Reversals (%)	98.66	69.64	89.29	100.00	76.92	100.00	93.91
NMACS/ 1 Rev. (%)	1.06	15.38	6.67	0.00	40.00	2.33	7.41
Induced NMAC/ NMACs (%)	100.00	83.33	100.00	0.00	100.00	100.00	100.00
2 Reversals/ Reversals (%)	1.34	30.36	10.71	0.00	19.23	0.00	6.09
NMACS/ 2 Rev. (%)	0.00	11.76	11.11	0.00	40.00	0.00	0.00
Induced NMAC/ NMACs (%)	0.00	100.00	100.00	0.00	100.00	0.00	0.00
3+ Reversals/ Reversals (%)	0.00	0.00	0.00	0.00	3.85	0.00	0.00
NMACS/ 3+ Rev. (%)	0.00	0.00	0.00	0.00	100.00	0.00	0.00
Induced NMAC/ NMACs (%)	0.00	0.00	0.00	0.00	100.00	0.00	0.00

* NMACs and average alt. sep. at CPA are based on simulation truth

Figure 3-1. Multiple TCAS–TCAS Reversals.

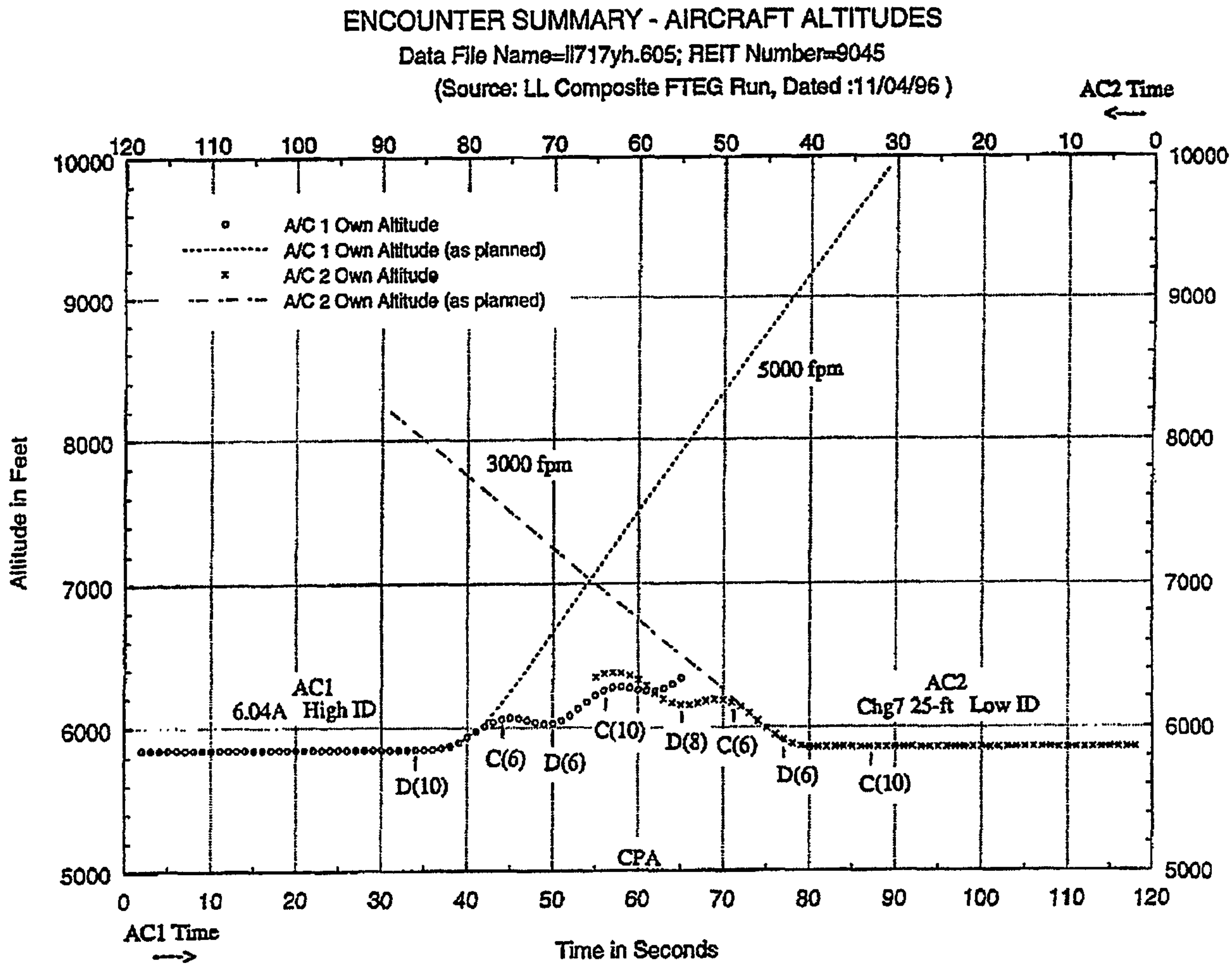


Figure 3-2. Encounter Summary V7IR10 Multiple Sense Reversal.

Table 3-1. V7IR10-Mod 1 Reversed Encounters Planned Separation vs. Achieved Separation

	Reversed Enc.		Rev. NMAC		Achieved Separation (AC1 – AC2)							
Plan. Sep.	All	Multi	All	Multi	0 ..250	0 ..(-250)	0 ..500	0 ..(-500)	0 ..750	0 ..(-750)	0 ..1000	0 ..(-1000)
0	344	16	7	0	10	3	37	12				
250	583	90	19	6	33	25	91	73				
500	846	109	258	10	280	128	326	177				
750	913	69	128	8	386	66	583	132	667	161		
1000	76	0	0	0	1	0	14	0	30	0	39	0
-250	378	45	3	0	5	14	67	48				
-500	697	77	76	3	45	131	97	198				
-750	940	115	41	39	56	45	97	513	137	540		
-1000	13	0	0	0	0	0	0	3	6	4	9	4
Total	4790	521	532	66								

3.3.1 Resolution of Multiple Reversal Performance

During December 1996 and January 1997 in order to study the effect of reversals, Lincoln Laboratory, MITRE, and WJHTC proposed five candidate revisions to the V7IR10-mod1 logic. Mod A allowed TCAS–TCAS geometric reversals only during the first three seconds of an encounter when the low ID aircraft wanted to switch from a crossing RA to a non-crossing RA. Mod B allowed reversals whenever the low ID aircraft wanted to switch from a crossing RA to a non-crossing RA. Mod C contained a hard limit of one reversal. Mod D did not allow geometric TCAS–TCAS reversals, only coordination reversals as in 6.04a. Mod E was the same as mod B, but with a hard limit of one reversal. As simulation results comparing the performance of these alternative designs became available, Lincoln Laboratory, MITRE, WJHTC, and the TCAS program office had frequent conference calls to discuss the merits and drawbacks of all five candidate logic modifications.

Mod C was eliminated quickly during one of the early conference calls due to the poor results of the MITRE safety study. The six encounter classes with the worst performance for V7IR10-mod1 (3/13, 6/16, and 9/19) were chosen as test cases. WJHTC collected data for the test cases with the four remaining candidates (A, B, D, and E). Lincoln Laboratory and WJHTC studied the results. MITRE performed operational acceptability and safety studies for the four candidates as well. Due to extreme time pressure, the Lincoln Laboratory analysis was restricted to the Hot-Spot Program and Reversal Analysis Program Variation One. These two programs were run using all 12 test data files (3 data files each containing two encounter classes, four logic versions). The tables showing the outcome of reversed encounters by planned separation and achieved separation were produced manually for candidates A, B, and E only, since D precluded TCAS–TCAS reversals. These tables, which were faxed to MITRE, WJHTC and the TCAS program office before a conference call showed clearly that encounters with single or multiple reversals still had an overwhelming tendency to lose separation.

Mod A was eliminated because the results from the six test classes were poor. Mod B was eliminated because the safety analysis results for this class were identical to the safety analysis results for Mod E, and the TCAS program office considered that, without some added benefit in scenarios where both pilots were already responding, multiple TCAS-TCAS reversals were undesirable from a human factors perspective. This left Mod D and Mod E as "finalists". Neither version allowed for the possibility of multiple sense reversals, so this issue was effectively resolved.

3.4 PERFORMANCE WITH SINGLE REVERSALS

By studying the final two versions, Mod D (no reversals) and Mod E (reversals), it was possible to decide if TCAS–TCAS geometric reversals should be included in the Change 7 CAS logic.

Table 3-2 shows planned separation vs. achieved separation for Mod E reversed RAs. Table 3-2 shows clearly that most encounters with reversed RAs, even those that did not result in NMACs, lost vertical separation. For example, looking at Table 3-2, for Mod E there are 230 reversed encounters with 500 feet of planned separation. Note that 99 of these encounters resulted in NMACs. Of these 230 encounters 205 (151 + 54) achieved less than 500 feet of separation, i.e., 205 encounters out of 230 have less separation with TCAS involved.

Table 3-2. Mod E Reversed Encounters Planned Separation vs. Achieved Separation, Classes 3/13, 6/16, and 9/19 Only

	Reversed Enc.		Rev. NMAC		Achieved Separation (AC1 – AC2)							
Plan. Sep.	All	Multi	All	Multi	0 ..250	0 ..(-250)	0 ..500	0 ..(-500)	0 ..750	0 ..(-750)	0 ..1000	0 ..(-1000)
0	4	0	0	0	0	0	0	3				
250	2	0	1	0	2	0	0	0				
500	230	0	99	0	115	54	151	54				
750	200	0	0	0	16	0	142	0	196	0	24	0
1000	25	0	0	0	0	0	9	0	22	0		
-250	38	0	8	0	4	14	0	27				
-500	285	0	112	0	49	148	51	189	0	169		
-750	177	0	1	0	0	1	0	114	0	10	0	10
-1000	10	0	0	0	0	1	0	9				
Total	971	0	221	0								

Now that there were only two versions of the Change 7 logic under study (V7IR10-Mod D and V7IR10-Mod E), WJHTC was able to collect data for sixteen of the twenty encounter classes. Classes 0/10 and 1/11 were not run because they have no NMACs. A limited analysis of candidates D and E was performed at Lincoln Laboratory. Table 3-3 shows the percent of encounters with induced NMACs tabulated for 6.04a, Mod D-100, Mod E-100, Mod D-25, and Mod E-25. Table 3-4 shows the percent of encounters with unresolved NMACs for the same five versions. Under the comments column in Tables 3-3 and 3-4 the weight entry in square brackets is taken from Appendix M, Class Weights, converted to a percentage of the encounters observed in the United States airspace.

Note that each class weight shown in Appendix M represents the percentage of pairwise encounters out of the total ARTS database sampled by MITRE in the 1980s that exhibited the geometry of that class. In the original database, within each class, the exact breakdown of aircraft rates, accelerations, times of acceleration, etc. is not known. For the WJHTC simulation, for each class, aircraft rates and accelerations were used which spanned a range slightly exceeding the range of expected values. In addition, in the WJHTC simulation, the times of acceleration were chosen to be the worst possible times, i.e., 20 or 25 seconds prior to closest approach. Thus, it is not known how well the class weights in Appendix M apply to the classes in the WJHTC simulation. Nevertheless, the weights are considered a useful evaluation tool and are considered in the Lincoln Laboratory logic evaluation.

Looking at Table 3-3, seven of the sixteen encounter classes have the same number of induced NMACs with Mod D and Mod E. Three classes have mixed behavior, meaning one Mod is better with the 100-foot tracker and the other is better with the 25-foot tracker. Three classes (7, 13, and 16) with a combined weight of 13.39 percent have better performance with Mod D. Three classes (15, 17, and 19) with a combined weight of 2.98 percent have better performance with Mod E. The poor performance of the TCAS–TCAS reversals in class 13 (the "Dallas bump-up" class), the fourth most common encounter class in the United States airspace, should be noted as a weakness for the V7IR10-Mod E logic.

Table 3-3. Percent of Encounters with Induced NMACs, 6.04a, Mod D and Mod E Both Pilots Responding

Class	6.04a	Mod D-100	Mod E-100	Mod D-25	Mod E-25	Comments [Weight]
2	1.71	1.55	1.55	1.22	1.22	SAME
3	0.00	0.00	0.00	0.00	0.00	SAME
4	0.00	0.00	0.00	0.00	0.00	SAME
5	0.37	0.30	0.30	0.33	0.33	SAME
6	0.15	0.15	0.15	0.10	0.10	SAME
7	1.95	1.93	2.00	1.04	1.04	D BEST [0.02%]
8	1.65	1.82	1.69	1.23	1.25	MIXED
9	0.28	0.16	0.19	0.09	0.08	MIXED
12	0.00	0.00	0.00	0.00	0.00	SAME
13	0.10	0.05	0.38	0.05	0.30	D BEST [10.51%]
14	0.00	0.00	0.00	0.00	0.00	SAME
15	0.73	0.57	0.49	0.65	0.49	E BEST [2.05%]
16	0.04	0.08	0.16	0.00	0.00	D BEST [2.56%]
17	0.25	0.18	0.16	0.22	0.11	E BEST [0.19%]
18	0.41	0.77	0.96	0.24	0.17	MIXED
19	0.49	0.84	0.38	0.46	0.26	E BEST [0.74%]

Table 3-4. Percent of Encounters with Unresolved NMACs, 6.04a, Mod D, Mod E Both Pilots Responding

Class	6.04a	Mod D-100	Mod E-100	Mod D-25	Mod E-25	Comments [Weight]
2	0.58	0.00	0.00	0.00	0.00	SAME
3	0.00	0.00	0.00	0.00	0.00	SAME
4	0.00	0.00	0.00	0.00	0.00	SAME
5	0.00	0.00	0.00	0.00	0.00	SAME
6	0.81	0.58	0.58	0.69	0.64	E BEST [0.29%]
7	0.16	0.00	0.00	0.00	0.00	SAME
8	1.16	0.23	0.23	0.23	0.23	SAME
9	0.00	0.00	0.00	0.00	0.00	SAME
12	0.00	0.00	0.00	0.00	0.00	SAME
13	0.00	0.00	0.00	0.00	0.00	SAME
14	0.00	0.00	0.00	0.00	0.00	SAME
15	0.00	0.00	0.00	0.00	0.00	SAME
16	0.00	0.00	0.00	0.00	0.00	SAME
17	0.00	0.00	0.00	0.00	0.00	SAME
18	0.00	0.00	0.00	0.00	0.00	SAME
19	0.00	0.00	0.00	0.00	0.00	SAME

Looking at Table 3-4, fifteen out of sixteen encounter classes have the same number of unresolved NMACs for Mod D and Mod E. Class 6 has better performance for Mod E, but this is a difference of hundredths of a percent meaning there is no significant difference between Mod D and Mod E with respect to unresolved NMACs. Therefore, overall performance for both pilots responding with reversals is a little worse than without reversals.

As mentioned in Section 3.1, the main reason for allowing TCAS–TCAS reversals was to provide some protection against a non-responding intruder. If the reversals in Mod E achieved this goal, then perhaps this would be reason enough to allow reversals, despite the slightly worse performance against responding intruders.

As mentioned earlier in Section 1.1.2, WJHTC collected a second set of data containing encounters where one pilot does not respond to the TCAS RA. These data only contain 6.04a and C7-25 data. The pilot non-responding data were processed for Mod D and Mod E using the Hot-Spot Program. The results are summarized below in Table 3-5 (Induced NMACs) and Table 3-6 (Unresolved NMACs).

Table 3-5. Percent of Induced NMACs, 6.04a, Mod D-25, and Mod E-25, One Pilot Non-Responding

Class	6.04a One NR	C7-25D One NR	C7-25E One NR	6.04a/ C7-25DNR	6.04a/ C725ENR	C7-25D/ 6.04aNR	C7-25E/ 6.04aNR
2	11.662	7.764	7.539	11.211	11.082	7.861	7.668
3	0.135	0.709	0.709	0.135	0.135	0.676	0.676
4	1.974	0.987	0.987	1.974	2.303	0.987	0.987
5	5.351	3.774	3.787	5.218	5.281	3.774	3.774
6	4.141	2.646	2.595	4.448	4.410	2.518	2.480
7	14.399	9.277	9.093	14.045	13.996	9.028	8.864
8	7.655	6.322	6.112	7.817	7.765	6.30	6.138
9	1.379	1.449	1.433	1.160	1.121	1.542	1.503
12	0.192	0.048	0.048	0.192	0.192	0.048	0.048
13	2.024	2.050	1.556	1.923	1.594	2.176	1.733
14	0.00	0.00	0.00	0.00	0.00	0.781	0.391
15	0.546	0.445	0.634	0.485	0.303	0.485	0.445
16	2.909	2.752	0.845	2.653	2.044	2.732	1.553
17	0.318	0.563	0.400	0.527	0.436	0.490	0.436
18	6.304	4.581	2.507	6.545	4.966	4.532	3.218
19	5.126	3.917	1.803	4.194	2.830	4.160	2.911

Comparing the performance of Mod D and Mod E for the C7-25 one non-responding (NR) columns, for the planned crossing classes Mod E has better performance in five cases. However, these are only tenths or hundredths of a percent improvements; Mod D had better performance in only one case. Comparing Mod D and Mod E for the C7-25 one NR columns, for the planned non-crossing classes Mod D was better than Mod E in only one case (class 15). However, Mod E was better in five classes, with 18 and 19 showing the most dramatic difference.

Comparing the performance of Mod D and Mod E in Table 3-5 for the 6.04a / C7-25 NR columns, Mod D is better in only one class (14), Mod E is better in 11 classes, with 18 and 19 again showing the most dramatic improvement. Comparing the C7-25 / 6.04aNR columns, whenever there is a difference in performance Mod E is better, and the planned non-crossing classes show the most improvement.

Table 3-6. Percent of Unresolved NMACs, 6.04a, Mod D-25, and Mod E-25, One Pilot Non-Responding

Class	6.04a One NR	C7-25D One NR	C7-25E One NR	6.04a/ C7-25DNR	6.04a/ C7-25ENR	C7-25D/ 6.04aNR	C7-25E/ 6.04aNR
2	2.315	1.968	1.968	1.678	1.678	2.431	2.431
3	0.543	0.00	0.00	0.543	0.543	0.00	0.00
4	6.667	6.667	6.667	6.667	6.667	6.667	6.667
5	7.946	8.543	8.386	8.009	8.197	8.354	8.040
6	3.877	3.762	3.848	3.443	3.675	3.646	3.559
7	8.416	8.663	8.622	6.972	7.013	9.158	8.787
8	4.090	2.701	2.758	2.894	3.086	3.356	3.337
9	1.986	1.036	1.036	1.554	1.554	1.123	1.123
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	33.333	33.333	33.333	33.333	33.333	33.333	33.333
15	30.882	30.882	30.882	31.618	31.618	30.147	30.147
16	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	22.619	23.214	23.214	23.214	23.214	22.619	22.619
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Looking at Table 3-6, all of the planned non-crossing unresolved NMAC columns are identical for Mod D and Mod E. Class 15 shows a degradation in performance in the 6.04a / C7-25 NR columns. Class 17 shows a degradation in performance, relative to 6.04a, in the C7-25 one NR and 6.04a / C7-25NR columns. Four of the planned crossing classes (2, 3, 4, and 9) show no difference in performance between Mod D and Mod E, while the other classes (5, 6, 7, and 8) have mixed performance.

Lincoln Laboratory pointed out to the TCAS community the relatively poor performance of TCAS–TCAS reversals in class 13 (the "Dallas bump up" class) and the marginal improvement in only five of the twenty encounter classes for a non-responding intruder in TCAS-TCAS coordinated encounters. Lincoln Laboratory also pointed out that the overall performance for both pilots responding was worse with reversals than without reversals. Based on the MITRE safety study results, and the lack of overwhelming evidence for the removal of TCAS–TCAS reversals, the TCAS community decided to proceed with Mod E. (The subject of reversal performance will be revisited in Section 3.6.) Once the decision was made to keep TCAS–TCAS reversals, Lincoln Laboratory was tasked to perform the full logic evaluation on the complete set of encounter classes for logic candidate E, which became known as Version 7 Mod 10. This effort was delayed by work necessary to prepare the DO-185A Minimum Operational Performance Standards (MOPS) for approval by SC-147.

3.5 FULL LOGIC EVALUATION

In April 1997, after the completion of the MOPS work, the WJHTC data for all 20 encounter classes for Version 7 Mod 10 were analyzed using Lincoln Laboratory's high level analysis tools: the Reversal Analysis Programs, the Hot-Spot Program and the Performance Statistics Program. Once the high level results were studied, we were able to proceed to the in-depth NMAC analysis. For every Change 7 NMAC encounter, a set of three plots was produced: the encounter with 6.04a/6.04a, the encounter with C7-100/C7-100, and the encounter with C7-25/C7-25. The encounter summary pages were also produced for each encounter plotted to allow comparison of the behavior of all three versions of the logic.

In order to understand the failures better, these encounter plots and associated summaries were sorted into several groups. The first group contained encounters where all three logic versions had an NMAC. This group was not alarming since the behavior of Version 7 Mod 10 was no worse than 6.04a.

A second group contained encounters where C7-100 did not have an NMAC, but C7-25 did have an NMAC. In this group the 6.04a encounters were mixed; some had NMACs some did not. However, the important factor is that the 25-foot tracker, which one would expect to have better performance than the 100-foot tracker, did not always live up to expectations.

A third group was identified where both Change 7 versions had NMACs, but 6.04a did not have an NMAC. This group was studied in depth because the Change 7 performance was worse than the 6.04a performance and because several of the failures came from Class 13, a planned non-crossing, statistically significant group of encounters.

From these studies, Lincoln Laboratory identified some specific areas of performance weakness with the Version 7 Mod 10 TCAS–TCAS logic. These areas were discussed with the TCAS program office, MITRE, WJHTC, and our European colleagues after SC-147 in May of 1997. The Centre D'Etudes de la Navigation Aerienne/ Direction Generale de L'Aviation Civile. (CENA/DGAC) ACAS representatives to SC-147 had previously identified weaknesses with the TCAS-unequipped performance based on their analysis of Version 7 Mod 10. It was agreed that both areas of weakness should be examined to determine if further revision of the Change 7 logic was required.

3.6 RESOLUTION OF SINGLE REVERSAL PERFORMANCE

During the early stages of the TCAS–TCAS reversal analysis work, (see Section 2.1) one of the most powerful analytical tools available was the table showing the achieved separation for reversed encounters grouped by planned separation. The computation of these tables was time consuming, so the process was automated in the Separation Differences program, also known as the Reversal Analysis Program Variation Two. For this program, the NMAC was replaced by another measure of performance: the separation difference. The separation difference is defined as the absolute value of the achieved separation minus the absolute value of the planned separation. Here, a positive value indicates that we gained separation, a negative value means we lost separation. For example, if two aircraft achieved -250 feet of separation with TCAS and they had a planned separation of +500 feet, the separation difference is abs(-250) - abs(500) or -250 feet. Here, the aircraft were 250 feet closer with TCAS than they would have been without TCAS – a poor result.

In order to be able to fairly compare separation losses and gains for reversed encounters and non-reversed encounters two sets of four tables were produced for every encounter class. The first set of tables is for encounters with non-reversed RAs, the second set of tables is for encounters with reversed RAs. Each set contains four tables, showing the number of (1) planned crossing encounters with separation gains, (2) planned crossing encounters with separation losses, (3) planned non-crossing encounters with separation gains, and (4) planned non-crossing encounters with separation losses. Each table shows the data tabulated by planned separation and achieved separation. This combination of tables enabled Lincoln Laboratory to pinpoint planned separation values where the logic is more trouble-prone.

These separation difference tables allowed us to answer our earlier question, "Are the TCAS–TCAS reversals helping"? During the full logic evaluation of Version 7 Mod 10 the answer was, "No, the TCAS–TCAS reversals are not helping". Few reversed encounters increased separation (eleven percent) and most reversals in the WJHTC data caused separation loss. As an example, Figure 3-3 shows the results for Class 13, one of the more common non-crossing classes in the U.S. airspace. In this example, for non-reversed RAs only 30 encounters out of 9944 (0.3%) lost separation, there was only 1 NMAC, and many encounters significantly increased separation. In contrast for reversed RAs 100% lost separation, there were 68 NMACs, and there were no encounters with separation gains. This discouraging result was shared during a conference call with the TCAS program office, MITRE and WJHTC.

During the summer of 1997, both WJHTC and MITRE proposed modifications to the Version 7 Mod 10 TCAS logic to address the reversal performance problem. The WJHTC proposal was targeted for TCAS–TCAS encounters, it allowed own aircraft to reverse sense earlier if it determined that own aircraft had maneuvered contrary to the sense of the RA during the pilot response delay. Both WJHTC and Lincoln Laboratory were encouraged by the results of this modification. The Separation Differences program (Reversal Analysis Program Variation Two) was run on the test data and the improvement was dramatic. The reversed encounters showed significant gains in separation, and the separation losses for reversed encounters were comparable to those in non-reversed encounters. This improvement did not come without a cost – an increase in the number of reversed encounters, but this was considered acceptable because the reversed encounters no longer tended to lose vertical separation as before.

The proposed MITRE modification was targeted for the TCAS-unequipped encounters. This modification was tested mostly by MITRE and our CENA/DGAC ACAS colleagues and resulted in a one geometric reversal cap on TCAS-unequipped encounters. In August 1997, Lincoln Laboratory, MITRE, WJHTC, the TCAS program office, plus CENA/DGAC and Defense Evaluation and Research Agency (DERA) ACAS representatives agreed to accept both the WJHTC and MITRE modifications. The designation for this baseline of the logic was Version 7 Mod 11.

RA REVERSAL RESULTS
CLASS 13

CHANGE 7 MOD 10

NON REVERSED RAs	RA COUNT 9944	NMAC COUNT 1
REVERSED RAs	RA COUNT 87	NMAC COUNT 68

GAINS	PLAN SEP	NO GAIN	>0..250	>250..500	>500..750	>750..1000	> 1000
NON-REVERSED	0 FT	0	0	54	422	36	0
	250 FT	0	114	2018	918	312	46
	500 FT	894	1116	886	494	181	54
	750 FT	144	626	513	228	88	0
	1000 FT	140	243	299	84	4	0

GAINS	PLAN SEP	NO GAIN	>0..250	>250..500	>500..750	>750..1000	> 1000
REVERSED	0 FT	0	0	0	0	0	0
	250 FT	0	0	0	0	0	0
	500 FT	0	0	0	0	0	0
	750 FT	0	0	0	0	0	0
	1000 FT	0	0	0	0	0	0

LOSSES	PLAN SEP	>0..250	>250..500	>500..750	>750..1000	> 1000
NON-REVERSED	0 FT	0	0	0	0	0
	250 FT	16	0	0	0	0
	500 FT	13	1	0	0	0
	750 FT	0	0	0	0	0
	1000 FT	0	0	0	0	0

LOSSES	PLAN SEP	>0..250	>250..500	>500..750	>750..1000	> 1000
REVERSED	0 FT	0	0	0	0	0
	250 FT	0	0	0	0	0
	500 FT	5	82	0	0	0
	750 FT	0	0	0	0	0
	1000 FT	0	0	0	0	0

Figure 3-3. Reversal Analysis Program Variation Two – Separation Differences Version 7 Mod 10.

Lincoln Laboratory performed a complete evaluation of the Version 7 Mod 11 logic for all twenty classes. The most dramatic improvement is shown in Figure 3-4, the Separation Differences results for class B. The reversed encounters now have less separation losses than for Mod 10, and those losses are smaller. The reversed encounters now have many significant separation gains that were not present for Mod 10. This improvement in performance was seen also in the hot-spot tables. For Version 7 Mod 10 several classes (6, 13, 16, and 18) had higher induced NMAC counts than 6.04a, but with Version 7 Mod 11 for all classes, with no exceptions, we see a reduction in induced NMACs compared to 6.04a.

RA REVERSAL RESULTS
CLASS 13

CHANGE 7 MOD 11 (MITRE + WJHTC mods)

NON REVERSED RAs	RA COUNT 9149	NMAC COUNT 0
REVERSED RAs	RA COUNT **856**	NMAC COUNT **6**

GAINS	PLAN SEP	NO GAIN	>0..250	>250..500	>500..750	>750..1000	> 1000
NON-REVERSED	0 FT	0	0	52	428	32	0
	250 FT	0	37	1585	762	308	46
	500 FT	898	1055	870	490	181	54
	750 FT	146	626	491	226	88	0
	1000 FT	142	239	299	84	4	0

GAINS	PLAN SEP	NO GAIN	>0..250	>250..500	>500..750	>750..1000	> 1000
REVERSED	0 FT	0	0	0	0	0	0
	250 FT	0	123	458	68	0	0
	500 FT	0	104	62	0	0	0
	750 FT	0	0	0	0	0	0
	1000 FT	0	0	0	0	0	0

LOSSES	PLAN SEP	>0..250	>250..500	>500..750	>750..1000	> 1000
NON-REVERSED	0 FT	0	0	0	0	0
	250 FT	6	0	0	0	0
	500 FT	0	0	0	0	0
	750 FT	0	0	0	0	0
	1000 FT	0	0	0	0	0

LOSSES	PLAN SEP	>0..250	>250..500	>500..750	>750..1000	> 1000
REVERSED	0 FT	0	0	0	0	0
	250 FT	31	0	0	0	0
	500 FT	10	0	0	0	0
	750 FT	0	0	0	0	0
	1000 FT	0	0	0	0	0

Figure 3-4. Reversal Analysis Program Variation Two – Separation Differences Version 7 Mod 11.

4. GENERAL ANALYSIS

4.1 DESCRIPTION

The second goal of the Change 7 (Version 7 Mod 11) logic analysis using the Lincoln Laboratory analysis programs was to detect and explain any areas of poor performance remaining in the Change 7 TCAS logic. These "areas of poor performance" were defined in Section 2.3 to be any matrix cell for which logic Version 7 Mod 11 had more NMACs than 6.04a, the current baseline.

4.2 RESULTS - BOTH PILOTS RESPONDING

4.2.1 Hot-Spot and Matrix Generator Programs

There were no hot-spots for TCAS–TCAS encounters where both aircraft were Version 7 Mod 11 equipped.

The hot-spot tables are useful for locating interoperability problems. In general the intermix performance fell between that of the corresponding single versions (6.04a/6.04a, C7-100/C7-100, or C7-25/C7-25). There are three exceptions to this pattern. In Table 5.3, there are unresolved NMACs for 6.04a/C7-100 (0.063%) where there are no NMACs for either 6.04a/6.04a or C7-100/C7-100. This falls below the 2% significance threshold, so it is not a true hot-spot. In Table 7-3, the percent of unresolved NMACs for 6.04a/C7-100 (0.206%) is higher than 6.04a/6.04a (0.165%) and C7-100/C7-100 (0.0%). This represents a 25% increase in NMACs, but still falls below the 2% significance threshold, so it is not a true hot-spot. Finally, in Table 17.4 the percent of induced NMACs is higher for C7-25/C7-100 (0.136%) than for C7-25/C7-25 (0.109%) and C7-100/C7-100 (0.127%). This represents an 8% increase in NMACs, but still falls below the 2% significance threshold, so it is not a true hot-spot either.

Figures 4-1 and 4-2 show histograms of the number of NMACs (as a percentage of the number of planned encounters) for each of the 20 encounter classes for all three versions of the TCAS logic. Figure 4-1 shows induced NMACs and Figure 4-2 shows unresolved NMACs. As you can see in both Figures 4-1 and 4-2 Version 7 Mod 11 consistently performs as well as, or better than 6.04a.

4.2.2 NMAC Characterization Programs

Since there were no TCAS–TCAS hot-spots left for Version 7 Mod 11, the analysis programs that were previously used to understand hot-spots were run over all of the data. The output from these programs was useful in studying the Version 7 Mod 11 Representative NMACs, which will be described in Section 6 of this report.

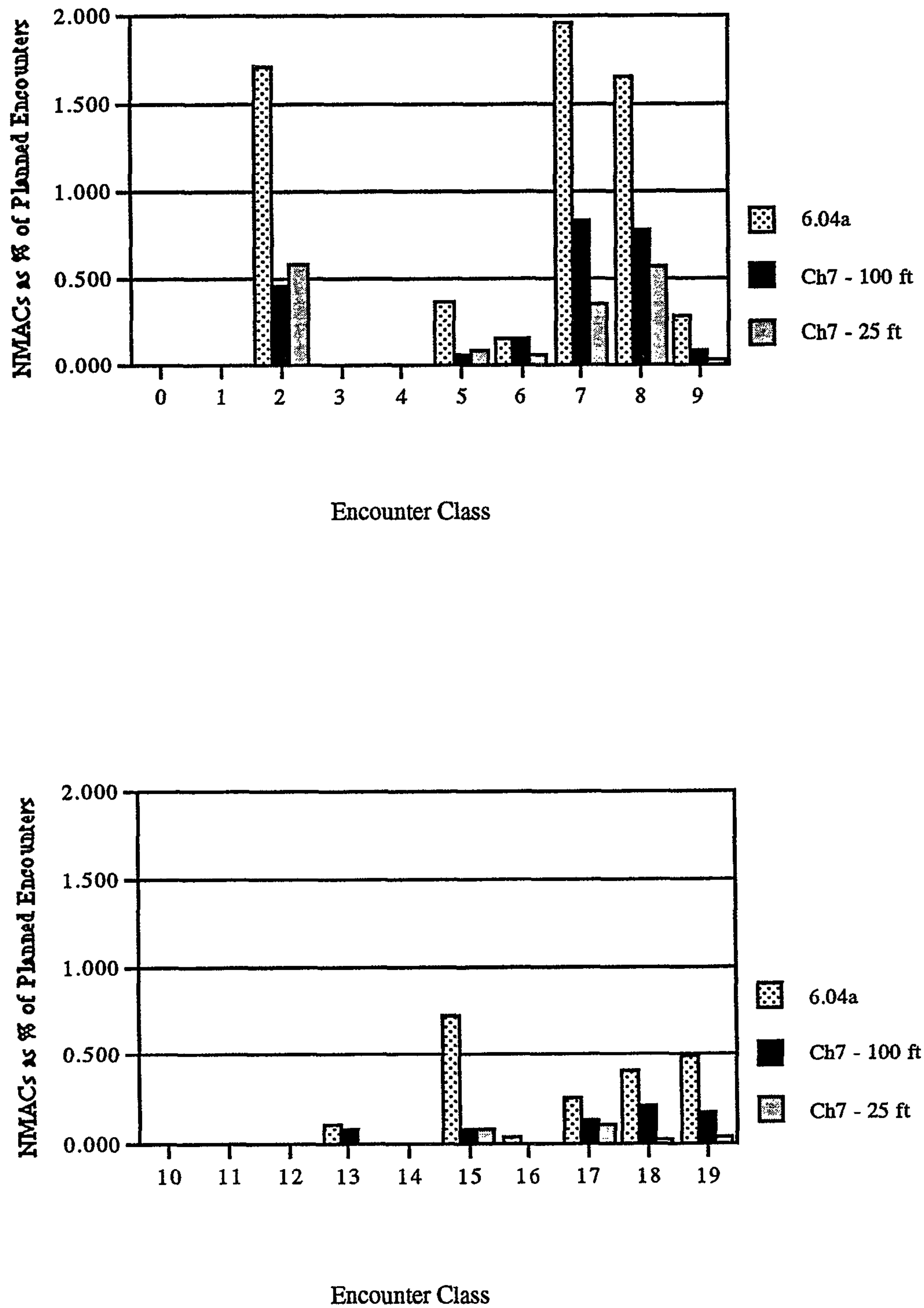
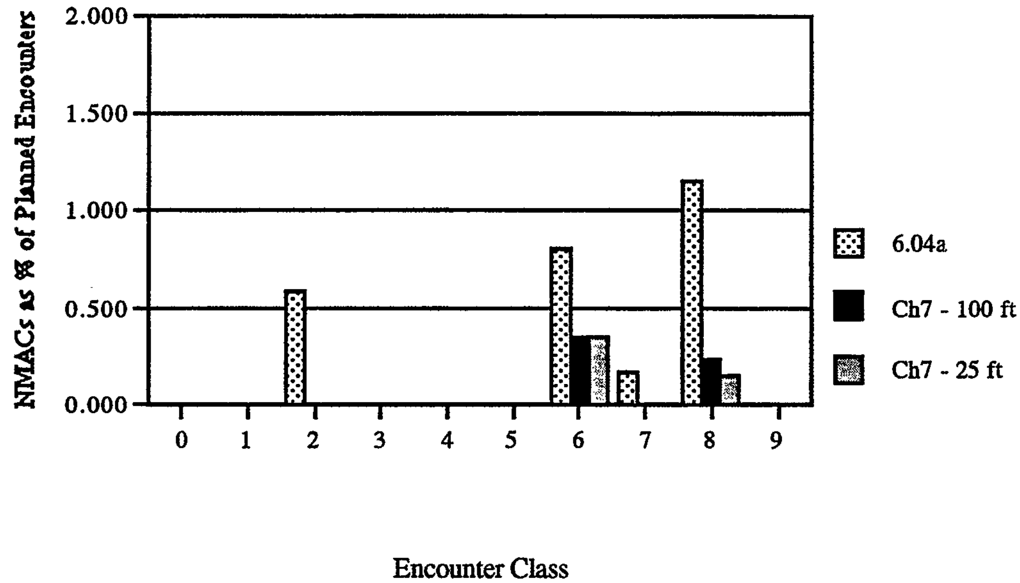


Figure 4-1. Induced NMACs.



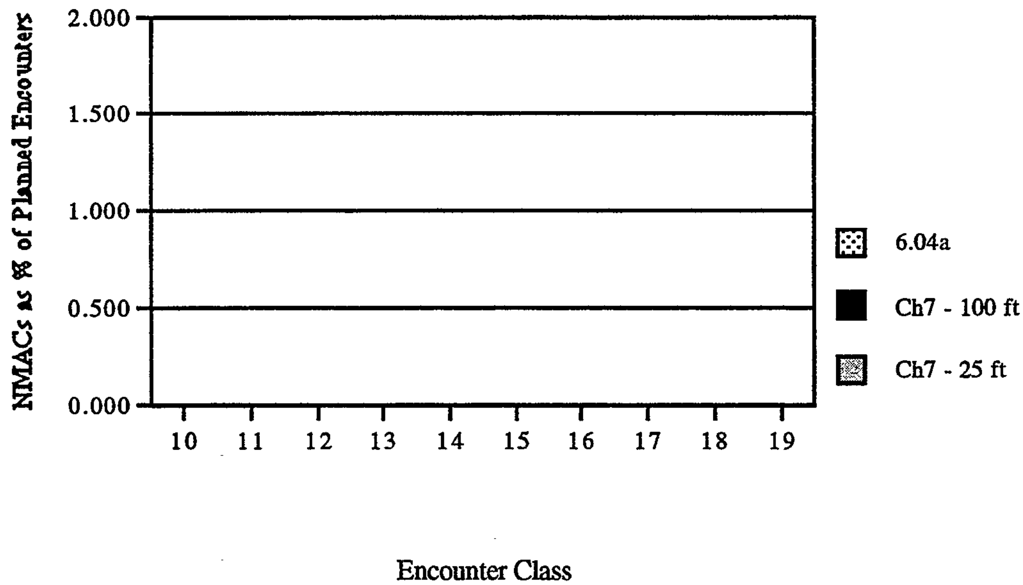


Figure 4-2. Unresolved NMACs.

4.2.2.1 NMACs as a Function of Parameter Value

Appendix H contains the results of NMAC Characterization Program One (NMACs as a function of parameter values) for all twenty encounter classes for Version 7 Mod 11. A sample output was provided in Figure 2-7. The first two values in each line identify the encounter class and matrix table. Note that in the aircraft 1 equipage column (AC1 EQ) and the aircraft 2 equipage column (AC2 EQ), 65 represents version 6.04a, 71 represents C7-100, and 75 represents C7-25. The parameters found in NMACs for a given matrix table and equipage are printed, along with a count of the number of times the parameter value occurred.

From the printout in Appendix H, we can answer questions about the NMACs of 6.04a or Version 7 Mod 11 fairly easily. For example, "What was the distribution of planned separations for Version 7 Mod 11 NMACs"? Scanning through Appendix H, Table 4-1 summarizing the absolute value of the planned separation by table number for all Version 7 Mod 11 NMACs is easily constructed. From Appendix A, we observe that only classes 3/13 and 9/19 have planned encounters with +/- 1000 feet of separation. Entries in Table 4-1 for classes without planned encounters of +/- 1000 feet of separation are indicated by a dash (-).

From Table 4-1, we can state that for Version 7 Mod 11 there were no NMACs with a planned separation of +/- 1000 feet. This is important because 1000 feet is the normal separation in the airspace and previous versions of the TCAS logic did have problems with these encounters.

Table 4-1. Distribution of NMACs by Absolute Value of Planned Separation

	Number of NMACs by Absolute Value of Planned Separation									
	Version 7 Mod 11 100-foot Tracker					Version 7 Mod 11 25-foot Tracker				
Table	0 ft	250 ft	500 ft	750 ft	1000 ft	0 ft	250 ft	500 ft	750 ft	1000 ft
2.4	0	0	10	4	-	0	0	14	4	-
5.4	0	0	0	4	-	0	0	1	6	-
6.3	6	0	0	0	-	6	0	0	0	-
6.4	0	0	12	0	-	0	0	4	0	-
7.4	0	16	24	44	-	0	0	5	30	-
8.3	6	0	0	0	-	4	0	0	0	-
8.4	0	12	60	17	-	0	6	38	21	-
9.4	0	5	0	0	0	0	2	0	0	0
13.4	0	3	0	0	0	0	0	0	0	0
15.4	0	0	2	0	-	0	0	2	0	-
17.4	0	0	7	0	-	0	0	6	0	-
18.4	-	0	3	6	-	-	0	0	1	-
19.4	0	2	11	0	0	0	3	0	0	0
Total	12	38	129	75	0	10	11	70	62	0
Percent	4.70	15.00	50.80	29.50	0.00	6.50	7.20	45.80	40.50	0.00

Similarly, we may ask, "What is the distribution of intruder aircraft vertical rates for Change 7 NMACs"? From Appendix H, we can generate Table 4.2, which shows the vertical rate of the intruder aircraft for C7-100/C7-100 and C7-25/C7-25 NMAC encounters. From Table 4.2 we can conclude that nearly all Version 7 Mod 11 NMACs the intruder had vertical rate of

+/- 3000 fpm or +/- 5000 fpm. The only exceptions to this are four NMACs in Table 7.4 and three NMACs in Table 18.4, all with vertical rates of -1000 fpm. This is consistent with earlier versions of the logic.

Table 4-2. Distribution of Intruder Aircraft Vertical Rates

	Version 7 Mod 11 100-foot Rate (fpm)			Version 7 Mod 11 25-foot Rate (fpm)		
Table	+/- 1000	+/- 3000	+/- 5000	+/- 1000	+/- 3000	+/- 5000
2.4	0	0	14	0	0	18
5.4	0	0	4	0	1	6
6.3	0	0	6	0	1	5
6.4	0	0	12	0	0	4
7.4	4	14	66	0	3	32
8.3	0	0	6	0	0	4
8.4	0	2	87	0	0	65
9.4	0	0	5	0	0	2
13.4	0	0	3	0	0	0
15.4	0	0	2	0	0	2
17.4	0	6	1	0	6	0
18.4	3	4	2	0	1	0
19.4	0	2	11	0	1	2

4.2.2.2 NMACs as a Function of Logic Version

Three different comparisons of NMACs by logic version were generated. Figure 4-3 provides the results for the 6.04a/6.04a and C7-100/C7-100 comparison. Looking at Figure 4-3, we can make several observations. C7-100 eliminated all NMACs that were present in Tables 2.3, 7.3, and 16.4 for 6.04a. None of the NMACs in Tables 13.4 and 18.4 are common to both 6.04a and C7-100. There were no tables where C7-100 had NMACs where 6.04a had none.

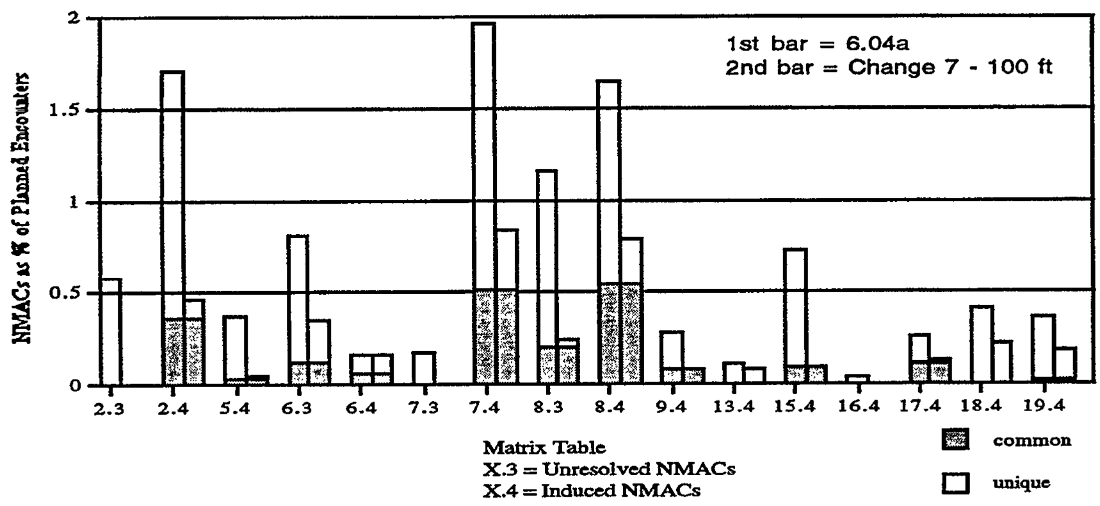


Figure 4-3. NMAC Comparison 6.04a vs. Change 7 100-foot tracker.

Figure 4-4 provides the results of the 6.04a/6.04a and C7-25/C7-25 comparison. Looking at Figure 4-4 we can make several observations. C7-25 eliminated all NMACs that were present for 6.04a in Tables 2.3, 7.3, 13.4, and 16.4. None of the NMACs in Tables 6.4 and 19.4 are common to 6.04a and C7-25. There were no tables where C7-25 had NMACs where 6.04a had none.

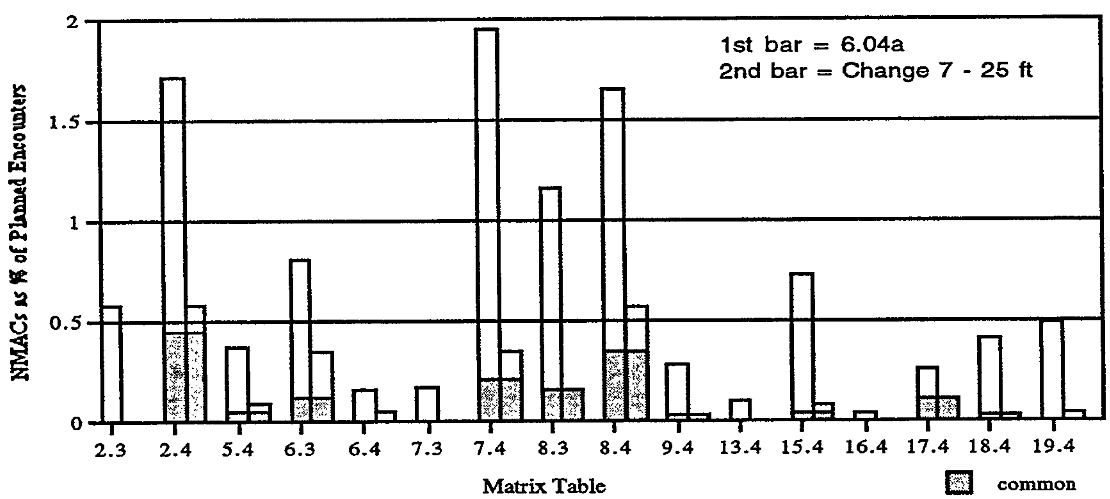


Figure 4-4. NMAC Comparison 6.04a vs. Change 7 25-foot tracker.

Figure 4-5 provides the results of the C7-100/C7-100 and C7-25/C7-25 comparison. Looking at Figure 4-5 we can make several observations. One observation is that for Tables 6.4, 18.4, and 19.4 there are no NMACs in common. In most cases, the 25-foot tracker has fewer NMACs than the 100-foot tracker as expected; the exceptions to this are Table 6.3 and 15.4 where the NMAC totals are the same for both trackers and Tables 2.4 and 5.4 where the 25-foot tracker logic has more NMACs than the 100-foot tracker logic.

It seems unusual that the encounters with the 100-foot tracker would have a better outcome than encounters with the 25-foot tracker. In order to understand how this could occur, the encounter summaries from Tables 2.4 and 5.4 where Change 7-25 had an NMAC and Change 7-100 did not have an NMAC were examined.

In the Tables 10 and 11, there are a total of twelve encounters in which Change 7-25 had an NMAC, but Change 7-100 did not have an NMAC (eight encounters in Table 2.4 and four encounters in Table 5.4). In all twelve encounters, both logic versions picked the same initial RA. After that, there was wide variation in the presence and/or timing of a follow-on RA (increase or reversal) with no correlation to logic version. Lincoln Laboratory personnel discussed this behavior with the developer of MITRE's 25-foot and 100-foot vertical trackers. It was MITRE's sense that the variation in the follow-on RAs occurred because of the interaction between the altitude quantization and the thresholds in the detection logic. Therefore, this is not a deficiency in the 25-foot tracker.

For Table 5.4, there are four encounters where Change 7-100 did not have an NMAC, but Change 7-25 did have an NMAC. In all four cases the difference was that Change 7-25 did not strengthen the initial RA.

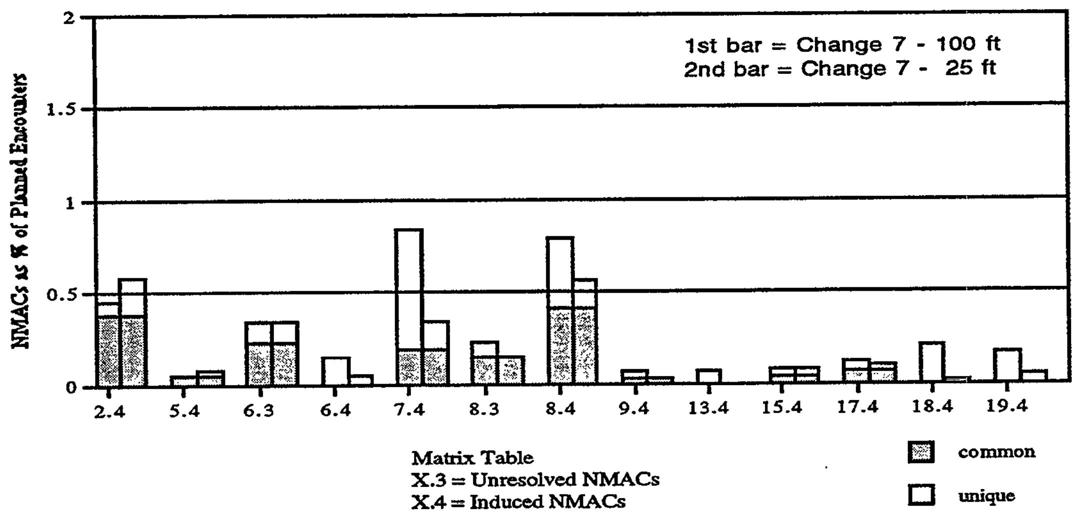


Figure 4-5. NMAC Comparison Change 7 100-foot tracker vs. Change 7 25-foot tracker.

4.2.3 Performance Statistics Program Results

The Performance Statistics Program, described in Section 2, provides information on the frequency and effectiveness of altitude crossing TCAS advisories. Table 4-3 summarizes the two most significant statistics generated for all twenty encounter classes: the percent of RAs that were altitude crossing and the percent of altitude crossing RAs that were NMACs. Remember, for classes 0 – 9 the aircraft intended to cross in altitude, for classes 10 - 19 the aircraft did not plan to cross in altitude.

The number of crossing RAs for Version 7 Mod 11 is comparable to or greatly reduced compared to 6.04a with two exceptions. First, encounter class 15, C7-100 has a slight increase in altitude crossing RAs. Also, for encounter class 3, both C7-100 and C7-25 have increased crossing RAs (41% and 54%, respectively). Class 3 is a planned crossing class, so an increase in altitude crossing RAs is not a cause for concern. The increase in altitude crossing RAs for classes 3 and 15 is not alarming because the percent of crossing RAs resulting in NMACs for encounter class 3 remains at 0 for both C7-100 and C7-25 and the percent of crossing RAs resulting in NMACs for encounter class 15 is greatly reduced for both C7-100 (82% less than 6.04a) and C7-25 (78% less than 6.04a).

Looking at the percent of crossing RA NMACs, there are several encounter classes (2, 5, 8, and 16) that had crossing RA NMACs with 6.04a, but none for either C7-100 or C7-25. From Table 4-3 we can conclude that Version 7 Mod 11 reduced the overall number of crossing RAs, and those crossing RAs that remain are more effective, i.e., they result in fewer NMACs.

Table 4-3. Summary of Performance Statistics Results

	Percent of RAs That Were Crossing			Percent of Crossing RAs Resulting in NMACs		
		Version 7 Mod 11			Version 7 Mod 11	
Class	6.04a	100 ft	25 ft	6.04a	100 ft	25 ft
0	0.00	0.00	0.00	0.00	0.00	0.00
1	8.92	5.14	4.86	0.00	0.00	0.00
2	2.45	2.39	1.94	3.09	0.00	0.00
3	7.50	10.60	11.56	0.00	0.00	0.00
4	7.67	5.81	5.79	0.00	0.00	0.00
5	4.97	4.86	4.72	0.22	0.00	0.00
6	16.41	16.01	14.67	0.61	0.14	0.15
7	3.32	3.29	2.29	0.00	0.00	0.00
8	8.89	7.21	6.73	0.70	0.00	0.00
9	28.98	27.88	28.26	0.86	0.34	0.14
10	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00
13	14.97	10.39	11.33	1.06	0.38	0.00
14	10.42	6.25	5.73	0.00	0.00	0.00
15	8.84	8.94	7.32	6.67	1.19	1.45
16	15.44	8.35	8.99	0.33	0.00	0.00
17	1.89	1.02	1.39	17.11	14.29	10.34
18	14.66	13.03	12.90	2.65	2.01	0.22
19	23.59	18.82	18.71	2.51	1.17	0.28

4.2.4 Reversal Analysis Programs

4.2.4.1 Variation One

After the multiple TCAS–TCAS reversals were eliminated, and the MITRE and WJHTC improvements were made to the reversal logic, Lincoln Laboratory ran the Reversal Analysis Program Variation One for all twenty encounter classes. The complete set of results for the

Reversal Analysis Program Variation One are in Appendix C. Since TCAS–TCAS reversals were not allowed in 6.04a, no meaningful comparison of reversal performance can be made from that perspective.

Reversals against unequipped threats were allowed in 6.04a, so we can compare the performance of Version 7 Mod 11 to 6.04a for the TCAS-unequipped cases. Table 4-4 summarizes both the percent of RAs that reversed and the percent of reversed RA NMACs for 6.04a vs. Mode C, C7-100 vs. Mode C, and C7-25 vs. Mode C. Under the comments column "Same", "Better", and "Worse" refer to the performance of Change 7 compared to 6.04a. Also under comments, the [Class Weight] entry is taken from Appendix M, converted to a percentage of the encounters observed in the United States airspace. For example, in the row for class 9, Worse [0.01] means that the Change 7 performance was worse than 6.04a (because there were more reversed RAs that were NMACs) and class 9 represents 0.01 percent of the encounters in the airspace.

Table 4-4. Effectiveness of Reversals Against Unequipped Threats

	Percent of RAs That Reversed			Percent Reversed RAs That Were NMACs			Comments
Class	6.04a	100 ft	25 ft	6.04a	100 ft	25 ft	[Class Weight]
0	0.00	0.00	0.00	0.00	0.00	0.00	Same
1	0.00	0.00	0.00	0.00	0.00	0.00	Same
2	2.06	5.18	5.88	0.00	0.98	2.16	Worse [0.04%]
3	1.60	1.24	0.82	0.00	0.00	0.00	
4	0.00	0.00	0.00	0.00	0.00	0.00	Same
5	0.85	2.78	2.70	0.00	3.57	2.04	Worse [0.25%]
6	1.40	2.34	2.50	3.17	2.37	2.21	Better [0.29%]
7	2.67	7.59	9.09	2.73	2.44	2.66	Better [0.02%]
8	4.16	7.51	7.49	3.69	2.43	2.22	Better [0.05%]
9	2.32	3.85	2.70	0.00	2.50	2.88	Worse [0.01%]
10	0.00	0.00	0.00	0.00	0.00	0.00	Same
11	0.00	0.00	0.00	0.00	0.00	0.00	Same
12	1.25	0.66	0.30	0.00	0.00	0.00	
13	11.62	13.30	16.09	0.00	0.00	0.00	
14	0.00	0.00	0.00	0.00	0.00	0.00	Same
15	2.54	4.62	3.66	0.00	2.22	0.00	Worse [2.05%]
16	12.53	10.67	10.82	0.00	0.00	0.42	Worse [2.56%]
17	0.76	2.16	2.34	12.50	8.60	6.06	Better [0.19%]
18	18.35	19.82	16.82	0.16	1.45	0.17	Worse [0.94%]
19	18.58	18.24	15.35	0.00	0.38	0.46	Worse [0.74%]

Looking at the percent of RAs that reversed, some classes still had no reversed RAs for Version 7 Mod 11 (0, 1, 4, 10, 11, and 14). Some classes had fewer reversed RAs than 6.04a (3, 12, 16, and 19). Class 18 had more reversed RAs with Change 7-100 and fewer reversed RAs with Change 7-25. The rest of the encounter classes (2, 5, 6, 7, 8, 9, 13, 15, and 17) had more reversed RAs with Version 7 Mod 11 than with 6.04a. This result in itself is not alarming. This result was expected, as described in Section 3.6. However, looking at the percent of NMACs with reversed RAs for the planned crossing classes three (2, 5, and 9) have more NMACs with reversed RAs than 6.04a; four classes (0, 1, 3, and 4) have no reversed RA NMACs; and only two classes (6 and 7) have fewer NMACs with reversed RAs compared to 6.04a. For the planned non-crossing classes with Version 7 Mod 11 five classes (10, 11, 12, 13, and 14) have no reversed RA NMACs; four classes (15, 16, 18, 19) have more reversed RA NMACs than 6.04a; and only one class (17) has less reversed RA NMACs with Version 7 Mod 11 than with 6.04a.

The European airspace currently has more TCAS–unequipped encounters than the United States airspace. Our European colleagues expected to see an increase in the number of reversed sense RAs in their simulated encounters. Their conclusion was that the other benefits of Change 7 far outweigh the increase in reversed RA NMACs in the TCAS–unequipped encounters. Looking at the results from the WJHTC data Appendix E NMAC Tables, for all twenty encounter classes the total number of NMACs for 6.04a vs. Mode C is 3360 (783 unresolved and 2577 induced), the number of Change 7-100 vs. Mode C NMACs is 2586 (783 unresolved and 1803 induced) and the number of Change 7-25 vs. Mode C NMACs is 1580 (384 unresolved and 1196 induced). The Version 7 Mod 11 100-foot tracker data show a 23% reduction in NMACs against unequipped threats compared to 6.04a and the Version 7 Mod 11 25-foot tracker logic shows a 53% reduction in NMACs against unequipped threats. This supports the conclusion of our European colleagues.

4.2.4.2 Variation Two – Separation Differences

The results of the Separation Differences program (Reversal Analysis Program Variation Two) for Version 7 Mod 11 are quite encouraging. The complete set of results is in Appendix D. The left half of Figure 4-6 contains a summary of the Separation Difference results for Version 7 Mod 10, and the right half of Figure 4-6 contains a summary of the Separation Differences results for Version 7 Mod 11.

At first glance, Version 7 Mod 11 classes 2/12 had higher separation losses than we expected (75.3%) for reversed RAs. However, we are not overly concerned for several reasons. First, Version 7 Mod 10 had 100% separation losses, so Mod 11 is an improvement. Second, in looking at the gains and losses tables, all the losses occurred in encounters with 750 feet of planned separation and most of the losses were less that 500 feet. In addition, for non-reversed RAs in the same encounter class the 750 feet planned separation encounters had comparable losses.

Most of the other classes have improved gains. The most dramatic improvement occurs in classes 3/13. Where 100% of encounters lost separation with Version 7 Mod 10, but only 4.4% of encounters lost separation with Version 7 Mod 11.

Reversal Analysis Program Results

Class	Rev.?	Version 7 Mod 10 (May 1997) RAs	NMACs	%	Sep Loss	%	Sep Gain	%	Version 7 Mod 11 (November 1997) RAs	NMACs	%	Sep Loss	%	Sep Gain	%
010	no	480	0	0.0	0	0.0	336	70.0	480	0	0.0	0	0.0	336	70.0
	Rev.	0	0	0.0	0	0.0	0	0.0	0	0	0.0	0	0.0	0	0.0
111	no	1800	0	0.0	0	0.0	1360	75.6	1800	0	0.0	0	0.0	1360	75.6
	Rev.	0	0	0.0	0	0.0	0	0.0	0	0	0.0	0	0.0	0	0.0
212	No	22359	0	0.0	1302	5.8	16805	75.2	22320	62	0.3	1215	5.4	16853	75.5
	Rev.	34	0	0.0	34	100.0	0	0.0	73	2	2.7	55	75.3	18	24.7
313	No	19654	1	0.0	34	0.2	16104	81.9	18777	0	0.0	10	0.1	15169	80.8
	Rev.	87	68	78.2	87	100.0	0	0.0	938	6	0.6	41	4.4	897	95.6
414	no	3596	0	0.0	6	0.2	3038	84.5	3596	0	0.0	6	0.2	3038	84.5
	Rev.	0	0	0.0	0	0.0	0	0.0	0	0	0.0	0	0.0	0	0.0
515	no	43413	78	0.2	1513	3.5	36414	83.9	43237	30	0.1	1329	3.1	36422	84.2
	Rev.	79	5	6.3	57	72.2	22	27.8	255	0	0.0	11	4.3	244	95.7
616	no	44560	82	0.2	960	2.2	37338	83.8	43888	46	0.1	892	2.0	36754	83.7
	Rev.	46	5	10.9	37	80.4	9	19.6	737	8	1.1	24	3.3	713	96.7
717	no	65937	310	0.5	5317	8.1	53052	80.5	65853	220	0.3	5028	7.6	53255	80.9
	Rev.	43	6	14.0	20	46.5	23	53.5	127	2	1.6	44	34.6	83	65.4
818	no	66150	412	0.6	3581	5.4	53321	80.6	64672	333	0.5	2957	4.6	52518	81.2
	Rev.	360	192	53.3	352	97.8	8	2.2	1899	19	1.0	381	20.1	1518	79.9
919	no	43763	43	0.1	831	1.9	38509	88.0	42350	14	0.0	687	1.6	37216	87.9
	Rev.	426	65	15.3	372	87.3	54	12.7	1843	34	1.8	214	11.6	1629	88.4
Total	Non	311712	926	0.3	13544	4.3	256277	82.2	306973	705	0.2	12124	3.9	252921	82.4
	Rev	1075	341	31.7	959	89.2	116	10.8	5872	71	1.2	770	13.1	5102	86.9
		312787	1267						312845	776					
		0.3% of RAs are reversals							1.9% of RAs are reversals						

Figure 4-6. Comparison of Version 7 Mod 10 and Version 7 Mod 11.

4.3 RESULTS - ONE PILOT NON-RESPONDING

As mentioned in Section 1.1.2, the data collected with one pilot not responding to the TCAS advisory were collected for 6.04a and Version 7 Mod 11 with the 25-foot tracker only. When one pilot does not comply with the advisory the results have always been poor. In fact, one of the most compelling reasons for allowing TCAS–TCAS sense reversals was to allow the compliant aircraft some means of escape when involved in an encounter with a non-compliant aircraft.

The presence of an unresolved NMAC when one pilot does not follow the RA is not overly troubling, due to the geometry of the encounter there was going to be an NMAC without TCAS. On the other hand, the presence of an induced NMAC when one pilot does not follow the RA is very disturbing. In this case, without TCAS there would have been no NMAC.

The only analysis tools used on the non-responding data set were the WJHTC Matrix Generator program and Lincoln Laboratory's Hot-Spot Program. The complete set of "one pilot non-responding" hot-spot tables are provided in Appendix L.

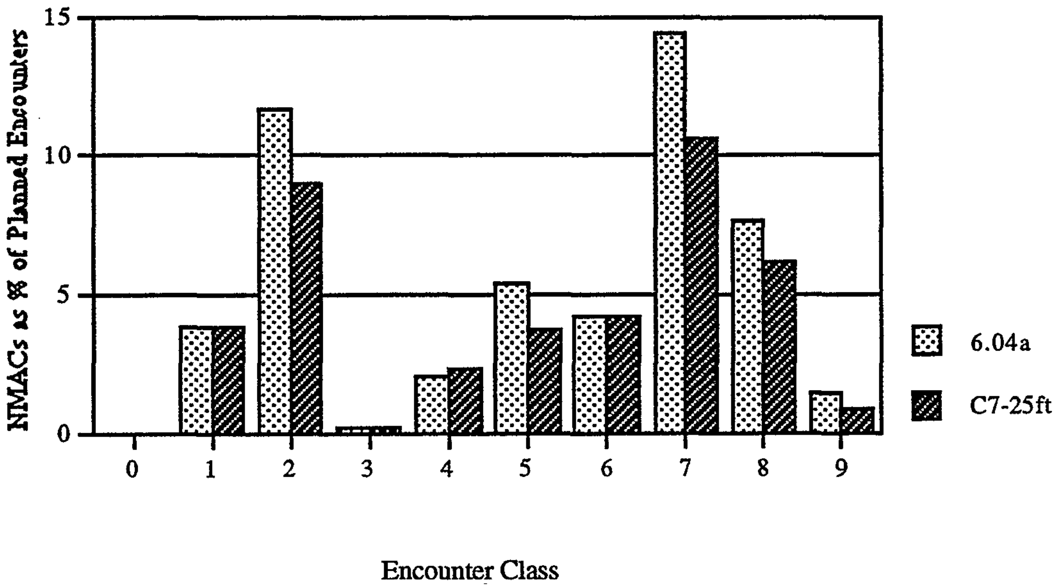
A summary of the hot-spot results for both unresolved and induced NMACs for all twenty encounter classes, including the mixed 6.04a and C7-25 equipages, is provided in Table 4-5. Looking at Table 4-5, any cell with degraded performance, compared to 6.04a, is indicated by a bold border. Overall, the "one pilot non-responding" results are quite good.

Table 4-5. Summary of Non-Responding Hot-Spot Data

	UNRESOLVED NMACs (percent of planned encounters)				INDUCED NMACs (percent of planned encounters)			
Class	6.04a Only	C7-25 Only	6.04a vs. C7-25 NR	C7-25 vs. 6.04a NR	6.04a Only	C7-25 Only	6.04a vs. C7-25 NR	C7-25 vs. 6.04a NR
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	3.75	3.75	3.75	3.75
2	2.32	1.16	1.68	1.16	11.66	9.02	11.08	8.99
3	0.54	0.00	0.54	0.00	0.14	0.14	0.14	0.15
4	6.67	6.67	6.67	6.67	1.97	2.30	2.30	1.97
5	7.95	7.38	8.35	6.82	5.35	3.69	5.28	3.49
6	3.88	2.34	3.82	2.00	4.14	4.20	4.43	3.90
7	8.42	5.57	7.01	5.69	14.40	10.55	13.93	10.51
8	4.09	1.91	2.89	2.16	7.66	6.12	7.80	5.78
9	1.99	0.95	1.64	0.86	1.38	0.80	1.06	0.90
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.19	0.00	0.19	0.00
13	0.00	0.00	0.00	0.00	2.02	0.22	1.09	0.80
14	33.33	33.33	33.33	33.33	0.00	0.00	0.00	0.00
15	30.88	30.88	31.62	30.15	0.55	0.30	0.24	0.24
16	0.00	0.00	0.00	0.00	2.91	0.24	1.63	1.37
17	22.62	23.21	23.21	22.62	0.32	0.44	0.42	0.38
18	0.00	0.00	0.00	0.00	6.30	0.78	4.24	2.28
19	0.00	0.00	0.00	0.00	5.13	0.35	2.42	1.55

Figures 4-7 and 4-8 show histograms of the hot-spot data for 6.04a – one pilot non-responding and C7-25 one pilot non-responding. Figure 4-7 shows induced NMACs and Figure 4-8 shows unresolved NMACs.

Most of the United States encounters are in classes 10 – 19, there are very few planned crossing encounters. Our biggest concern is the induced NMACs in the one pilot non-responding data. The most significant improvement was observed in the induced, planned non-crossing encounters.



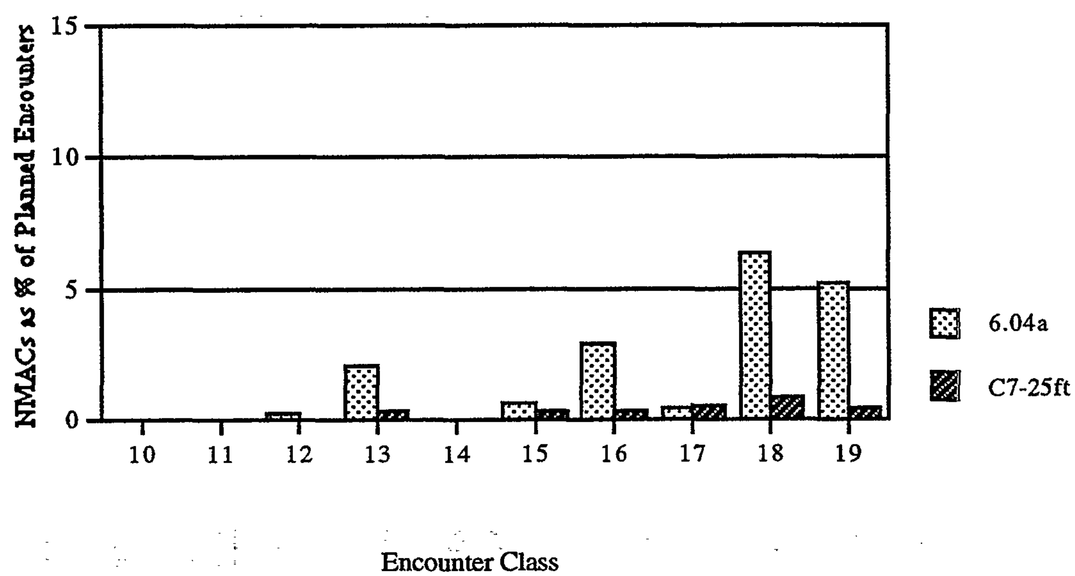
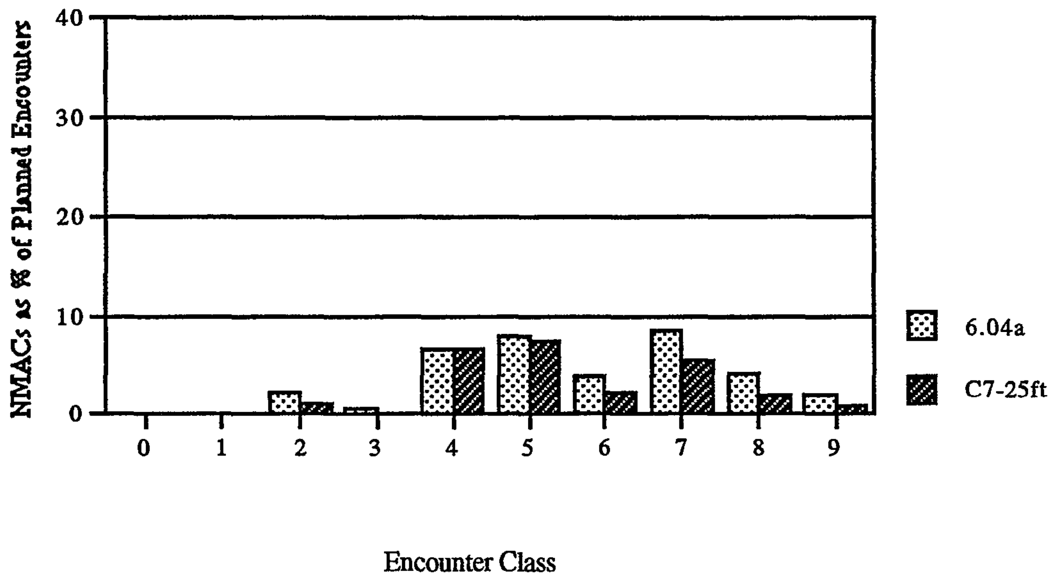


Figure 4-7. Hot-Spot Results, One Pilot Non-Responding Induced NMACs.



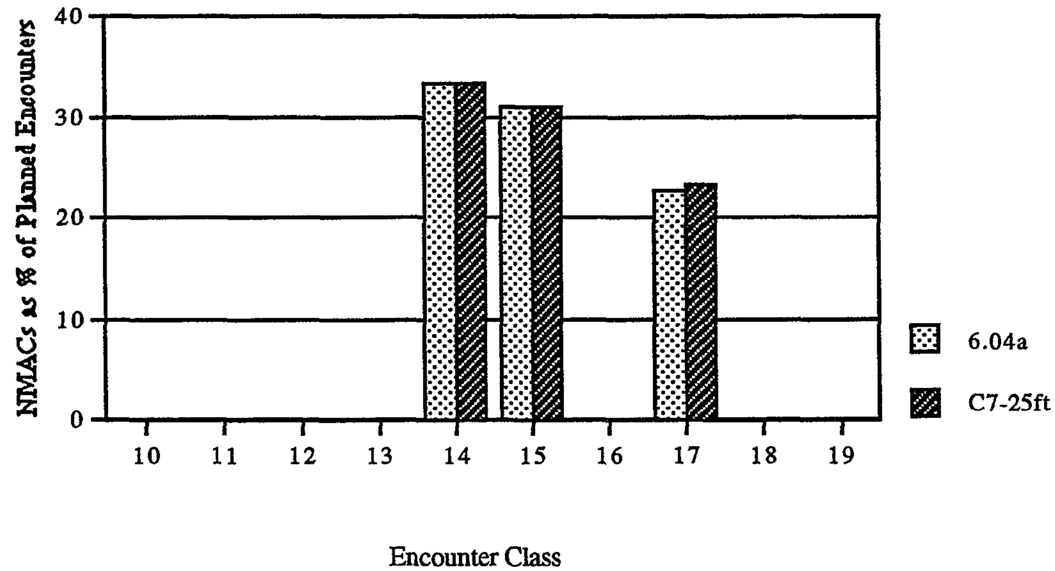


Figure 4-8. Hot-Spot Results One Pilot Non-Responding Unresolved NMACs.

4.4 TCAS VS. UNEQUIPPED ENCOUNTERS

The main focus of the Change 7 logic evaluation at Lincoln Laboratory was the TCAS–TCAS encounters. However, there is simulated data for TCAS-unequipped encounters. From the NMAC Tables in Appendix E, we can compute the total NMAC counts for TCAS–unequipped encounters. There was an overall reduction in NMAC counts from 3360 for 6.04a against unequipped intruders (783 unresolved, 2577 induced) to 2586 for Change 7-100 (783 unresolved, 1803 induced) and 1580 for Change 7-25 (384 unresolved, 1196 induced). However, the performance of sense reversals against unequipped intruders is mixed. Ten classes had no NMACs with reversed RAs for all three versions of the logic. Six classes had more NMACs for Change 7 than 6.04a. Four classes had fewer NMACs for Change 7 than 6.04a.

5. RESOLUTION OF 6.04A REPRESENTATIVE NMACS

5.1 DESCRIPTION

During the 6.04a logic evaluation, Lincoln Laboratory identified thirty distinct groups of NMACs. These groups were defined based on their encounter class, the type of NMAC (induced or unresolved), the shape of the encounter plot, and the RAs generated by the two aircraft. Within each group of NMACs, one encounter that best represented the group was selected and studied in detail. At the time of the 6.04a analysis the TCAS community expected that Change 7 would improve the outcome of most of these Representative NMAC encounters. As mentioned in Section 1.2, the third goal of the Lincoln Laboratory Change 7 logic analysis was to examine the performance of Change 7 for these thirty Representative NMAC encounters.

5.2 RESULTS

All thirty 6.04a representative NMAC encounters were run using versions 6.04a, Change 7-100 and Change 7-25. Table 5.1 shows identifying information for each of the 6.04a Representative NMAC encounters and the vertical separation achieved by each version of the logic. An R in the left side of the Change 7 achieved Separation column indicates that there was a sense reversal during the sequence of RAs observed for the encounter.

All seven unresolved 6.04a representative NMACs (1, 6, 7, 9, 12, 13, and 14) were resolved by the Change 7 logic.

Most of the twenty-three induced 6.04a representative NMAC encounters showed the expected improvement with a few exceptions. Representative NMAC 2 was an NMAC for both Change 7-100 and Change 7-25. Figure 5-1 shows the encounter summary for 6.04a Representative NMAC 2. In this encounter, aircraft 1 is level, aircraft 2 is level, then accelerates at 0.25g to 5000 fpm 20 seconds before CPA. This type of encounter, known as a "kamikaze maneuver," has been troublesome for TCAS since version 6.04 when the protection volume about the aircraft was reduced.

Representative NMAC 15 was no longer an NMAC for Change 7-100, but Change 7-25 still induced an NMAC. Figure 5-2 shows the encounter summary for 6.04a Representative NMAC 15. In this encounter, aircraft 1 is descending at 1000 fpm, then levels off, aircraft 2 is level then accelerates at 0.25g to 5000 fpm 20 seconds before CPA. The RAs chosen by the 3 versions of the logic are interesting. Aircraft 2 maneuvered 5 seconds before aircraft 1, so the commands selected by aircraft 2 are critical. Version 6.04a had a three second display deferral for aircraft 2 at 44 seconds that contributed to the poor outcome. Change 7-100, which did not have an NMAC for this encounter, had a "descend" command at 44 seconds. Change 7-25, which did have an NMAC, had a "don't climb" command at 46 seconds, followed by a "descend" command at 47 seconds.

Finally, Representative NMAC 26 showed no improvement for Change 7-100 or Change 7-25. Figure 5-3 shows the encounter summary for 6.04a Representative NMAC 26. In this encounter both aircraft are initially level. Aircraft 1 accelerates at 0.15 g to 5000 fpm at 25 seconds before CPA. Aircraft 2 accelerates at 0.15g to 3000 fpm at 30 seconds before CPA. In all three versions of the logic, aircraft 1 with the higher rate of climb, gets the "descend" command.

Table 5-1. Results for 6.04a Representative NMACs Run with Version 7 Mod 11 Logic

6.04a RNMAC	NMACs in Group	CLASS TABLE	AC 1 ID	REIT NUM	Planned Separation	Achieved Separation 6.04A	C7-100	C7-25
1	5	2.3	L	123	0.00	82.53	179.05	309.63
2	52	2.4	L	1196	-500.00	-48.15	81.99	56.62
3	5	5.4	L	1006	-250.00	31.50	169.84	188.85
4	4	5.4	L	1195	-250.00	21.86	220.87	220.87
5	17	5.4	L	1952	-500.00	98.41	538.71	727.22
6	4	6.3	L	81	0.00	90.58	203.89	284.32
7	10	6.3	L	5863	0.00	22.51	-417.27	-741.74
8	12	6.4	L	4612	-500.00	18.15	184.58	600.90
9	4	7.3	L	2538	0.00	-35.39	-113.41	-344.25
10	5	7.4	L	2014	-250.00	94.30	194.84	172.61
11	191	7.4	L	8982	750.00	-67.85	759.78	-464.46
12	4	8.3	L	641	0.00	77.21	-113.61	-175.99
13	7	8.3	L	7305	0.00	82.53	249.83	299.78
14	19	8.3	L	8712	0.00	-82.53	-249.83	-299.78
15	27	8.4	L	1385	-500.00	39.36	396.02	62.78
16	152	8.4	L	2655	500.00	-38.78	-230.07	-564.99
17	4	8.4	L	3615	250.00	82.28	293.43	329.63
18	5	8.4	H	4970	-750.00	62.99	910.56	731.68
19	14	9.4	H	1509	-250.00	-27.82	-1321.76	-1301.11
20	4	9.4	H	3523	250.00	-54.29	R 576.24	733.05
21	1	12.4	L	1421	-750.00	-25.63	R -825.64	-1001.52
22	4	13.4	L	1614	500.00	-85.07	R 842.51	R 886.95
23	18	15.4	L	4283	-500.00	-39.93	R -728.67	R -728.67
24	3	15.4	L	5543	-500.00	63.21	355.18	366.28
25	1	16.4	L	2491	-500.00	-85.41	-839.26	-500.00
26	14	17.4	L	2732	500.00	-33.01	-33.01	-33.01
27	12	18.4	L	1520	750.00	-30.53	R 1118.80	1948.98
28	5	18.4	H	3978	500.00	85.41	500.00	855.93
29	11	19.4	H	2883	500.00	-28.78	R 625.00	675.00
30	25	19.4	H	7162	-500.00	88.47	R -189.09	R -759.30

Total 639

R indicates a sense reversal occurred

These results are very encouraging, however there are variations in the timing of vertical maneuvers within a group of NMACs. It is possible that while the encounter chosen as representative of the other NMACs may have a successful outcome with Change 7, other members of the group may still be NMACs.

```
DATA FOR RNMAC02

1196   6.04A RL VS 6.04A RH    2    -48.15    CROSSING_ENCOUNTER

SL =  4  ZTHR =  600.0   TAUR =  20.0   TAUV =  20.0   ALIM = 300.0

 -500.0 (0.0,0.0)  (0.0,5000.0)  0.00   0.25   0.0  -20.0   3720.0

A/C1:          1165022 TA TIME :30 |RELZ | CL    @48   [NXRA]| ICL   @50

A/C2:          1265122 TA TIME :30 |RELZ | POTRA @46   (DFD) | DES   @48
                    [NXRA]| IDES  @53

1196   C7 100 FT RL VS C7 100 FT RH   2   81.99  NON_CROSSING_ENCOUNTER

SL =  4  ZTHR =  600.0   TAUR =  20.0   TAUV =  20.0   ALIM = 300.0

 -500.0 (0.0,0.0)  (0.0,5000.0)  0.00   0.25   0.0  -20.0   3720.0

A/C1:          1171033 TA TIME :30 |RELZ | CL    @47   [NXRA]| ICL   @50

A/C2:          1271133 TA TIME :30 |RELZ | DCL   @46   [NXRA]| DES   @47

1196   C7 25 FT RL VS C7 25 FT RH    2    56.62  CROSSING_ENCOUNTER

SL =  4  ZTHR =  600.0   TAUR =  20.0   TAUV =  20.0   ALIM = 300.0

 -500.0 (0.0,0.0)  (0.0,5000.0)  0.00   0.25   0.0  -20.0   3720.0

A/C1:          1175044 TA TIME :30 |TAUV | POTRA @46   (VTT) | CL    @47
                   [NXRA]| ICL   @53

A/C2:          1275144 TA TIME :30 |TAUV | DCL   @46   [NXRA]| DES   @47
```

Figure 5-1. 6.04a Representative NMAC 2.

```
DATA FOR RNMAC15


1385    6.04A RL VS 6.04A RH     8      39.36     CROSSING_ENCOUNTER

SL =  4  ZTHR =  600.0   TAUR =  20.0   TAUV =  20.0   ALIM = 300.0

 -500.0 (-1000.0,0.0)  (0.0,5000.0)  0.05   0.25  -25.0  -20.0    3700.0

A/C1:         1165022 TA TIME :32 |RELZ | CL     @47   [NXRA]| ICL    @49

A/C2:         1265122 TA TIME :34 |TAUV | POTRA @44   (DFD) | DES    @47
                      [NXRA]| IDES  @54

1385    C7 100 FT RL VS C7 100 FT RH    8  396.02    NON_CROSSING_ENCOUNTER

SL =  4  ZTHR =  600.0   TAUR =  20.0   TAUV =  20.0   ALIM = 300.0

 -500.0 (-1000.0,0.0)  (0.0,5000.0)  0.05   0.25  -25.0  -20.0    3700.0

A/C1:         1171033 TA TIME :32 |RELZ | CL     @47   [NXRA]| ICL    @50

A/C2:         1271133 TA TIME :34 |TAUV | DES    @44   [NXRA]| IDES   @53
                     | DCL   @63


1385    C7 25 FT RL VS C7 25 FT RH     8      62.78     CROSSING_ENCOUNTER

SL =  4  ZTHR =  600.0   TAUR =  20.0   TAUV =  20.0   ALIM = 300.0

 -500.0 (-1000.0,0.0)  (0.0,5000.0)  0.05   0.25  -25.0  -20.0    3700.0

A/C1:         1175044 TA TIME :33 |RELZ | CL     @47   [NXRA]| ICL    @52

A/C2:         1275144 TA TIME :34 |RELZ | DCL    @46   [NXRA]| DES    @47
```

Figure 5-2. 6.04a Representative NMAC 15.

```
DATA FOR RNMAC26

2732   6.04A RL VS 6.04A RH    17    -33.01    CROSSING_ENCOUNTER

SL =  4  ZTHR =  600.0   TAUR =  20.0   TAUV =  20.0   ALIM = 300.0

  500.0 (0.0,5000.0)  (0.0,3000.0)  0.15   0.15  -25.0  -30.0    3700.0

A/C1:        1165022 TA TIME :35 |TAUR | DES   @45   [XRA] | IDES  @54

A/C2:        1265122 TA TIME :35 |TAUR | CL    @45   [XRA] | ICL   @49

2732   C7 100 FT RL VS C7 100 FT RH   17   -33.01   CROSSING_ENCOUNTER

SL =  4  ZTHR =  600.0   TAUR =  20.0   TAUV =  20.0   ALIM = 300.0

  500.0 (0.0,5000.0)  (0.0,3000.0)  0.15   0.15  -25.0  -30.0    3700.0

A/C1:        1171033 TA TIME :35 |TAUR | DES   @45   [XRA] | IDES  @54

A/C2:        1271133 TA TIME :35 |TAUR | CL    @45   [NXRA]

2732   C7 25 FT RL VS C7 25 FT RH    17    -33.01    CROSSING_ENCOUNTER

SL =  4  ZTHR =  600.0   TAUR =  20.0   TAUV =  20.0   ALIM = 300.0

  500.0 (0.0,5000.0)  (0.0,3000.0)  0.15   0.15  -25.0  -30.0    3700.0

A/C1:        1175044 TA TIME :35 |TAUR | DES   @45   [XRA] | IDES  @54

A/C2:        1275144 TA TIME :35 |TAUR | CL    @45   [XRA]
```

Figure 5-3. 6.04a Representative NMAC 26.

6. CHANGE 7 REPRESENTATIVE NMACS

The methodology of choosing representative NMACs was beneficial in the 6.04a logic evaluation, so the same technique was applied in the Change 7 evaluation. Every encounter that generated an NMAC for either Change 7-100 or Change 7-25 was plotted for all three versions of the logic (6.04a, Change 7-100, and Change7-25). These groups of plots were sorted first by encounter class and NMAC type (induced or unresolved), and then they were sorted by the shape of the encounter plots and the sense of the RAs generated by the two TCAS aircraft. Out of twenty encounter classes there were only seventeen different categories of NMACs, three groups of unresolved NMACs and 14 groups of induced NMACs.

Keeping in mind that the WJHTC simulation is designed to stress the limits of the logic, for each of the 17 representative NMACs, we attempted to answer the following questions:

1. Did we understand the NMAC? Do we know the cause of the NMAC? Was there anything about the performance of the logic that seemed wrong? In other words are these NMACs the types of encounters that TCAS cannot reasonably be expected to resolve?

2. How frequently will the encounter be observed in the airspace? Would the encounter geometry occur during normal operations or only during some breakdown or error in the air traffic control system? In other words are these NMACs unlikely to occur in the airspace?

3. Is this NMAC type new to Change 7 or similar to NMACs observed in 6.04a?

Only one Representative NMAC group was new to Change 7 (see Representative NMAC I14 below). All seventeen Representative NMACs for Change 7 fell into the "unlikely to occur" or "impossible to fix" categories. Each of the 17 Representative NMACs are described below in Table 6-1.

Table 6-1 gives a summary of the common features of each NMAC group including: the Matrix table from which the group of encounters came; the number of NMACs in the group; the planned separation of the encounters in the group; the presence of crossing RAs in the group; the presence of geometric reversals for most encounters in the group; the vertical rates observed for aircraft 1 and aircraft 2 in the group; and the comparable 6.04a NMAC group number, if applicable.

Table 6-1. Change 7 Representative NMAC Encounters

UNRESOLVED NMACs (Total 22)

Group (table)	No. Of NMACs	Planned Separation	Crossing RA?	Geom Rev?	Aircraft Rates		6.04a NMAC group
					AC1	AC2	
1. (6.3-1)	8	0	Non-cross	No	5000	5000	7
2. (6.3-2)	4	0	Crossing	Yes	>= 3000	<= -3000	7
3. (8.3-1)	10	0	Non-cross	No	<= -3000	-5000	12

INDUCED NMACs (Total 385)

Group (table)	No. Of NMACs	Planned Separation	Crossing RA?	Geom Rev?	Aircraft Rates		6.04a NMAC group
					AC1	AC2	
1. (2.4-1)	32	-500, -750	Non-cross	No*	0, +/-400	5000	2
2. (5.4-1)	1	500	Non-cross	No	5000	3000	4
3. (5.4-2)	10	-750	Non-cross	No	-1000	5000	5
4. (6.4-1)	16	-500	Non-cross	No	-5000	-5000	8
5. (7.4-1)	1	500	Non-cross	No	5000	3000	26
6. (7.4-2)	118	250 - 750	Non-cross	No	>= 1000	<= -1000	9
7. (8.4-1)	24	-500	Non-cross	No*	<= -1000	-5000	17
8. (8.4-2)	130	250 - 750	Non-cross	No*	<= -1000	<= -3000	16
9. (9.4-1)	7	-250	Crossing	No*	5000	-5000	19
10. (13.4-1)	3	250	Crossing	Yes	0,400	5000	22
11. (15.4-1)	4	-500	Crossing	No	5000	5000	23
12. (17.4-1)	13	500	Crossing	No*	5000	3000	26
13. (18.4-1)	10	750	Crossing	Yes	-5000	<= -1000	27
14. (19.4-1)	16	-250, -500	Crossing	Yes	>= 1000	<= -3000	none

* Means a small number of encounters had reversals that came too late to be effective.

Appendix N contains five pages that describe each Change 7 Representative NMAC. The first page gives the Encounter class and unique encounter number of the representative NMAC, then provides statistics on the parameters of the NMAC group as a whole. In addition, relevant performance statistics for the whole encounter class are listed, and comments are provided. The second page is the Encounter Summary for the Representative NMAC. These were described previously in Section 2.5. The third page is a plot of the Representative NMAC encounter, but with version 6.04a for reference purposes. The fourth page is a plot of the Representative NMAC encounter with the Change 7 100-ft tracker logic. The fifth page is a plot of the Representative NMAC encounter with the Change 7 25-ft tracker logic. The unresolved Representative NMACs are indicated with UNR or U on the top line of each page. Induced Representative NMACs are indicated by IND or I on the top line of the page.

6.1 UNRESOLVED REPRESENTATIVE NMACS

Representative NMAC U1 has eight members in the group. For these NMACs, the RAs came too late to be effective.

Representative NMAC U2 has four members in the group. All encounters in this group had sense reversals that occurred late in the encounter.

Representative NMAC U3 has ten members in the group. All of these encounters had late maneuvers at high rates.

All of the unresolved NMACs in these three groups had vertical rates for both aircraft of 3000 fpm or higher.

6.2 INDUCED UNRESOLVED NMACS

Representative NMAC I1 has 32 encounters with aircraft 1 level or nearly level (+/- 400 fpm), but aircraft 2 accelerating at .25 g or .35 g 20 seconds prior to CPA. This type of encounter was also a problem for the 6.04a logic.

Representative NMAC I2 is a group with only one member. In this case the Change 7-25 logic picked a different sense than 6.04a or Change 7-100 which were non-NMACs.

Representative NMAC I3 has ten members in the group. These encounters all had late maneuvers at high rates. In the example shown on the plots, the 6.04a logic picked the same commands as Change 7-100 and Change 7-25. The only difference is that 6.04a issued the initial command or the increase command a second earlier than Change 7.

Representative NMAC I4 has 16 members in the group. All of these encounters had late maneuvers at high rates by aircraft 2.

Representative NMAC I5 is another group with only one member. Again the Change 7-25 logic picked a different sense than 6.04a or Change 7-100 which were non-NMACs.

Representative NMAC I6 has 118 members in the group. The NMACs in this group cover all vertical rates used in the simulation (1000, 3000 and 5000 fpm climb or descend), three different planned separations (250, 500, and 750 feet), and several rates of acceleration. The common mechanism in the NMAC is that the two aircraft were intending to cross in altitude and TCAS issued non-crossing RAs.

Representative NMAC I7 has 24 members in the group. In this case, aircraft 2 climbed through aircraft 1's altitude, the two aircraft wanted to cross and TCAS issued non-crossing RAs. This type of encounter was also a trouble spot for 6.04a.

Representative NMAC I8 is the largest group with 130 members. Again several planned separations and several combinations of vertical rates and accelerations are present. The reason these encounters failed is that the aircraft planned to cross in altitude and TCAS issued non-crossing RAs.

Representative NMAC I9 has seven members. These encounters are high rate level-offs that fail because the logic delays issuing a crossing RA while waiting for the level-off. This type of encounter was also a trouble spot for 6.04a.

Representative NMAC I10 has three members in the group. These encounters have aircraft 1 level or nearly level with aircraft 2 rapidly changing from 5000 fpm to level flight. All of the failures had 250 feet of planned separation and all had the 100-foot tracker. More significantly, all encounters had sense reversals. The 6.04a version of the logic issued commands that crossed the aircraft in altitude. Change 7 picked the same initial sense commands as 6.04a but reversed sense and barely failed.

Representative NMAC I11 has four members in the group. All of these encounters had late maneuvers at high rates by aircraft 2.

Representative NMAC I12 has 13 members in the group. Both aircraft were level then began accelerating to 5000 fpm at the same time. This type of encounter was also a problem for 6.04a.

Representative NMAC I13 has ten members in the group, 9 occurred with the 100-foot tracker. These encounters are somewhat troubling because the aircraft did not intend to cross in altitude, a command was selected that was contrary to the planned aircraft motion, the command was reversed, but too late to correct the problem. In this case, a strengthening (as in the 6.04a plot) would have lead to a better conclusion than the sense reversal. The best outcome is obtained when sense of the command matches the planned aircraft motion, as in the Change 7-25 plot.

Finally, Representative NMAC I14 has 16 members, most (81%) occurred with the 100-foot tracker. There is no comparable representative NMAC group from 6.04a. Again, this is an encounter where the two aircraft do not intend to cross in altitude, a command was selected that was contrary to the planned aircraft motion, then command was reversed, but too late to correct the problem.

7. PERSPECTIVE

7.1 CHRONOLOGY OF REVISIONS

A thorough study of the proposed Change 7 logic was carried out at Lincoln Laboratory. During the evaluation, Lincoln Laboratory focused on the TCAS–TCAS reversals section of the logic. Lincoln Laboratory detected problems with the reversal logic (the occurrence of multiple reversals) that were corrected by revisions in the reversal logic.

An FAA-sponsored assessment team (including MITRE, WJHTC, and Lincoln Laboratory) then undertook an effort to decide if reversals should be included in the Change 7 logic. Lincoln Laboratory pointed out the relatively poor performance of TCAS–TCAS reversals in class 13 (the "Dallas bump up" class) and the marginal improvement in only five of the twenty encounter classes for a non-responding intruder in TCAS-TCAS coordinated encounters. Lincoln Laboratory also pointed out that the overall performance for both pilots responding was worse with reversals than without reversals. Based on the MITRE safety study results that showed overall satisfactory performance, and the lack of overwhelming evidence for the removal of TCAS–TCAS reversals, the assessment team decided to proceed with the implementation of Change 7 with TCAS-TCAS reversals.

Lincoln Laboratory then studied the behavior of all reversed RA encounters and non-reversed RA encounters. The study showed that reversed RA encounters had an overwhelming tendency to lose separation, while non-reversed RA encounters predominantly increased separation. These findings led to another fix of the logic. The performance of TCAS-TCAS reversals then improved dramatically. With this improvement, the assessment team deemed the Change 7 logic to be suitable for implementation.

7.2 PERFORMANCE TRENDS

The focus of the Change 7 analysis was to compare the performance of the Change 7 logic to version 6.04a. There were two previously implemented versions of the TCAS logic, namely 6.02 and 6.04. In order to gain some perspective on the evolution of TCAS, the behavior of all five versions of TCAS logic is summarized in three tables. Table 7.1 shows the number of unresolved NMACs by encounter class and logic version, expressed as a percentage of the number of planned encounters. Table 7.2 shows the number of induced NMACs by encounter class and logic version, expressed as a percentage of the number of planned encounters. Finally, Table 7.3 shows the total number of NMACs by logic version.

In Table 7-1, note there were no unresolved encounters for logic version 6.02. For 6.04, the protection volume was reduced in size to mitigate the nuisance RAs characteristic of 6.02. This introduced unresolved NMACs. Since version 6.04, with the exception of encounter class 6, there has been a distinct reduction in unresolved NMACs.

In Table 7-2, note that from version 6.02 to version 6.04, there was an increase in induced NMACs in every encounter class. The general trend from 6.04 to 6.04a to Change 7 is a reduction in induced NMAC counts. The most dramatic example of improvement is observed in encounter class 19.

In Table 7-3, note that with Change 7, the total NMACs observed are below the totals for 6.02.

Table 7-1. Unresolved NMAC History

Class	6.02	6.04	6.04a	C7-100	C7-25
0	0.0	0.0	0.0	0.0	0.0
1	0.0	0.0	0.0	0.0	0.0
2	0.0	0.579	0.579	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0
6	0.0	0.289	0.810	0.347	0.347
7	0.0	0.166	0.165	0.0	0.0
8	0.0	1.157	1.157	0.231	0.154
9	0.0	0.173	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0	0.0
14	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0
16	0.0	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0	0.0

Table 7-2. Induced NMAC History

Class	6.02	6.04	6.04a	C7-100	C7-25
0	0.0	0.0	0.0	0.0	0.0
1	0.0	0.0	0.0	0.0	0.0
2	0.396	1.715	1.707	0.451	0.580
3	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0
5	0.053	0.347	0.367	0.051	0.089
6	0.379	0.813	0.153	0.153	0.051
7	0.971	1.912	1.951	0.836	0.348
8	0.378	2.031	1.649	0.780	0.570
9	0.017	0.224	0.280	0.078	0.031
10	0.0	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0
12	0.0	0.046	0.0	0.0	0.0
13	0.0	0.467	0.101	0.076	0.0
14	0.0	0.0	0.0	0.0	0.0
15	0.0	0.972	0.728	0.081	0.081
16	0.503	0.771	0.039	0.0	0.0
17	0.090	0.377	0.254	0.127	0.109
18	0.254	0.527	0.410	0.217	0.024
19	2.458	2.907	0.486	0.176	0.041

Table 7-3. Total NMACs by Logic Version

TCAS Logic Version	Total NMACs	Percent
6.02	411	0.449
6.04	848	0.926
6.04a	639	0.698
C7-100	254	0.277
C7-25	153	0.167

EPILOGUE

During TCAS certification testing, the logic is run through detailed end-to-end system tests involving all components of the system (e.g., TCAS unit, Mode S transponder) in a deliberate attempt to expose the logic to various kinds of surveillance and environmental error conditions. This process tests parts of the logic that are not covered by WJHTC or MITRE testing.

During manufacturer certification testing using the RTCA-approved Version 7 Mod 11 logic (described in the body of this report), three problems were identified that were considered to represent potential safety problems. The FAA Certification Office indicated they would not approve TCAS units for certification until these problems were resolved.

The three problems were as follows:

1. A problem with "pop-up" targets was observed. Specifically, there were circumstances under which the Change 7 CAS logic failed to issue an RA or issued an RA later than previous logic versions. This situation was addressed in CP 73

2. A problem was observed when the Change 7 logic was exposed to a faulty communications link between two TCAS-equipped aircraft. CP 83 was proposed to ensure that even if own aircraft's communication link with the threat aircraft is faulty (own aircraft receiving one out of three surveillance replies), own aircraft will issue an RA because the threat aircraft had previously sent its intent.

3. A problem was observed in the multi-aircraft logic. In this situation the logic failed to change a Don't Climb/Don't Descend RA to a Descend RA when one of the threat aircraft suddenly maneuvered toward own aircraft. This situation was addressed in CP 63.

MITRE, Lincoln Laboratory, WJHTC and our European colleagues at CENA/DGAC were tasked to analyze the effectiveness of the three proposed solutions, as well as their impact on the overall Change 7 performance. Since these three problems were being addressed, other less critical Change Proposals (CPs) in the queue were also addressed.

Early in November 1998, WJHTC provided Lincoln Laboratory with FTEG simulated encounter data for a version of the logic that incorporated the CPs mentioned above. Both WJHTC and Lincoln Laboratory noted new reversed RA NMACs that appeared in encounter classes where we previously did not observe any NMACs.

Our CENA/DGAC ACAS colleagues, noting these new NMACs, ran some tests using the European model simulations with the same logic as used by WJHTC, except with a modified CP 73. Their results were promising enough to merit a new collection of FTEG encounters by WJHTC, also with the modified CP 73. This logic became known as TSO-C119B, referring to the name of the TSO for TCAS Change 7.

The Lincoln Laboratory logic evaluation found that the results for TSO-C119B were comparable to or better than the results for Version 7 Mod 11. Specifically, as shown in Table 7.3 (both pilots responding), there were 254 NMACs for Change 7 Mod 11 with the 100-foot tracker and 153 NMACs for Change 7 Mod 11 with the 25-foot tracker. The TSO-C119B Change 7 logic had 254 NMACs with the 100-foot tracker and 117 NMACs with the 25-foot tracker. Likewise, for one pilot not responding, the results for TSO-C119B were comparable to or better than the results for Version 7 Mod 11.

Thus, the TSO-C119B logic appeared to resolve the three potential safety problems while at the same time improving the overall Change 7 performance. During a teleconference in late November 1998, members of the Requirements Working Group of SC-147 (including Lincoln Laboratory) unanimously agreed to accept the TSO-C119B logic. The changes required to upgrade Version 7 Mod 11 to TSO-C119B have been included on a CD made available to the FAA Certification Office for use in certification of manufacturers' TCAS Change 7 units.