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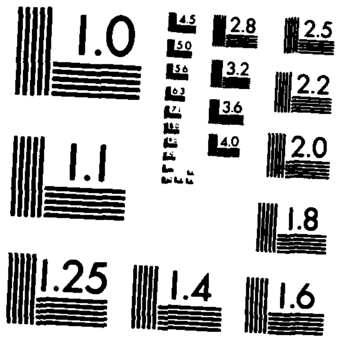

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Traffic Alert and Collision Avoidance System (TCAS) Evaluation: Volume II, Equipped Threat Phase and an Assessment in an Error-Degraded Environment

Barry R. Billmann

Prepared By
FAA Technical Center
Atlantic City Airport, N.J. 08405

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16. Abstract

This report presents the results of certain aspects of Traffic Alert and Collision Avoidance System (TCAS) logic testing. It represents the second volume in a series of three reports. The report presents the results of analysis of both simulation and flight testing of the TCAS logic. The analysis was conducted between November 1981 and January 1982, at the Federal Aviation Administration ~~(FAA)~~ Technical Center. The new TCAS logic significantly improved the resulting separation during encounters with TCAS equipped threats. Simplified command coordination procedures have increased command coordination reliability. Some minor logic modifications have been identified to further enhance TCAS logic performance for TCAS equipped threats.

The performance of the logic in the presence of reduced surveillance link reliability was also analyzed. The link reliability level required to affect adequate resolution and separation was identified. This analysis was conducted in a measurement error-degraded environment. Review of flight test results indicate surveillance link reliability exceeds that required to affect adequate separation performance.

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METRIC CONVERSION FACTORS

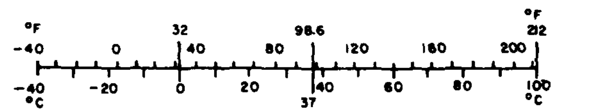
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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EXECUTIVE SUMMARY

The purpose of this report is twofold: (1) To describe the performance of the TCAS logic for TCAS equipped threats. (2) To present an analysis of the performance of the logic in an error-degraded environment.

The analysis of the TCAS logic performance is based on a simulation study using the Fast Time Encounter Generator (FTEG). The research was designed both as a prelude to flight tests and to augment the flight testing of TCAS. Simulation study permitted the evaluation of the TCAS collision avoidance logic to proceed economically in a highly controlled environment. Additionally, many scenarios which cannot be accurately or safely duplicated in flight testing can easily be analyzed via simulation.

Initial logic testing led to the detection of several logic discrepancies. The following logic problems were detected and corrected during this period.

1. A wide variety of TCAS encounters with TCAS equipped threats led to the selection of incompatible sense choices. The logic did not adequately consider all possible maneuver conditions by a TCAS equipped threat which had transacted its sense selection. Logic additions were made to improve the selection of compatible sense maneuvers. These additions have eliminated the possibility of the selection of incompatible maneuvers.

2. In both simulation and flight testing, numerous encounters resulted in the oscillation of the TCAS commands being displayed. This fault was traced to the impact of the pilot response (to the TCAS command) on the command being displayed on subsequent logic cycles. The pilot response caused an overestimation on the projected vertical separation at CPA. Better methods of controlling command oscillations induced by pilot response to TCAS commands have been developed and integrated into the logic.

3. Besides pilot response, several other factors tend to cause oscillations in the projected vertical miss distance at CPA. These oscillations in turn can cause confusing and cyclic command patterns. Logic additions were developed to limit the use of projected vertical miss distance in the selection of commands.

Following the correction of the above deficiencies, a general evaluation of the separation performance of the collision avoidance logic for TCAS equipped threats was made. For the most part, timely and correct resolutions resulted. However, two additional problems were detected. Recent logic changes have been designed to eliminate the problems.

1. During the resolution process, the sense (maneuver direction) of the command is first selected. Then the magnitude of the command (positive, negative, vertical speed limit, etc.) is selected. However, the magnitude of the command was selected independently of the command sense. This caused problems during encounters in which sense selection required vertical track crossing to resolve the threat. An example of this is a climbing TCAS receiving a climb sense command although it is below the threat. In these cases, the initial command received was a do not descend command. This command does nothing to resolve the encounter. Logic was developed to require the selection of positive commands when the sense selection required vertical track crossing.

2. The collision avoidance logic included special logic for resolving encounters with equipped threats. This logic, called negative sufficiency logic permitted the use of negative commands to resolve encounters with TCAS equipped intruders in cases where positive commands would otherwise have been selected. The intent of the logic was to reduce the number of positive commands for encounters with TCAS equipped threats, since with two aircraft responding, sufficient separation would result without resorting to positive commands. However, a delay in responding to the negative command on the part of one aircraft could critically reduce the resulting separation. Negative sufficiency logic for the resolution of encounters with TCAS equipped threats has been eliminated.

Analysis of the impact of surveillance link reliability on CAS logic performance indicates the logic can effectively resolve encounters with up to 50 percent of the surveillance reports missing. Test flight results indicate the surveillance link reliability level is considerably above this level.

INTRODUCTION

This report is a second of a three-part series reporting the performance of the improved Traffic Alert and Collision Avoidance System (TCAS) logic. The analytical results are used to highlight and correct logic deficiencies and provide a measure of performance of the corrected logic in resolving collision and near collision encounter scenarios. The first volume of the series evaluated TCAS logic performance for Air Traffic Control Radar Beacon System (ATCRBS or unequipped) threats (reference 1). This report presents the evaluation of the TCAS logic performance for TCAS equipped threats. Analysis of TCAS performance in an error-degraded environment is also made. A future volume will analyze TCAS performance in a multiple threat environment.

PURPOSE.

The purpose of this report is twofold:

1. To describe the performance of the TCAS logic for TCAS equipped threats.

2. To present an analysis of the performance of the logic in an error-degraded environment.

The analysis of the TCAS logic performance is based on a simulation study using the Fast Time Encounter Generator (FTEG). The research was designed both as a prelude to flight tests and to augment the flight testing of TCAS. Simulation study permitted the evaluation of the TCAS collision avoidance logic to proceed economically in a highly controlled environment. Additionally, many scenarios which cannot be accurately or safely duplicated in flight testing can easily be analyzed via simulation.

BACKGROUND.

The baseline logic used in this evaluation was developed by the Mitre Corporation (reference 2). This logic departed from previous Active Beacon Collision Avoidance System (BCAS) logic concepts and established the Maneuver Intent Register as the central element in coordinating commands between two conflicting TCAS aircraft. Extensive simulation and flight testing has validated the maneuver intent coordination concept. The design has streamlined and simplified the TCAS-to-TCAS communications requirements to support command coordination. As a result, coordination reliability has increased. Because of findings reported in reference 1, along with analysis by Mitre Corporation, several enhancements to the baseline logic have been incorporated into the logic used in this analysis. The enhancements are documented in references 3 to 9. The major benefits of the TCAS logic, when compared to previous Active BCAS logic, are reviewed in reference 1.

In order to provide a simulation environment for evaluating collision avoidance logic, the FTEG was developed (reference 10). The FTEG permits the analyst to define encounter scenarios in terms of aircraft performance characteristics, approach paths to the closest point of approach (CPA), and separation conditions that exist at CPA. The FTEG can automatically alter scenarios in a systematic fashion. This permits the analyst to test logic sensitivity to those scenario changes.

OBJECTIVES AND SCOPE.

The simulation study which addressed the logic performance for TCAS equipped threats was conducted in an error-free environment. The basic criterion for declaring performance failure during this evaluation was the detection of scenario conditions which resulted in less than 200 feet vertical separation at CPA following TCAS command action. Other criteria for performance failure included the detection of scenario conditions which resulted in a significant reduction in existing CPA vertical separation because of TCAS action and the occurrence of incompatible commands between the encountering TCAS aircraft.

Logic deficiencies which caused poor performance were intitially detected and logic modifications to correct the logic deficiencies were developed and tested. These modifications were reviewed by Systems Research and Development Service (SRDS) and Mitre Corporation, which had the formal responsibility for preparing official revisions to the baseline logic. Five modifications were incorporated during the evaluation period. These modifications are reviewed in references 7 to 9 and references 11 and 12.

The performance results identified in this report reflect the performance of the revised baseline logic. The analysis was conducted between October 1981 and January 1982. During this period, more than 3,600 equipped encounter scenarios were simulated and analyzed. Throughout this phase, surveillance accuracy was assumed to be perfect. However, quantization of range and altitude measurement inputs were modeled. Altitude input data were in the form of Mode C altitude reports.

During the initial testing, the encounter scenarios were staged in various airspace regions. As a result, a sampling of performance at each TCAS performance level setting could be obtained. The report does not attempt to review all results. The report does provide an overview of the results obtained. Each detected deficiency is also reviewed, and the results of many example encounters are presented.

During the error-degraded performance testing, input measurement error models were used to identify TCAS logic performance in an error-degraded environment. Intruder range and altitude measurement errors indicative of surveillance accuracy (reference 13) were introduced into the simulation study using autoregressive (correlated in time) error models developed in reference 14. The error models are presented in appendix A. Although surveillance accuracy will increase with the directional interrogation capability of TCAS, the error models used will identify the lower limits of performance for the collision avoidance logic.

In previous testing, surveillance link reliability was considered perfect. In the error-degraded simulation study, an analysis of logic sensitivity to surveillance link reliability is made. This is accomplished by varying the probability of missing or garbled replies from 0.1 to 0.9 in 0.05 increments. Based on results from live flight tests, track acquisition is modeled as a function of range and relative altitude of the intruder.

Error analysis did not include the investigation of collision avoidance logic coordination message link reliability. These investigations were performed by Mitre during their discrete event simulation testing. The results of this testing are reported in reference 15.

Throughout the report, TCAS algorithm terms are used in the context described in the baseline logic document (reference 2). A glossary of TCAS algorithm terms is included at the end of the report to assist the reader. This report uses the convention that an encountering aircraft, which is being tracked but requires no TCAS action, is called an "intruder." The term "threat" applies to those intruders which require or have a current TCAS resolution posted. The term "command" is used to represent any TCAS resolution that is posted whether it causes flight path deviations for the TCAS aircraft or not.

SUMMARY.

Initial logic testing led to the detection of several logic discrepancies. The following logic problems were detected and corrected during this period.

1. A wide variety of TCAS encounters with TCAS equipped threats led to the selection of incompatible sense choices. The logic did not adequately consider all possible maneuver conditions by a TCAS equipped threat which had transacted its sense selection. Logic additions were made to improve the selection of compatible sense maneuvers. These additions have eliminated the possibility of the selection of incompatible maneuvers.

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DISCUSSION

GENERAL.

The evaluation of the TCAS logic required the interfacing of two software packages: first, the FTEG (simulation algorithm) controlling the operation of the simulation model; second, the collision avoidance logic being evaluated. The simulation system is resident on the Honeywell 66/60 computer at the FAA Technical Center. Certain data reduction and analysis routines, such as the encounter plotting, are part of the on-line simulation system. Figure 1 presents the high-level interaction between the simulation test bed and the collision avoidance logic.

TCAS MANEUVER INTENT REGISTER.

Figure 2 depicts the Maneuver Intent Register, which is used to affect command coordination between two encountering TCAS aircraft. The TCAS column identifies resolutions which are currently posted because of the own TCAS logic. The other TCAS column depicts the negative complements of the commands which have been posted by an intruding TCAS aircraft to resolve the encounter with the own aircraft. It should be noted that the register can contain another TCAS entry with no own TCAS entry and vice versa. In multiple encounter situations, the own TCAS column represents the composite resolution the own aircraft has currently made for all threats. The other TCAS column represents composite resolutions for all threat TCAS's which have coordinated their intent's with the own TCAS.

This simulation study used the explicit message order and content which had been described in the Draft TCAS National Standard to affect coordination between two TCAS aircraft. Figure 3 presents the overview of message order required to affect TCAS coordination. In figure 3, the aircraft called primary TCAS is the first aircraft in a pair to declare the other aircraft a threat.

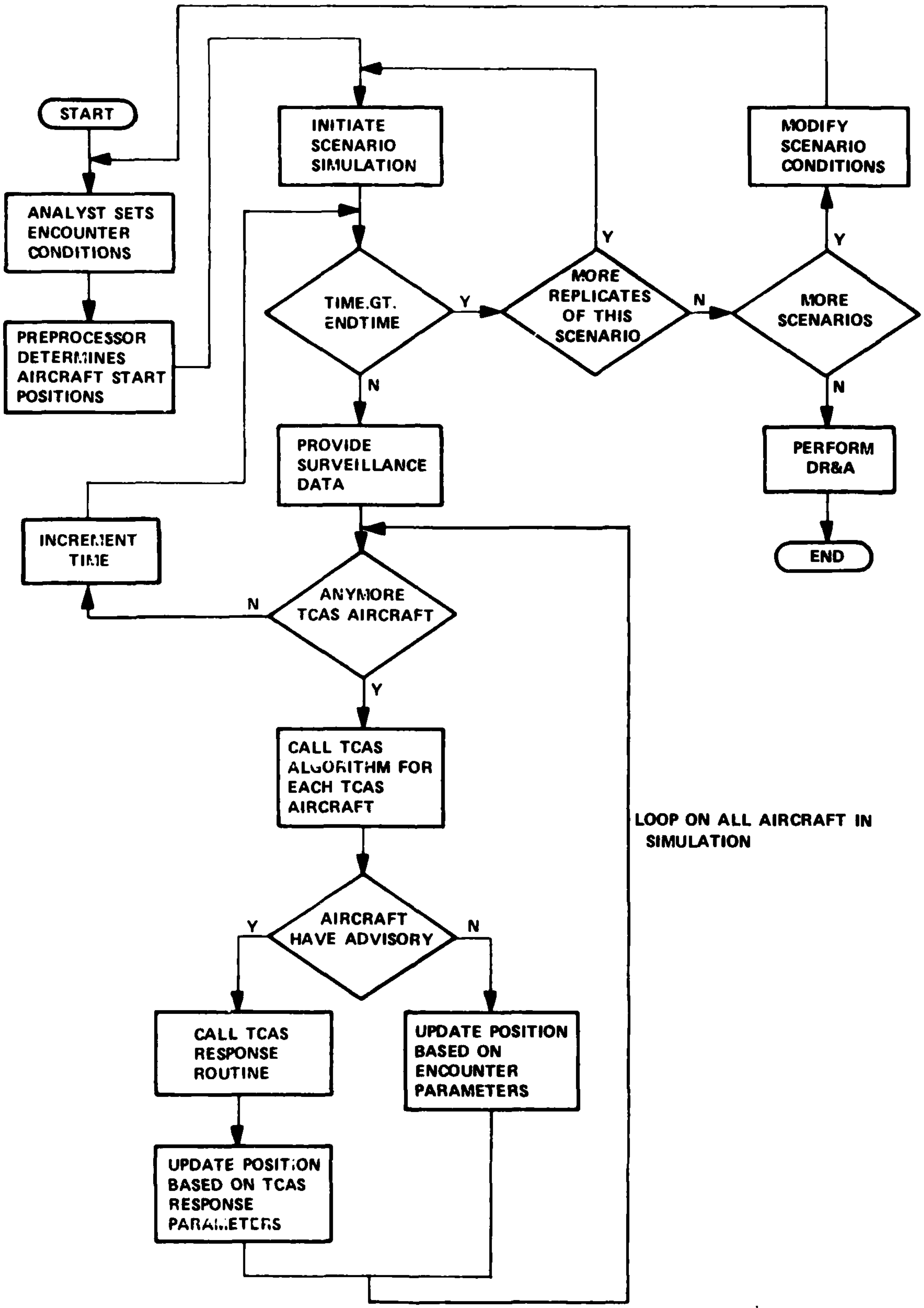

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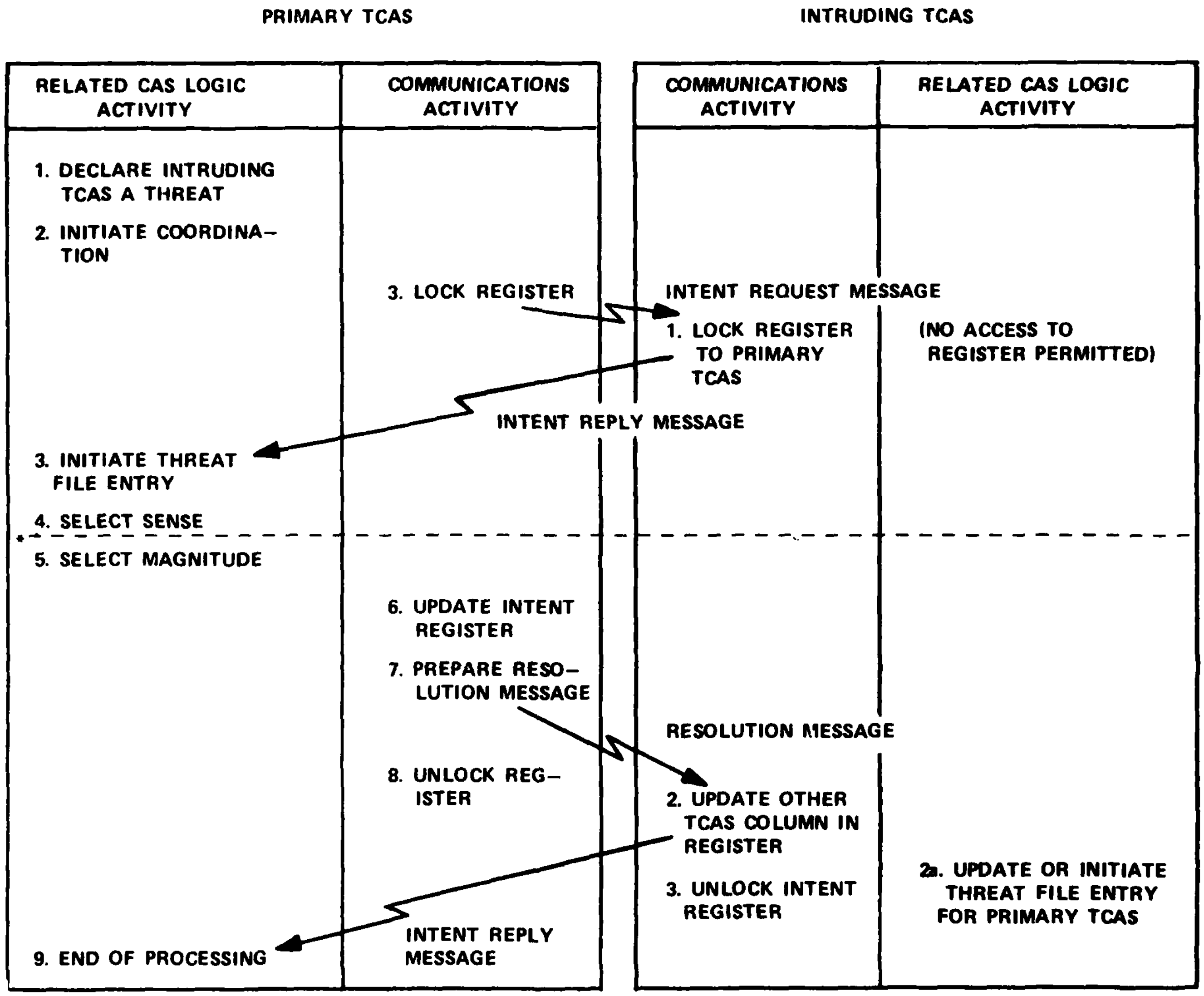
FIGURE 1. HIGH LEVEL SIMULATION LOGIC FLOW

	OWN TCAS	OTHER TCAS
CLIMB		
DO NOT DESCEND		
LIMIT DESCENT TO 500 FPM		
LIMIT DESCENT TO 1000 FPM		
LIMIT DESCENT TO 2000 FPM		
DESCEND		
DO NOT CLIMB		
LIMIT CLIMB TO 500 FPM		
LIMIT CLIMB TO 1000 FPM		
LIMIT CLIMB TO 2000 FPM		
TURN LEFT		
TURN RIGHT		
DO NOT TURN LEFT		
DO NOT TURN RIGHT		

(REFERENCE 1 FIGURE 2.1–1)

82-52-II-2

FIGURE 2. MANEUVER INTENT REGISTER



* TRANSACTION BELOW DASHED LINE IS ONLY TRANSACTION ON SUBSEQUENT LOGIC CYCLES FOLLOWING SENSE SELECTION

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FIGURE 3. TCAS-TO-TCAS INTENT COORDINATION PROTOCOL

The primary TCAS declares the intruding TCAS a threat and locks its own register to the identity of the intruding TCAS and requests the intent of the intruding TCAS (message type 16). Upon receiving this message, if its register is not locked, the intruding TCAS locks its register to the identity of the primary TCAS and responds with its intent (message type 21). If the intruding TCAS's register was locked to another TCAS identity, it would respond with a busy message. Special tie-breaking procedures prevent the primary TCAS and intruding TCAS from locking their registers to each other's identity indefinitely.

Upon receiving the intent reply message, the primary TCAS selects a maneuver sense, taking into consideration any constraints formed by the intruder's reply. After determining the magnitude of the command, the primary TCAS updates its own TCAS column, unlocks its register, and transmits a resolution message. This message is a type 16 message and contains the negative complement of the command the primary TCAS has selected to resolve the encounter. Upon receipt of the resolution message, the intruding TCAS immediately responds with its intent only to complete the communications transactions.

The only difference between the resolution and intent request message is that in the resolution message, the lock bit is not set. Hence, the intruding TCAS recognizes this message as an intent from the primary TCAS. The intruding TCAS updates its other TCAS column with the intent, initiates a threat file for the primary TCAS, and unlocks its register.

On subsequent logic cycles during this encounter, the primary TCAS aircraft only sends the resolution message. Since maneuver sense is only selected when the intruder is first detected, the intent request message is not sent on subsequent logic cycles. Once the intruding TCAS declares the primary TCAS a threat, the entire initial two-message transaction will be repeated with the roles of the primary TCAS and the intruding TCAS reversed.

It should be pointed out that the reception of a resolution message by the intruder in itself will not cause the intruding TCAS to post a command. The intruder must first detect the TCAS aircraft that sent the resolution message. The intruding TCAS will then initiate coordination procedures from its end by requesting the intent of the other TCAS.

The new TCAS logic includes several enhancements over previous logic:

1. Numerous improvements in the vertical tracking routines within the collision avoidance logic have been made.

2. The concept of a working list now provides for a structured division of all intruders which have progressed to threat status. Once an intruder has been declared a threat, it is placed on the threat file. The working list places a threat in one of three categories: new threat, continuing threat, and terminating threat.

3. The new logic has established an explicit pointer system for interfacing the CAS logic with the surveillance logic. The pointer arrays uniquely identify a one-to-one correspondence between a surveillance track file entry and an intruder track file entry.

4. Warnings to the pilot that the TCAS system has failed or the collision avoidance logic is not functioning properly have been included.

5. Within the new logic, complete logic initialization procedures have been identified.

TCAS EQUIPPED THREAT LOGIC SHAKEDOWN PHASE

Prior to formally evaluating logic performance, a wide variety of scenarios were analyzed. These scenarios were designed to highlight previous problems detected in logic testing. Most of these problems were corrected; however, a couple of new problems were detected and addressed. After correction of the known deficiencies, the second phase of the logic evaluation focused on the measurement of logic performance.

SELECTION OF INCOMPATIBLE SENSE CHOICES.

A significant group of encounters with TCAS equipped threats did not result in compatible sense selection for the two aircraft. Incompatible sense choices occurred when the following conditions were present.

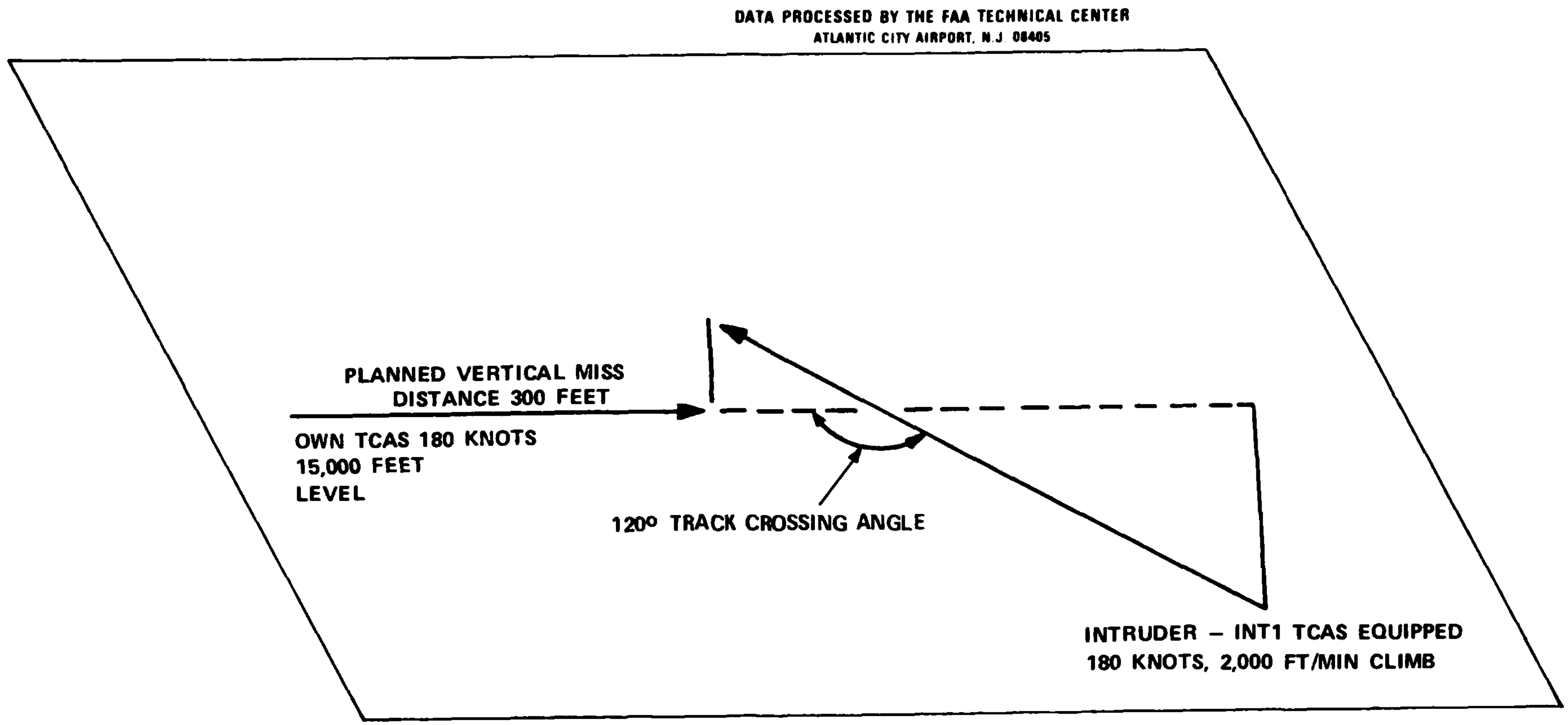
1. The first aircraft to select sense is in level flight.

2. The threat is TCAS equipped and in a vertical maneuver with the vertical rate greater than 1,000 feet per minute (ft/min).

3. Without TCAS intervention, the TCAS threat would have passed through the level flight TCAS's altitude prior to CPA and have 300 to 500 feet vertical separation at CPA.

An example of such a geometry is shown in figure 4. The results of the TCAS command response modeling is shown in figure 5. The upper group of vertical position projections is for the level flight TCAS aircraft. As a result, the level flight TCAS aircraft selects a descent sense but chooses a no climb command because the current relative separation, RZ, is greater than the threshold for positive commands, ALIM. The second group of projections is for the climbing TCAS. Its first choice is also a descent sense. The second choice, climb, is not permitted because the separation it would generate satisfies neither of the following two conditions: (1) second choice separation greater than 400 feet; and (2) second choice separation greater than 0.6 times the first choice separation.

Because of the above sense choice procedures, both aircraft select desent sense maneuvers. Figure 6 reviews the scenario results. When the intruder, INT1, selects the incompatible sense descend and begins to descend, the projected vertical separation measured by the level flight TCAS decreases and is reduced below the threshold for positive commands. This causes the level flight TCAS's command to change from do not climb to descend. With both aircraft descending, only 60 feet, vertical separation at CPA results.



82-52-II-4

FIGURE 4. ENCOUNTER CAUSING SENSE SELECTION PROBLEMS

	TPROJ (SECONDS)	Z (FEET)	ZD (FPS)	INTENT REGISTER	DELAY (SECONDS)	ZPROJ (FEET)
LEVEL FLIGHT TCAS PROJECTION WITH CLIMB	26.9	15,000	0.0	1 0 0 0 0 0 0 0 0 0	8	15,299
LEVEL FLIGHT TCAS PROJECTION WITH DESCENT	26.9	15,000	0.0	0 0 0 0 0 1 0 0 0 0	8	14,700
INT1 PROJECTION WITH CURRENT INTENT	26.9	14,403	33.2	0 0 0 0 0 0 0 0 0 0	1	15,303

ZMPCLM = 15,299 – 15,303 = –4 FT   ZMPDES = 15,303 – 14,700 = 603 FT

SINCE ZMPDES IS GREATER THAN ZMPCLM, A DESCENT SENSE CHOICE RESULTS.

A DO NOT CLIMB COMMAND RESULTS BECAUSE RZ IS GREATER THAN ALIM.

DATA PROCESSED BY THE FAA TECHNICAL CENTER
ATLANTIC CITY AIRPORT, N.J. 08405

INT1 PROJECTION WITH CLIMB	26.9	14,392	33.0	1 0 0 0 0 0 0 0 0 0	8	15,292
INT1 PROJECTION WITH DESCENT	26.9	14,392	33.0	0 0 0 0 0 1 0 0 0 0	8	14,498
LEVEL FLIGHT TCAS PROJECTION BASED ON ITS CURRENT INTENT	26.9	15,000	0.0	0 0 0 0 0 0 1 0 0 0	1	15,000

ZMPCLM = 15,292 – 15,000 = 292 FT   ZMPDES = 15,000 –14,498 = 502 FT

SINCE ZMPDES IS GREATER THAN ZMPCIM, INT1'S FIRST SENSE CHOICE IS ALSO DESCEND.

THE SECOND CHOICE CLIMB IS NOT PERMITTED BECAUSE

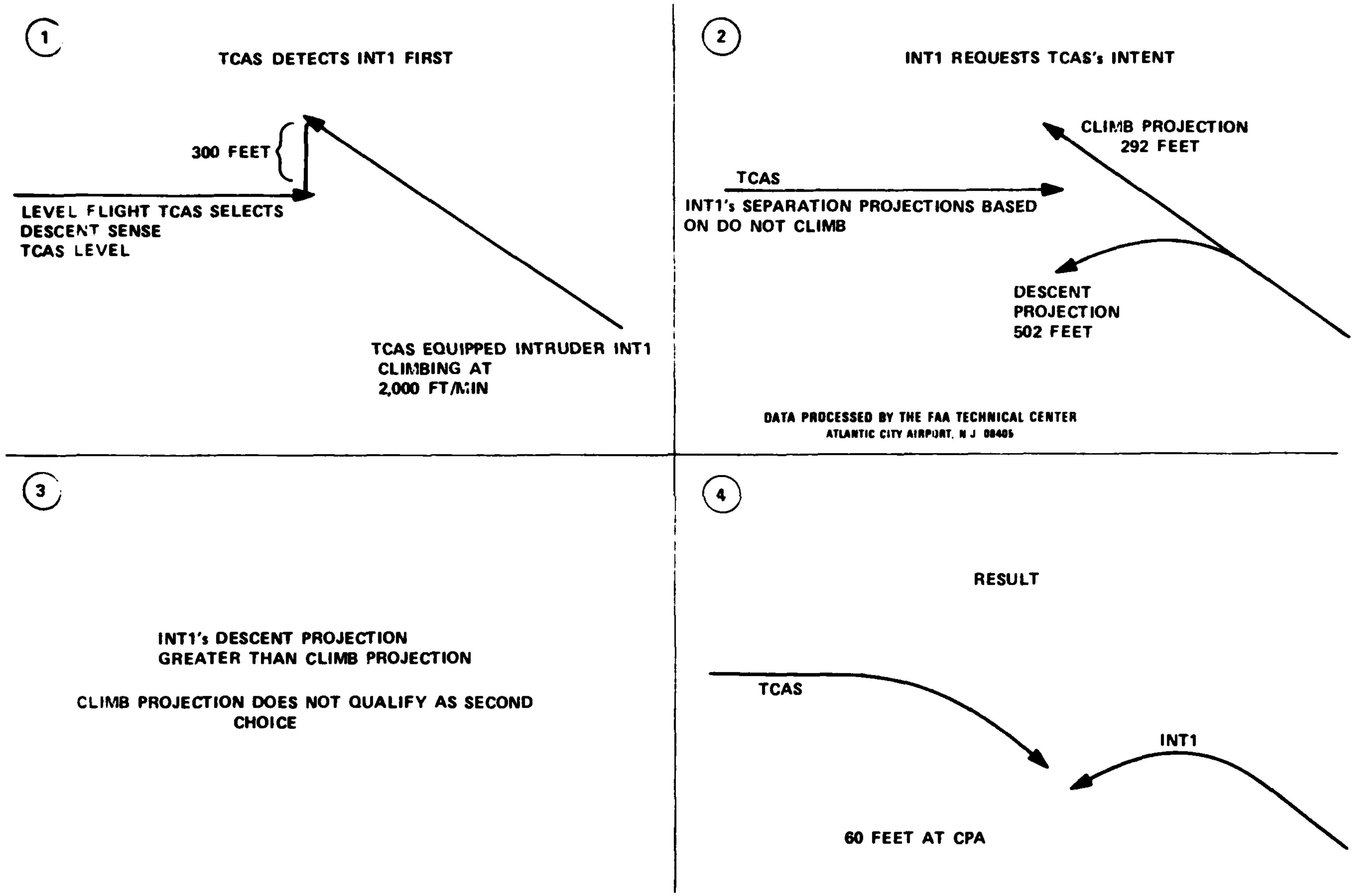
(1) ZMPCLM IS LESS THAN 400 FT.

(2) ZMPCLM IS LESS THAN 0.6 * ZMPDES.

RESULT: BOTH AIRCRAFT SELECT DESCENT SENSE MANEUVERS.

82-52-II-5

FIGURE 5. SENSE CHOICE RESPONSE MODELING RESULTS



82-52-II-6

FIGURE 6. ENCOUNTER RESULTS FOLLOWING INCOMPATIBLE SENSE CHOICE

To solve this problem, Mitre prepared logic modifications (reference 11) to enhance sense selection and coordination procedures. The essence of the logic change is presented in figure 7. At the top of the figure, the previous sense modeling procedure is shown. INT1 has information that TCAS has selected a descent sense maneuver; however, since TCAS is level, INT1 projected the level flight condition. This results in INT1 having a larger modeled separation with a descent sense than with a climb sense maneuver (ZMPDES = 502 feet, ZMPCLM = 292 feet) and the descent command selection by INT1 resulted. The logic used to project the position of TCAS did not use the fact that the do not climb command could change to a descend command, causing TCAS to descend rather than remain level.

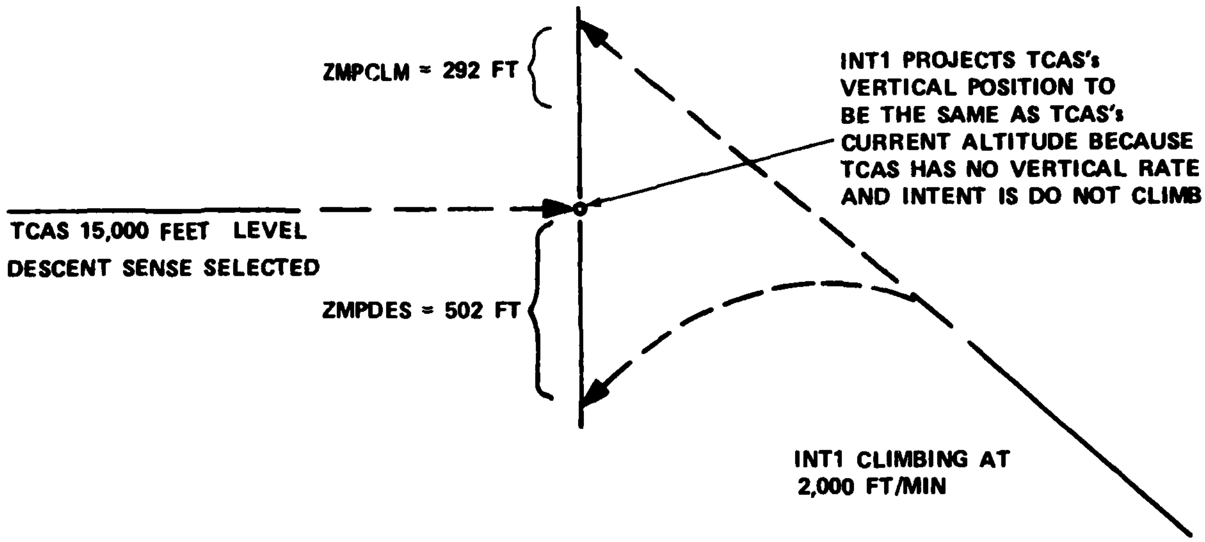
At the bottom of figure 7, the new sense modeling procedure is shown. This procedure uses the fact that TCAS could descend in response to a TCAS command at any time during the encounter period. Since TCAS currently has a do not climb command displayed, INT1 models the extremes in possible TCAS responses. That is, INT1 models a level flight projection of TCAS (its current situation) and the most significant response that TCAS could make (a descent in response to a descent command). This modeling procedure results in a vertical region rather than a point to be avoided by INT1 at CPA. Next, INT1's possible climb and descent responses are modeled as before. However, the estimated projected vertical separations, ZMPCLM and ZMPDES, are determined by comparison with the level TCAS's response limits rather than a single point in space.

The new procedure results in ZMPCLM = 292 feet and ZMPDES = 46 feet. Since the climb response will generate more separation, it is selected by INT1. The compatible sense selection resulted in 498 feet vertical separation at CPA.

CLOSED LOOP PILOT RESPONSE PROBLEM.

The TCAS pilot command display is actually the input to a closed-loop feedback control system. A command is generated which may elicit a pilot response, causing a deviation in the aircraft's vertical profile. The rapidity and magnitude of the pilot response in turn causes a change in the own aircraft's vertical position and rate information. This information is used by the collision avoidance system on subsequent logic cycles. A hysteresis condition between the pilot response and the status of the display may develop. This condition has occurred numerous times during TCAS flight testing, both at the Technical Center and at Lincoln Laboratory. In figure 8, the tracked relative vertical rate (ADOT), the projected separation (VMD), and the current tracked vertical separation are plotted for two aircraft which exhibited these response characteristics during flight testing at the Technical Center. Nominal thresholds for positive commands (440 feet) and no commands (750 feet) are shown. The pattern of displayed commands which resulted are shown at the top of the figure.

The aircraft in the scenario of interest were in level flight with 400 feet vertical separation. The primary TCAS aircraft received a climb command at t = 1. At t = 10 seconds, the first Mode C transition occurs and the relative vertical separation rate is set to 16.67 feet per second (ft/sec). At this time, the projected vertical separation at CPA exceeds 750 feet and a first miss is declared. At t = 11 seconds, the second miss occurs and the climb command is removed. Both aircraft respond by returning to level flight. The vertical separation rate decays and a second hit requiring command resolution occurs at t = 15 seconds. Since VMD exceeds 440 feet, a limit descent command results for the primary TCAS aircraft. The null display between t = 11 and t = 15 seconds could be confusing to the pilot. It is interesting to note that the tracked vertical separation smoothly increased from 400 to 610 feet.



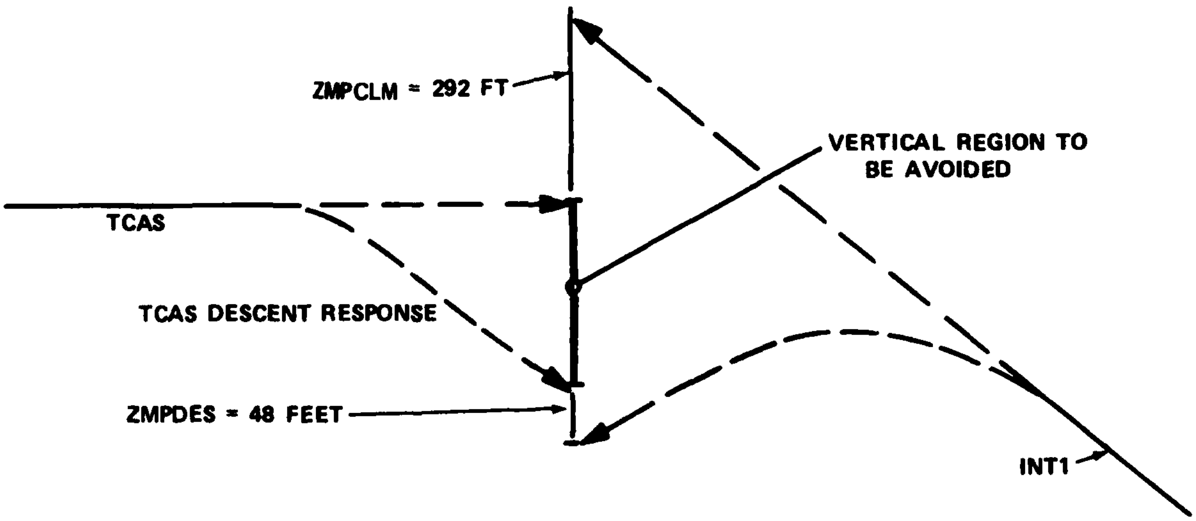


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FIGURE 7. IMPROVED SENSE SELECTION PROCEDURES

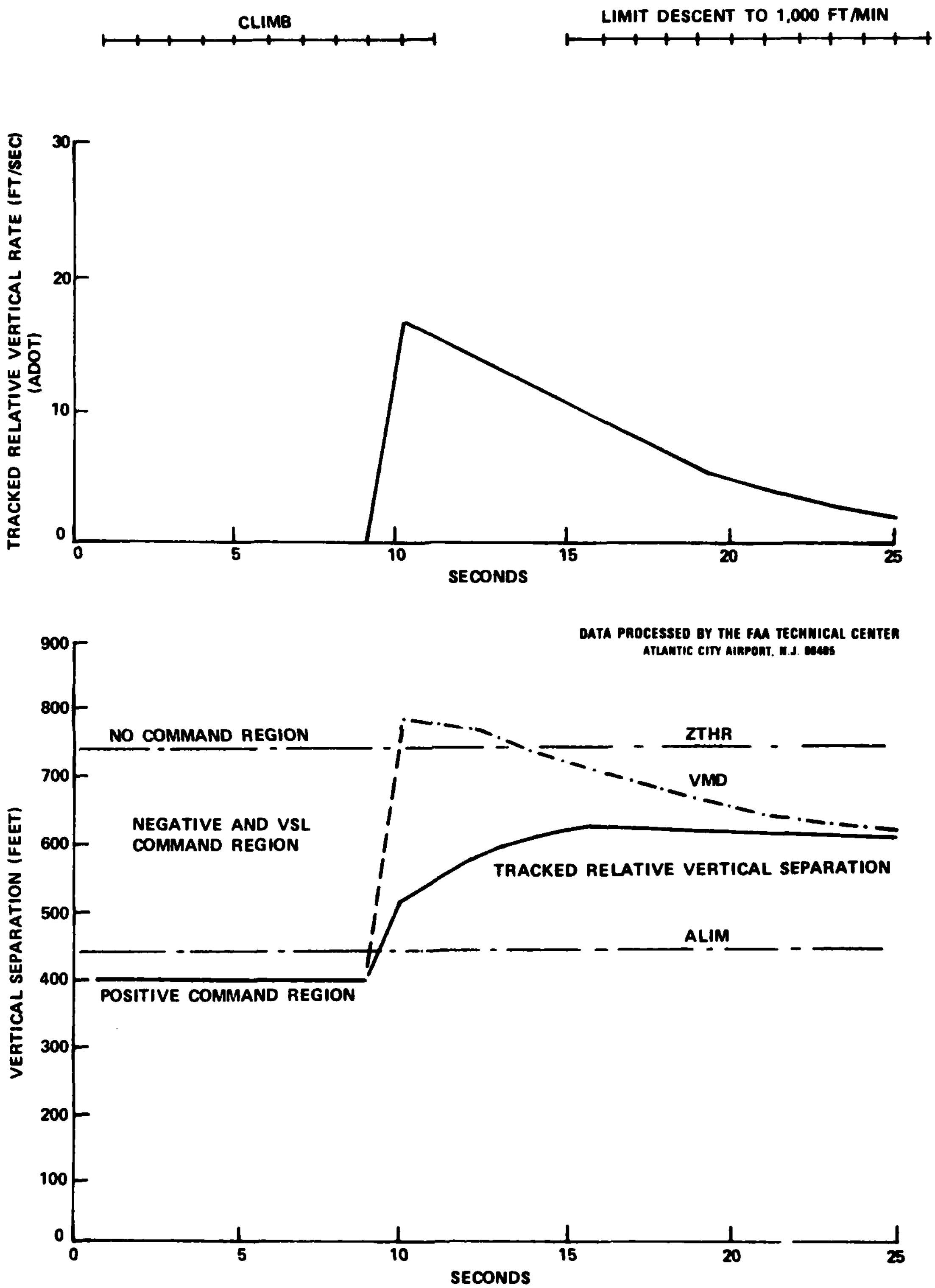

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FIGURE 8. IMPACT OF PILOT RESPONSE ON COMMAND STATUS

In figure 9, similar conditions are depicted. The aircraft are in level flight with 100 feet vertical separation when the primary TCAS aircraft receives a climb command. At t = 10 seconds, the first Mode C transition occurs. Since the aircraft are only 100 feet apart initially, the projected vertical separation does not exceed 750 feet simultaneously with the first Mode C transition. Although VMD exceeds 440 feet at t = 10 seconds, the command does not transition to a negative command because the minimum display time prior to weakening positive commands (10 seconds) has not been exceeded. At t = 11 seconds, the decay in the vertical rate estimate results in VMD being less than 440 feet and the positive command is retained.

At t = 16 seconds, the second Mode C occurs. The vertical separation rate is established at 32 ft/sec. Simultaneously, the projected vertical separation exceeds 750 feet. A first miss is declared and the climb command is replaced with a limit descent to 2,000 ft/min command. The alarm lasts only 1 second since the second miss is declared at t = 17 seconds. The pilot responds by returning to level flight. Six seconds later, the rate has decayed to 16 ft/sec and VMD is again less than 750 feet, resulting in a do not descend command at t = 23 seconds.

Throughout the encounter, the tracked vertical separation has smoothly increased from 100 to 523 feet. The increase beyond 500 feet and then the slight decrease in tracked vertical separation between t = 19 and t = 23 seconds represents position estimate changes while the vertical rate is being readjusted. The magnitude of this error is limited to 65 feet by tracker design.

The apparent solution to the problem is to use tracked separation rather than projected vertical separation in controlling command changes and removal. If this were the case, a smooth transition from a climb command to a do not descend or limit descent command would have occurred at t = 17 seconds. By using slightly larger thresholds (ALIM + 65 feet and ZTHR + 65 feet) to remove or change commands than to initiate them, the minor oscillations caused by the position tracker rebound could also be eliminated. These changes would prevent the early removal of positive commands before ALIM separation has resulted.

PERFORMANCE RESULTS FOR EQUIPPED THREATS

Following the logic modifications which were previously discussed, a general assessment of the performance of TCAS logic for equipped threats was made. In the following analysis, performance was considered adequate if maneuver sense selection was properly coordinated and the resulting separation at CPA exceeded 200 feet. Discussion of results will focus on the primary TCAS aircraft and the command sequences that it received. Unless otherwise indicated, the threatening TCAS aircraft received complementary alarms.

The TCAS logic has several different performance levels to permit the desensitization of the TCAS logic based on altitudes of the encountering aircraft. Different threat volumes are parametrically defined for each performance level. The levels simulated provide variations for three flight conditions: high altitude en route (performance level 6), low altitude en route (level 5), and terminal area (level 4). The performance level used with each set of data presented below is identified. The parameter settings for the various performance levels are shown in table 1. Also included is the nominal response to commands that was modeled during the analysis.

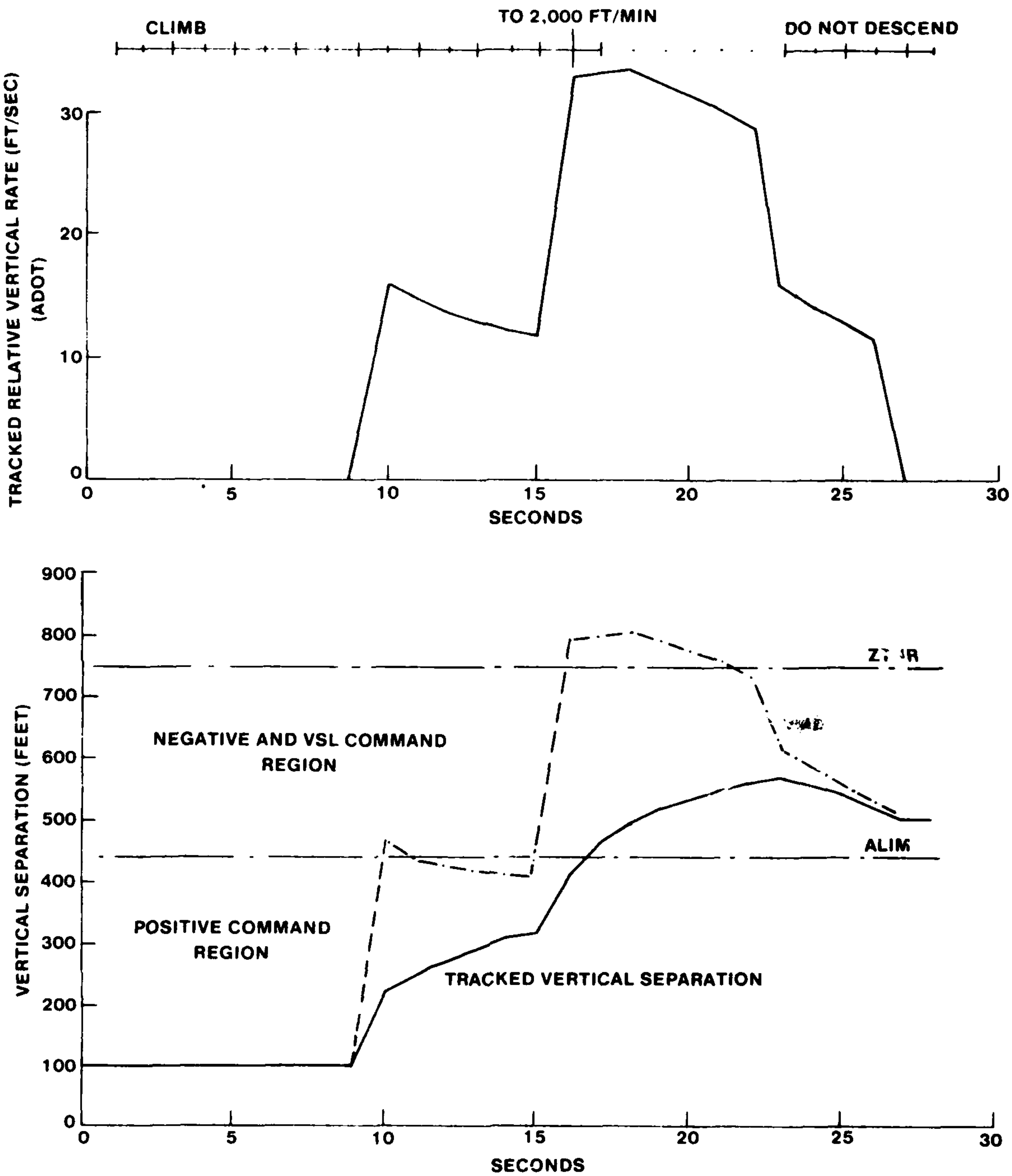

FIGURE 9. PILOT RESPONSE CAUSING OSCILLATING COMMAND PATTERNS

TABLE 1. TCAS LOGIC PERFORMANCE LEVEL PARAMETER SETTINGS AND NOMINAL AIRCRAFT RESPONSE PARAMETERS

Parameter	Definition	Performance Levels 4	5	6	
DMOD	Modification distance for modified tau	0.1	0.3	1.0	nmi
TRTHRE	Maximum predicted time to closest approach for definfing equipped threats	18	25	30	secs
TVTHRE	Maximum predicted time to coaltitude for defining equipped threats	18	25	30	secs
TVPCMD	Maximum path prediction time for computing minimum vertical separation	40	40	45	secs
TVPESC	Maximum escape time permitted for escape maneuver	30	30	35	secs
HI	Maximum divergence hyperbola of range and range ate defining a threat	0.00278 nmi^2/secs			

ALTITUDE SENSITIVE PARAMETERS

Parameter	Definition	Altitude Bands (Feet) 0 – 10,000	10,000 – 18,000	18,000 – 29,000	29,000 – 100,000
ALIM	Threshold for altitude separation for positive commands	340	440	640	740
ADIV	Threshold for issuing vertical speed minimum commands	200	300	400	500
ZTHR	Threshold for altitude separation for threat definition	750	750	850	950

REPONSE PARAMETERS

Measure	Parameter
Pilot Response Delay	5 seconds initial command 2 seconds secondary command
Aircraft Vertical Acceleration	0.25g
Escape Rate for Positive Commands	± 1,000 feet/minute

VERTICAL ENCOUNTER RESULTS.

The logic changes made during the shakedown phase were added to the collision avoidance logic. The ability of the primary TCAS level flight aircraft to coordinate commands with the vertically maneuvering threat TCAS was reevaluated. The basic geometry used in this analysis is shown in figure 10. The results for three vertical rates (500, 1,000, and 2,000 ft/min) and a 90° crossing angle will be reviewed. Similar results occurred with variations to the crossing angle except for tail-chase conditions which will be discussed later. The 500-ft/min rate results were obtained with performance level 6 parameter settings. Performance level 4 parameter settings were used for the other rates.

Problems in sense coordination which were previously identified have been eliminated. In figures 11, 12, and 13, the resulting separation following TCAS action is plotted as a function of the planned scenario separation. Planned scenario separation is the vertical separation that would have occurred at CPA without TCAS action. Isolated points on the figures identify conditions examined which resulted in no TCAS action. Points connected with a dashed line represent scenario conditions which were resolved without positive TCAS commands. Points connected with solid lines identify regions in which positive TCAS commands resulted. The split between the two curves plotted on each figure indicates the conditions where the sense choice of the primary TCAS aircraft changed from a climb sense to a descend sense. These plotting conventions will be used throughout the remainder of the report.

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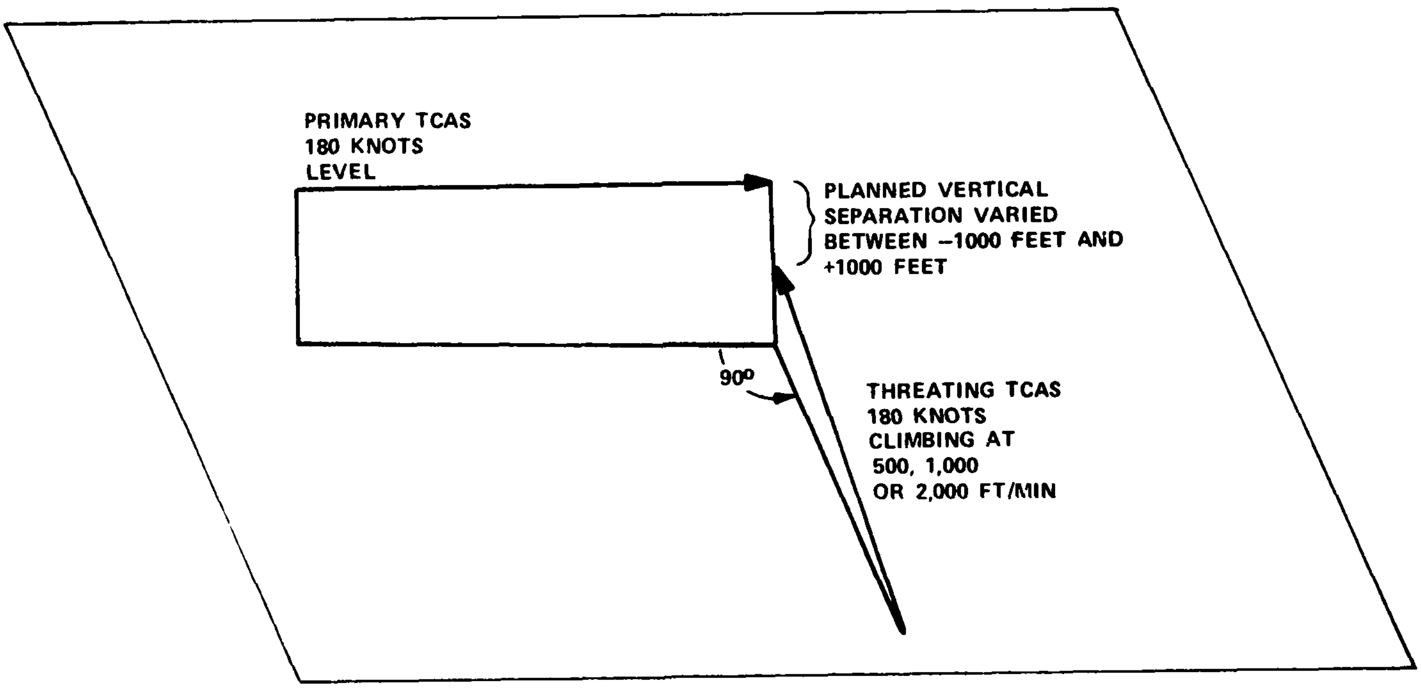

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FIGURE 10. PRIMARY TCAS LEVEL — CLIMBING EQUIPPED THREAT SCENARIO

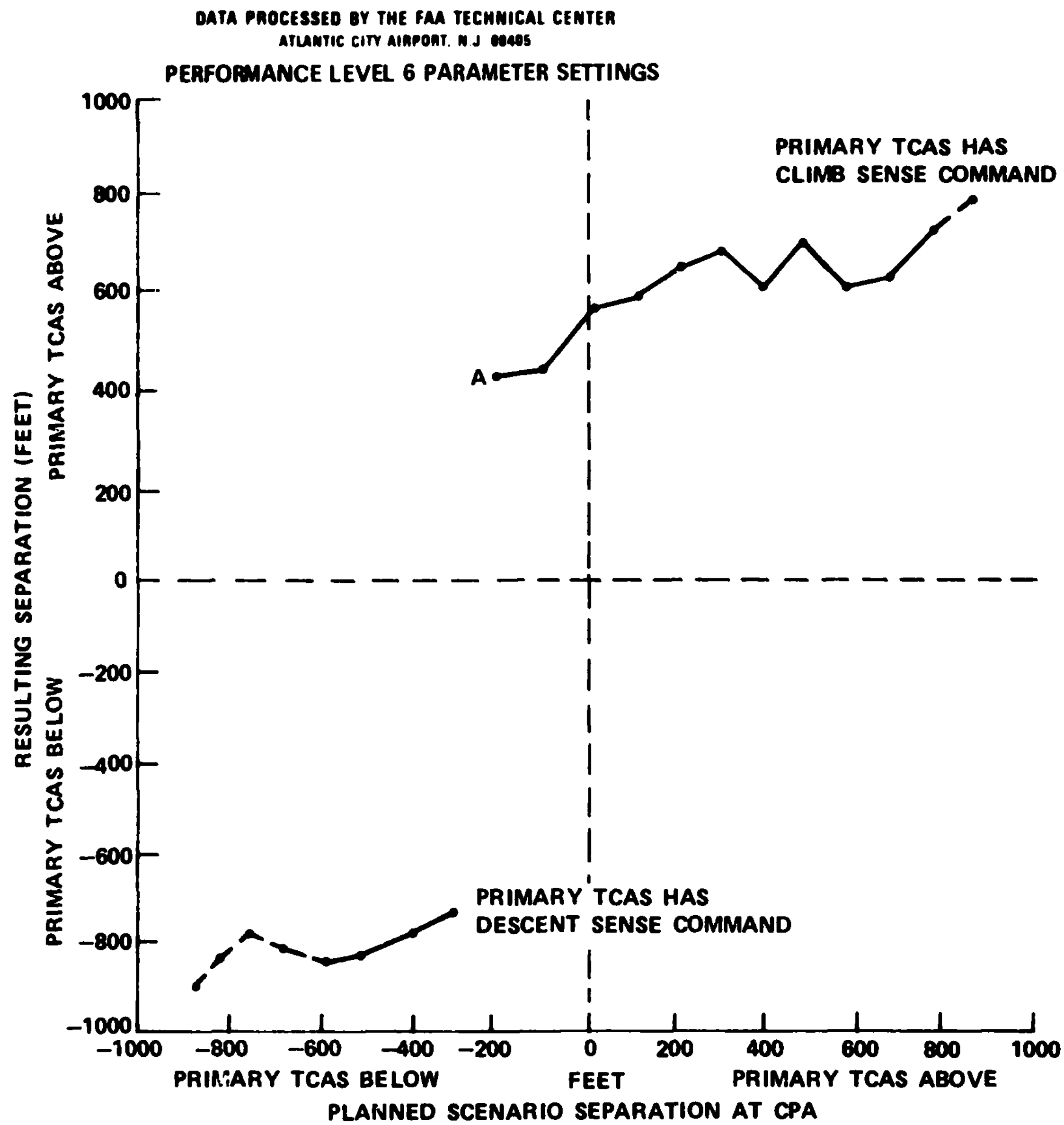

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FIGURE 11. RESULTS — PRIMARY TCAS LEVEL; INTRUDER CLIMBING AT 500 FT/MIN

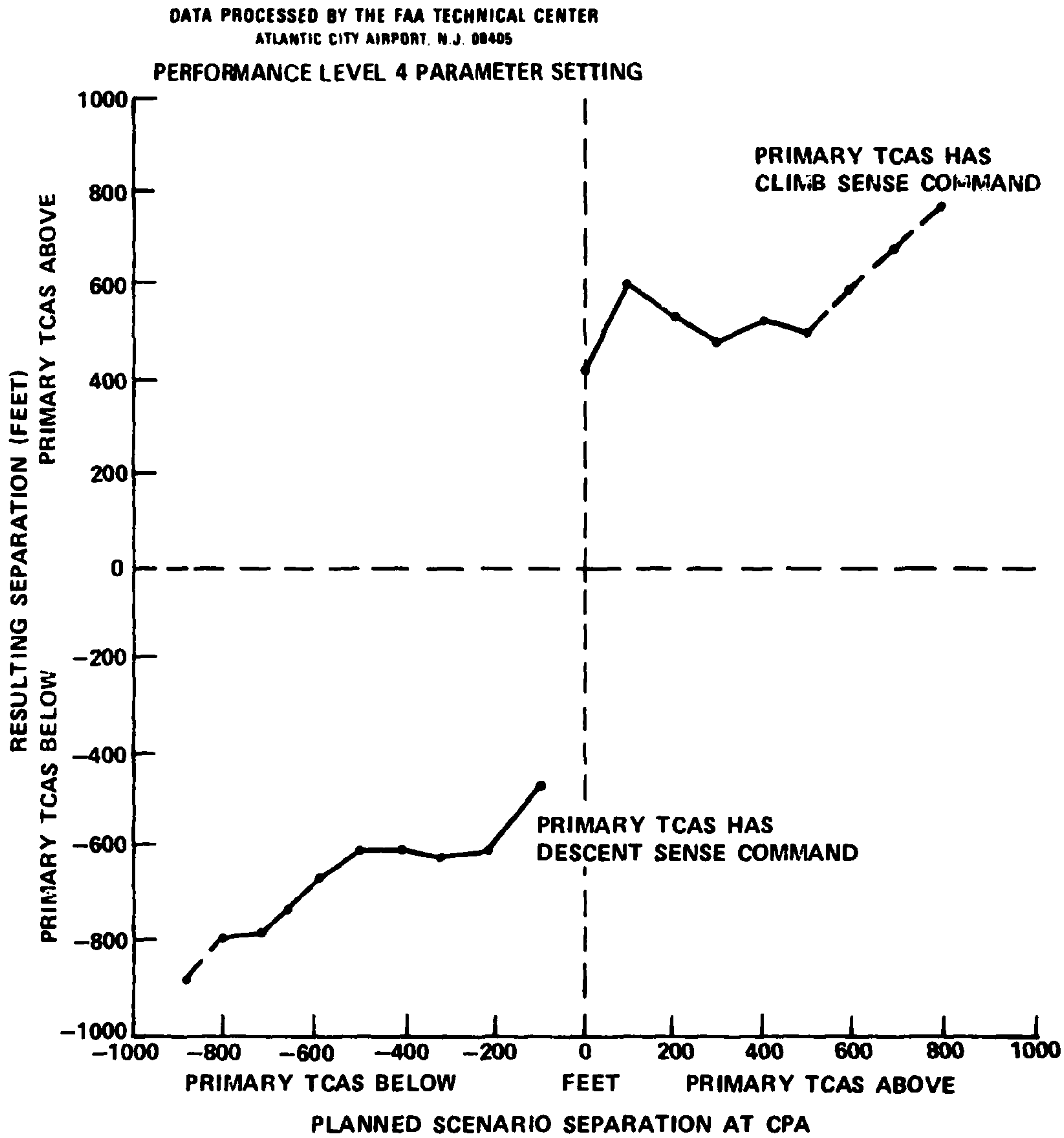

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FIGURE 12. RESULTS — PRIMARY TCAS LEVEL; INTRUDER CLIMBING AT 1,000 FT/MIN

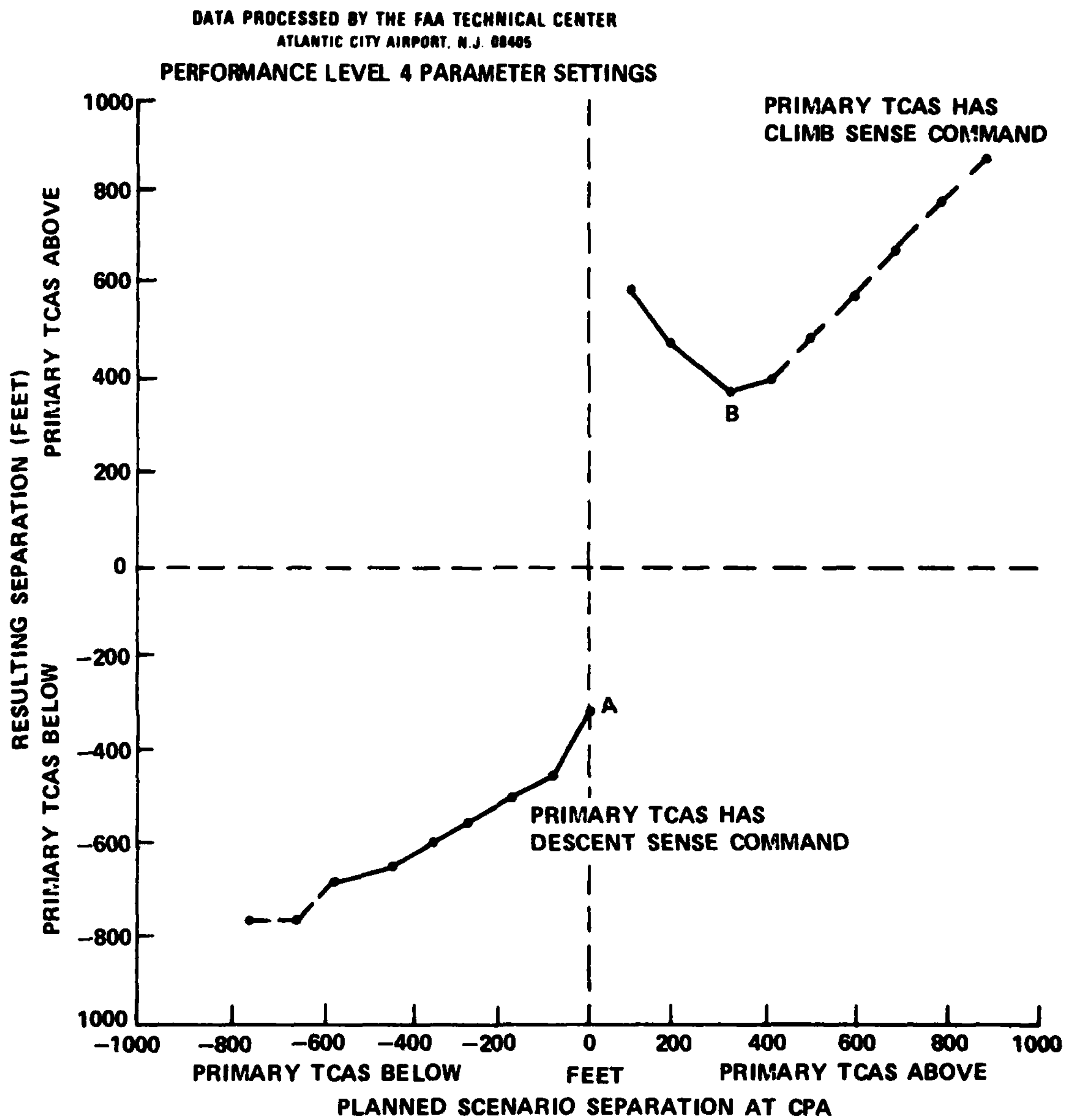

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FIGURE 13. RESULTS — PRIMARY TCAS LEVEL; INTRUDER CLIMBING AT 2,000 FT/MIN

PRIMARY TCAS LEVEL — THREATENING TCAS CLIMBING. The results when the TCAS equipped intruder was climbing at 500 ft/min indicate excellent performance. Since current vertical position is the prominent factor in sense selection when the vertical rate of the intruder is below 600 ft/min, the primary TCAS received a climb command even though the scenario called for the primary TCAS to be 200 feet below the intruder at CPA. This scenario is denoted by A on figure 11. For this scenario, the primary TCAS was 86 feet above the intruder at time of sense selection. Since the rate of the intruder was below 600 ft/min, the primary TCAS received the climb command. The same result occurred when the encounter scenario called for the primary TCAS to be 100 feet below the intruder at CPA. As the vertical rate of the TCAS equipped intruder was increased to 1,000 ft/min and 2,000 ft/min (figures 12 and 13), the location of the switch from climb to descend sense commands changed because vertical rate was now the prominent factor in the determination of command sense.

On figure 13, the scenario condition marked with the letter A resulted in 267 feet vertical separation at CPA. The planned separation was 0 feet. The sense selected by the level flight TCAS aircraft, descend, required vertical track crossing to resolve the encounter. The initial alarm occurred 24 seconds prior to CPA. Performance level 4 parameters were used (Tau = 20 seconds). Hence, the command timing was correct. The level flight TCAS aircraft received a do not climb command. The negative command resulted even though the sense choice required vertical track crossing and the projected vertical separation at CPA is -3.6 feet. The intruding TCAS also selected a compatible negative command, do not descend. The baseline logic was designed to permit negative commands to suffice in certain situations where stopping the vertical rate of one aircraft would suffice and generate adequate separation. The problem in this case is that the sense selections require vertical track crossing to occur, and the only way that will occur is with positive commands being issued to both aircraft. In table 2, a review of the sequential TCAS data for this encounter shows that positive commands did not occur until 13 seconds prior to CPA. The issuance of positive commands was delayed because in the case of equipped intruders positive commands do not occur until the current tracked relative vertical separation is less than ALIM (440 feet). This fact also causes the concave shape of the curve in the region denoted by the letter B.

The command pattern for the climbing TCAS intruder was the same. A climb command did not occur until 13 seconds prior to CPA. It is noted, however, that the late climb command had no effect on resulting separation since the climbing TCAS intruder continued its climb throughout the entire encounter. This condition, which delayed the issuance of positive commands, was most acute for the condition where the planned vertical separation was 0 feet.

In figure 14, two separate climbing intruder scenario profiles are shown. In both cases, sense selection required vertical track crossing. The original complementary negative commands which result because of the negative sufficiency logic are shown along with the position relative to CPA when the commands transitioned to positive commands. When the scenario separation was 0 feet at CPA, the positive command occurred 13 seconds prior to CPA resulting in 267 feet vertical separation. When the scenario separation was increased to 400 feet, the positive command occurred 25 seconds prior to CPA resulting in 610 feet vertical separation. This demonstrates how positive commands occur earlier in the presence of increased vertical miss distance.

TABLE 2. SEQUENTIAL TCAS DATA SHOWING LATE TRANSITION TO POSITIVE COMMAND

Time to CPA (Secs)	TAUR (Secs)	Tracked Vertical Separation (Feet)	Projected Vertical Miss Distance (Feet)	Command
25	20.77	828	-5.0	---
24	19.77	796	-3.61	Do Not Climb
23	18.77	774	7.37	Do Not Climb
22	17.77	728	-4.92	Do Not Climb
21	16.77	696	-3.53	Do Not Climb
20	15.77	674	-7.45	Do Not Climb
19	14.77	628	-4.84	Do Not Climb
18	13.77	596	-3.46	Do Not Climb
17	12.77	574	7.52	Do Not Climb
16	11.77	528	-4.78	Do Not Climb
15	10.77	497	-3.40	Do Not Climb
14	9.77	474	7.58	Do Not Climb
13	8.77	428	-4.73	Descend

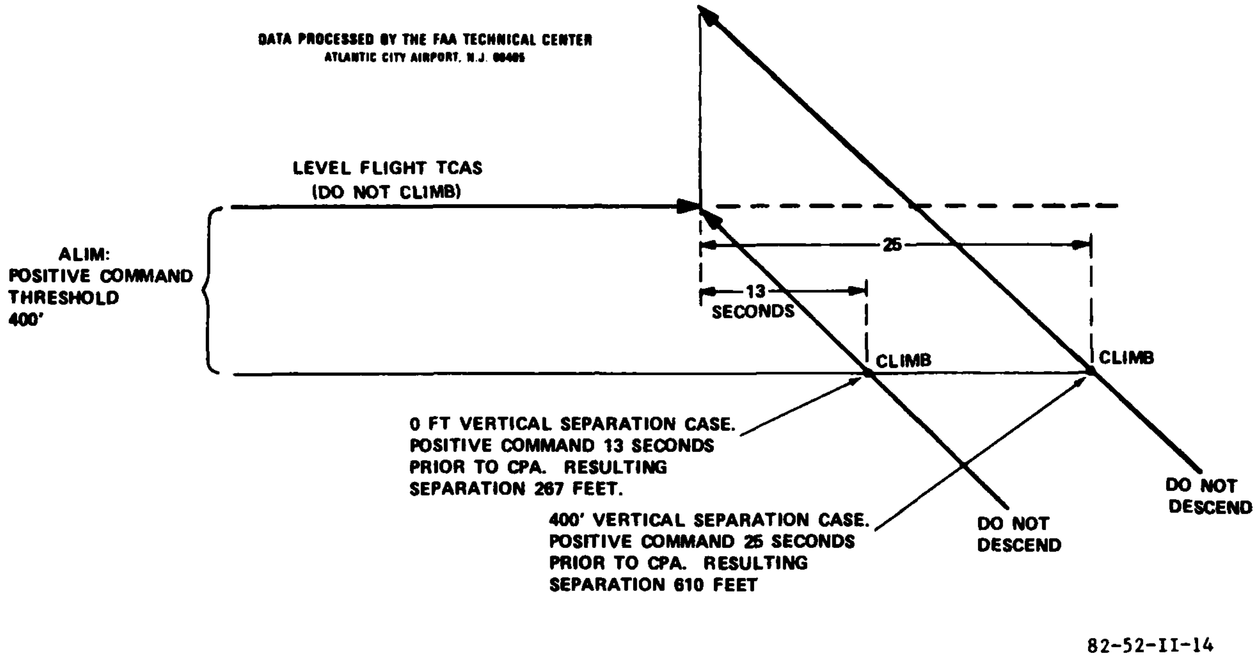

FIGURE 14. DEMONSTRATION OF EARLIER POSITIVE ALARMS IN THE PRESENCE OF INCREASED VERTICAL SEPARATION

Not only does the delay in the positive commands cause a reduction in separation at CPA but it also causes a reduction in the range at time of coaltitude. Figure 15 presents the range at time of coaltitude as a function of vertical miss distance for those conditions which resulted in sense selection requiring vertical track crossing. When the climbing TCAS was climbing at 500 ft/min, the initial commands were always positive since threat detection occurred after the aircraft had closed to within ALIM feet vertical separation. As a result, the ranges at coaltitude for these cases are quite large. For the 1,000 ft/min climb, the range at coaltitude always exceeded 1 nautical mile. For the 2,000 ft/min climb rate, the results are quite different. Due to the high vertical rate, the climbing intruder was more than ALIM feet below the level flight TCAS when detected for several planned scenario conditions. The conditions are marked with an asterisk on figure 15. For these cases, the initial commands were not positive commands.

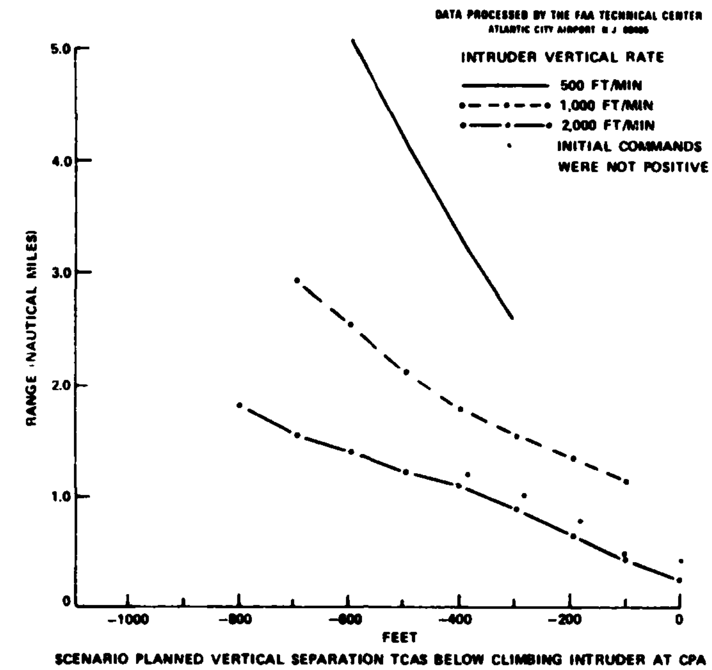

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FIGURE 15. RANGES AT COALTITUDE FOR CONDITIONS WHICH REQUIRED VERTICAL TRACK CROSSING

The delayed transition to positive commands caused late vertical track crossing and reduced separation at CPA. The logic required modification so that sense choices which require vertical track crossing result in immediate positive commands. Initial positive commands in this case will hasten vertical track crossing, maximize range at time of coaltitude, and increase vertical separation at CPA.

Mitre Corporation prepared logic modifications to address this problem (reference 12). These modifications were coded and tested. With the modifications, early positive commands occurred when the sense selected required vertical track crossing. Generally, vertical separation at CPA exceeded 400 feet for all cases tested.

Figure 16 presents the results when the modifications provided by Mitre were tested. The results are for the 2,000 ft/min climbing intruder and can be compared directly with figure 13. A significant increase in vertical separation at CPA has occurred. This is due to early initial positive commands resulting when the projected vertical separation was less then 440 feet.

The earlier positive commands have resulted in a significant increase in the range at time of coaltitude for resolutions requiring vertical track crossing. Figure 17 shows the ranges at time of coaltitude obtained with the new logic. In all cases initial commands were positive for resolutions requiring vertical track crossing. As a result of this analysis the performance of the new logic provided in reference 12 is considered excellent.

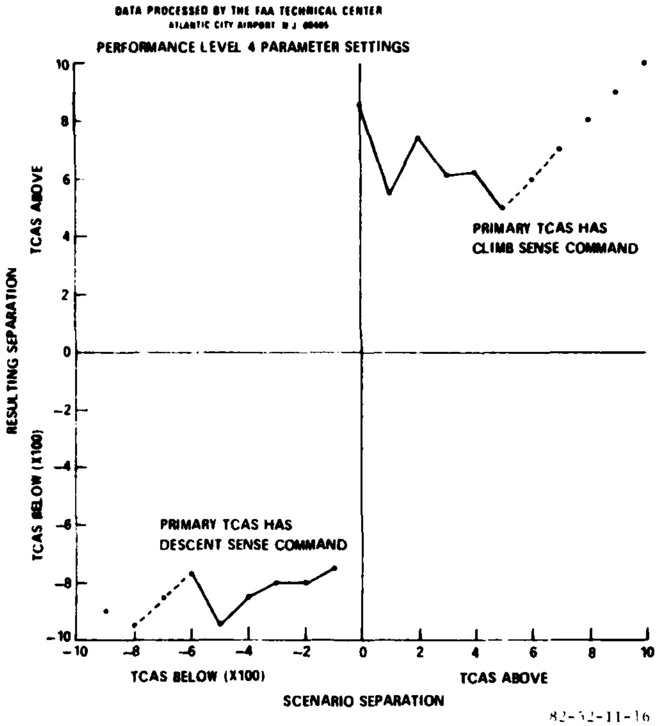

FIGURE 16. RESULTS PRIMARY TCAS LEVEL -- INTRUDER CLIMBING AT 2,000 FT/MIN (NEW LOGIC)

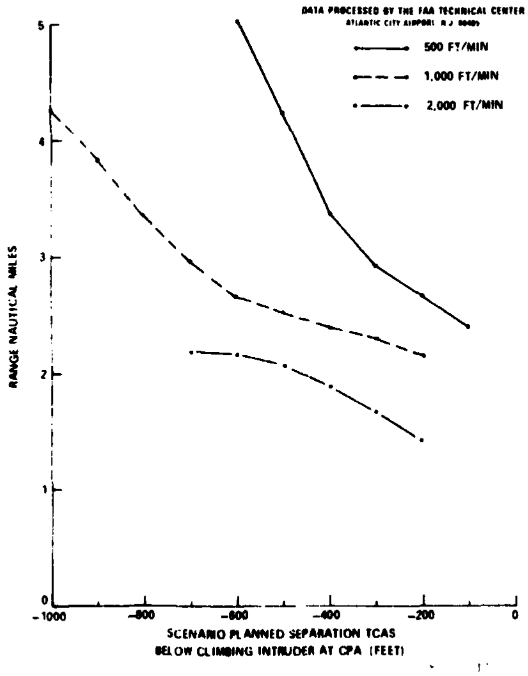

FIGURE 17. RANGES AT COALTITUDE FOR CONDITIONS WHICH REQUIRED VERTICAL TRACK CROSSING (NEW LOGIC)

PRIMARY TCAS CLIMBING -- THREATENING TCAS LEVEL. This scenario reversed the roles roles of the aircraft in the encounter scenario shown in figure 10. Three vertical rates for the primary TCAS aircraft were analyzed. The rates were 500, 1,000, and 2,000 ft/min. The only difference caused by the role reversal is that the first aircraft to select sense is now climbing. This does not imply that the aircraft that is maneuvering vertically will always select sense first. The order of sense selection is controlled in the test environment. The results with the reversed roles are shown in figures 18, 19, and 20. One should note that the resulting separation is dependent on the order of sense selection.

In all cases, the results were excellent. For one resolution, the climbing TCAS crossed the altitude track of the level flight intruder twice. With a 500-ft/min climb rate and the climbing TCAS planned to cross 200 feet above the level flight intruder at CPA, the climbing TCAS received a descend command. By the time the descent was established, the primary TCAS had climbed 8 feet above the level flight intruder. The range at time of coaltitude for this case exceeded 1.7 nautical miles. As a result, the resolution is considered safe.

In figures 18 to 20, a shift in location where the selected sense changes from climb to descend can be detected. For the 2,000 ft/min climb by the primary TCAS, a descend sense was selected even though the planned scenario condition called for the primary TCAS to pass 400 feet above the threat at CPA. This condition is denoted by the letter A on figure 18. For the case where the primary TCAS is climbing at 1,000 ft/min, the switch in sense occurs between the 300 feet above and 400 feet above scenario conditions. Finally, for the 500 ft/min climb, the primary TCAS only receives descend sense commands up to and including the scenario where the primary TCAS would have passed 200 feet above the threat without TCAS action.

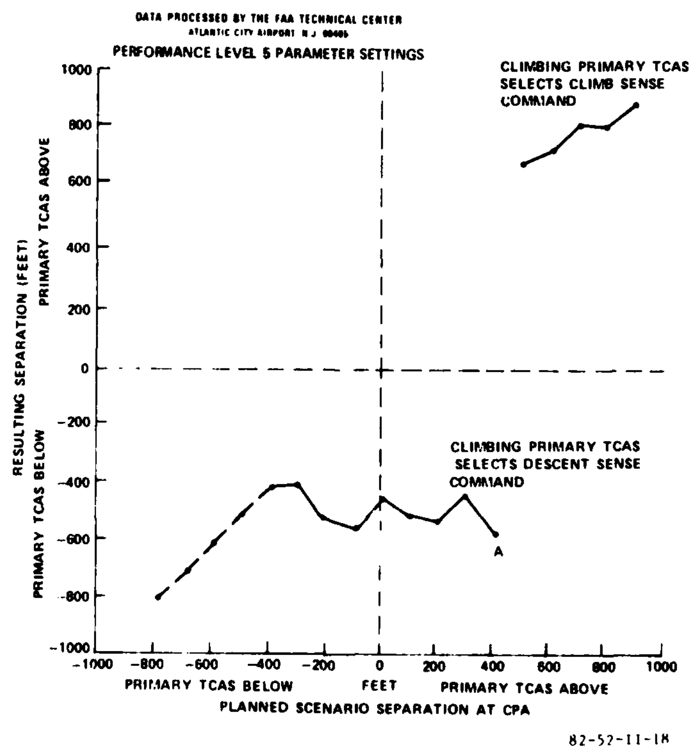

FIGURE 18. RESULTS -- PRIMARY TCAS CLIMBING AT 2,000 FT/MIN; INTRUDER LEVEL

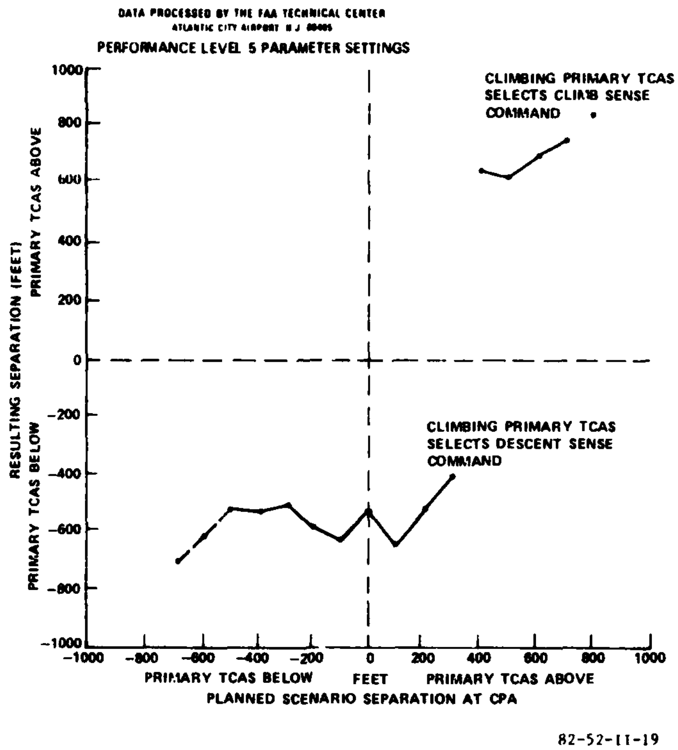

FIGURE 19. RESULTS --- PRIMARY TCAS CLIMBING AT 1,000 FT/MIN; INTRUDER LEVEL

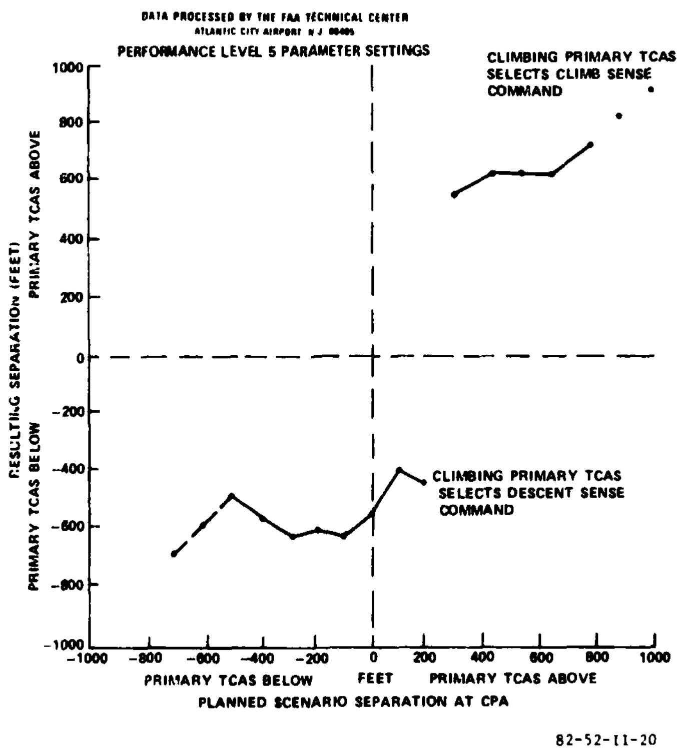

FIGURE 20. RESULTS — PRIMARY TCAS CLIMBING AT 500 FT/MIN; INTRUDER LEVEL

This shift characterizes a desirable feature in the logic. The logic can select maneuvers which will prevent vertical track crossing but still result in sufficient vertical separation at CPA. The shift occurs because of the different climb rates for the primary TCAS aircraft. The higher climb rates cause larger vertical separations to exist when command sense is selected. This larger existing vertical separation permits sense selection which prohibits vertical track crossing over a wider range of scenario conditions.

All resolutions which required vertical track crossing were identified. Only five scenario conditions required vertical track crossing. The ranges at coaltitude for these cases are presented in table 3. The minimum range at time of coaltitude exceeds 1.2 nautical miles for all cases. As a result, overall logic performance is considered excellent.

PARALLEL VERTICAL MANEUVERS.

Analysis was made of encounters when both aircraft were in steady-state climbs at the same rate. The scenario conditions investigated are shown in figure 21. Compatible sense choices always resulted. The resulting separations are shown in figure 22 (1,000 ft/min rates) and figure 23 (2,000 ft/min rates). For the 2,000 ft/min rates, vertical speed limit commands generated sufficient separation when the primary TCAS was 500 to 800 feet above the threatening TCAS. Minimum vertical separation for all cases tested exceeded 400 feet at CPA. Performance level 5 parameters were used for this analysis.

TABLE 3. RANGE IN NAUTICAL MILES AT TIME OF COALTITUDE FOR RESOLUTIONS REQUIRING VERTICAL TRACK CROSSING

Planned Scenario Separation Primary TCAS Above Level TCAS at CPA	Primary TCAS Vertical Rates		
	2,000 Ft/Min	1,000 Ft/Min	500 Ft/Min
700 Feet	1.54	--	--
600 Feet	1.37	--	-
500 Feet	1.24	--	--
400 Feet	--	1.70	--
300 Feet	--	--	--
200 Feet	--	--	1.70

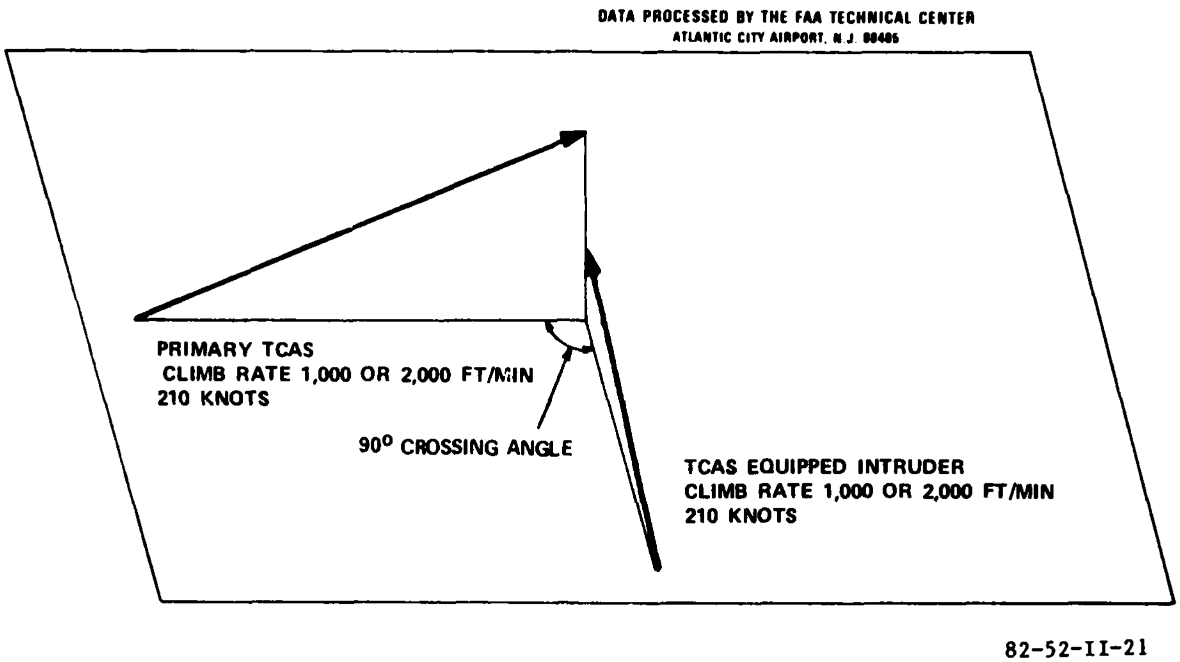

FIGURE 21. PARALLEL VERTICAL MANEUVER SCENARIO

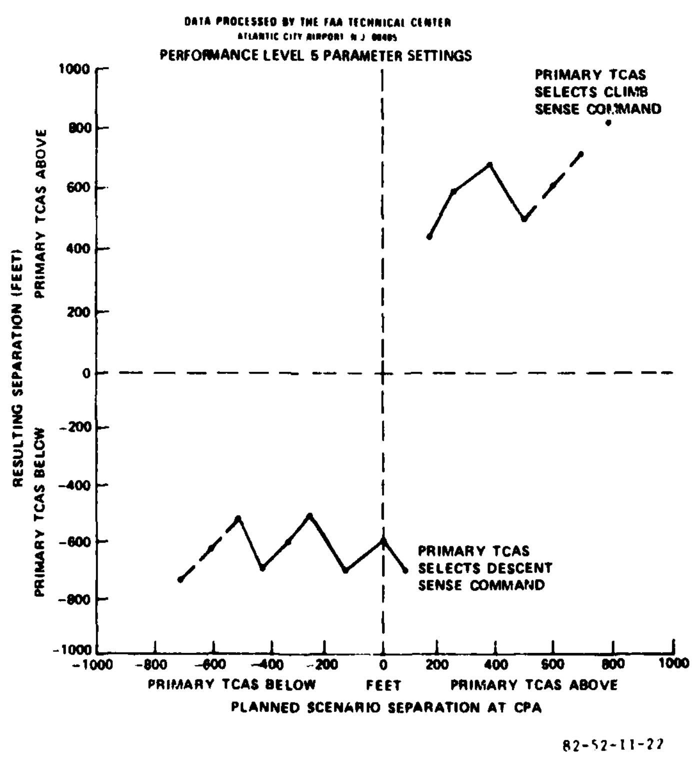

FIGURE 22. RESULTS FOR PARALLEL VERTICAL MANEUVERS (1,000 FT/MIN CLIMBS)

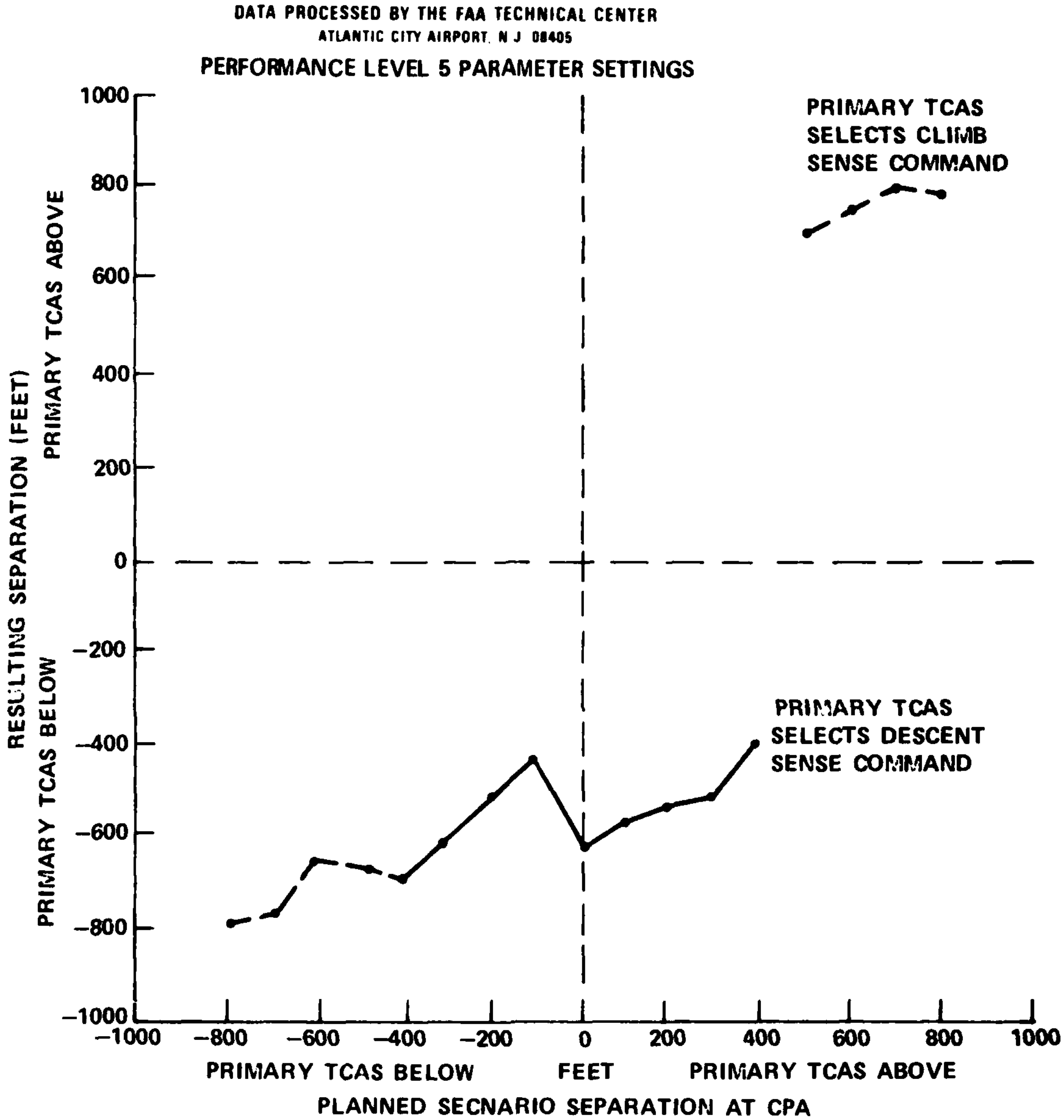

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FIGURE 23. RESULTS FOR PARALLEL VERTICAL MANEUVERS (2,000 FT/MIN CLIMBS)

Although sense selection was always compatible, a problem was detected in the sense choice logic. With a 2,000-ft/min rate and the primary TCAS planned to be 400 feet above the threatening TCAS at CPA, the primary TCAS selects a descend command. This maneuver requires vertical track crossing which results in a range of 1.13 nautical miles at time of coaltitude. The resulting separation is 407 feet at CPA. If the crossing angle is varied from the 90° condition shown in figure 21, the ranges at the time of coaltitude can be significantly reduced, especially for low crossing angles including tail chase.

Figure 24 presents the climb and descent modeling projections that resulted for the primary TCAS when it was planned to be 400 feet above the threatening intruder at CPA. Since the primary TCAS selects first, the threatening TCAS has a null Maneuver Intent Register at this time. The escape modeling logic makes two assumptions that lead to the descend sense choice and the unnecessary vertical track crossing.

1. Since the primary TCAS's vertical rate (2,000 ft/min) exceeds the assumed escape rate (1,000 ft/min) and the intruder's Maneuver Intent Register is null, the climb sense projection has no effect on the vertical profile. Since both aircraft are climbing at the same rate, the separation with a projection is no greater than current separation.

2. The threatening TCAS is modeled as a noncooperative intruder even though it is TCAS equipped. This results because its Maneuver Intent Register is null.

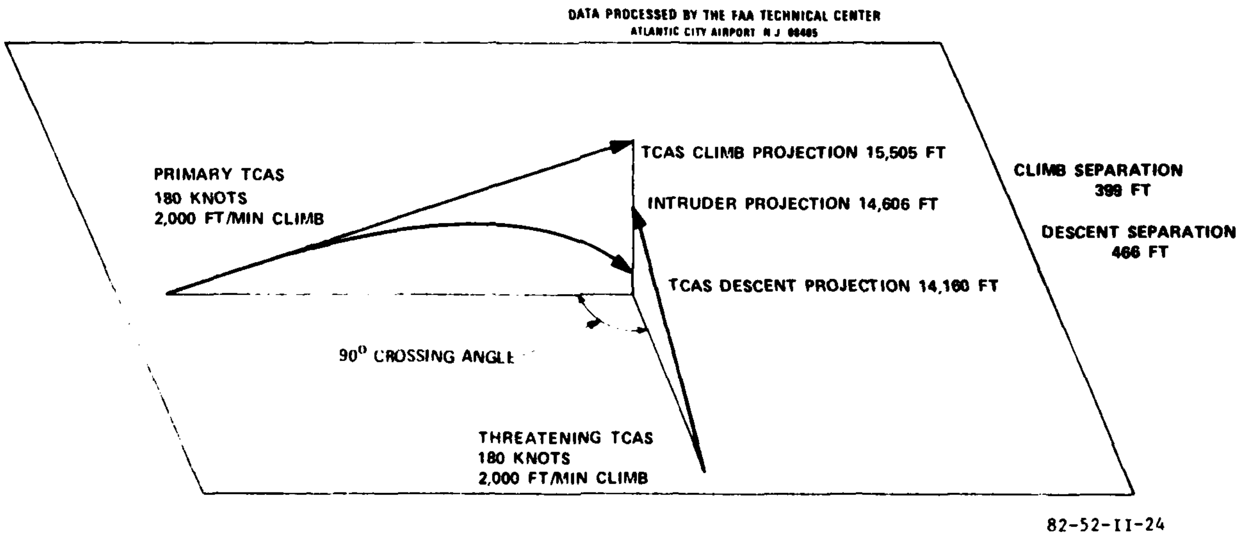


FIGURE 24. PARALLEL CLIMB ENCOUNTER LOGIC PROJECTION MODELING RESULTS

To correct these unnecessary track crossing situations, the sense selection logic was modified. The additions required are shown in figure 25. The modification only impacts sense selection when the intruder is equipped but has not yet selected sense. If the primary TCAS is not in a multiple threat situation (MACSET = 0), sense selection is based on the fact that the primary TCAS is projected to remain above the threatening TCAS from the time of sense selection to CPA. If this is the case, the climb sense is selected. If the primary TCAS was currently below the threat and could remain below until CPA, a descend sense selection would have resulted.

OPPOSITE DIRECTION VERTICAL RATES. Analyses of encounters with the primary TCAS climbing and the intruder TCAS descending were made. A subset of the scenarios investigated is shown in figure 26. The primary TCAS was climbing at 1,000 ft/min and the intruding TCAS was descending at 1,000 or 2,000 ft/min. The logic performance level used for the results that will be discussed was performance level 5 (tau = 25 seconds).

The generally good performance which resulted is shown in figures 27 and 28. The minimum vertical separation was 297 feet. The scenario conditions associated with this separation are marked with an asterisk on figure 27. The scenario called for the primary TCAS to cross 400 feet above the intruder which was descending at 2,000 ft/min. When threat detection occurred, the primary TCAS was 746 feet below the intruder resulting in the proper descend sense selection by the primary TCAS. Those resolutions which required vertical track crossing (climb sense commands for primary TCAS on figures 27 and 28) resulted in large vertical separations at CPA. The minimum range at time of coaltitude exceeded 1.37 nautical miles for all cases which required vertical track crossing.

LEVEL AND LOW VERTICAL RATE ENCOUNTERS.

Analyses of logic performance were made in cases where both aircraft were in level flight or had low vertical rates. For the low vertical rate cases, the results that will be reviewed are associated with performance level 5 logic parameter settings. The scenario conditions are the same as shown in figure 26 except that the primary TCAS is climbing at 500 ft/min and the intruder is descending at 500 ft/min. Excellent results were obtained and are shown in figure 29. The minimum vertical separation always exceeded 430 feet. The resolutions which required vertical track crossing (primary TCAS selects climb sense) resulted in large vertical separations at CPA. The range at time of coaltitude exceeded 1.7 nautical miles for these cases.

The results for the level flight encounters are shown in figure 30. The results were obtained with level 4 logic parameter settings. The minimum vertical separation observed was 426 feet.

HORIZONTAL MANEUVER ENCOUNTERS.

Many scenarios involving horizontal maneuvers by one or both aircraft were analyzed. The results from two of these scenarios will be reviewed. The two scenarios are presented in figure 31.

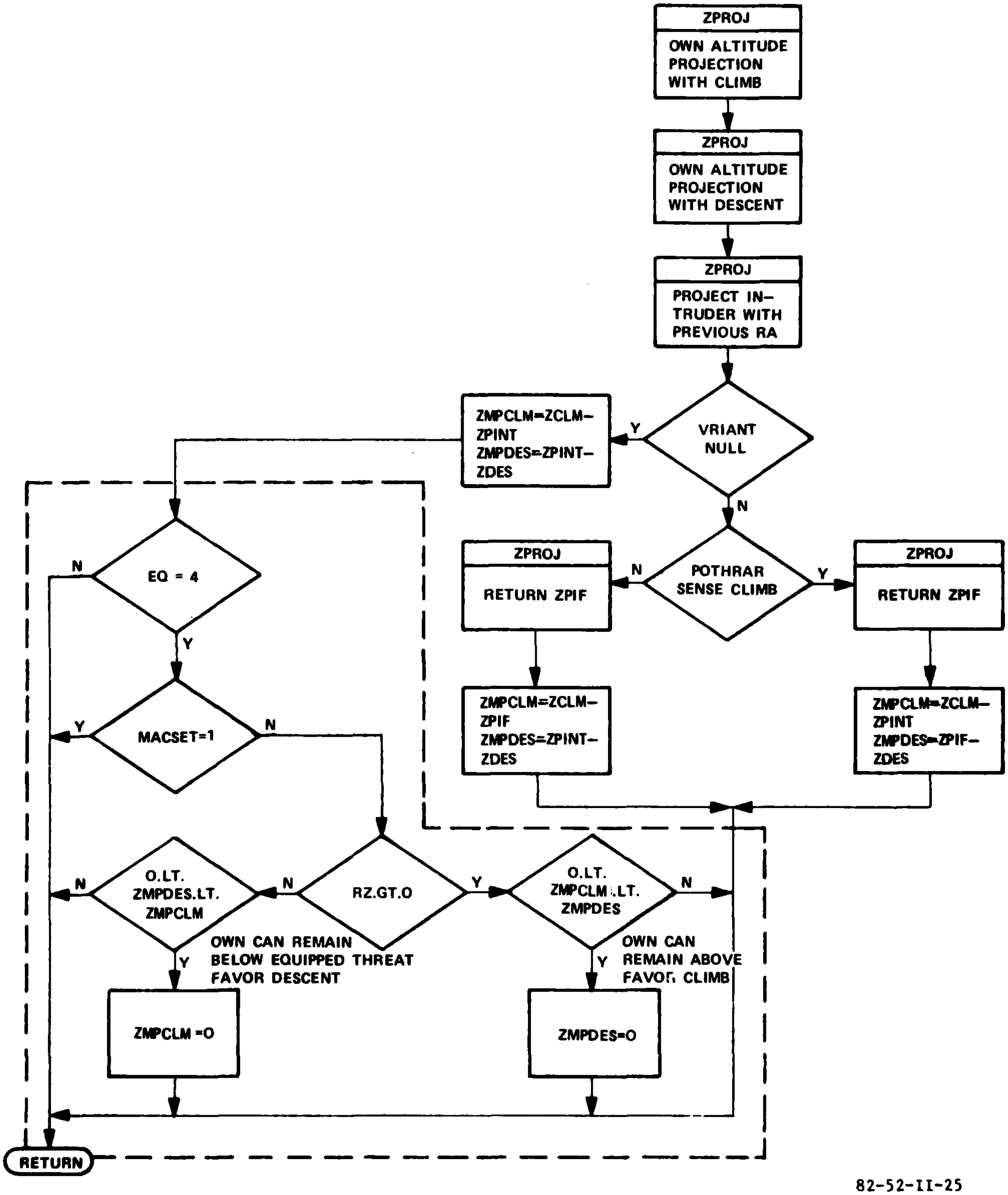


FIGURE 25. LOGIC ADDITIONS TO MODAC TO PREVENT UNNECESSARY VERTICAL TRACK CROSSING

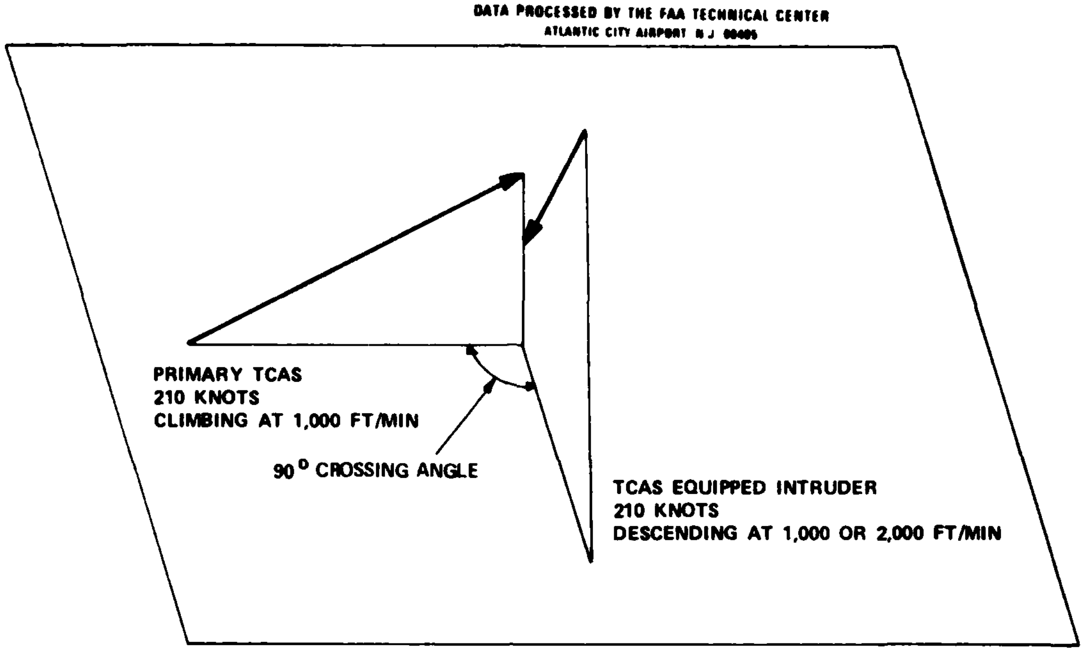


FIGURE 26. OPPOSITE DIRECTION VERTICAL RATE SCENARIOS

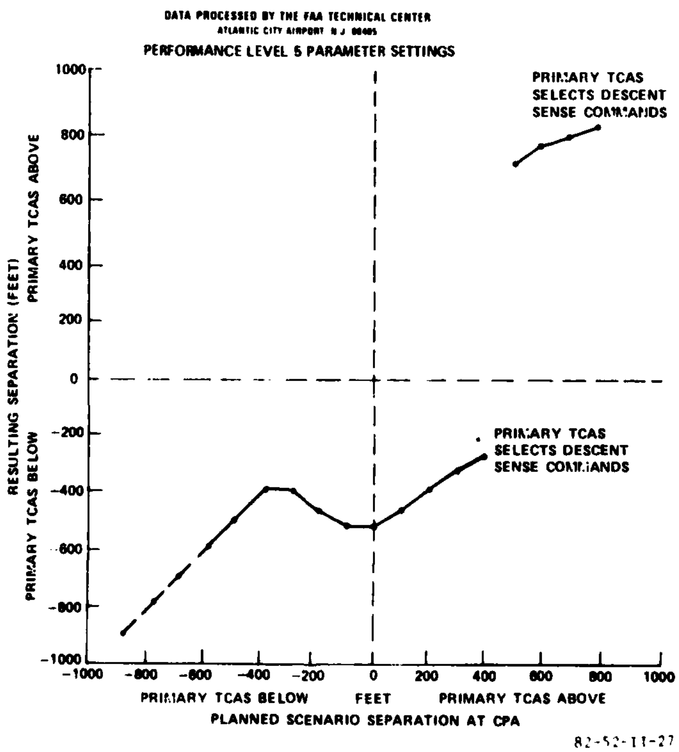


FIGURE 27. OPPOSITE DIRECTION VERTICAL RATE RESULTS (THREAT DECENDING AT 2,000 FT/MIN)

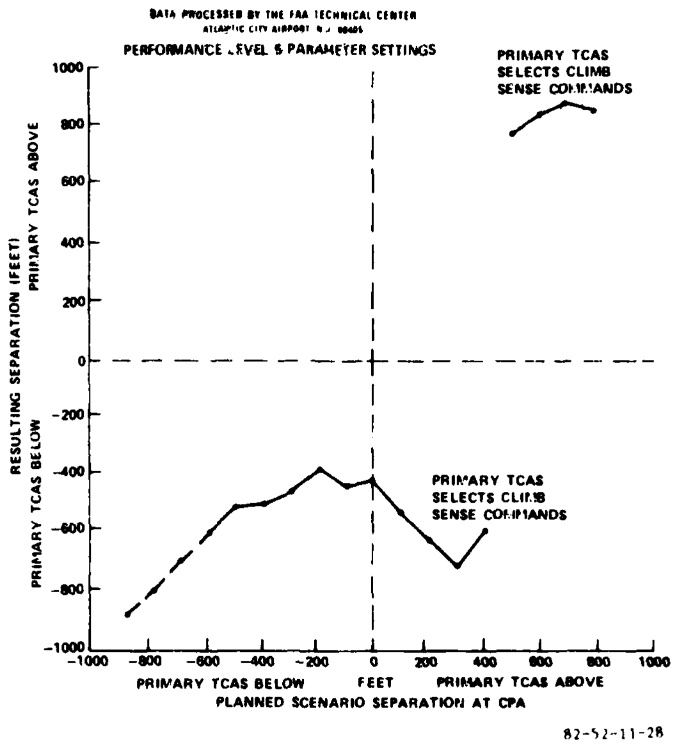


FIGURE 28. OPPOSITE DIRECTION VERTICAL RATE RESULTS (THREAT DECENDING AT 1,000 FT/MIN)

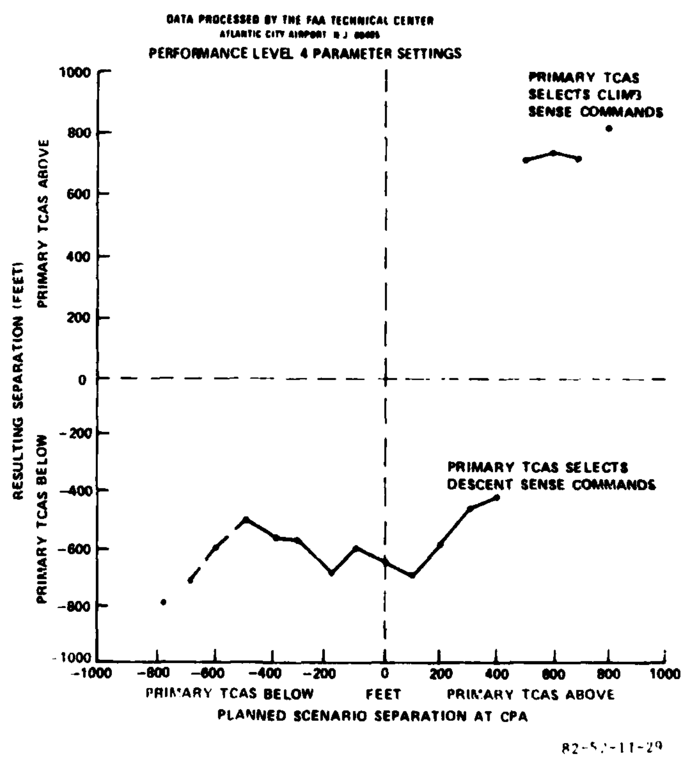


FIGURE 29. LOW VERTICAL RATE MANEUVER RESULTS

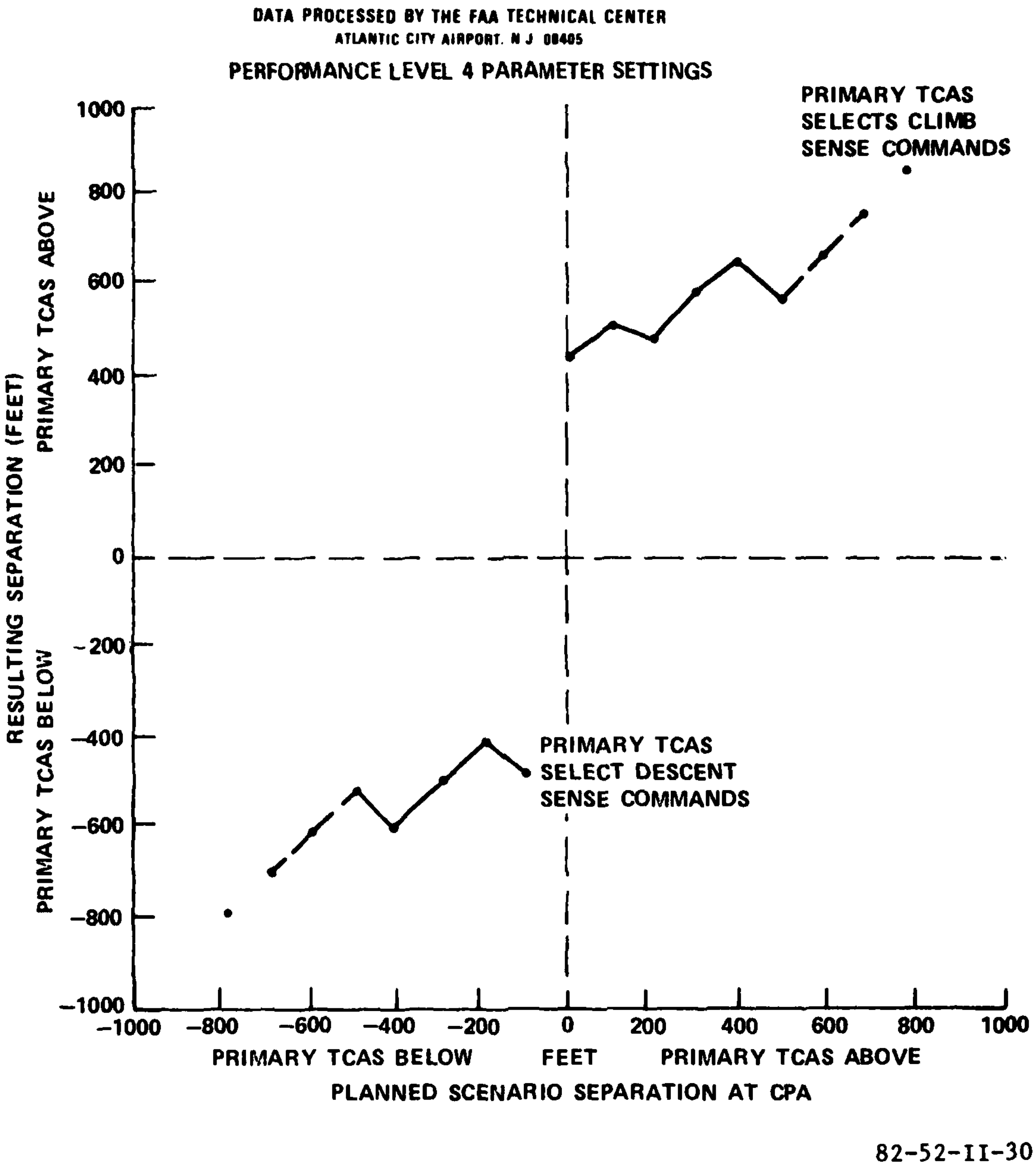
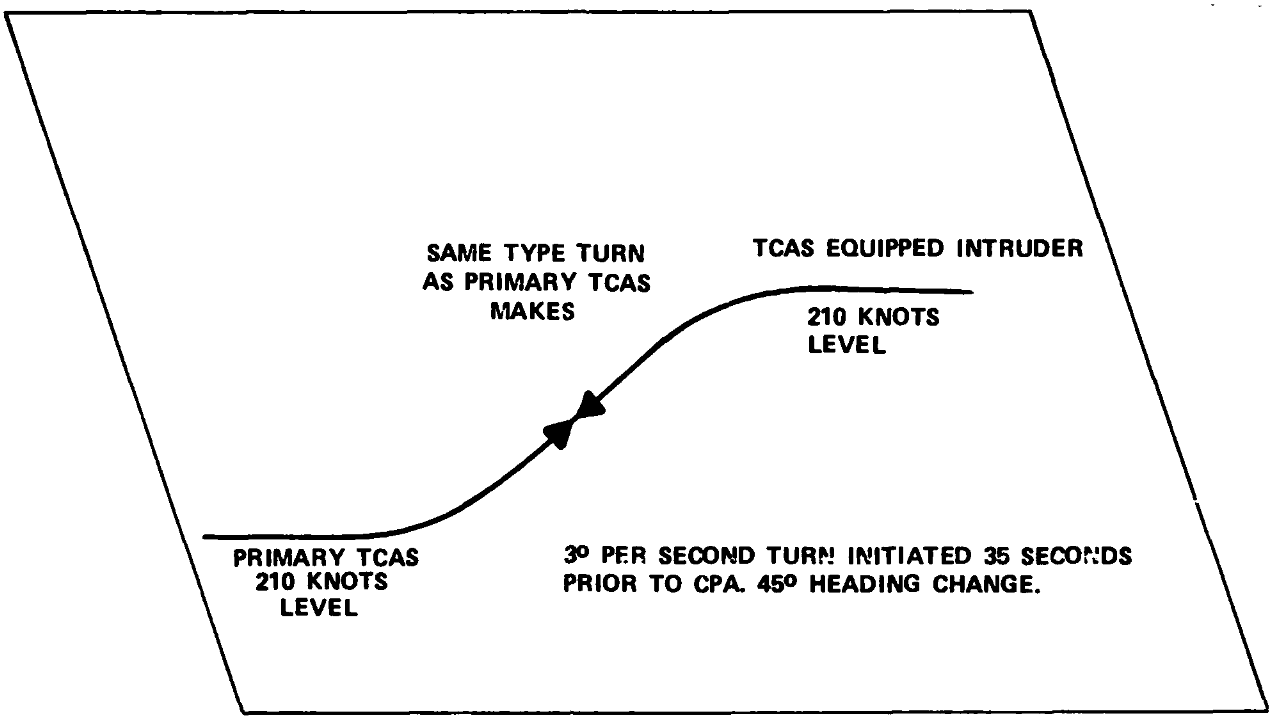


FIGURE 30. LEVEL FLIGHT ENCOUNTER RESULTS



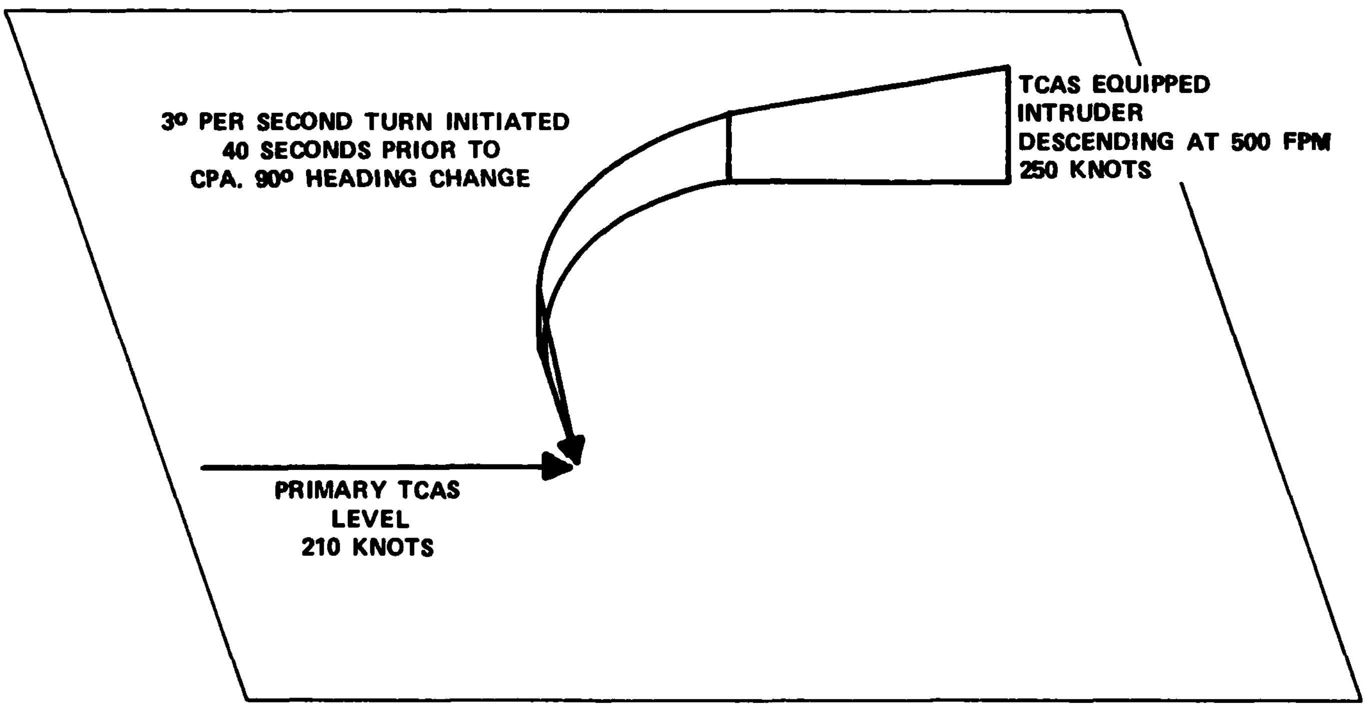


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FIGURE 31. HORIZONTAL MANEUVER SCENARIOS

SIMULTANEOUS HORIZONTAL MANEUVER RESULTS. The results for the case where both aircraft were maneuvering horizontally are shown in figure 32. Performance level 5 parameter settings (tau = 25 seconds) were used in this scenario. The minimum vertical separation observed at CPA exceeded 400 feet.

DESCENDING AND HORIZONTALLY MANEUVERING THREAT RESULTS. The results for the second scenario are presented in figure 33. This encounter was more difficult to resolve than the previous encounter. The range rate change was more gradual in the previous scenario. In the second scenario, the range rate increased more suddenly later in the encounter causing a slight delay in the issuance of TCAS commands. Moreover, this scenario involved a vertical rate on the part of the threatening TCAS. Despite these complexities, the minimum vertical separation observed was 327 feet.

SURVEILLANCE LINK RELIABILITY AND MEASUREMENT ERROR ANALYSIS

Studies were conducted to identify the impact that surveillance link reliability and errors in logic input measures had on TCAS logic performance. Specific scenarios were selected to amplify the impact of link reliability and measurement errors on logic performance. Two of the scenarios included both horizontal and vertical accelerations timed to occur at the most critical portion in the encounter. The most critical portion is the time when threat detection occurs and command sense selection must be made.

TEST METHODS.

Surveillance link reliability is the probability of updating an intruder track during a logic cycle of 1-second duration. Low track reliability implies a high track coast rate. Range and altitude measurement models included measurement errors, a bias in the transponder reply delay, and Mode C altitude quantitization. Autoregressive models were used to model range and altitude measurement errors associated with the surveillance track data (reference 15). Transponder reply delay, a constant for a given aircraft, was generated using Monte Carlo techniques. Altimeter bias can cause only a linear transformation of the vertical position of the aircraft; therefore, it was not modeled. A second order autoregressive error model was used for modeling altitude error.

In an encounter between a TCAS aircraft and an unequipped intruder, separation generation occurs solely due to the TCAS response. Throughout this study, TCAS performance was analyzed against an unequipped threat. Assuming that proper coordination occurs, logic performance against TCAS equipped threats should not be any worse than the results presented here. Analysis of the impact of coordination link failure between two encountering TCAS aircraft has been performed by Mitre Corporation (reference 15).

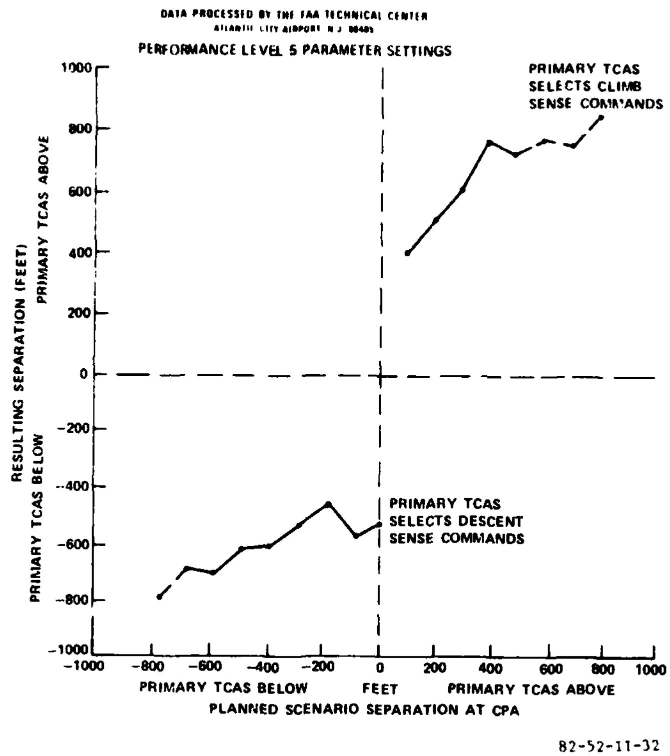

FIGURE 32. RESULTS FOR ENCOUNTERS INVOLVING SIMULTANEOUS HORIZONTAL MANEUVERS

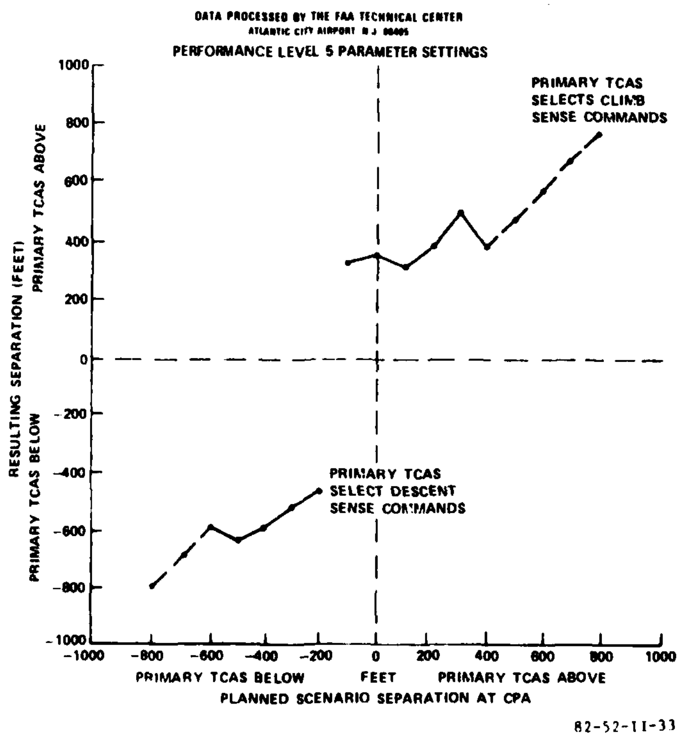

FIGURE 33. RESULTS FOR DESCENDING AND HORIZONTALLY MANEUVERING THREAT

An adequate model of surveillance link reliability was not available; therefore, the effects of surveillance link reliability on logic performance was analyzed by varying the reliability level while holding other experimental conditions fixed. Throughout an encounter period, the percentage of track coasts (surveillance link reliability) was held constant. The encounter was then repeated with an adjusted link reliabilty level. Reliability levels tested ranged from 100 percent (no coasting) to 10 percent (90 percent coasting) in 5 percent increments. To eliminate variations in performance due to pilot response delay and acceleration characteristics, the pilot delay was fixed at 5 seconds and the aircraft accelerated at 0.25g in reponse to TCAS commands. A block diagram of the error modeling procedures is presented in figure 34. The error models are reviewed in detail in appendix A.

TCAS logic performance for three separate scenarios was analyzed. At each level of surveillance link reliability, the encounter was replicated 500 times and the distribution of vertical separation at CPA was obtained. The fifth percentile of this distribution represents the vertical separation associated with the 25th smallest vertical separation observation. Performance was considered adequate if the fifth percentile exceeded 200 feet. To provide an error-free baseline for performance comparison, each scenario was run in an error-free environment with 100 percent surveillance link reliability.

SCENARIO 1 --- LOW VERTICAL RATE ENCOUNTER.

The first scenario depicted in figure 35 did not involve accelerations. The scenario vertical rates of both aircraft were low so that the maximum effect of altitude measurement error could be observed. The planned vertical separation at CPA was 0 feet. Since accelerations are not present, separation performance should remain relatively unaffected by variations in surveillance link reliability, at least at the higher reliability levels. Performance level 5 logic parameter settings were used. The results for scenario 1 are presented in figure 36.

The baseline error-free vertical separation obtained was 574 feet. This separation was obtained with a descend command that occurred 27 seconds prior to CPA. The average separation for the 500 replications remained consistently close to 430 feet, down to the 40 percent link reliability level. Some fluctuation was observed in the fifth percentile separation; however, it never decreased below 200 feet until the surveillance link reliability level had diminished to 30 percent.

The dropoff in separation performance below 40 percent link reliability can be attributed to the increased probability of consecutive coasts causing a loss of the intruder track file. Since the stochastic model of surveillance link reliability did not consider the impact of consecutive coasts, an interesting question arose. How well does the time dependent model approximate the flight test observed probability of consecutive coasts? All flight data between August 19, 1981, and December 16, 1981, were reviewed. The probability of specific coast durations was obtained and compared with the probability of consecutive coasts that result from the stochastic model. The stochastic model consecutive coast probabilities are dependent on the surveillance link reliability level being modeled. Table 4 compares the flight test results with the stochastic model for two link reliability levels.

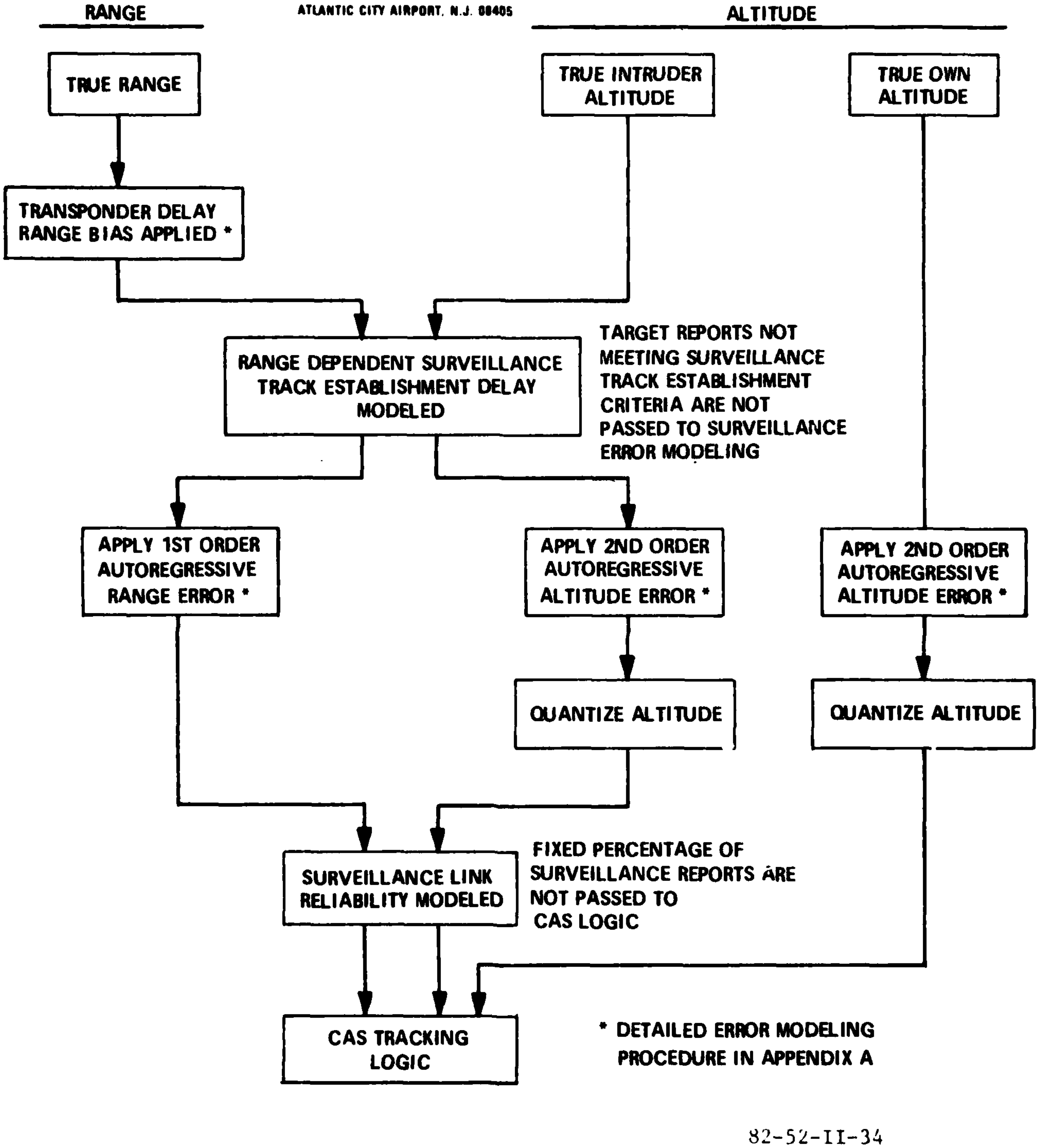

FIGURE 34. ERROR MODELING PROCEDURES

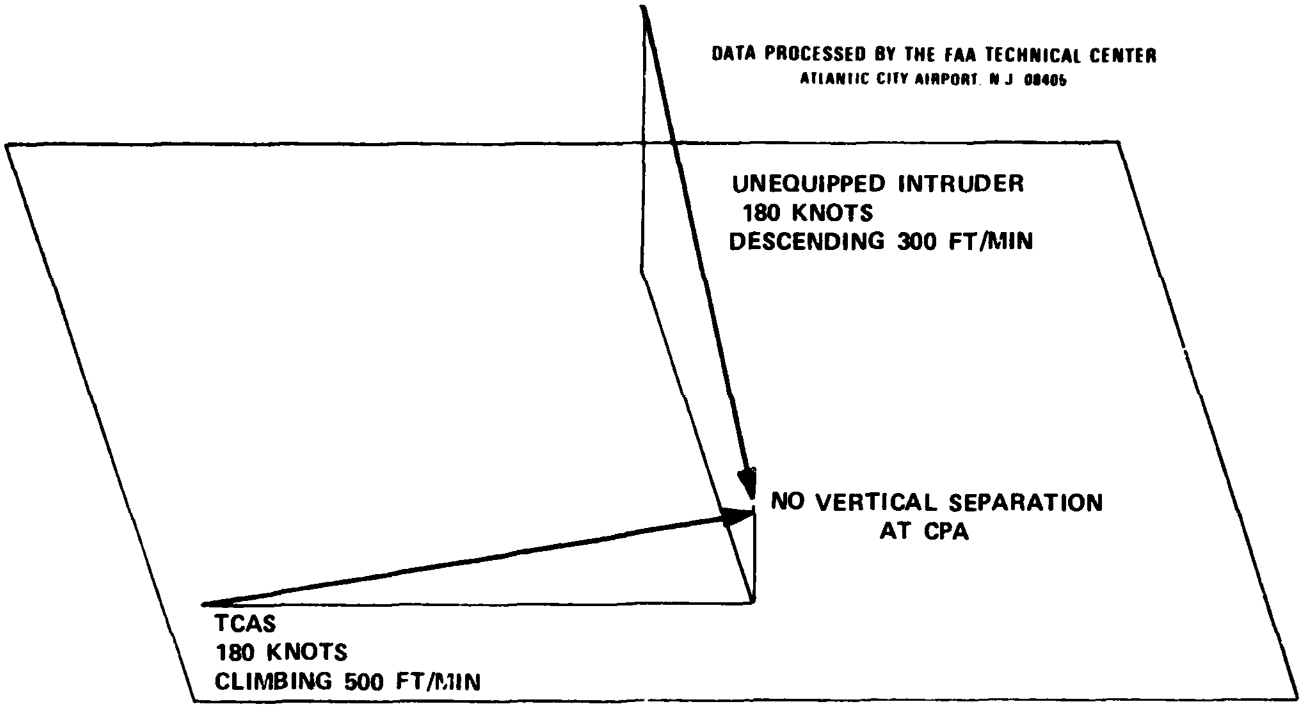

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FIGURE 35. LOW VERTICAL RATE ERROR ASSESSMENT ENCOUNTER

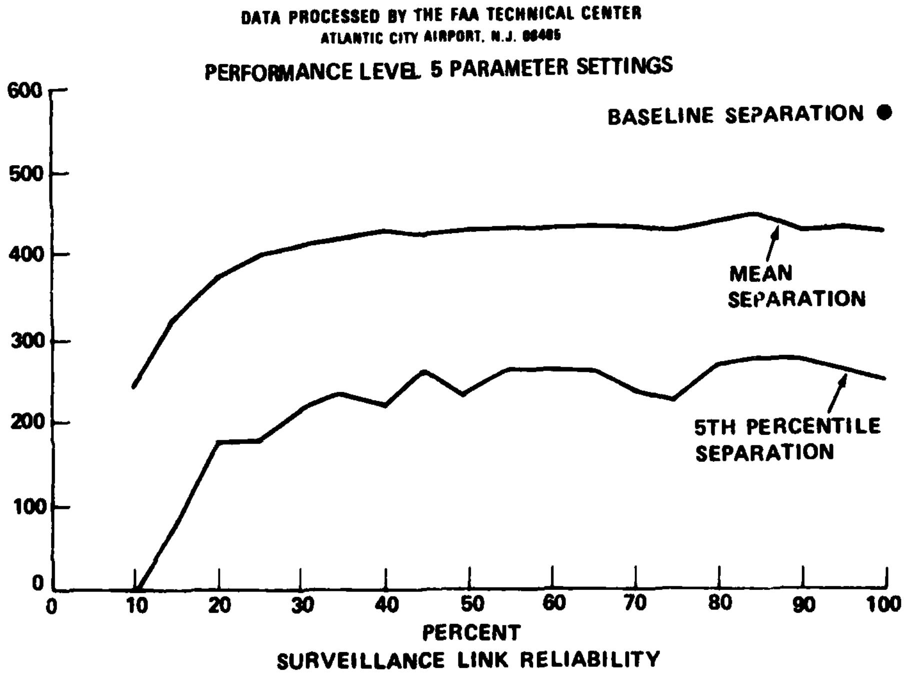

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FIGURE 36. SCENARIO 1 RESULTS

TABLE 4. COMPARISON OF CONSECUTIVE COAST PROBABILITIES

Coast Durations (Seconds)	Stochastic Model 50%	Stochastic Model 40%	Flight Test Results
1	0.500	0.600	0.273
2	0.250	0.360	0.113
3	0.125	0.216	0.057
4	0.068	0.130	0.048
5	0.031	0.076	0.042
6	0.020	0.045	0.037

Since tracks are deleted after six consecutive coasts, the maximum coast duration compared was 6 seconds. At the 50 percent surveillance link reliability level, the probabilities of coast durations between 1 and 4 seconds are considerably higher than observed in flight tests. Only for the 5- and 6-second durations did the observed frequency exceed the modeled frequency and then only slightly. The 40 percent link reliability level consecutive coast probabilities always exceeded the observed probabilities. This analysis indicates that link liabilities of 50 percent or less provide a harsher environment for TCAS performance than was observed in flight tests.

SCENARIO 2 — ACCELERATING ENCOUNTER.

The second scenario investigated involved a vertical acceleration by the TCAS aircraft approximately 30 seconds prior to CPA. Meanwhile, the intruder experiences a horizontal acceleration about 35 seconds prior to CPA. The geometry is depicted in figure 37. The scenario called for no vertical separation at CPA. This scenario was designed to measure the impact of surveillance link reliability on TCAS sense choice and subsequent resolution performance. The proper TCAS response should have been a descend command. Again, the performance level 5 parameter set was used.

The results for the second scenario are presented in figure 38. The error-free logic performance resulted in a descend command yielding 548 feet vertical separation at CPA. The mean separation stabilized around 510 feet down to the 40 percent link reliability level. Below the 40 percent level, a significant loss in mean vertical separation occurs. Initially, the fifth percentile vertical separation exceeds 300 feet. However, it quickly drops to below 250 feet for 80 percent link reliability. This is expected and demonstrates the impact of coasting on logic performance for encounters which involve vertical accelerations. Reduced link reliability, at the very least, causes a delay in command generation and reduced separation. In the extreme case, reduced link reliability can cause inappropriate sense selection. However, it should be noted that the fifth percentile vertical separation did remain above 200 feet with link reliabilities as low as 40 percent.

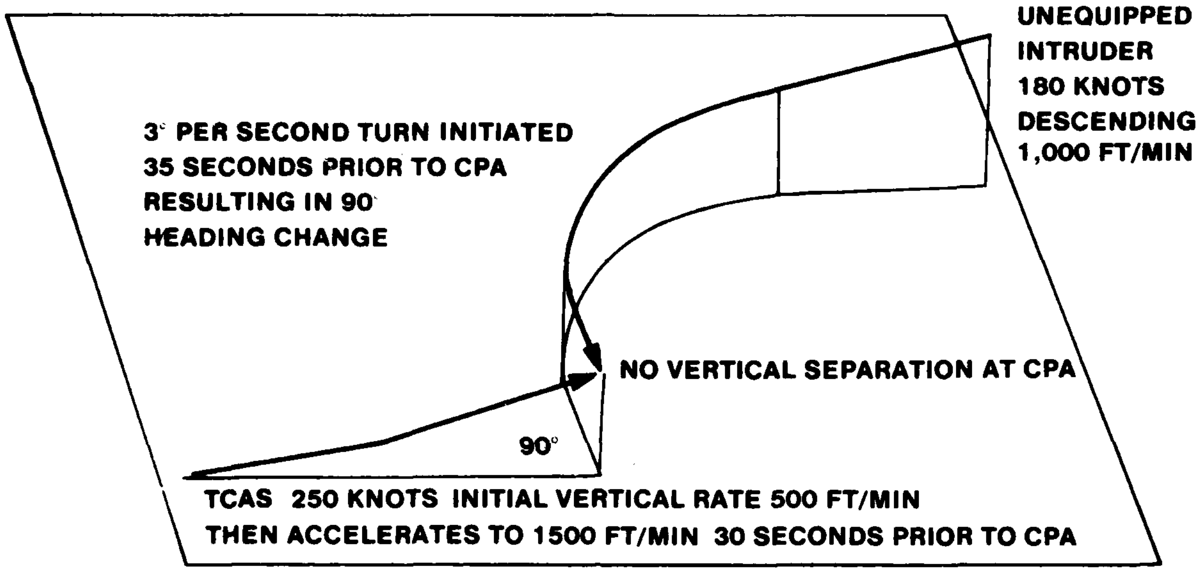

FIGURE 37. ACCELERATING THREAT ERROR ASSESSMENT ENCOUNTER

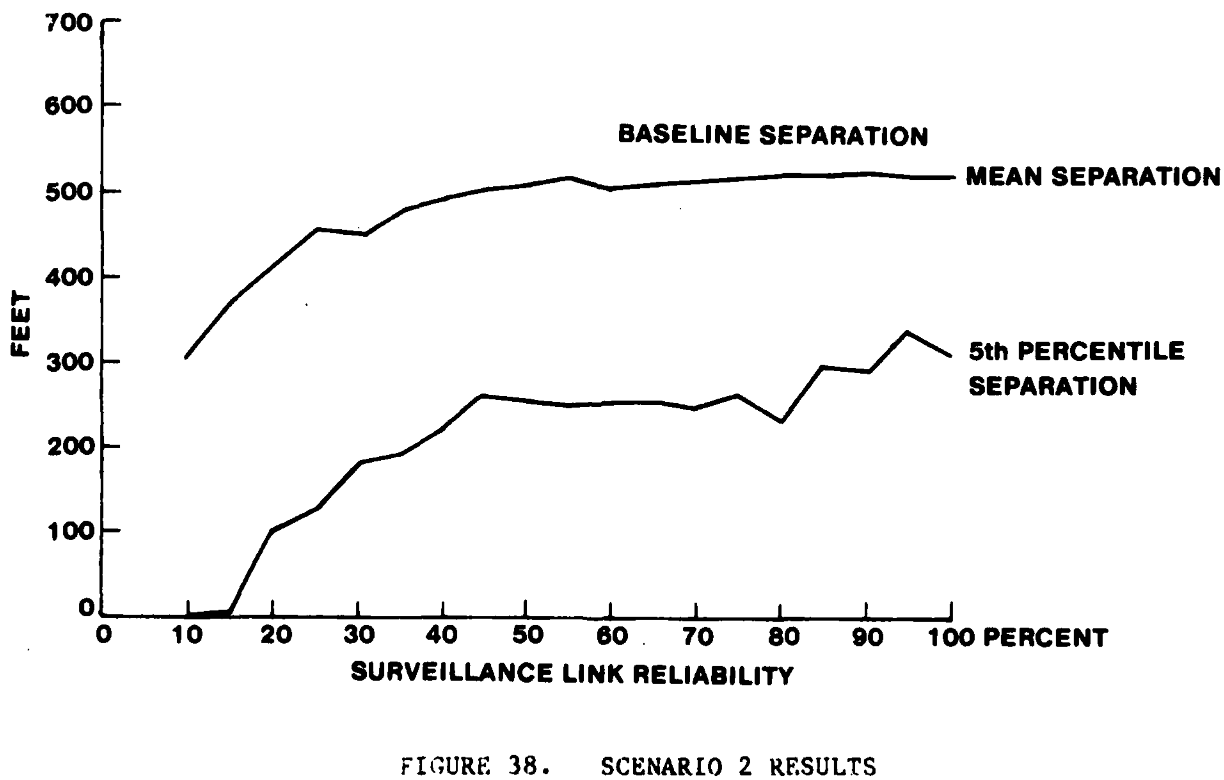

FIGURE 38. SCENARIO 2 RESULTS

SCENARIO 3 -- POPUP THREAT ENCOUNTER.

The scenario presented in figure 39 was designed to provide a most severe test for the TCAS vertical tracking logic. The intruder and TCAS were initially in level flight vertically separated by 900 feet. This places the intruder just outside the threat detection region. Thirty seconds prior to CPA, the intruder initiates a 0.25g vertical acceleration resulting in a 1,500 ft/min climb. Without TCAS action, the intruder would have climbed through the TCAS aircraft's altitude and been 250 feet above TCAS at CPA. The range at time of coaltitude would have been 0.68 nautical miles. The challenge in with this encounter is that degraded surveillance link reliability not only causes detection delays but also impacts vertical tracking and may cause the selection of an incorrect sense choice, climb.

The results for scenario 3 are presented in figure 40. In an error-free environment, TCAS receives a descent command resulting in 445 feet vertical separation at CPA. The mean separation ranges from near 420 feet for 100 percent link reliability to slightly more than 350 feet separation with 10 percent link reliability. No sharp dropoff in mean separation is observed as in the previous scenarios. This results because even without any TCAS action, which can be expected for low link reliability levels, 250 feet vertical separation exists at CPA. Note that the fifth percentile vertical separation for 10 percent link reliability is 250 feet (no TCAS action). The dropoff in the fifth percentile vertical separation to below 200 feet occurs at 75 percent link reliability and reflects the impact of link reliability on vertical tracking performance during accelerations. The overall track coasting probability observed in flight tests was 0.316 (68.4 percent surveillance link reliability) and approximates the level at which the fifth percentile vertical separation first dropped below 200 feet. The increase in the fifth percentile vertical separation for the lowest link reliability levels result because without TCAS action 250 feet vertical separation exists at CPA.

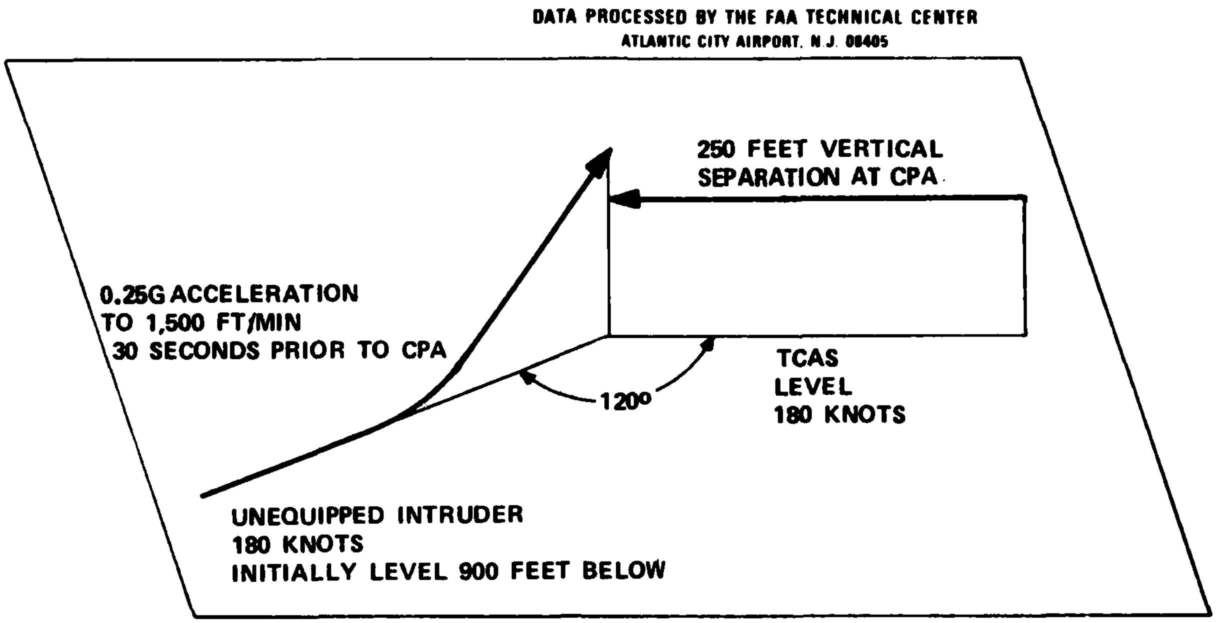

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FIGURE 39. VERTICAL TRACK CROSSING ERROR ASSESSMENT ENCOUNTER

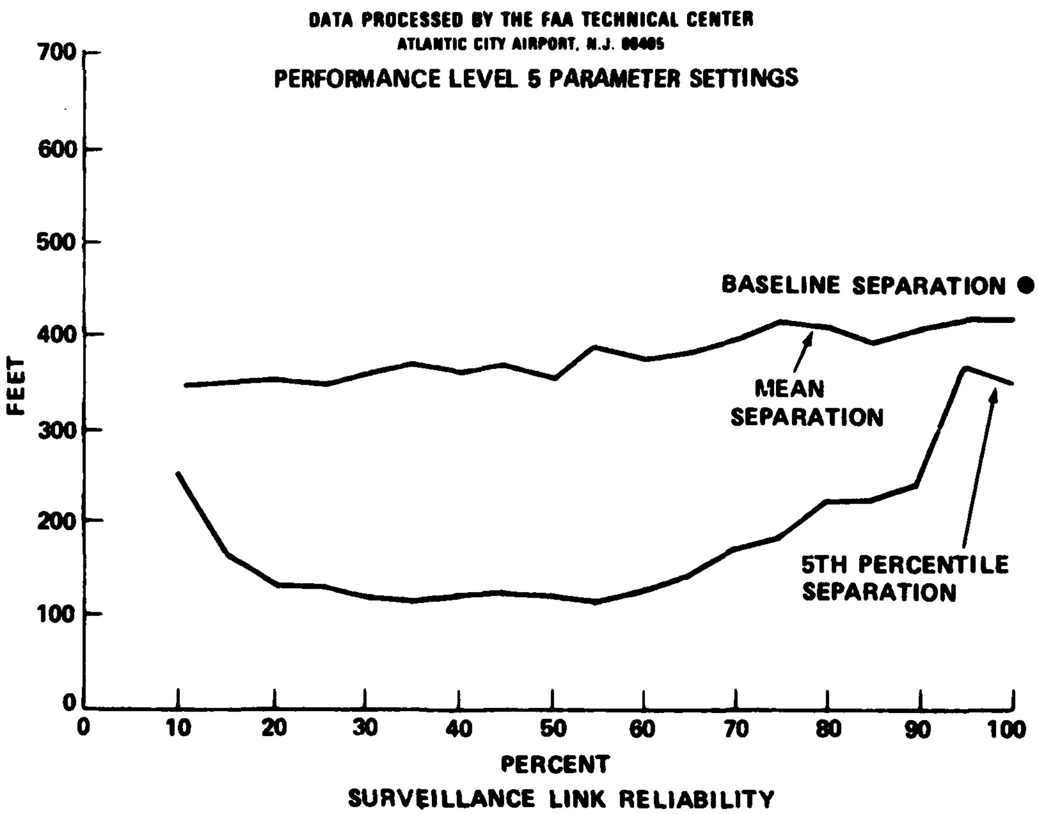

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FIGURE 40. VERTICAL TRACK CROSSING RESULTS

CONCLUSIONS AND RECOMMENDATIONS

TCAS LOGIC COORDINATION AND RESOLUTION PERFORMANCE.

The new TCAS logic (reference 2) described in the baseline logic document and the several additions and modifications formalized by Mitre (references 3 to 9, 11, and 12) have resulted in significant improvement in TCAS-to-TCAS resolution coordination and vertical separation performance. The initial two-message exchange required to affect command coordination and sense selection followed by the single message transactions on subsequent logic cycles have reduced coordination logic complexity when compared to previous Active BCAS coordination requirements. The reduction in complexity has increased coordination reliability.

The new TCAS logic design is better structured to insure efficiency and accuracy in hardware implementation. The new internal structures, such as the threat file and working list, permit the division of all targets being tracked into two groups; intruders (nonthreats) and threats. The working list further divides threats into three groups; new threats, continuing threats, and terminal threats. Other TCAS logic additions include self-test procedures to detect own unit failure and warn the pilot, an explicit pointer system to establish a one-to-one correspondence between surveillance track file and intruder track file entries, and logic initialization procedures to provide for automatic in-flight system restarting. Except for the specific problems reviewed below, separation performance during encounters with TCAS equipped threats was excellent.

SENSE SELECTION.

Initial testing identified a problem in sense selection and coordination for a variety of TCAS equipped threat encounters with an established vertical rate. Logic modifications were developed by Mitre to change sense selection procedures for equipped threats which had established intents (intentions). The modifications were tested and coordinated sense selections always resulted for the encounters in question. As a result, logic corrections developed by Mitre in reference 11 should become permanent additions to the TCAS logic.

In some rare low crossing angle encounters when the TCAS equipped threat has a high vertical rate established (greater than 1,500 ft/min), the initial sense selection caused unnecessary vertical track crossing with minimal ranges at coaltitude and reduced vertical separation at CPA. To correct this problem, it is recommended that the logic discussed under Performance Results for Equipped Threats and shown in figure 25 be added to the TCAS logic.

COMMAND OSCILLATION INDUCED BY PILOT RESPONSE TO TCAS COMMANDS.

Pilot response to TCAS commands can cause command oscillation. This fact, discovered in simulation testing, has been verified in flight tests at both the FAA Technical Center and Lincoln Laboratory. Command selection and/or removal are based on projected vertical separation at CPA. Following TCAS positive command presentation, the nominal pilot response can cause the projected vertical separation to exceed the threshold for detection causing command removal. This occurs even though current vertical separation is less than the threshold for positive commands. Once vertical tracking detects the return to level flight, secondary positive commands occur. As a result of this testing, that logic was added to use current vertical separation rather than projected vertical separation to control command removal or transition.

LATE TRANSITION TO POSITIVE COMMANDS (NEGATIVE SUFFICIENCY LOGIC).

During certain encounters with equipped threats, late transitions to positive commands resulted in less than ALIM separation at CPA. This occurred despite the fact that both aircraft were TCAS equipped and responded properly. The late transitions to positive commands occurred because the negative sufficiency logic prevented the selection of positive commands for equipped threats until the aircraft had closed to within ALIM vertical separation. Logic developed by Mitre (reference 12) reduced the occurrence of delayed positive commands and inadequate separation. However, some encounters with equipped threats may still exhibit reduced vertical separation. Until analysis indicates that excessive deviations from the intended flight path are occurring, positive commands should not be delayed just because the threat is TCAS equipped. Based on test results, modifications were made that resolution logic treats equipped threats in the same fashion as unequipped threats.

SURVEILLANCE LINK RELIABILITY.

Analysis of logic performance in the presence of input measurement errors and missing track reports has identified the required link reliability necessary to affect adequate resolution performance. For complex encounters involving a variety of horizontal and vertical accelerations, adequate separation performance resulted with as much as 50 percent reduction in surveillance link reliability. Flight testing at the FAA Tech ical Center indicates surveillance link reliability exceeded this level even in some moderately dense air traffic terminal areas.

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15. Pohoryles, D., Discrete Event Simulation Testing of the Resolution Advisory Register, Mitre Report MTR 82-W00078, April 1982.

16. Colby, G. R. and Crocker, E. A., Transponder Test Program (Final Report), FAA Report, FAA/RD-72/30, April 1972.

GLOSSARY OF TCAS TERMS

A	Absolute value of tracked relative vertical separation. An element of the intruder track file.
ADOT	Tracked relative vertical rate. Negative values imply vertical closure. An element of the intruder track file.
ALIM	An altitude dependent parameter used as the threshold for generation of positive commands. Parameter values are shown in Table 1.
ADIV	An altitude dependent parameter used as the threshold for selection of vertical speed minimum commands. The parameter values are shown in table 1.
ATCRBS	Air Traffic Control Radar Beacon System
CPA	Closest Point of Approach
DELAY	A parameter used in the modeling of responses to TAS commands. Nominally set to 8 seconds.
DMOD	A parameter used to modify the tau calculation. The parameter provides for horizontal acceleration by the intruder. The parameter values are shown in table 1.
DR&A	Data Reduction and Analysis
ENDTIME	The parameter used to identify the end time of a simulation run.
EQ	Flag used in the TCAS logic to identify the equipment status of an intruder. An element of the intruder track file. 0 = ATCRBS Equipped intruder 1 = Mode S Equipped intruder 3 = TCAS Equipped disabled intruder 4 = TCAS Equipped intruder
FTEG	Fast Time Encounter Generator
HI	Parameter identifying the maximum divergence of range and range rate defining a threat. The parameter values are shown in table 1.
INTENT	A 10-bit vector used in the coordination protocols to identify current intentions of the threat to the intent requesting TCAS. The intent is the negative complement of commands currently displayed.
INTHR	Flag used in safe side projection logic
MACSET	Flag when set that indicates a multiple threat situation exists.
MODAC	Command response modeling logic

NEGOK	Flag when set that indicates a negative command or VSL suffices.
NEW	The status of a threat which was detected on this logic cycle.
PERMTENT	Previous command due to a particular threat. An element of the threat file.
POSITN	Argument used in PROJCEK logic which represents a vertical distance measurement.
POTHRAR	Pointer to the current threat's resolution advisory in the other TCAS column of the Maneuver Intent Register.
PROJCEK	Safe side projection logic used to determine if the vertical miss distance projection corresponds with the sense selection.
RA	Resolution Advisory
RZ	Relative vertical separation. An element of the intruder track file.
TAU	Ratio of distance to rate. Positive values imply closure.
SELADV	Advisory Selection Logic
SRDS	Systems Research and Development Service
STATUS	A variable in the working list indicating the status of the threat.
TCAS	Traffic Alert and Collision Avoidance System
THRHLD	An argument in the safe side projection logic which identifies the threshold for positive commands.
TPROJ	An argument used in modeling vertical responses. Represents time to CPA.
TRTHRE	Maximum predicted time to closest pproach for defining equipped threats. The parameter values are shown in table 1.
TVPCMD	Maximum path prediction time for computing minimum vertical separation. Parameter values are shown in table 1.
TVPESC	Maximum escape time permitted for escape maneuver. Parameter values are shown in table 1.
TVTHRE	Maximum predicted time to coaltitude used for defining equipped threats. Parameter values are shown in table 1.
VERDIV	Vertical Divergence and Negative Sufficiency Logic
VMD	Projected vertical miss distance
VRA	Vertical resolution to be modeled

VRAINT	Vertical resolution of the threat to be modeled
VSL	Vertical Speed Limit
Z	Current altitude of aircraft to be modeled
ZCLM	Predicted altitude following climb command
ZD	Current vertical rate of aircraft
ZDES	Predicted altitude following a descent command
ZDINT	Intruder vertical rate. An element of the intruder track file.
ZMPCLM	Predicted vertical miss distance following a climb maneuver
ZMPDES	Predicted vertical miss distance following a descent maneuver
ZPIF	Predicted vertical miss distance due to first sense choice
ZPINT	Predicted vertical position of the threat
ZPROJ	Projected altitude of modeled aircraft
ZTHR	Threshold for altitude separation for threat detection. Parameter values are shown in table 1.

APPENDIX A

SUMMARY OF SURVEILLANCE TRACKED RANGE AND ALTITUDE MEASUREMENT ERRORS

The information in this appendix has been extracted from FAA Report, FAA/RD-80/83. It represents the procedures used to model range and altitude errors in the surveillance tracked range and altitude. The surveillance tracked range and altitude were the measures used as input by the collision avoidance logic.

ALTITUDE MEASUREMENT ERRORS.

Throughout the analysis it was assumed the "own" aircraft used Mode C input to determine own aircraft's vertical position. Altitude error analysis reported in FAA/RD-80/83 identified the similarities in own and intruder surveillance altitude tracked characteristics.

They have the same order autoregressive models, nearly equal autocorrelations and parameter estimates. This was expected since the own and intruder altitude information supplied to the TCAS are similar. As a result, it would be appropriate to represent both own and intruder altitude errors with the same model.

For the limited data that were available, the altitude measurement error process could be represented using the parameters developed from the intruder altitude error data. As a result, the active BCAS altitude measurement error process can be mathematically represented by the 2nd order autoregressive model.

$$\underset{\sim}{E}_A(t) = 1.066\ \underset{\sim}{E}_A(t-1) - 0.191\ \underset{\sim}{E}_A(t-2) + a_t;\ t \geq 3\ .\ .\ . \qquad (1)$$

where $\underset{\sim}{E}_A(t)$ = the altitude measurement errors at time t, and a_t, the process white noise, is a normally distributed random variable with mean of zero feet, variance = 111.1 ft^2.

As a result the quantized altitude output from surveillance at time t, A(t) can be expressed as

$$A(t) = 100 \bullet INT\left\{(\underset{\sim}{E}_A(t) + Z(t) + 50)/100\right\} \qquad (2)$$

where

Z(t) = true altitude at time t

and

$INT\left\{a\right\}$ = the greatest integer in a.

The only difference in the own altitude and intruder altitude error modeling process is that surveillance reliability on the own aircraft is always assumed to be 100 percent. (No missing altitude reports were modeled for own aircraft.)

RANGE MEASUREMENT ERROR MODEL.

The high bias present in the range error data is due to transponder reply delay. Hypothesizing that range measurement errors have zero mean and are normally distributed, the range measurement error process could be written as

$$\underset{\sim}{E}_R(t) = 0.681\ \underset{\sim}{E}_R(t-1) + b_t;\ t \geq 2 \qquad (3)$$

where $\underset{\sim}{E}_R(t)$ = the range measurement error at time t, and b_t, the process white noise, is a normally distributed random variable with mean = zero feet and variance = 4,829.9 ft^2.

The bias in the range error represents half of the distance that could be covered at the speed of light during the transponder reply delay period. Since the transponder reply delay was assumed to be 3 μs in BCAS, the bias in the range error depends on the deviations of the transponder reply delay from the assumed 3 μs. Thus, the range error bias is given by

$$R_b = 1/2\ (983.516)\cdot(d-3) \text{ feet}$$

where 983.516 feet is the distance covered in 1 μs at the speed of light and d is a random variable (expressed in microseconds) having the distribution of transponder reply delays. From reference 16, d is uniformly distributed on the range [2.5, 3.5] μs.

The biased range error at time t, $E_R(t)$ is given by

$$E_R(t = \underset{\sim}{E}_R(t) + R_b$$

Substituting for $\underset{\sim}{E}_R(t)$ from equation (3),

$$E_R(t) = 0.681\ \underset{\sim}{E}_R(t-1) + R_b + b_t;\ t \geq 2$$

and

$$\underset{\sim}{E}_R(t-1) = E_R(t-1) - R_b.$$

Hence

$$E_R(t) = 0.681\ E_R(t-1) + 0.319\ R_b + b_t;\ t \geq 2. \qquad (4)$$

The resulting range report to collision avoidance logic R(t) can be expressed as

$$R(t) = R_t(t) + E_R(t) \qquad (5)$$

where

$R_t(t)$ is the true range at time t.

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