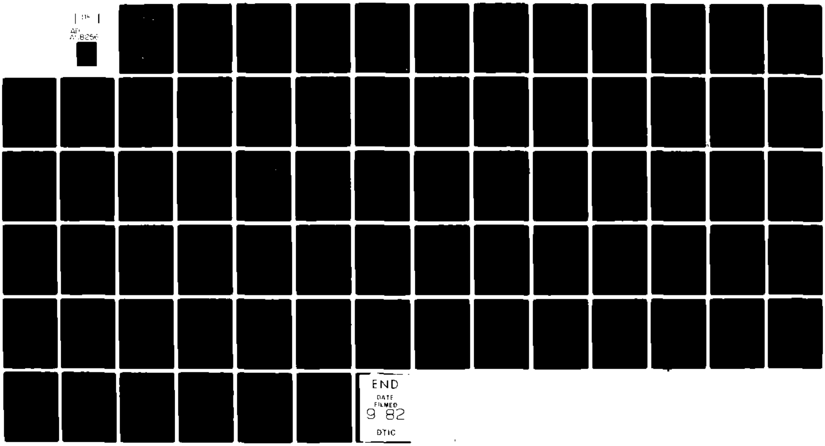
AD-A118 256 FEDERAL AVIATION ADMINISTRATION TECHNICAL CENTER ATL--ETC F/G 1/2
TRAFFIC ALERT AND COLLISION AVOIDANCE SYSTEM LOGIC EVALUATION. --ETC(U)
JUL 82 B R BILLMANN
UNCLASSIFIED DOT/FAA/CT-82/52-1 DOT/FAA/RD-82/30-1 NL



(15)

DOT/FAA/RD-82/30-I
DOT/FAA/CT-82/52-I

Traffic Alert and Collision Avoidance System Logic Evaluation: Volume 1, Unequipped Threat Phase

Barry R. Billmann

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

July 1982

Final Report

This document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

U.S. Department of Transportation
Federal Aviation Administration
Systems Research & Development Service
Washington, D.C. 20590

NOTICE

Technical Report Documentation Page

1. Report No. FAA/RD-82/30-I	2. Government Accession No. AD-A118256	3. Recipient's Catalog No.
4. Title and Subtitle TRAFFIC ALERT AND COLLISION AVOIDANCE SYSTEM LOGIC EVALUATION: VOLUME I, UNEQUIPPED THREAT PHASE		5. Report Date July 1982
		6. Performing Organization Code
7. Author(s) Barry R. Billmann		8. Performing Organization Report No. DOT/FAA/CT-82/52-I
9. Performing Organization Name and Address Federal Aviation Administration Technical Center Atlantic City Airport, New Jersey 08405		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. 052-242-320
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Systems Research and Development Service Washington, D.C. 20590		13. Type of Report and Period Covered Final March to December 1981
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The purpose of this report is to characterize the performance of the Traffic Alert and Collision Avoidance System (TCAS) logic which was developed by the Mitre Corporation. The evaluation was based on baseline logic documentation and logic changes made between January to October 1981.

The report is the first part of a three-volume series and reflects the evaluation of logic performance using the Fast-Time Encounter Generator as the logic test bed for unequipped threats. The study was conducted in two phases. The initial phase addressed the identification and correction of logic flaws. After the improvements in the logic were coordinated with or provided by Mitre, the second phase assessed the TCAS logic performance for a wide variety of two-aircraft encounters. The report identifies the logic deficiencies and the results of the analysis. In general, TCAS logic performance was excellent.

17. Key Words Collision Avoidance TCAS Vertical Miss Distance	18. Distribution Statement Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	70	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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

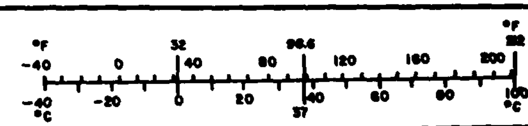


TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF TABLES

INTRODUCTION

This document is the first volume of a three-volume series reporting the performance of the latest version (version 9V) of the Traffic Alert and Collision Avoidance System (TCAS) logic. The analytical results include both the detection and correction of logic deficiencies and the performance of the corrected logic to resolve collision and near collision encounters. This volume is confined to the review of the performance of TCAS logic against single threat aircraft equipped only with air traffic control transponders (i.e., unequipped threats). Future volumes will analyze performance against TCAS equipped threats and multiple threats.

PURPOSE.

The purpose of this evaluation is to analyze and validate the performance of the new TCAS logic. The research is designed both to augment flight testing and act as a prelude to flight tests. Simulation study permitted the evaluation of the logic in a much less costly fashion. Additionally, many encounter scenarios cannot be accurately or safely duplicated in flight. The baseline collision avoidance logic analyzed in this report is the logic developed by Mitre Corporation (reference 1).

BACKGROUND.

Previously, TCAS logic performance has been evaluated in both a real-time and fast-time simulation environment. The immediate predecessor to the TCAS logic was the Beacon Collision Avoidance System (BCAS) Conflict Indicator Register (CIR) logic. The performance of the CIR logic has been analyzed and is reported in reference 2. Design of the BCAS coordination procedures in the CIR-based BCAS has been streamlined and simplified to increase TCAS-to-TCAS and TCAS-to-ground communications reliability. This simplification has led to the TCAS logic design. This design change necessitated the modification of the collision avoidance logic (reference 1).

Engineering models of the TCAS design have been developed by Dalmo Victor Operations of Bell Aerospace/Textron and Lincoln Laboratory. These units are currently undergoing flight test. The analysis reviewed in this report was designed to verify the collision avoidance logic performance prior to the flight tests.

Included in the new logic were several features designed to handle resolution deficiencies detected in the previous BCAS logic. The alpha-beta vertical tracker has been replaced with a nonlinear vertical tracker developed by Lincoln Laboratory (reference 3). The inclusion of this new tracking concept has significantly reduced the probability of incorrect sense (vertical direction) choice that existed with the alpha-beta vertical tracker (reference 4).

The new collision avoidance logic also implements the concept of commanding minimum vertical rates to achieve separation. When a TCAS aircraft is maneuvering vertically, resolution advisories such as "maintain climb rate of at least 1,000 feet per minute" may result. The addition of this resolution concept prevents premature return to level flight following aircraft response to a TCAS positive command.

Major changes to the sense (escape direction) selection logic have been made. The new logic models separation that would result for both a climb sense or descent sense maneuver by the TCAS aircraft. The sense that results in the largest separation is selected when the threat is not TCAS equipped. Other checks are made when the threat is TCAS equipped. In response to a TCAS command, the new sense selection logic nominally models 0.25 gravity (g) accelerations for TCAS and a minimum vertical escape rate of 1,000 feet per minute (ft/min).

In order to provide a simulation environment for evaluating collision avoidance logic, the Fast-Time Encounter Generator (FTEG) was developed (reference 5). This test bed has been used extensively in the validation of TCAS logic. The FTEG permits the analyst to define encounter scenarios in terms of aircraft performance characteristics and the encounter closest point of approach (CPA) conditions. The FTEG can automatically alter scenarios in a systematic fashion. This permits the analyst to test the logic sensitivity to these scenario changes. Extensive error modeling within the test bed permits logic validation in an error-degraded environment.

OBJECTIVES AND SCOPE.

The primary objective of the research documented in this report is to evaluate the TCAS logic. Specifically, this volume addresses performance for unequipped threats. The criterion for performance failure during the evaluation was the detection of scenarios that resulted in less than 200 feet of vertical separation at CPA following TCAS action. Logic deficiencies that resulted in inadequate separation were identified, and logic modifications designed to correct these deficiencies were then tested. After the logic modifications were reviewed by Systems Research and Development Service (SRDS) and Mitre, the formal revisions of the logic were provided by Mitre (references 6-11). These revisions were then implemented into the baseline logic.

The performance results identified in this report reflect analysis of the revised logic. This analysis was conducted between April and October 1981. During this period, logic performance for more than 8,400 scenarios was analyzed. Each scenario represented an encounter with a single unequipped intruder. Throughout this evaluation, surveillance accuracy was assumed to be perfect. However, quantization of range and altitude measurement inputs was modeled. The inputs to the TCAS logic included the Mode C altitude and range of the intruder. Initial time difference estimates of altitude rate and range rate were used to initialize the Collision Avoidance System (CAS) trackers. Since CAS tracks were initiated at least 80 seconds prior to CPA, the time difference rate estimates had no impact on logic resolution performance.

The previously mentioned 8,400 encounters were designed to occur at various altitudes and ranges from a fixed reference. This permitted the performance evaluation across all combinations of performance levels and altitude layer settings. As a result, many encounters were analyzed in which logic parameters were desensitized for terminal airspace conditions.

Throughout this report, TCAS algorithm terms are used as they exist in the baseline logic documentation. A glossary of TCAS algorithm terms is included at the end of the report to assist the reader. This report assumes the reader is familiar with the fact that the term "intruder" is used to identify other aircraft that have been detected but currently require no resolution: The term "threat" is applied to intruders that require resolution.

SUMMARY.

Following the implementation of the corrections identified in phase 1 of the analysis, the TCAS logic showed that the algorithms generally provided good performance during encounters with single unequipped threats. When the minimum protection threat volume parameters (performance level 3) were used, less than 300 feet of vertical separation at CPA resulted for the terminal area encounters. However, except for isolated failures which are fully discussed in this report, the minimum performance level setting still generated at least 200 feet of separation at CPA.

Improvements in nonlinear altitude tracking and maneuver sense selection logic have significantly reduced the number of incorrect sense choices in resolving the encounters. Some minor changes in the nonlinear tracker and sense choice logic are identified which will further reduce the occurrences of incorrect sense choices. Following periods of missing altitude reports, the current nonlinear tracker may induce spikes in the tracked vertical rate estimate. Some additional logic modifications to the nonlinear tracker will smooth the tracked vertical rate estimate following missing altitude data periods. Analysis is required to investigate the impact on logic performance when the own altitude track uses finer quality air data computer input rather than own Mode C input.

Resolution logic performance in terms of the generation of timely and correct alarms was generally excellent. To reduce the positive command rate, the TCAS logic includes a vertical divergence logic. The divergence logic does reduce the positive alarm rate but at the cost of possibly inducing cyclic command displays following a pilot response to TCAS commands. As a result of this analysis, it is suggested that vertical divergence logic be eliminated and current relative vertical separation be used to control command transitions and termination.

Resolution logic and the nonlinear tracker have improved TCAS resolution performance for vertically accelerating threats. The nonlinear tracker can detect variations in vertical rate rather quickly. Better resolution may result by delaying sense choice during the threat acceleration periods. (Vertical acceleration periods are generally short in duration. A constant 0.25g acceleration from 0 to 2,000 feet per second (ft/sec) lasts only 4 seconds.)

For near miss conditions, the collision avoidance algorithms can provide accurate estimates of time to closest approach. However, when large horizontal miss distances (approximately equal to (DMOD)) exist at CPA, the algorithms generate excessively large estimates of time to CPA in the vicinity of CPA. These poor estimates increase the number of unnecessary alarms (i.e., without TCAS interaction, aircraft were sufficiently separated). Without the inclusion of bearing information in the resolution logic, methods of controlling the overestimation of time to CPA should be identified and incorporated into the algorithms.

DISCUSSION

GENERAL.

The evaluation of the TCAS logic required the interfacing of two software packages. The first package is the FTEG or the simulation algorithm that controls the operation of the simulation model. The second package is the collision avoidance logic that is being evaluated. The simulation system is resident on the Honeywell 6600 computer at the Federal Aviation Administration (FAA) Technical Center. Certain data reduction and analysis routines such as encounter plotting are part of the on-line system. Figure 1 presents the high level interaction between the simulation test bed and collision avoidance logic.

This report only identifies logic performance for unequipped threats. However, all logic presented in reference 1 was coded and available during the evaluation. This permitted the identification and correction of several logic deficiencies which did not directly impact unequipped threat performance.

The new TCAS logic is an extensive improvement over previous BCAS logic. Improvements in the vertical tracking routines within the CAS logic have been made. The concept of a working list now provides for a structured division of all intruders which have progressed to threat status; e.g., an intruder which requires resolution. Once an intruder has been declared a threat, it is placed on the threat file. Similarly, a traffic advisory file lists the intruders and associated information for each intruder which causes the generation of a TCAS traffic advisory message. The working list places a threat in one of three groups--new threat, continuing threat, or terminating threat--based on the previous status of the threat and the current status. 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 a CAS track file entry. The inclusion of logic flags indicating the TCAS system operational status permits the display of warnings to the pilot that the TCAS system has failed or the CAS logic is not functioning properly. Within the new logic, complete logic initialization procedures have been defined.

Many of the deficiencies in previous BCAS logic have been corrected with the new TCAS logic. Sense choice logic has been enhanced. Different techniques are used to select resolution advisories during vertical track crossing encounters and when vertical rate estimates are low. The additional concept of commanding the maintenance of a minimum vertical rate to generate separation has been incorporated. This has been done in the form of resolution advisories such as "maintain rate of at least XXX feet per minute."

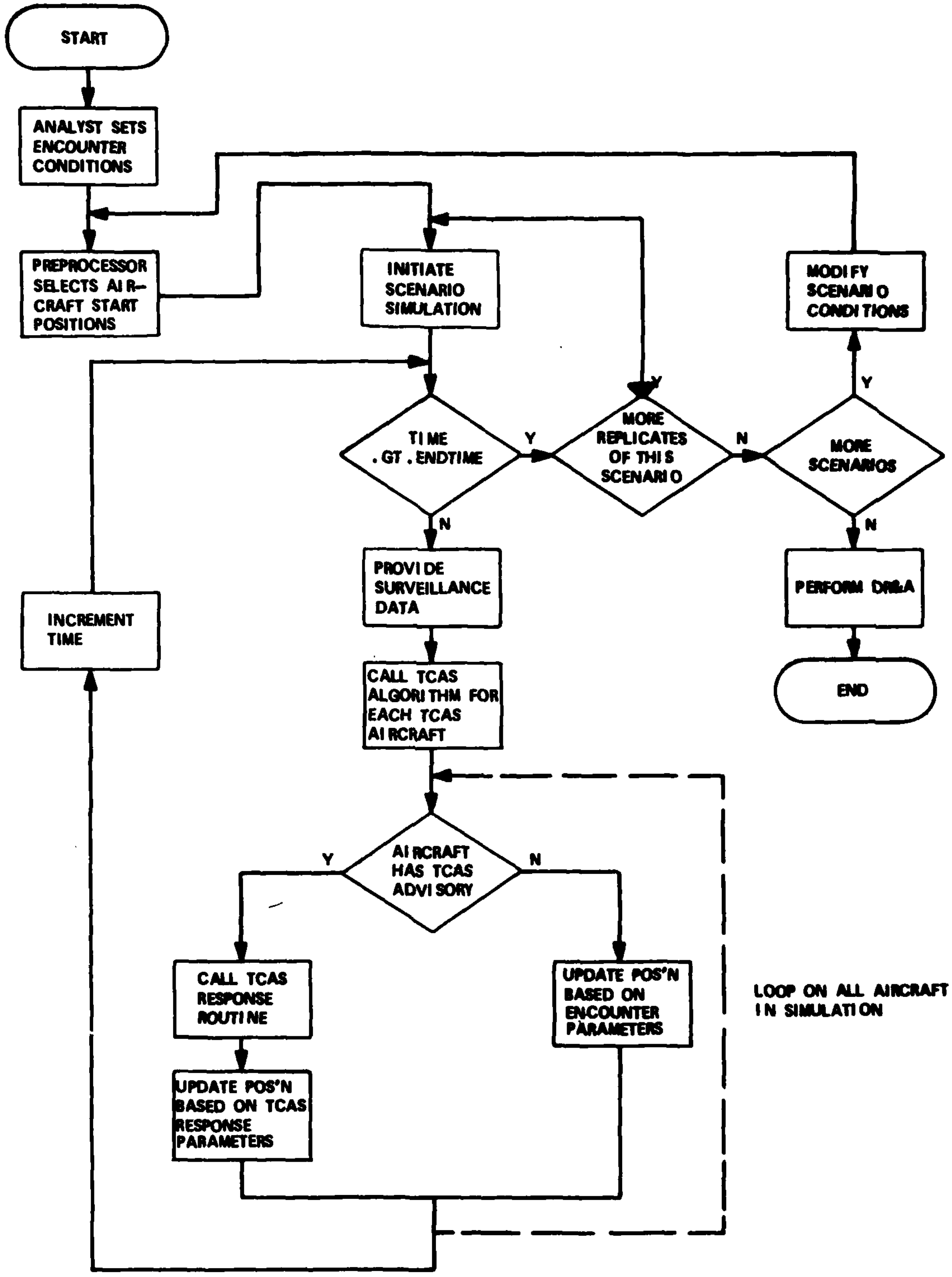


FIGURE 1. HIGH LEVEL LOGIC FLOW

Explicit logic housekeeping procedures have been implemented in the new TCAS coordination logic. The housekeeping provides for the purging of old data in the coodination and threat files. Housekeeping logic is also used to detect and remove erroneous entries in the coordination files.

RESULTS

LOGIC SHAKEDOWN AND MODIFICATION PHASE.

Initially, the FTEG was used to identify logic discrepancies. Once these problems were corrected, the general performance of the TCAS logic for unequipped threats was identified. The logic problems detected can be placed into one of six groups: tracking logic, advisory display sequences, vertical speed minimum advisory (VSM) logic deficiencies, display logic flaws, data structures and housekeeping logic, and traffic advisory logic:

TRACKING LOGIC.

Nonlinear Tracker. The inclusion of a nonlinear vertical tracking concept represented the most significant addition to the TCAS logic for unequipped threats. Modifications to the baseline logic were necessary to properly implement the nonlinear tracker. The baseline logic did not utilize the variable, ZFLG, to identify missing or garbled Mode C replies.

Problem 1 - No Tracking of Negative Altitude Replies. The measured altitude, ZM, was set to 0 feet whenever the Mode C reply for a particular threat was garbled or missing. This procedure prevented the tracking of negative altitude replies. Existing standards permit negative Mode C replies down to -1,200 feet. Modifications to the nonlinear tracking logic, TRACKZ, were made to utilize ZFLG and permit the tracking of negative altitudes. Additional improvements to TRACKZ were made to prevent division by 0. These changes were thoroughly tested at the Technical Center.

Problem 2 - Long Settling Time Following Isolated Mode C Transitions. A second problem with the nonlinear tracking logic was detected. The original intention of the nonlinear tracking logic was to prevent indefinite rate estimate limit cycles following a Mode C change due to an altitude oscillation across a Mode C boundary rather than Mode C change due to an established vertical rate. Flight test results of the Dalmo Victor TCAS units indicate that long nonzero rate estimates exceeding 40 seconds occur for an aircraft in level flight transitions across the Mode C boundary and remains there.

The problem has been traced to the NOTRANZ logic shown in figure 2. The problem is that the decay factor P_3 (=0.9) causes the rate of increase in Z7, the

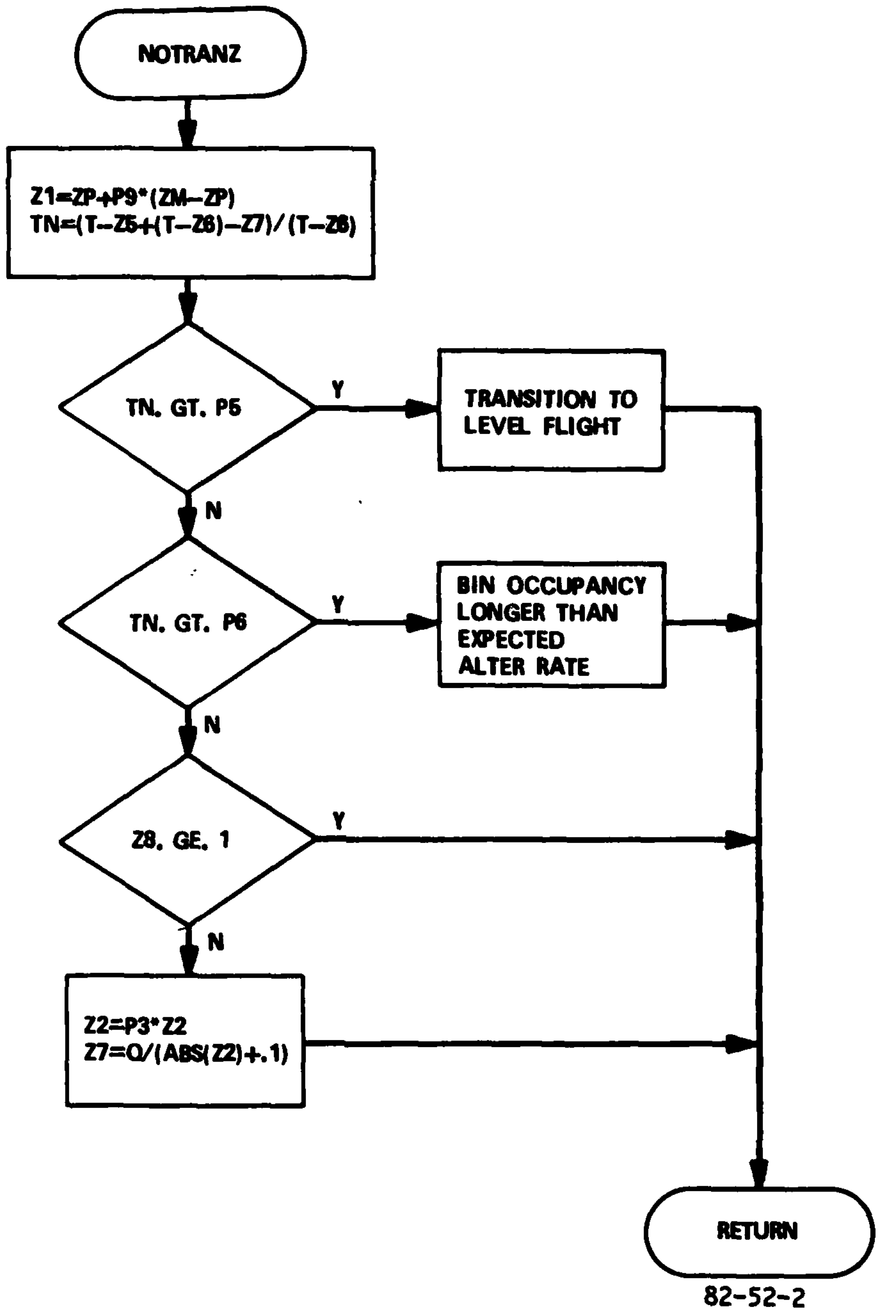


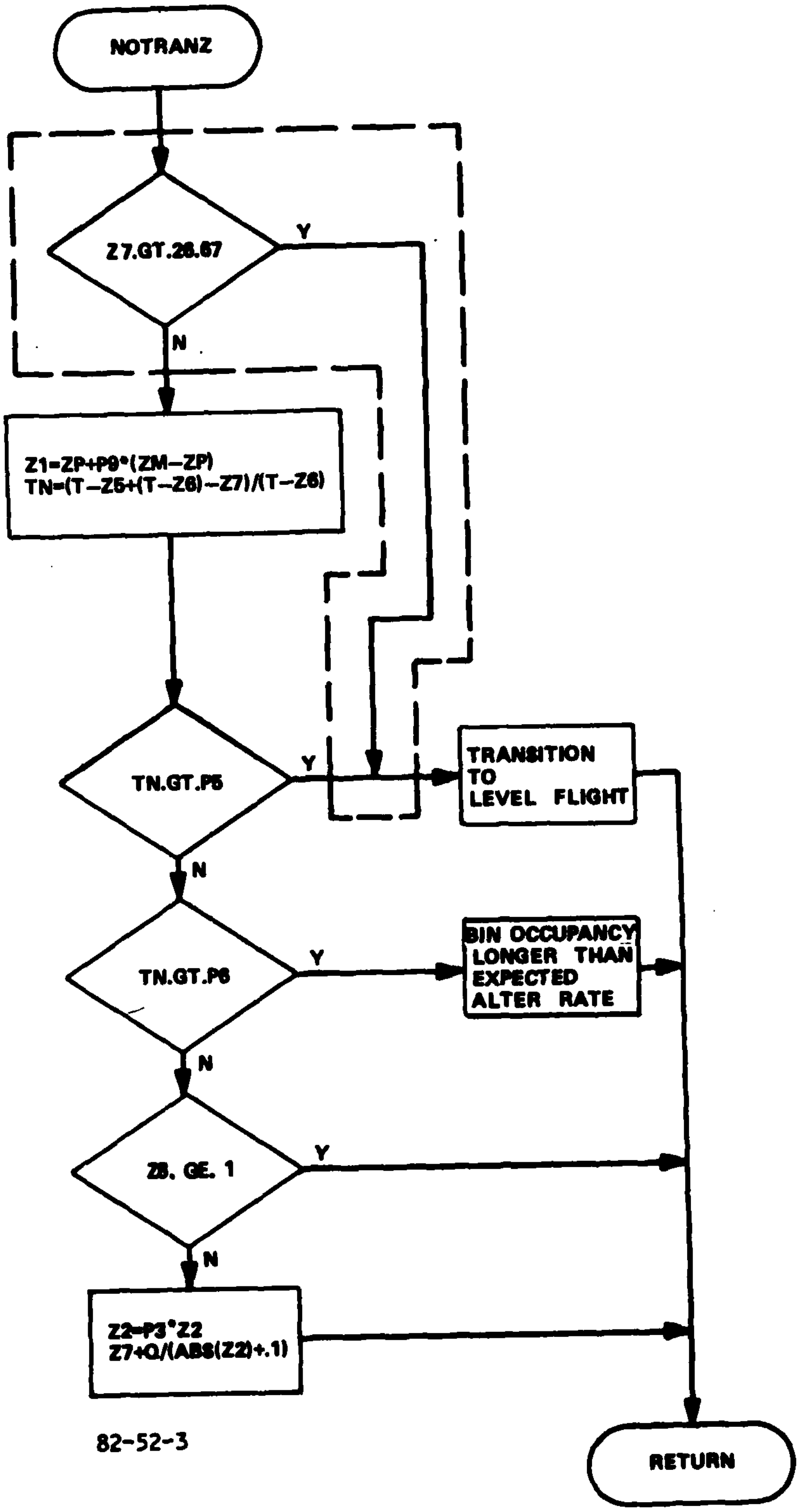
FIGURE 2. NO TRANSITION MODE C LOGIC

estimated bin occupancy time, to grow at a faster rate than real time. As a result TN will decrease continually preventing the tracker to reinitialize to level flight. Table 1 identifies the sequential values of Z7 following a single Mode C transition without an established rate. The Mode C transition occurs at t+3 and the vertical rate is set to $P_1 = 8$ ft/sec. The value of Z7 is 12.5 resulting in TN = -10.50 at t+4. Since $P_3 = 0.9$, the value of Z7 grows at a rate which causes TN to decrease exponentially. Hence, TN can never exceed P_5 (5 seconds) and a nonzero vertical rate estimate Z2 exists more than 20 seconds after the transition.

An additional check of Z7 was added to the logic as shown in figure 3. Whenever the expected bin occupancy time exceeded 26.667 seconds, the tracker was reinitialized to level flight. The bin occupancy time for a 225 ft/min rate is 26.667 seconds. The change permits the tracker to be reinitialized to level flight 8 seconds after the Mode C transition. The step responses to the original and modified logic are compared in figure 4.

Following a Mode C transition, this logic addition will result in the same response, as shown in figure 4, for any fixed rate less than 225 ft/min. The Mode C transition should occur, at most, once every 27 seconds. The logic addition does nothing to tracker performance for rates above 667 ft/min. For rates between 225 and 667 ft/min, the performance of the tracker, following the second Mode C transition, is the same as before the logic addition.

Own Aircraft Tracking Problem Improper Parameter Setting When Own Altitude is Negative. The own aircraft tracking logic, TROACT, had a discrepancy which prohibited the proper setting of altitude dependent parametric thresholds. The parameters ALIM, ADIV, and ZT are set based on the altitude strata in which the own aircraft is currently located. The strata is identified by the variable LAYER. LAYER is set by comparing the own tracked altitude, ZOWN, with tabled values for the top (TOP(•)) and bottom (BOT(•)) of each strata. When ZOWN is negative, the test BOT (LAYER) LE. ZOWN always fails since the smallest BOT value is 0. To provide for proper altitude parameter setting, when own altitude is negative, the change shown in figure 5 was added to the TROACT logic.



82-52-3

FIGURE 3. MODIFIED NO TRANSITION LOGIC

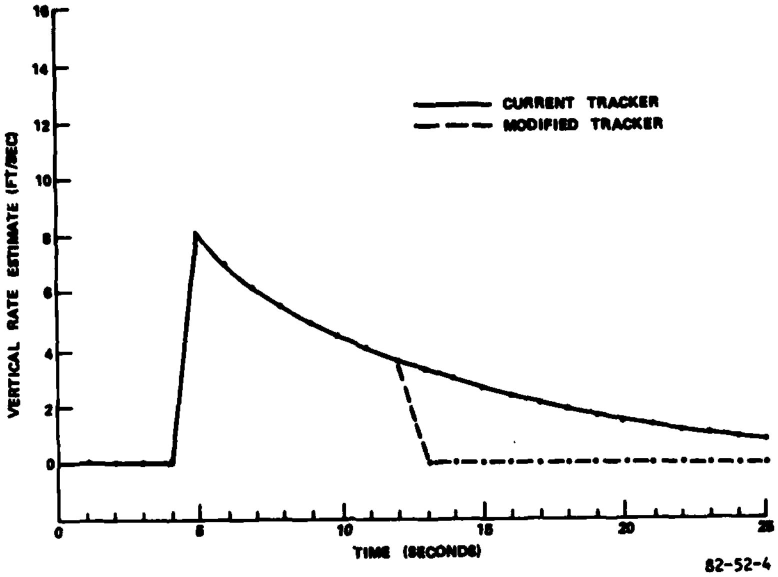


FIGURE 4. COMPARISON OF MODE C TRANSITION RESPONSES

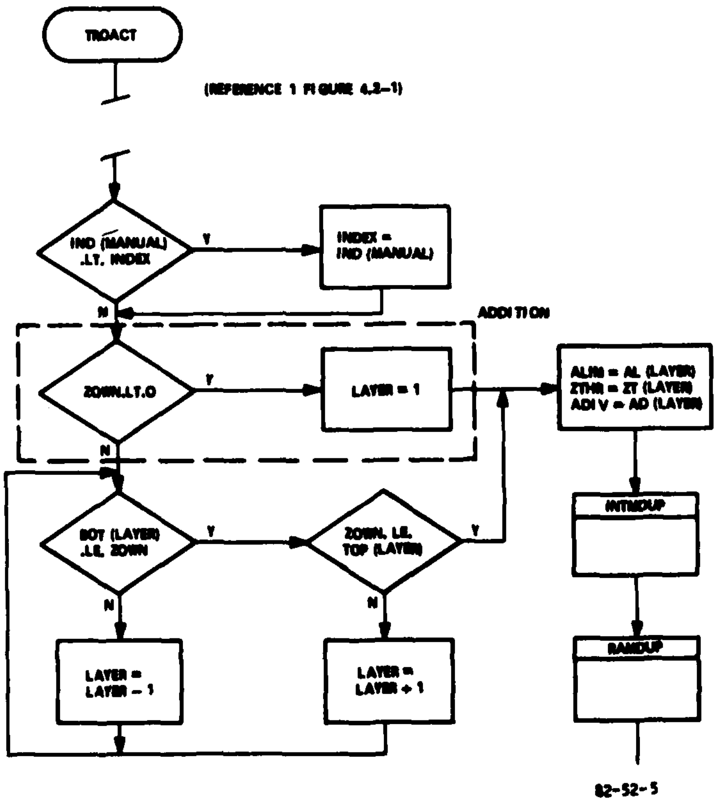


FIGURE 5. CHANGES TO TROACT LOGIC

TABLE 1. VARIABLE STATUS FOLLOWING A REINFORCED MODE C TRANSITION

TIME	MODE C	TN	Z5	Z2	Z7	Z8
t	3000	t-99	1	0	99	0
t+1	3000	t-99	1	0	99	0
t+2	3000	t-99	1	0	99	0
t+3	3100	-	t+3	8.00	12.50	0
t+4	3100	-10.50	t+3	7.20	13.69	0
t+5	3100	-10.69	t+3	6.48	15.43	0
t+6	3100	-11.43	t+3	5.83	17.15	0
t+7	3100	-12.15	t+3	5.25	19.05	0
t+8	3100	-13.05	t+3	4.72	21.18	0
t+9	3100	-14.18	t+3	4.25	23.54	0
t+10	3100	-15.54	t+3	3.83	26.14	0
t+11	3100	-17.14	t+3	3.45	29.01	0
t+12	3100	-19.01	t+3	3.10	32.23	0
t+13	3100	-21.23	t+3	2.79	35.84	0
t+14	3100	-23.84	t+3	2.51	39.82	0
t+15	3100	-26.82	t+3	2.26	44.27	0
t+16	3100	-30.27	t+3	2.03	49.16	0
t+17	3100	-34.16	t+3	1.83	54.73	0
t+18	3100	-38.73	t+3	1.64	60.81	0
t+19	3100	-43.82	t+3	1.48	67.57	0
t+20	3100	-49.57	t+3	1.33	75.19	0
t+21	3100	-56.19	t+3	1.20	83.54	0
t+22	3100	-63.54	t+3	1.08	92.82	0
t+23	3100	-71.82	t+3	0.97	103.26	0

Improper Coasting of Range Data. The intruder tracking logic had a few discrepancies which were detected early in simulation testing. The logic for coasting the intruder range during missing data periods was incorrect. Figure 4.3-1B of reference 1 calculated the range, R, and range rate, RD, based on the value, RR, the surveillance reported range. This element does not exist during missing data periods. The range should be coasted as shown in figure 6. The range rate should not be adjusted during missing data periods.

Track File Deletion. Initial testing revealed another discrepancy in the TRIACT logic. If surveillance reports for a specific intruder are not received for a consecutive 10-second (TDROP) period, the row (ITROW) in the intruder track file associated with that intruder is deleted. If an entry existed in the threat file for this intruder (TFROW=ITROW), the original logic reset the threat file pointer TFROW to 0 and added the threat to the working list with STATUS=TERM. Since the original logic set both ITROW and TFROW to 0, the resolution and coordination logic, RESCOOR, is entered without the ability to recover the identity or track file number of the threat for which an active command must be terminated. If the threat had been TCAS equipped, termination could not be properly supported.

To correct this deficiency, the additional changes in figure 7 were added to the TRIACT logic. If 10 (TDROP) consecutive missing reports occur and the intruder in question is not in the threat file (TFROW=ITROW), the intruder track file can be immediately deleted as it was in the previous logic. If there is a threat file entry for the intruder in question, the intruder track file entry is not deleted since the identity element, IDINT, is required by the resolution and coordination logic. The logic modification shown in figure 7 permits a two-step removal of data from the threat file and intruder track file. On the current logic cycle, threat file entries will be deleted as they normally would for terminal status threats. On the next cycle through TRIACT, the intruder track file will be purged since TFROW no longer equals ITROW.

To accomplish this two-step purge of the files, the logic modification retains TFROW and sets an additional flag DITF which is added to the intruder track file. The flag DITF (ITROW), when it is set, indicates the ITROW entry already has established a working list entry because of 10 consecutive missing reports. The flag is subsequently used by the detection logic, DETECT, on the current logic cycle to prevent formation of two working list entries for the same intruder. The incorporation of the DITF flag into the detection logic is shown in figure 7.

With the modification, the resolution and coordination logic is now entered with a terminal status working list entry which is properly supported with intruder track file and threat file entries. The deletion of the threat file entry can now proceed in the threat file updating logic, TFRUPO, as it does with any other terminal status threat. Since TFROW will be reset to 0, the intruder track file will be deleted on the next pass through the intruder tracking logic.

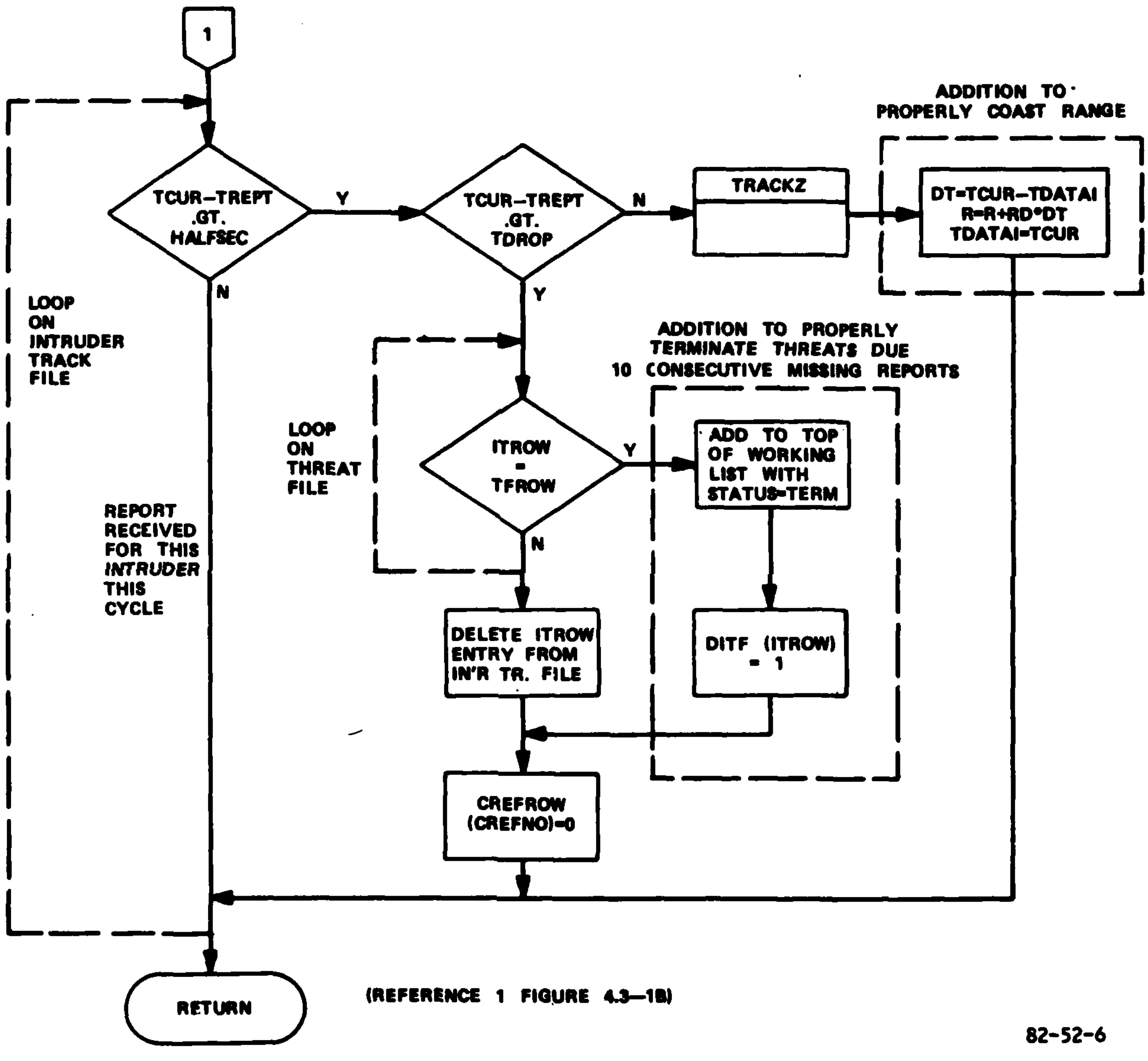


FIGURE 6. CHANGES TO TRIACT LOGIC

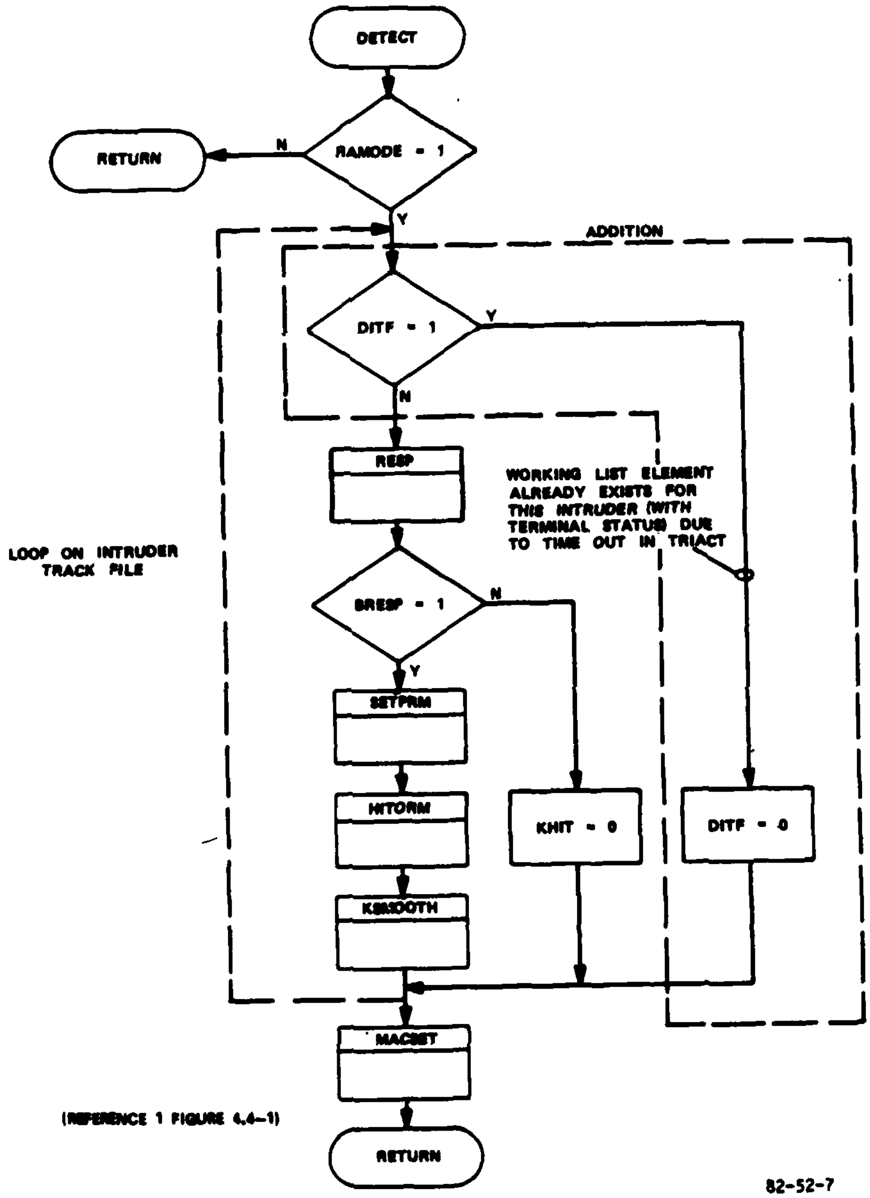


FIGURE 7. CHANGES TO DETECT LOGIC

Surveillance Tracking. Although the TCAS surveillance logic was not part of the evaluation, a discrepancy between the surveillance tracking and CAS logic intruder tracking module TRIACT was detected. During acceptance testing of the Dalmo Victor TCAS units, numerous short duration splits in intruder tracks were detected. These splits were traced to different track coast time limits in the surveillance tracking and intruder tracking logic. Surveillance tracking may drop a surveillance track after as little as four consecutive misses in surveillance correlation. However, the intruder tracking logic does not drop a track until 10 consecutive misses. As a result, intruder tracking can continue for 6 seconds after surveillance tracking has already dropped the track. If surveillance tracking initializes another track for the same intruder during this 6-second period, the intruder track files will contain two tracks for the same intruder. It is suggested that the track coasting time-limits in the surveillance tracking and intruder tracking routes be matched.

ADVISORY DISPLAY SEQUENCES.

Problem 1 - Advisory Timer. The variable which identifies the time when a particular advisory was generated for a specific threat is TCMD. The method of initializing entries in the threat file causes a delay in generating advisories. TRFNEWO is the logic which creates new entries in the threat file. When a new entry is created, TCMD is set to the current system time, TCUR. Subsequently on the same logic cycle, the select advisory logic, SELADV, is accessed. An immediate check is made to compare the difference between TCUR and TCMD. Only when it exceeds the minimum display time, TMIN (5 seconds), can an advisory be selected. As a result, no advisory results on the initial logic cycle. To correct the situation, TCMD should be set to 0 when creating a new threat file entry. SELADV can then be properly exercised. The time of command, TCMD, will then be properly set to TCUR by the threat file updating logic, TRFUPDO.

Problem 2 - 1-Second Alarm Transitions. The logic is designed to provide for a minimum 5-second display period. However, simulation has shown that a threat can be removed from the threat file independently of the duration of the alarm display. This occurs because the baseline logic did not use TCMD in determining when a threat was to be terminated. Two consecutive misses by the detection logic causes the removal of the threat from the threat file and elimination of the displayed advisory regardless of the alarm duration.

To correct the problem, KSMOOTH, the logic which sets the hit counter, KHIT, was modified. Figure 8 presents these changes. Unless TCUR-TCMD is greater than 4 seconds, KHIT is not reset to 1. KHIT is retained at 3. Hence, two consecutive misses are not declared until the advisory has been displayed for 5 seconds.

VERTICAL SPEED MINIMUM ADVISORY LOGIC DEFICIENCIES. The new collision avoidance logic has the capability of generating vertical speed minimum advisories (VSM). These advisories warn the pilot of specific vertical rates to be maintained in order to generate adequate vertical separation. A VSM can only be generated when the own aircraft's vertical rate exceeds the rate to be commanded. If this condition does not hold, a positive command results.

Initial logic testing of the VSM logic led to the detection of two deficiencies which have since been corrected. A problem with the original vertical minimum speed logic (POSVSL) was the sign in the vertical miss distance (VMD_i) (i = 5,10,20) vertical position projections. Prior to analyzing logic performance, the VSM logic was corrected as shown in figure 9.

Another deficiency identified was that VSM's had no minimum display time requirement. The TCAS logic did not incorporate a timer to limit cyclic, short duration VSM magnitude variations and VSM to positive advisory transitions. The minimum display time is determined by comparing the current system time, TCUR, with TCMD, the time the advisory was initially set. TCMD is a threat file element. Since the logic must treat VSM's of any magnitude as a positive advisory of the same sense, 1,000, 2,000, and 500 VSM's and positive advisories of the same sense are all considered to be the same. As a result, TCMD was not updated when the VSM magnitude changed or the VSM was replaced by a positive command. This caused short duration and oscillating advisories.

The sequential TCAS data for a particular encounter demonstrate the problem. The sequential TCAS alarm data are listed in table 2. At time 51, the first hit occurs.

TABLE 2. RESULTS DEMONSTRATING CYCLIC VSM ALARMS

TIME	ADVISORY	DURATION (seconds)
52	DESCENT	6
58	VSM 2000	3
61	DESCEND	2
63	VSM 2000	3
66	NONE	2
68	DESCEND	6
74	NO CLIMB	11

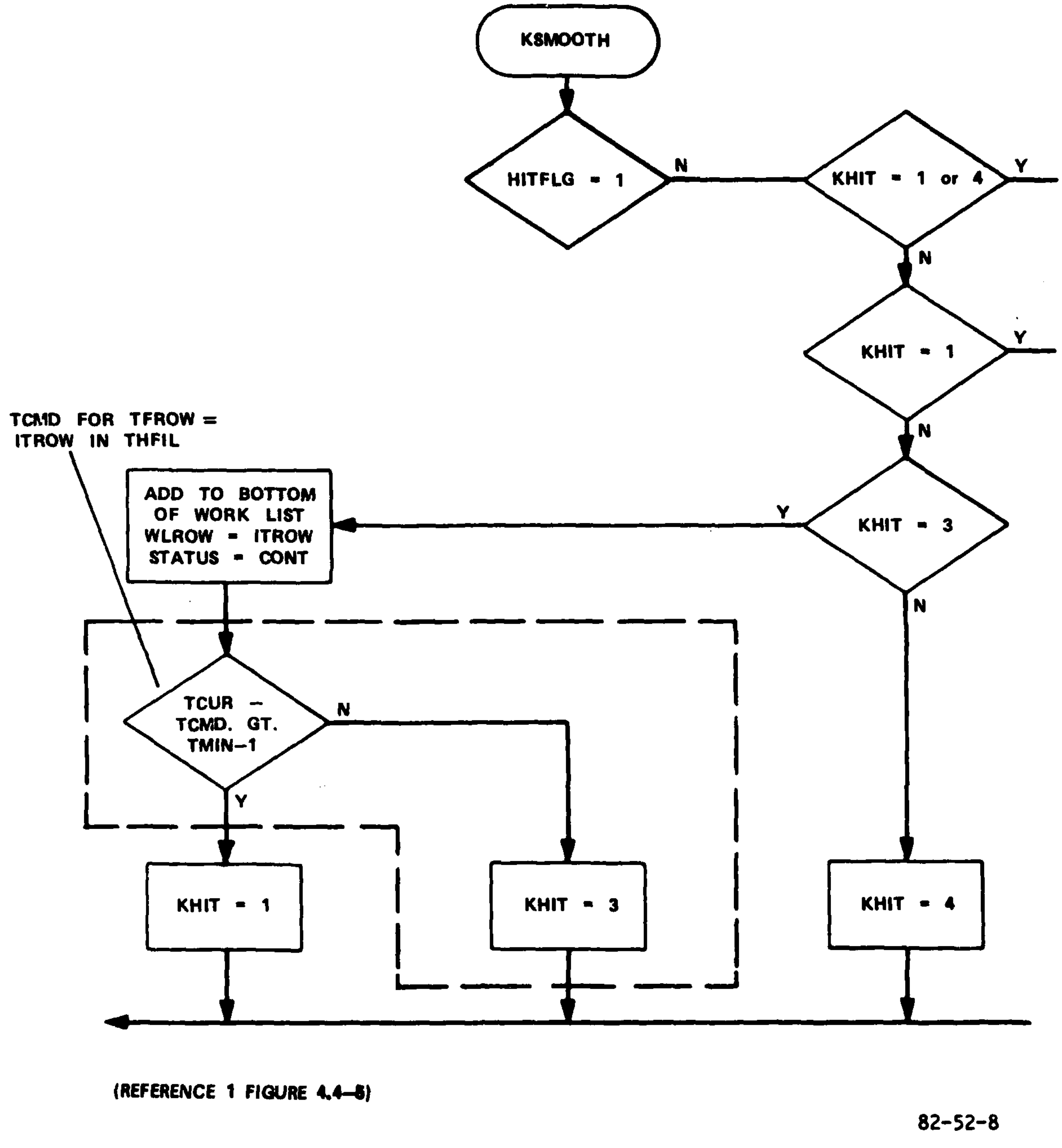


FIGURE 8. CHANGES TO KSMOOTH LOGIC

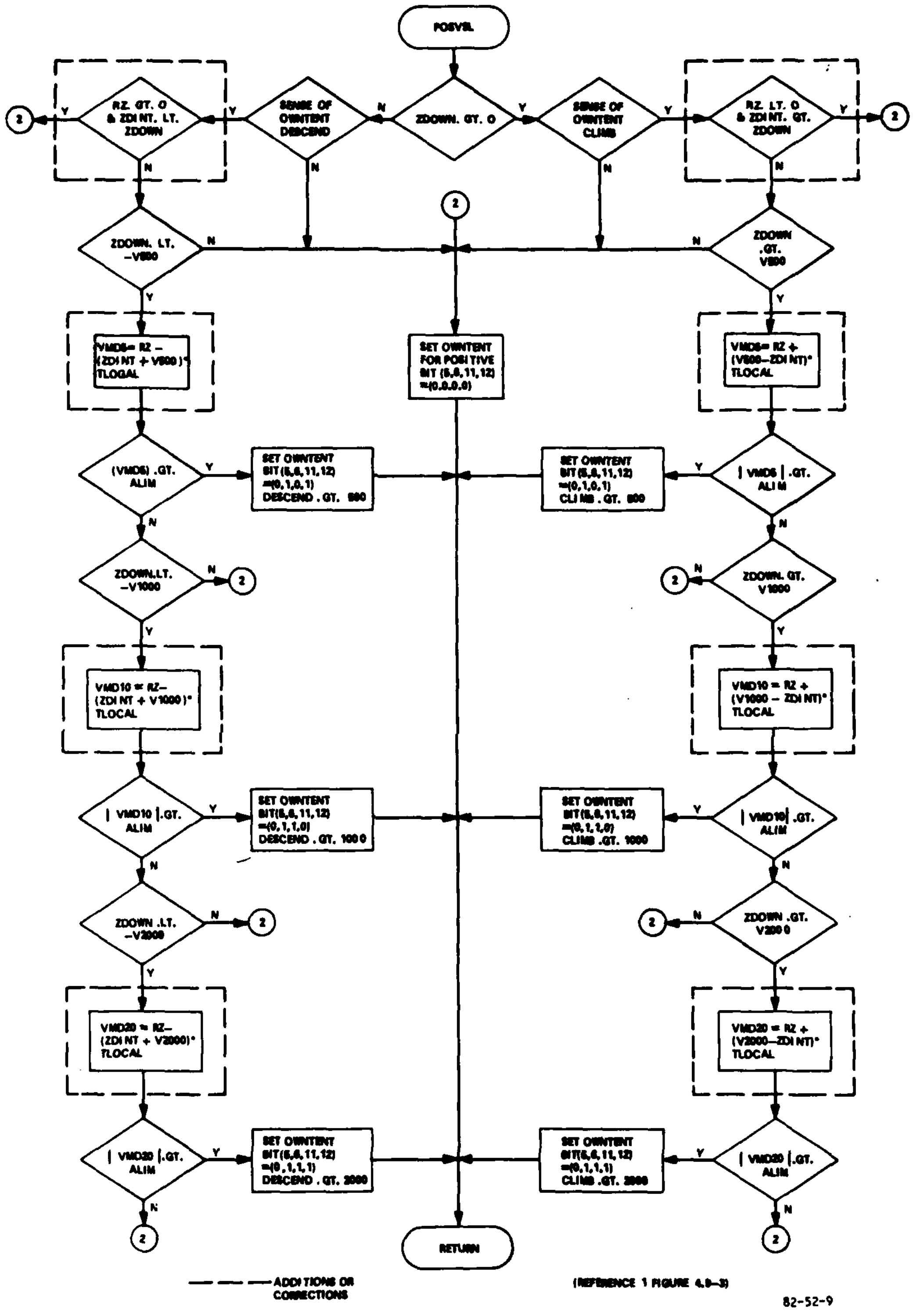


FIGURE 9. NEW VERTICAL SPEED MINIMUM LOGIC

In order to resolve this problem, Mitre developed additions to the threat file updating logic, TRFUPDO. Whenever the VSM magnitude changed or the VSM transitioned to a positive command, the time of command variable, TCMD, was updated. The logic additions are identified in figure 10. These additions were thoroughly tested and have eliminated the short cyclic advisory patterns that previously existed.

DISPLAY LOGIC FLAWS. At the end of the resolution logic cycle, the current status of the display register is read. Based on the status of the register, a display vector and audio alarm flags are set. The vector is used to drive the cockpit display device. If the audio alarm flag is set, an audio alarm may be triggered. Several discrepancies in the original display logic were detected and corrected.

The logic attempted to set the audio alarm flag by comparing the current system TCUR, with the variable TCMD. The problem with the approach is that TCMD is a threat dependent variable and identifies the time of command associated with a particular threat. It does not represent the global status of the cockpit display. It should be noted that the display logic is not exercised after each threat file is updated. The display logic is only called once after all threat files have been updated. As a result, the variable TCMD has no meaning during multiple threat periods. The audio flag must be set based on a change in the global status of the cockpit display on this logic cycle.

A proper method of setting the audio flag is shown in figure 11. DV is the current display vector. LDV is the image of the display vector on the last logic cycle. Only when $DV(I) \neq LDV(I)$ and $DV(I) = 0$ should the audio flag be set. More sophisticated methods of setting the audio alarm flag could be developed. However, this is a human factor question and will not be discussed here.

Another discrepancy that was isolated in the display logic was the incorrect use of the sense choice element of the PERMTENT array. VSM's are displayed only if positive commands of the same sense are not present. The discrepancy prevented the proper displaying of VSM's. Minor changes were made to the display logic to correct the deficiency. Testing showed the changes resulted in the proper displaying of VSM's.

DATA STRUCTURES AND HOUSEKEEPING LOGIC. Several modifications were made to the logic data structures and housekeeping logic prior to analyzing performance for unequipped threats. In the TCAS housekeeping logic, HSKBCA does not explicitly unlock the maneuver coordination register when a lock time-out occurs. To insure proper unlocking of the register following lock time-out, the modification shown in figure 12 was added to the HSKBCA logic. The logic now conforms to the explicit unlocking of the register that occurs in the resolution and coordination logic, RESCOOR.

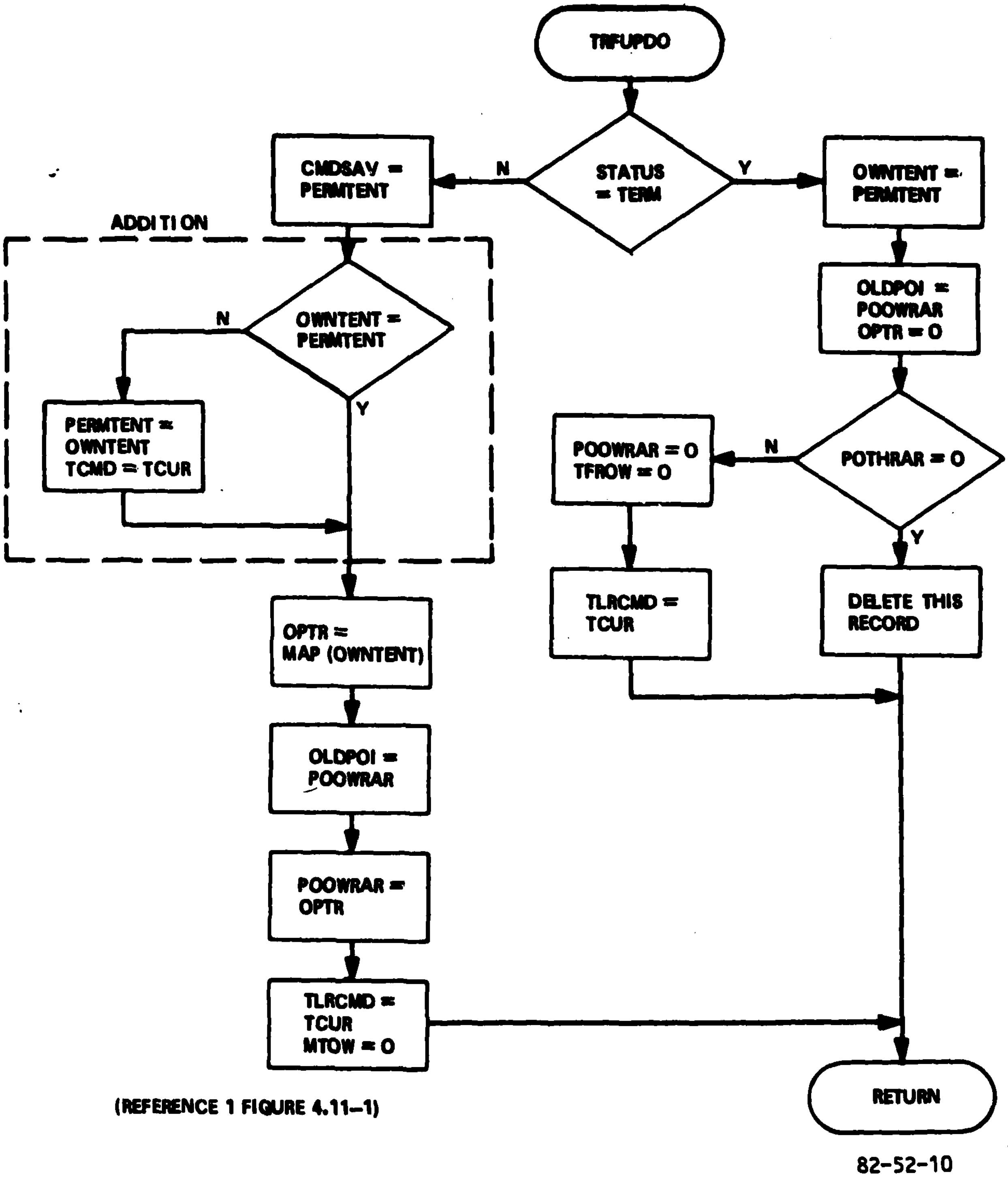
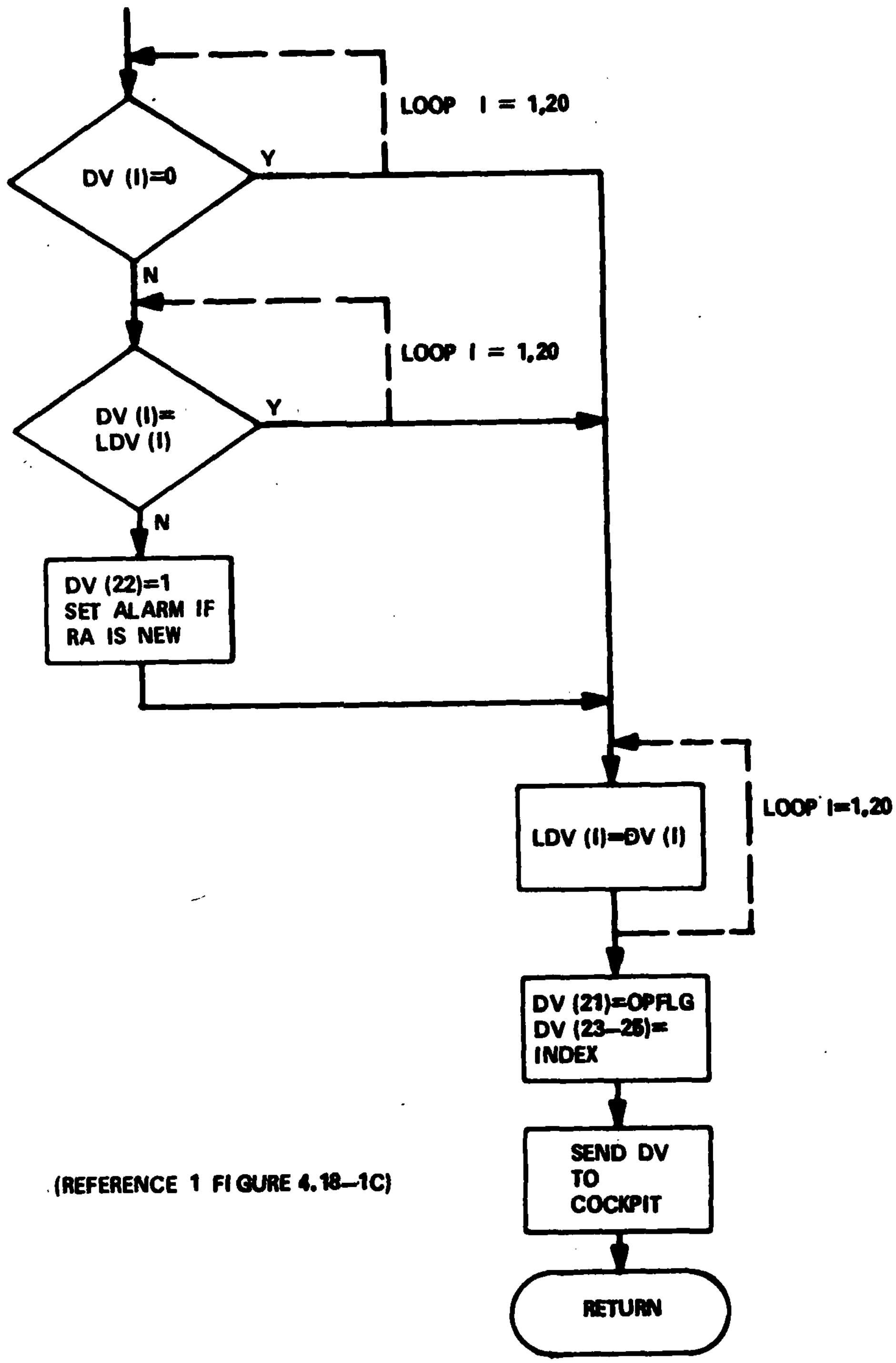
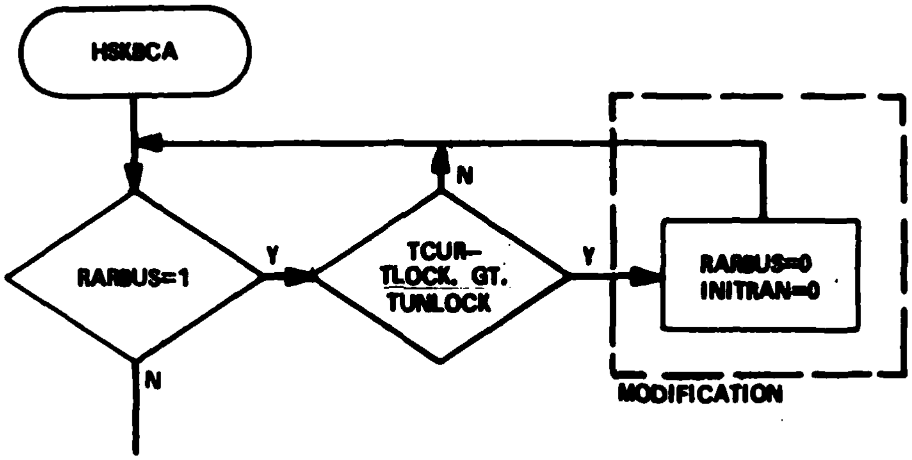


FIGURE 10. LOGIC ADDITIONS WHICH ELIMINATE SHORT CYCLIC VSM ADVISORIES



82-52-11

FIGURE 11. LOGIC MODIFICATIONS TO DISPLA LOGIC TO PROPERLY SET AUDIO ALARM TRIGGER



(REFERENCE 1 FIGURE 4.20-1)

82-52-12

FIGURE 12. MODIFICATION TO PROVIDE EXPLICIT UNLOCKING OF THE MANEUVER COORDINATION REGISTER

The interaction between the threat file housekeeping logic, HSKTRF, and the maneuver coordination register housekeeping logic, HSKRARB, did not properly delete timed-out advisories from the register. The HSKTRF is designed to build a vector of pointers to identify which register entries are to be purged. This list of pointers, which represent the register row number, is insufficient to delete a TCAS entry. The deletion module, RARDEL, requires both a row number and column number as input. Since the upper loop in the HSKTRF logic identifies advisories to be removed from column 5 of the register and the lower loop identifies entries to be purged from column 6, the HSKTRF logic should be modified as shown in figure 13. The advisories can now be deleted sequentially by calling RARDEL in each loop when necessary. This change permits the elimination of the HSKRARB logic. The reduced high level housekeeping logic, HSKBCA, is shown in figure 14.

The final data structure change was the development of a pointer which directly associated an intruder's position in the working list with its position in the threat file. The new pointer, WTROW, has been added to the working list array and points directly to the appropriate threat file entry. Figure 15 shows the new pointer usage. It is set in each cycle in the KSMOOTH logic.

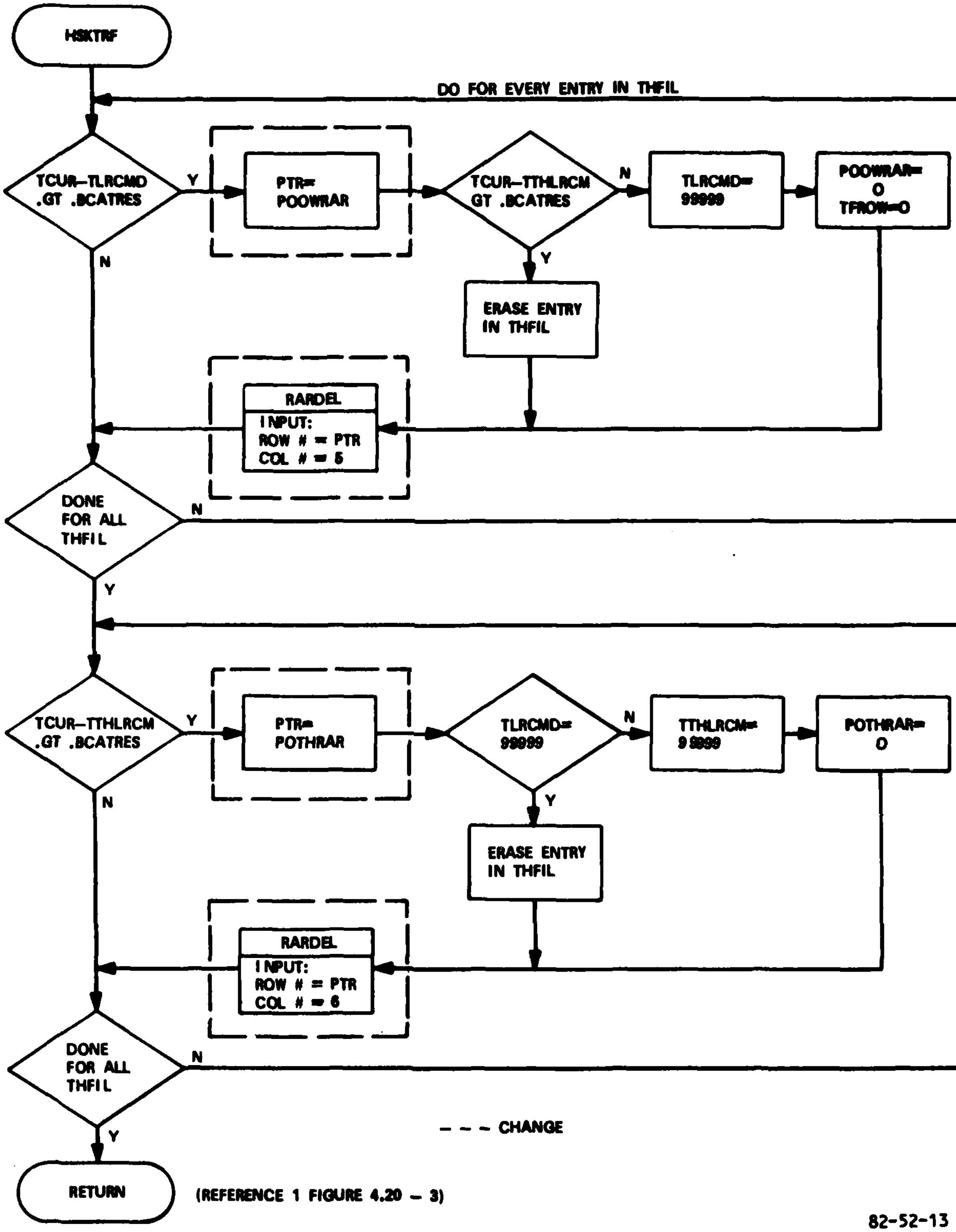


FIGURE 13. LOGIC MODIFICATION TO HSKTRF TO ENSURE PROPER DELETION OF MANEUVER COORDINATION REGISTER ENTRIES

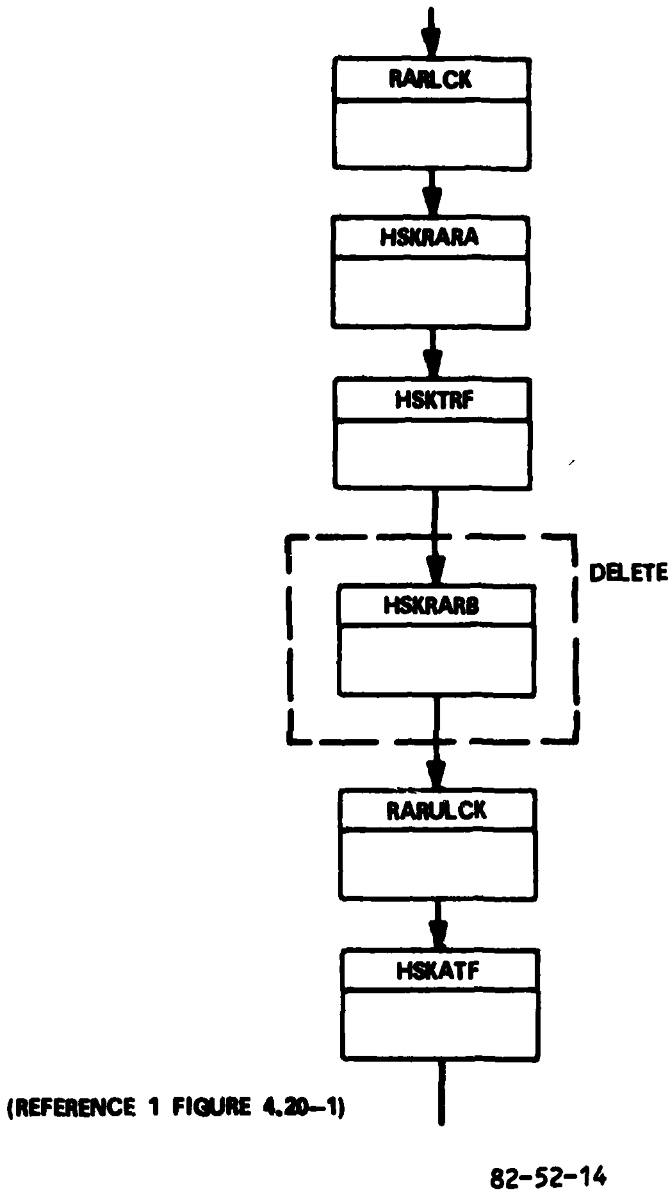


FIGURE 14. HIGH LEVEL HSKBCA LOGIC CHANGE

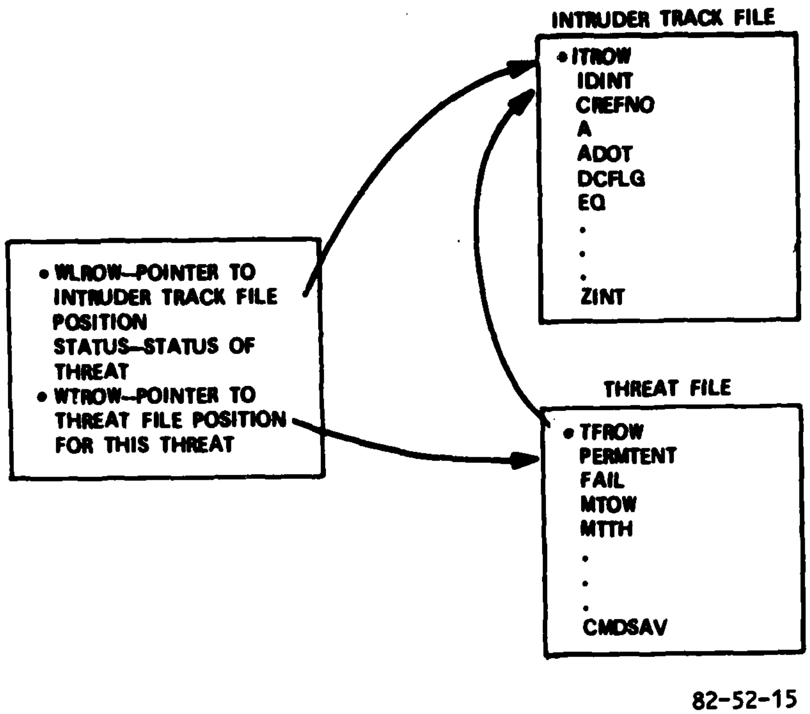


FIGURE 15. NEW LINKAGE BETWEEN THE WORKING LIST, THREAT FILE, AND INTRUDER TRACK FILE

TRAFFIC ADVISORY LOGIC. The baseline logic (reference 1) included optional logic for the generation of traffic advisories. If the logic is implemented range, range rate, bearing, altitude, and altitude rate, information of intruders satisfying certain criteria would be provided to a cockpit display. Analysis of the functional performance of the traffic advisory logic was made. The results of this analysis are described below.

TRAFADV is the high level logic for the display of TCAS traffic advisories. TRAFDET determines which intruders require traffic advisories by searching the Intruder Track File (ITF). When an intruder is found which requires an advisory, a Traffic Advisory File (TAF) entry is generated. The first element in this entry TAROW points to the ITF row associated with this advisory. Once a TAF entry is generated, it will remain displayed until the intruder no longer requires an advisory or until the TAF entry times-out due to no updating. The time-out parameter, TATLIM, is 30 seconds.

It is possible to display an advisory for 29 seconds and not update it at all. Once the intruder is detected within the traffic advisory volume airspace, the TAF entry is generated. If the ITF entry associated with this advisory is deleted on the next logic cycle, the advisory cannot be updated or deleted. This condition would last until TATLIM is exceeded.

The solution is to add a simple check to the TRAFADV logic. The addition is shown in figure 16. By looping on the TAF, any TAF entry which has a TAROW pointing to an empty ITF row can be deleted. This would prevent freezing a traffic advisory for which ITF data no longer exist for up to 29 seconds.

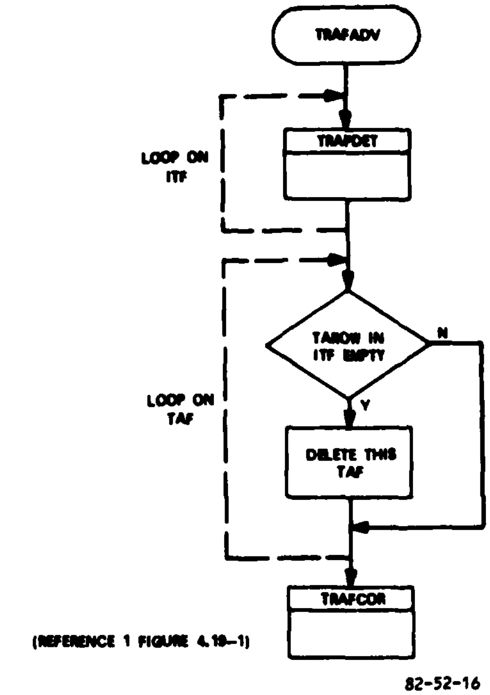


FIGURE 16. LOGIC ADDITION TO PREVENT FREEZING THE DISPLAY

In the traffic advisory detection logic, TRAFDET, the value TAURTA (a pseudo range tau) is calculated separately for each intruder. The value is required later in the traffic display logic, TRAFDIS, to prioritize traffic advisories. As a result, it should be added to the TAF as an intruder dependent variable. Two other problems exist. In the traffic advisory correlation logic, TRAFCOR, a TAF entry can be established without defining TAURTA. Also, certain logic paths in TRAFDET prevent updating or defining TAURTA.

Figure 17 identifies the logic additions to TRAFDET. When the current range is less than the range threshold for traffic advisories, then TAURTA should be set to zero since the traffic advisory associated with this threat should have a high priority. The same is true when the range is less than the tau distance modifier for traffic advisories, DMODTA.

TRAFCOR is designed to ensure a traffic advisory is generated for a threat that causes a TCAS command. Again, the value, TAURTA, must be defined. The same addition that was made to the traffic detection logic should also be made to the TRAFCOR logic. The addition is shown in figure 18.

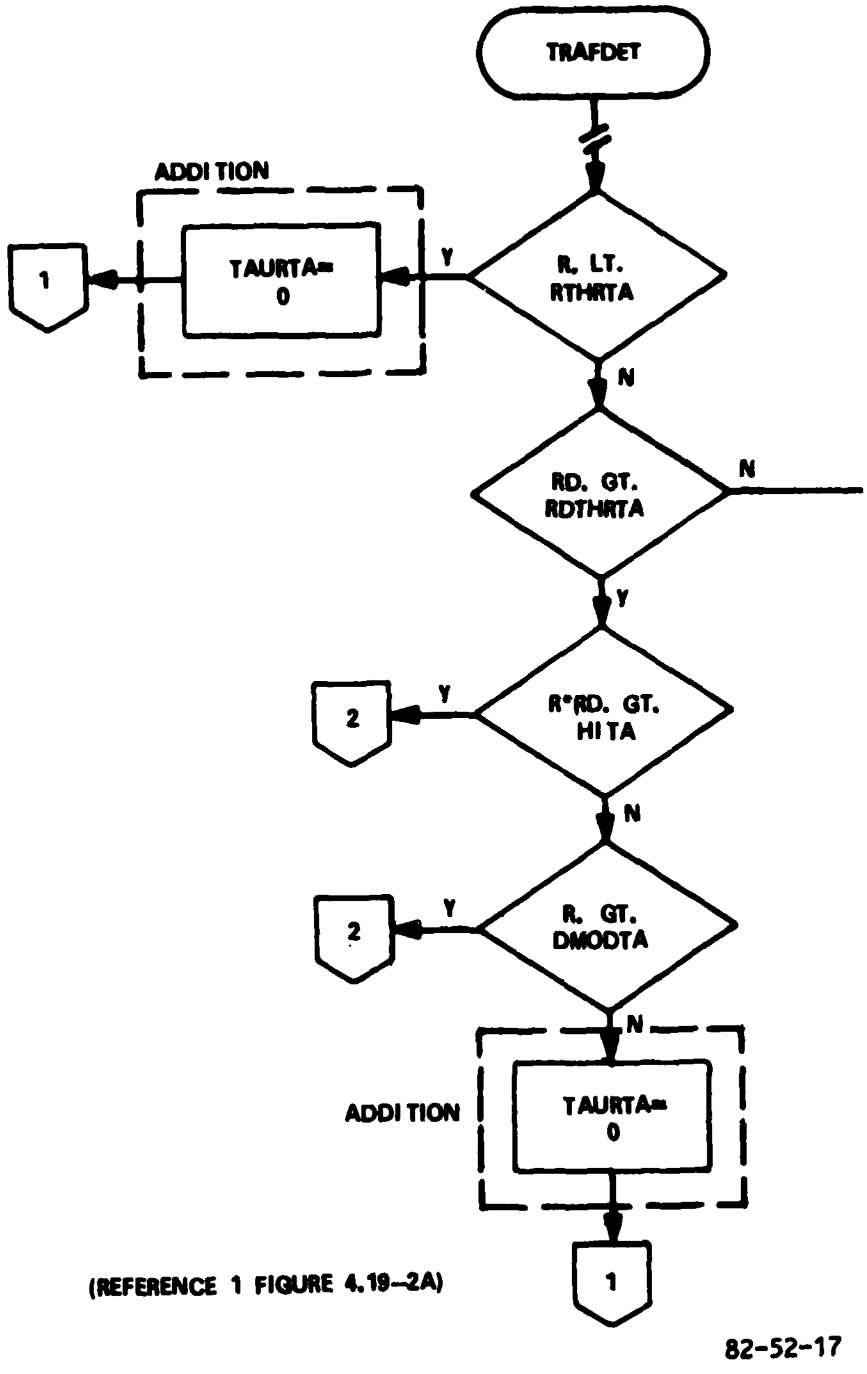
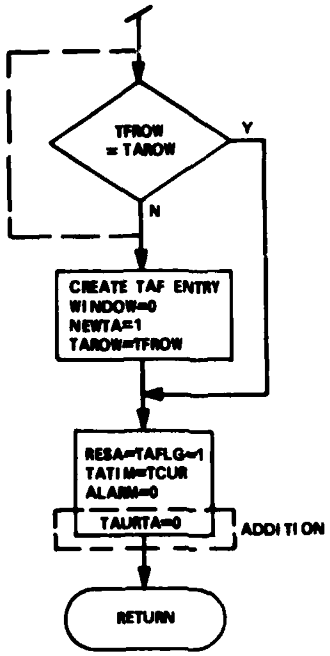


FIGURE 17. LOGIC ADDITIONS TO TRAFDET LOGIC



(REFERENCE 1 FIGURE 4.19-4)

82-52-18

FIGURE 18. LOGIC ADDITION TO THE TRAFCOR LOGIC

IMPROVED LOGIC PERFORMANCE TESTING PHASE.

Encounter geometries were designed to evaluate logic performance across a wide range of encounter conditions. All encounters were evaluated in an error-free environment; that is, on every logic cycle the proper range and Mode C altitude of the intruder were available.

As the result of previous TCAS logic testing, many encounter scenario conditions have been detected which could not be adequately handled by TCAS. Some of these scenarios include:

1. Tail-chase encounters which resulted in incorrect sense choice due to large vertical projection times or long duration vertical tail-chase encounters.

2. Vertical track crossing encounters which resulted in delayed or wrong sense choice commands.

3. Vertical rate encounters which resulted in cyclic command patterns.

4. Encounters in which slow vertical accelerations were not detected early enough by the tracking logic.

5. Horizontal maneuvering by the threat aircraft which was detected too late to permit the generation of adequate separation.

The encounter scenarios were analyzed at three logic sensitivity levels. Table 3 presents the parameter settings for the three sensitivity levels used. The results presented in the report represent a sampling of all results obtained. The text will identify the logic performance level used for the scenarios in question. Throughout the analysis, when a TCAS command necessitated a vertical profile deviation, the pilot response delay was fixed at 5 seconds. Following this delay period, the TCAS aircraft would accelerate at 0.25g to the TCAS escape maneuver rate. The escape rate was the TCAS commanded rate for negative and vertical speed limit commands and 1,000 ft/min for positive commands unless the aircraft was already in a vertical rate maneuver above 1,000 ft/min. In this case, the vertical rate was increased by 500 ft/min. The escape rates continued until the command changed or was removed. Following command removal, the TCAS aircraft would accelerate at 0.25g to its scenario vertical profile after a 3-second pilot delay.

TCAS performance for each scenario was tested with at least three performance level settings: level 4, level 5, and level 6. The sampling of results selected for presentation in this report uses the results obtained with a performance level setting which lead to the most noteworthy vertical separation performance.

The encounter scenarios can be divided into six groups: level flight encounters, vertical rate encounters, high altitude results, horizontal maneuvering encounters, vertical acceleration encounters, and large horizontal miss distances at CPA encounters. Throughout the remainder of the report, logic performance is evaluated in terms of resulting vertical separations at CPA versus the scenario separation conditions at CPA had TCAS action not occurred.

LEVEL FLIGHT ENCOUNTERS. The class of level flight encounters included those encounters in which both the intruder and own TCAS were in linear level flight prior to TCAS interaction. The planned vertical separation at CPA was varied from TCAS 1,000 feet below the intruder to TCAS 1,000 feet above the intruder in 100-foot increments. As a result, each scenario represents a set of 21 separate encounters. Figure 19 identifies the scenario conditions that will be reviewed. The results for four fixed crossing angles head-on (180°), tail chase (0°), quartering head-on (135°), quartering tail-chase (45°) and sensitivity level 5 parameters (25-second tau) will be presented. Additional analyses for high speed level flight encounters were also performed. The results were similar to that described below.

TABLE 3. LOGIC PARAMETER SETTINGS

Parameter		Sensitivity Level 4	5	6	Units
DMOD	- Modification distance for modified tau	0.1	0.3	1.0	nmi
TRTHRU	- Maximum predicted time to closest approach for unequipped threats	20	25	30	sec
TVTHRU	- Maximum predicted time to coaltitude for unequipped threats	20	25	30	sec
TVPCMD	- Maximum path prediction time for computing minimum altitude separation	40	40	45	sec
TVPESC	- Maximum time allotted for escape maneuver	30	30	35	sec
HI	- Maximum range diverging rate for threat declaration	.00278	.00278	.00278	nmi^2/sec
ALIM	- Predicted vertical separation threshold for positive commands		440*		feet
ADIV	- Vertical divergence thresholds for command removal		300*		feet
ZTHR	- Vertical threshold for threat definition		750*		feet

*Unless otherwise stated in text.

The results for the conditions shown in figure 19 are presented in graphical form on figures 20A and 20B. The abscissa is the planned separation at CPA, and the ordinate is the resulting separation at CPA. Graphic entries marked only with a point indicate conditions which resulted in no TCAS alarms. Points connected with a solid line represent encounter conditions which resulted in negative advisories or VSL advisories. Points connected by a dashed line represent conditions which resulted in positive alarms being generated. For instance, point A on figure 20A implies that for the 135° crossing angle and a scenario vertical separation of -300 feet (TCAS 300 feet below the intruder), a positive descent command occurred resulting in -467 feet (TCAS 467 feet below the intruder) vertical separation at CPA. The split in the graph between points B and C identifies the region in which the sense choice changed from descent (B) to climb (C). This convention of identifying separation performance and resulting advisory types will be continued throughout the remainder of the report.

Note on figure 20B, the intruder speed has been changed to 250 knots for the tail-chase condition. Hence, the TCAS aircraft is being overtaken by the intruder with a 70-knot closure rate. Except for the tail-chase condition, the performance pattern for the remaining crossing angles is quite consistent. In the tail-chase encounter, larger separations result for encounters with $|\text{scenario separation}| \leq$ 200 feet. This occurs because in tail-chase encounters, the true time to CPA (-range/range rate) at the time of the advisory is considerably larger than TAUR when the initial alarm occurs. This occurs because the alarm results when TAUR = -(range-DMOD)/range rate is less than THTHRU seconds. The error in the estimated time to CPA can be expressed as

$$E = -\ \text{DMOD/range rate} \qquad (1)$$

Hence, using (1) and letting DMOD = 0.3 nautical mile, table 4 identifies the error in the time to CPA when alarms occurred for each of the conditions analyzed. Table 4 also identifies the true time to CPA for sensitivity level 4 and 6 parameters.

Figures 20A and 20B represent the results of 84 separate encounters. In all cases, more than 300-foot vertical separation resulted at CPA. In all cases, when TCAS was below the intruder, descent sense advisories resulted, and when TCAS was above the intruder, climb sense advisories resulted.

TABLE 4. ERROR IN ESTIMATED TIME TO CPA WHEN INITIAL ALARM OCCURS

Crossing Angle (Degrees)	Range Rate (Knots)	Sensitivity Level 4 DMOD=0.1 THRHRU=20 (Secs)	Sensitivity Level 5 DMOD=0.3 THTHRU=25 (Secs)	Sensitivity Level 6 DMOD=1 THTHRU=30 (Secs)
0	-70	5.1	15.4	51.4
45	-138	2.6	7.8	26.1
135	-333	1.1	.2	10.8
180	-360	1.0	3.0	10.0

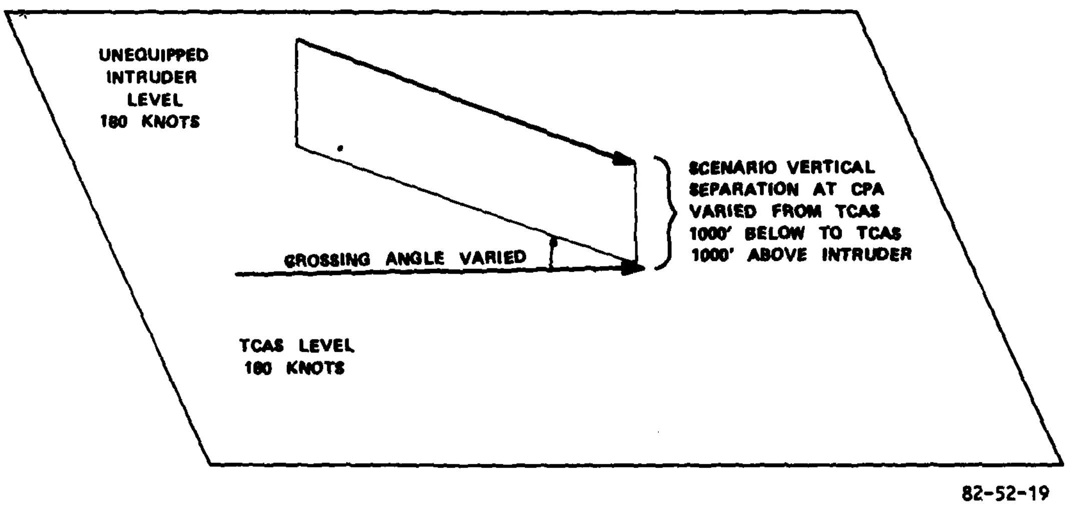
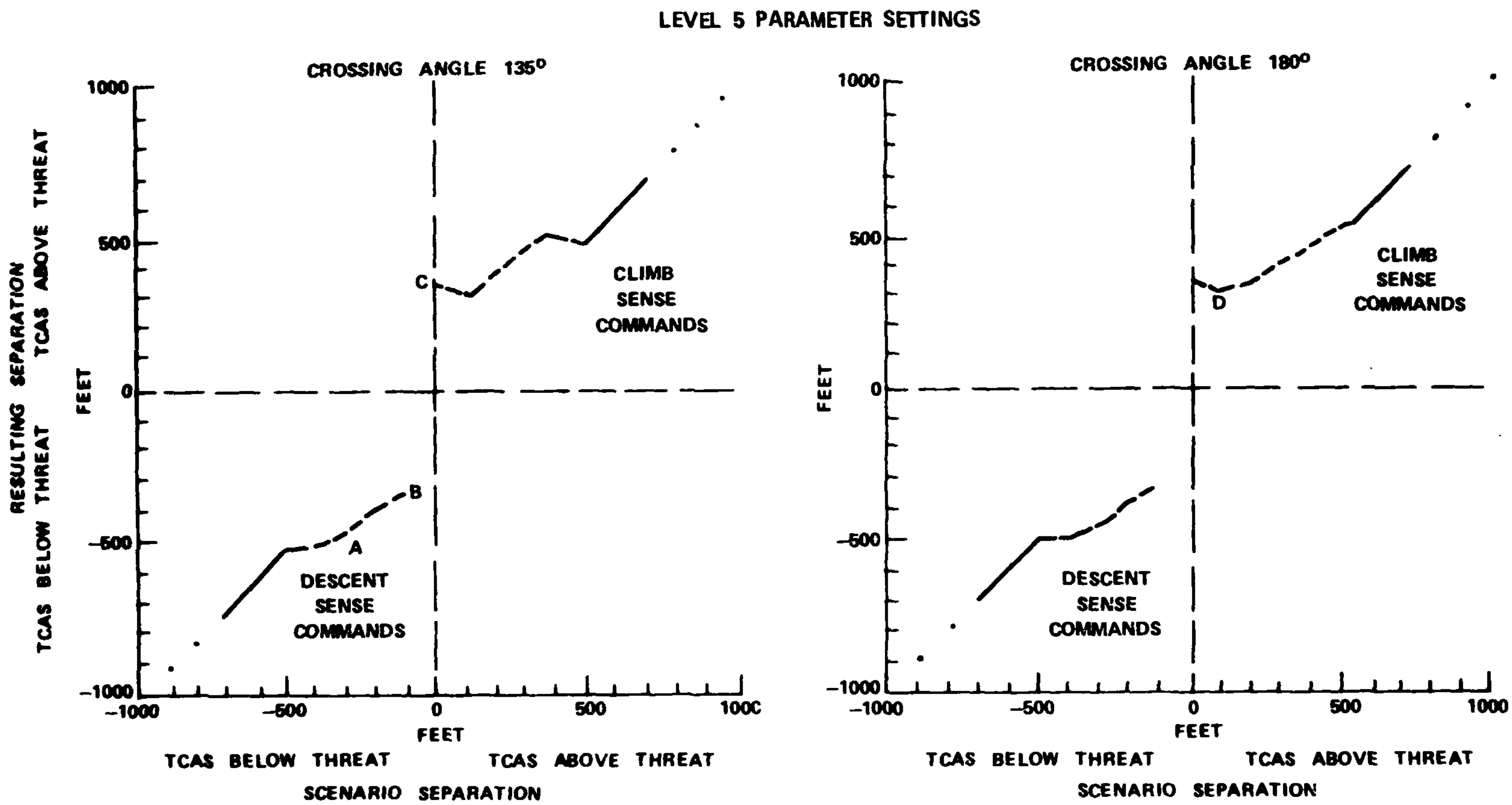


FIGURE 19. LEVEL FLIGHT ENCOUNTER CONDITIONS



82-52-20A

FIGURE 20A. LEVEL FLIGHT SCENARIO RESULTS (HIGH CROSSING ANGLES)

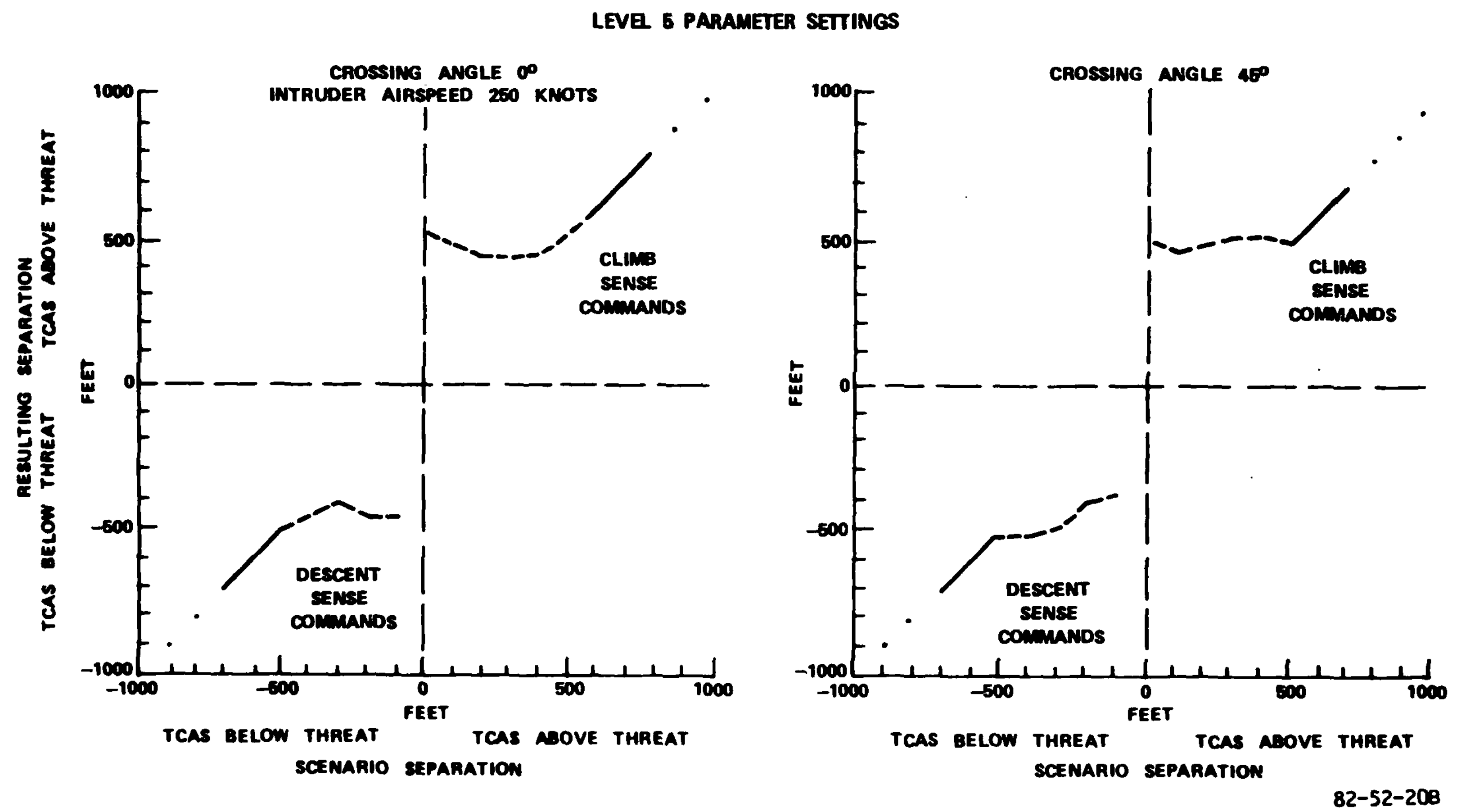


FIGURE 20B. LEVEL FLIGHT SCENARIO RESULTS (LOW CROSSING ANGLES)

Only minor variations in alarm patterns and resulting separations occurred for level flight encounters which involved speed differentials for the two aircraft. When the encounters were simulated in airspace in which 20-second tau criteria and DMOD = 0.1 nmi were used to identify threats, little loss in resulting separation occurred from the patterns shown in figures 20A and 20B. However, if the minimum alarm criteria identified in the baseline logic document (18-second tau and DMOD = 0.075 nmi) were used, numerous encounters resulted in vertical separation being less than 300 feet at CPA. For the smallest alarm thresholds, encounter conditions identified by point D on figure 20A resulted in the minimum observed vertical separation, 202 feet. This represented a reduction of more than 100 feet in vertical separation from the results for the level's parameter settings shown in figure 20A. The above analysis was based on review of over 1,300 level flight encounters.

VERTICAL RATE ENCOUNTERS. The vertical rate encounters involved those encounters in which the aircraft were in fixed vertical rate flight prior to TCAS interaction. The class can be divided into three cases: Case I - TCAS is in fixed vertical rate flight against a level flight intruder; Case II - TCAS is in level flight and the intruder is in fixed vertical rate flight; and Case III - both TCAS and the intruder are in fixed vertical rate flight.

For the first Case, the crossing angle was varied (45°, 90°, 135°, 180°,) and the TCAS vertical rate was varied in 500 ft/min increments from -500 to -3,000 ft/min. Figure 21 identifies all conditions analyzed for Case I vertical rate encounters. Over 500 encounters from this class were analyzed.

Little difference resulted with variations in crossing angle. Figure 22 identifies the performance for two specific scenarios: (1) TCAS descending at 1,500 ft/min and (2) TCAS descending at 3,000 ft/min. It is important to review the TCAS response model used in the simulation. If the TCAS command resulted in a change in the vertical rate, a 5-second pilot response delay with no change in vertical rate was modeled. This period was followed by an acceleration period during which the TCAS aircraft accelerated at 0.25g until the commanded rate was obtained. When positive commands occurred, the TCAS aircraft responded with a 1,000 ft/min vertical response unless the current rate was in the proper direction and greater than 1,000 ft/min. In this instance, the vertical rate of the TCAS aircraft was increased by 500 ft/min.

Figure 22 depicts results obtained with a 90° crossing angle and sensitivity level 5 parameter settings. In reviewing the results in figure 22, it is interesting to note the change in sense selection no longer corresponds with the planned CPA condition of 0 feet vertical separation. For the 1,500-ft/min descent rate, positive climb commands resulted even when the TCAS aircraft would have been 300 feet below the intruder at CPA. The current descent rate of the TCAS aircraft was not reinforced with a descent command until the TCAS was planned to be 400 feet or more below the intruder at CPA. When the TCAS aircraft was descending at 3,000 ft/min, a slightly different alarm pattern was observed. In this case, descent commands did not occur until the TCAS was planned to be 600 or more feet below the intruder at CPA. For Case I encounters, the region in which descent selection results is biased by TCAS's vertical rate. With higher descent rates, initial command selection occurs with more current vertical separation. This permits the sense selection logic to properly select climb maneuvers and generate adequate separation without crossing vertical track for a larger range of scenario

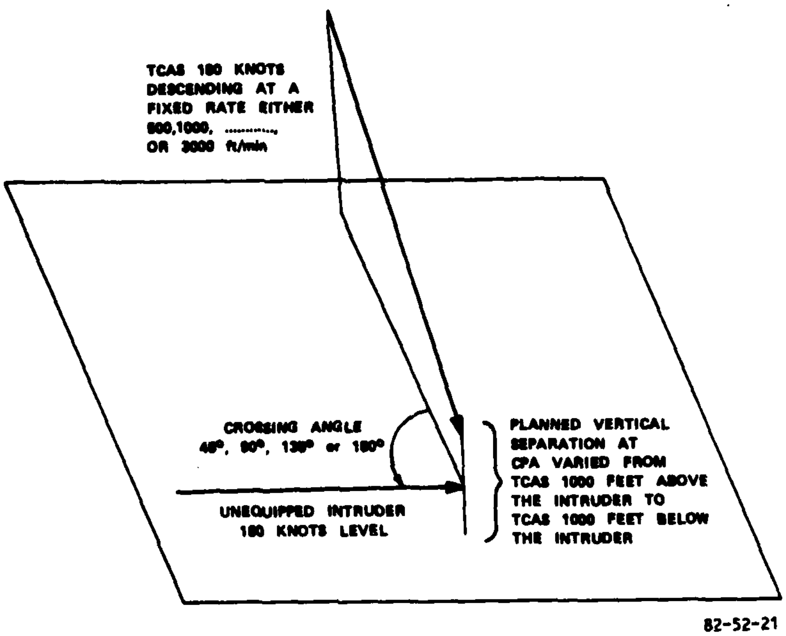


FIGURE 21. CASE I VERTICAL RATE ENCOUNTER SCENARIO CONDITIONS

conditions than at lower descent rates. The minimum vertical separation of 288 feet occurred for conditions identified by point A. In this case, the TCAS aircraft would have passed 500 feet below the intruder at CPA. The large change in resulting separation when compared to point B (288 feet versus 667 feet) is traced to the interaction between sense choice logic and command severity logic. For point B, a climb sense is selected, and since the projected separation at CPA (VMD is less than 440 feet), an immediate positive climb command, ALIM, results. For point A, a climb sense is selected, but VMD is initially greater than 440 feet and a do not descend command is selected. Initial command selection occurred 28 seconds prior to CPA. However, the positive climb command did not result until 12 seconds later. Point A identifies the minimum separation observed for Case I vertical rate encounters. The logic discrepancy which caused a delay in issuing a positive command has been corrected. Whenever sense selection prevents vertical track crossing, and VMD exceeds ALIM but is predicated on track crossing, a positive command now results. This logic change was added to the baseline logic. The change would increase vertical separation from 288 to near 667 feet.

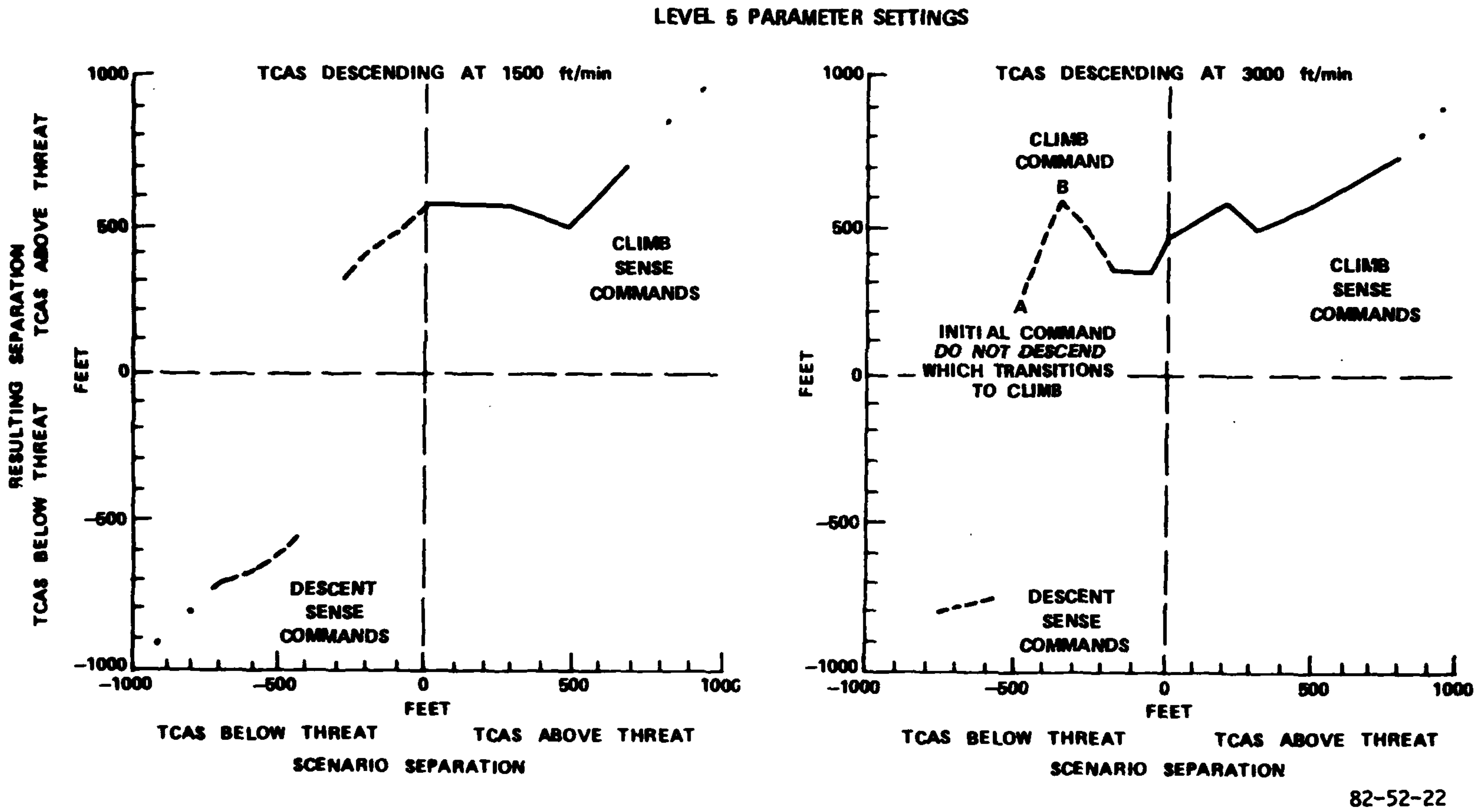


FIGURE 22. CASE I VERTICAL GEOMETRY RESULTS - 90° CROSSING ANGLE

The results for level flight TCAS and an unequipped descending intruder are now presented. Over 500 encounter scenarios were reviewed in the analysis of Case II vertical rate encounters. The results presented in figure 23 are based on the conditions reviewed in Case I except that the intruder is descending and TCAS is level. Again, figure 23 represents results with sensitivity level 5 parameter settings. In general, a slight increase in separation performance is observed when comparing Case II results with Case I results. This occurs because TCAS sense choice response modeling is not as complex for a level flight TCAS aircraft as it is for a vertically maneuvering TCAS. For the latter condition, vertical accelerations must be modeled. Positive commands occur over a wide range of planned vertical miss distances in Case II. TCAS must develop a vertical rate (positive command) to generate separation, whereas in Case I, TCAS need only alter its rate in many cases to generate separation at CPA.

In Case III vertical rate encounters, both TCAS and the intruder are established in fixed vertical rates prior to CPA. More than 1,000 separate scenarios were analyzed in the Case III vertical rate encounters. Two scenarios presented for review are shown figure 24. Logic results for both scenarios using sensitivity level 4 parameter settings are shown in figure 25. When both aircraft were descending, sufficient separation always resulted. The separation was obtained by climb commands being issued for the most part to the TCAS aircraft. Hence, except when the planned separation was -500 or -400 feet, the logic did not issue commands which would cause the TCAS aircraft to attempt to descend faster than the intruder which was already descending at a higher rate than TCAS.

A sharp peak occurred at the point marked by B in figure 25. Throughout the encounter, sufficient separation was obtained through the issuance of a limit descent to 1,000 ft/min. Since TCAS was already descending at 1,000 ft/min, no change in the scenario separation resulted. As soon as the scenario vertical separation decreased below 400 feet, a positive climb command resulted.

For the scenario where TCAS is climbing and the intruder is descending, the minimum separation of 214 feet occurred for conditions marked with point A. Without TCAS action, the TCAS aircraft would have passed 300 feet above the intruder at CPA. The initial alarm occurred when TCAS was 908 feet below the intruder. A positive descent command resulted. Eleven seconds prior to CPA, the tracked vertical rate estimates caused the projected VMD to slightly exceed the threshold for positive commands, ALIM, (452 feet versus 440 feet). This caused the positive descent command to change to a do not climb. If the alarm had not transitioned to a negative climb command, an additional 83 feet of vertical separation would have occurred at CPA. The latest logic changes provided by Mitre, subsequent to this analysis, (reference 10) minimize the effect of such alarm transitions. Now, a negative command immediately changes back to a positive command when VMD becomes less than ALIM.

HIGH ALTITUDE RESULTS. To allow for higher velocities at higher altitudes, parameters which shape the threat volume are increased. The analysis in this section used sensitivity level 6 parameters (Tau = 30 seconds, DMOD = 1 nautical mile, ALIM = 640 feet, and ZTHR = 850 feet). Analysis of high altitude encounters indicates that TCAS logic generates sufficient separation provided surveillance acquisition of the intruder occurs early enough and the surveillance data are of sufficient quality.

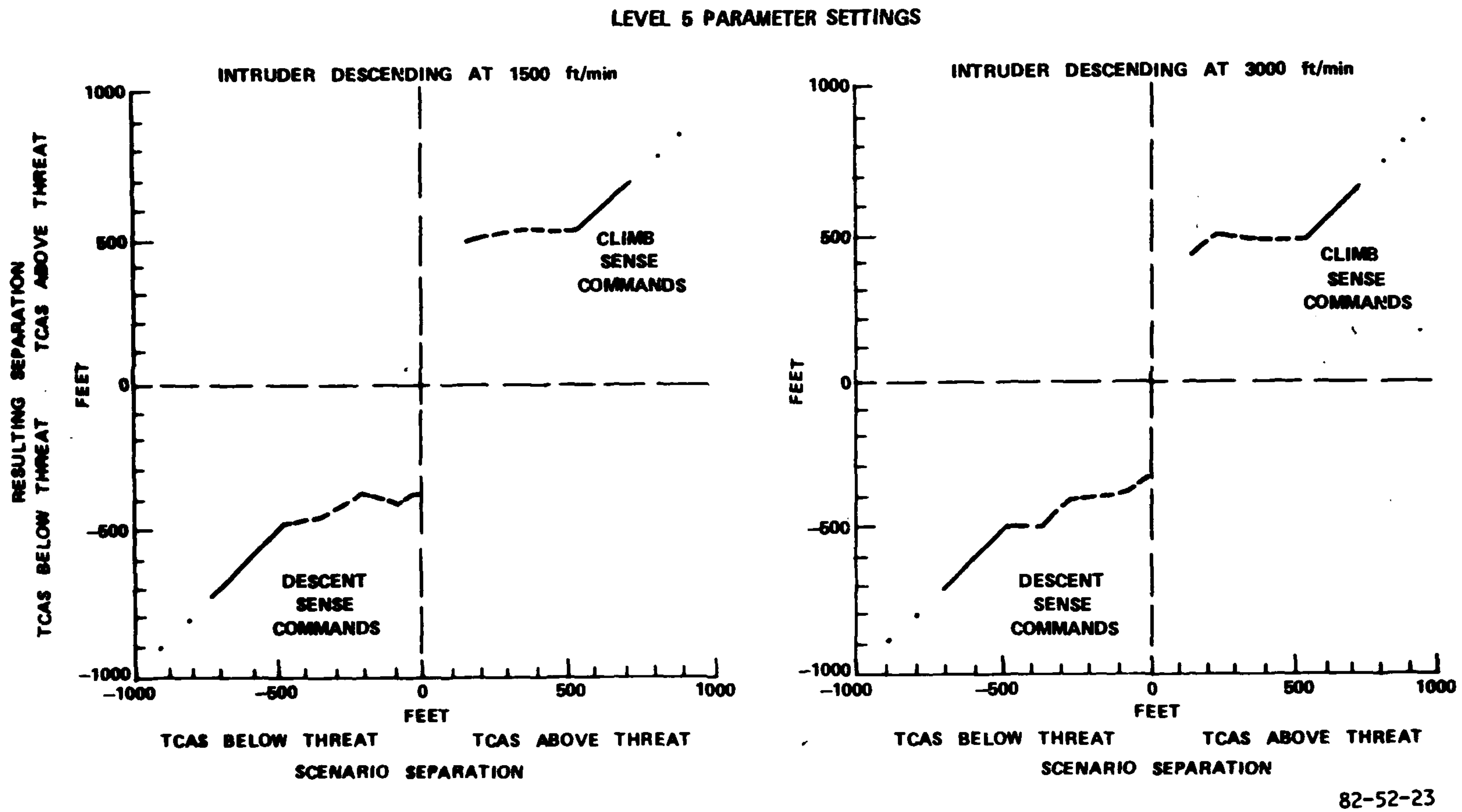


FIGURE 23. CASE II VERTICAL GEOMETRY RESULTS - 90° CROSSING ANGLE

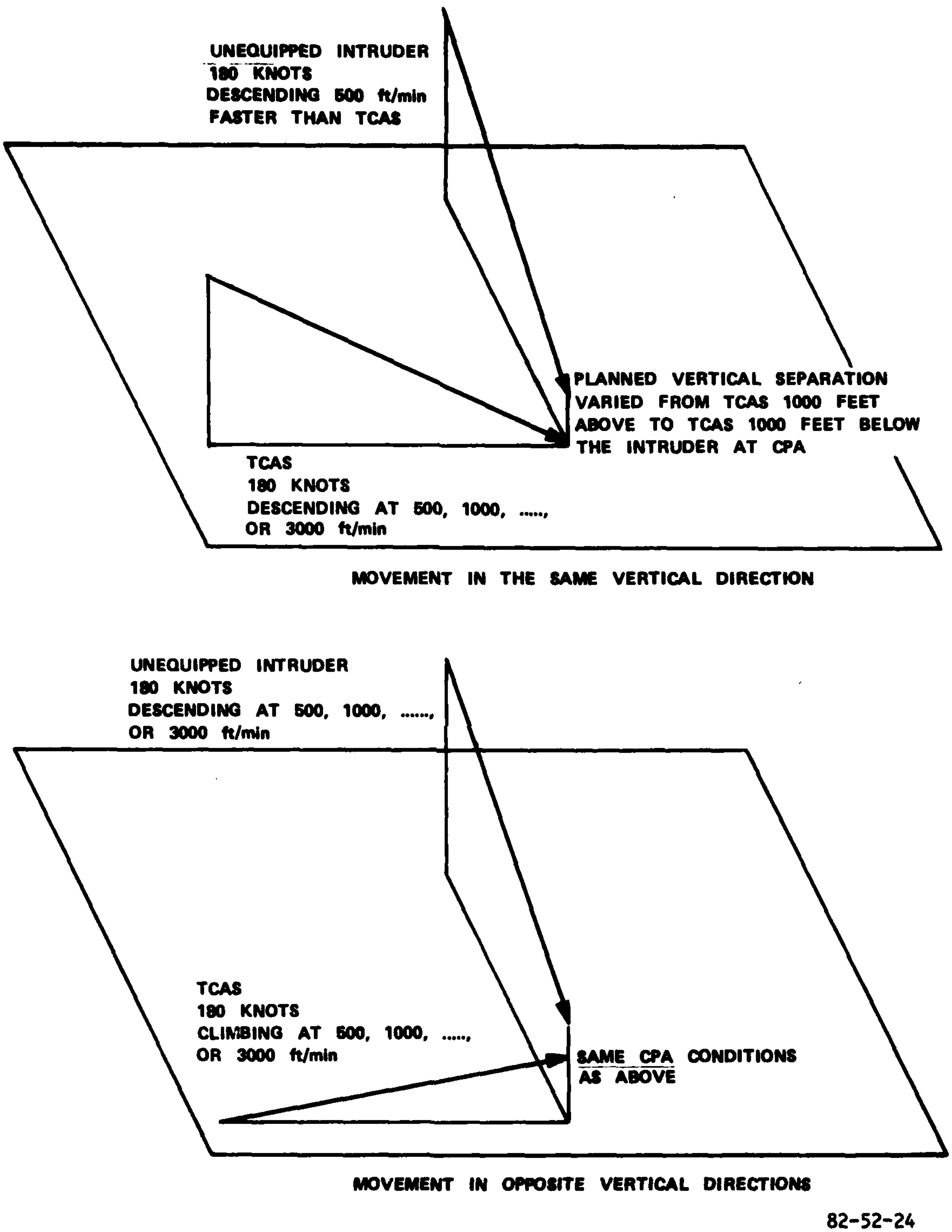


FIGURE 24. CASE III VERTICAL RATE ENCOUNTER SCENARIO CONDITIONS

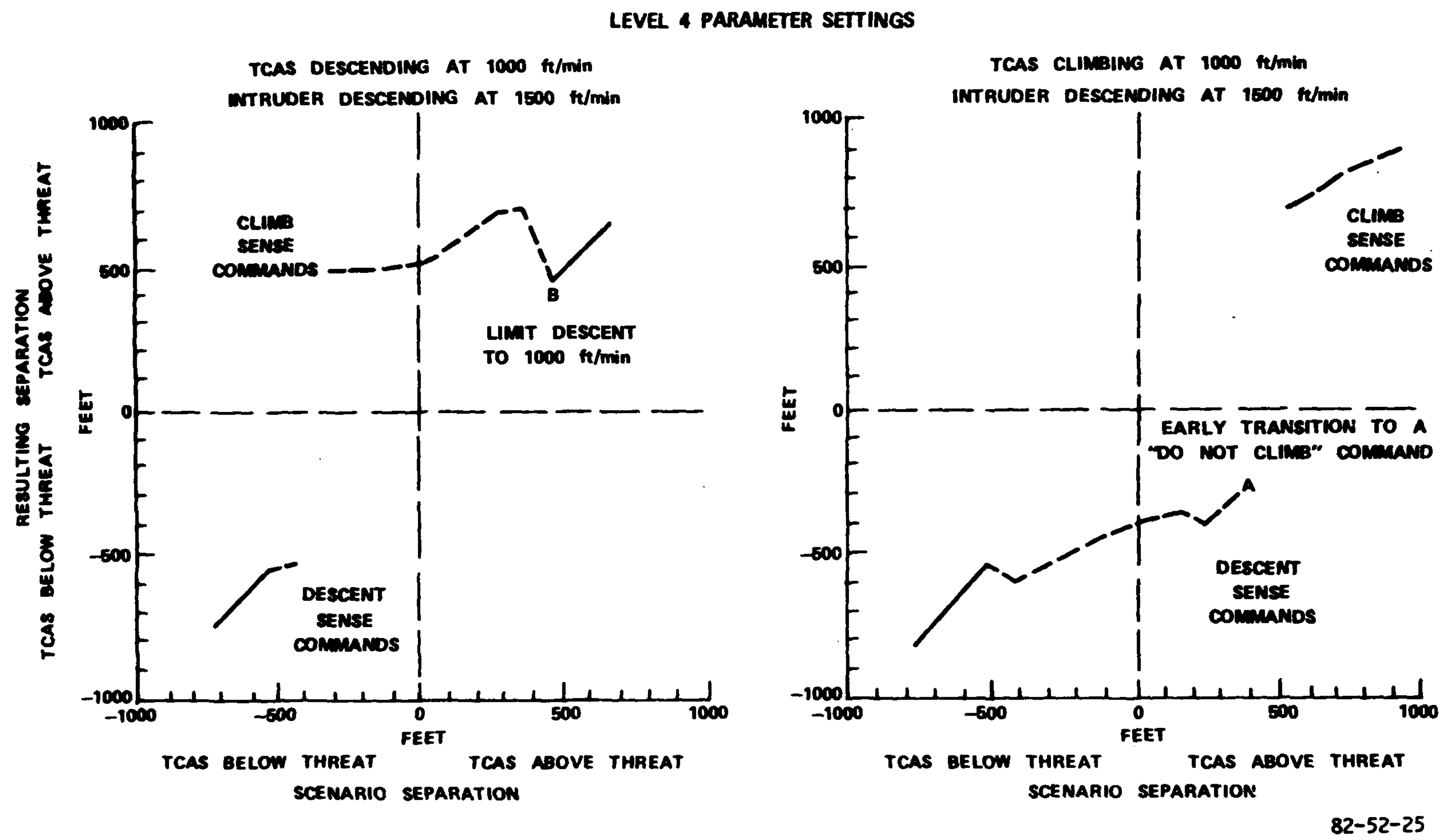


FIGURE 25. CASE III VERTICAL GEOMETRY RESULTS - 90° CROSSING ANGLE

Figure 26 presents the results for a high altitude scenario in which the TCAS and threat were closing head-on at 1,020 knots. The intruder is established in a 500 ft/min descent, and TCAS is in level flight. The minimum observed separation of 256 feet occurred for conditions marked A. When the alarm first occurred, the TCAS aircraft was 97 feet below the intruder. Since the vertical rate of each aircraft was below 600 ft/min, sense choice was based solely on the relative vertical separation. Because TCAS was below the intruder, a descend results. In responding to the descent command, the TCAS aircraft's final escape rate is -1,000 ft/min, yielding an escape rate of 500 ft/min in descent. Logic changes prepared by Mitre Corporation now use vertical rate information in selecting sense even when the rate is below 600 ft/min. This change would have increased vertical separation from 256 feet to about 450 feet for scenario conditions marked with the letter A on figure 26.

<u>HORIZONTAL MANEUVERING ENCOUNTERS</u>. Many scenarios involving horizontal maneuvering by either or both aircraft were investigated. In figure 27, TCAS logic is required to resolve a horizontal maneuver by a level flight intruder while TCAS is established in a 1,500 ft/min descent. The intruder begins a 3° per second right turn 20 seconds prior to the CPA. Generally, initial TCAS alarms occurred 19 to 17 seconds prior to CPA. The results of this scenario are presented in figure 28. Sensitivity level five parameters were used for this analysis. The minimum observed vertical separation was 283 feet.

Analysis of TCAS performance with horizontally maneuvering threats that were established in a descent was also made. Figure 29 presents an example of such a scenario. For this particular geometry, the intruder initiates a 6° per second turn 25 seconds prior to CPA. The results are depicted in figure 30. The minimum observed vertical separation was 313 feet.

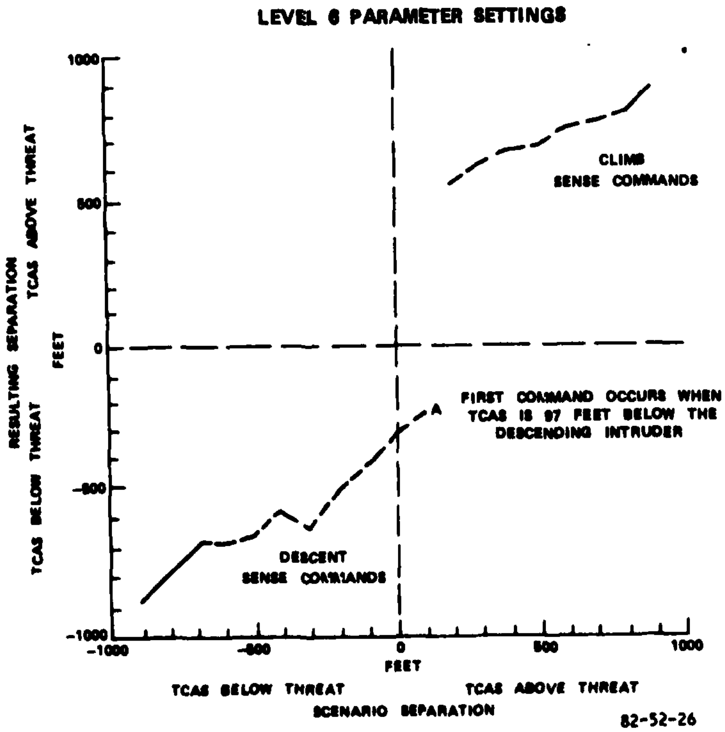


FIGURE 26. HIGH ALTITUDE, HIGH AIRSPEED, DESCENDING INTRUDER RESULTS

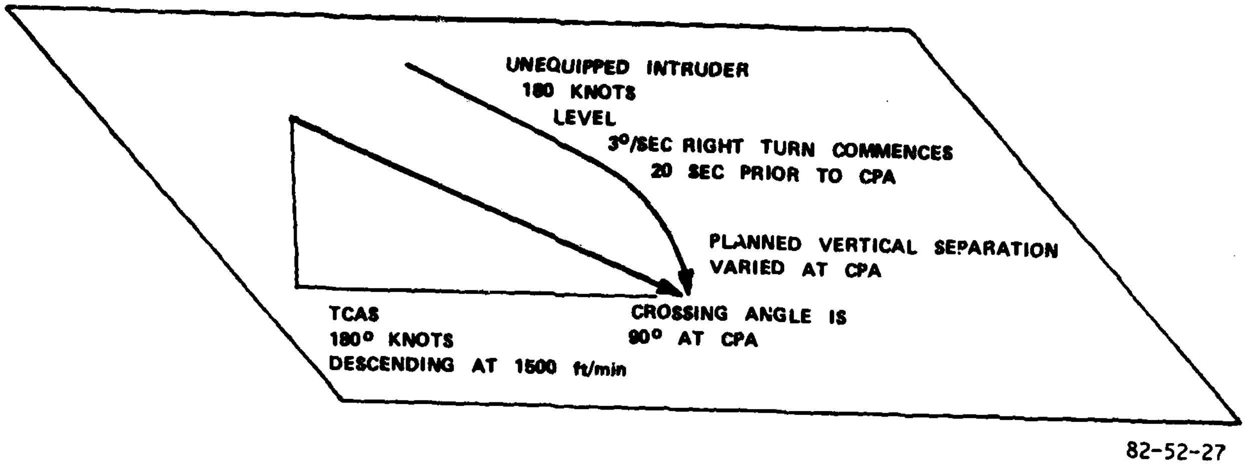


FIGURE 27. DESCENDING TCAS--LEVEL FLIGHT HORIZONTALLY MANEUVERING INTRUDER SCENARIO

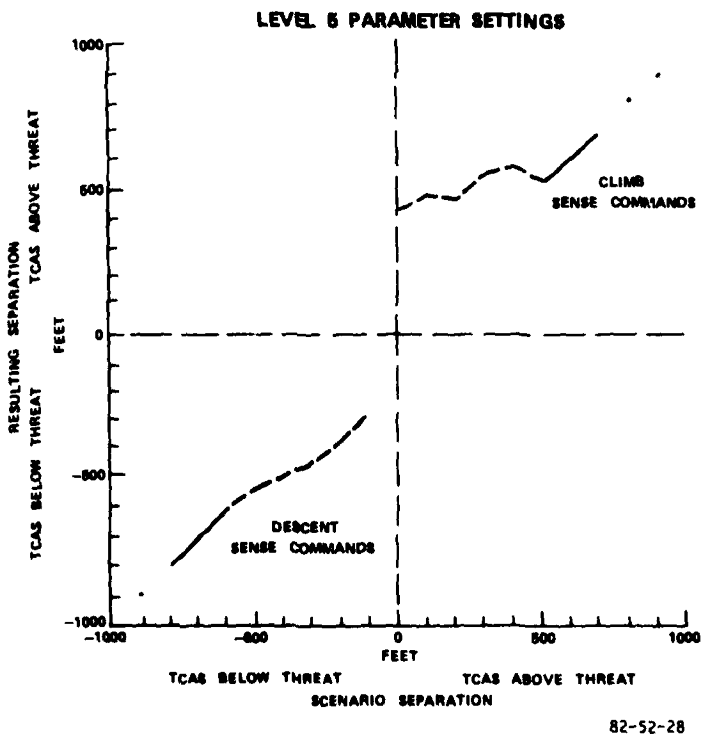


FIGURE 28. LEVEL FLIGHT HORIZONTALLY MANEUVERING THREAT RESULTS

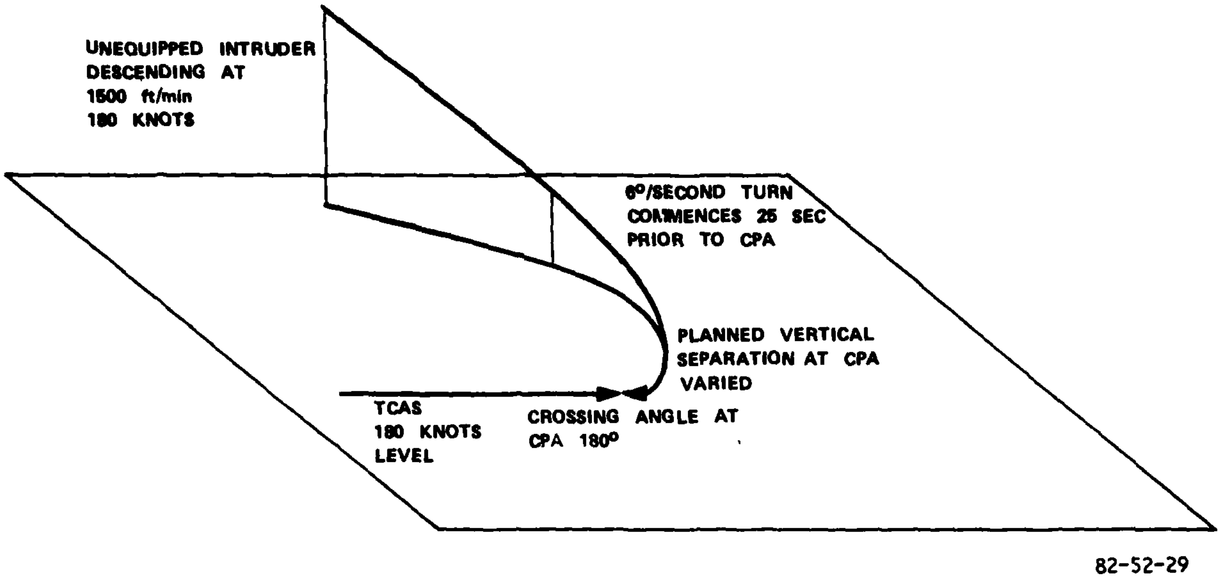


FIGURE 29. DESCENDING HORIZONTALLY MANEUVERING INTRUDER SCENARIO

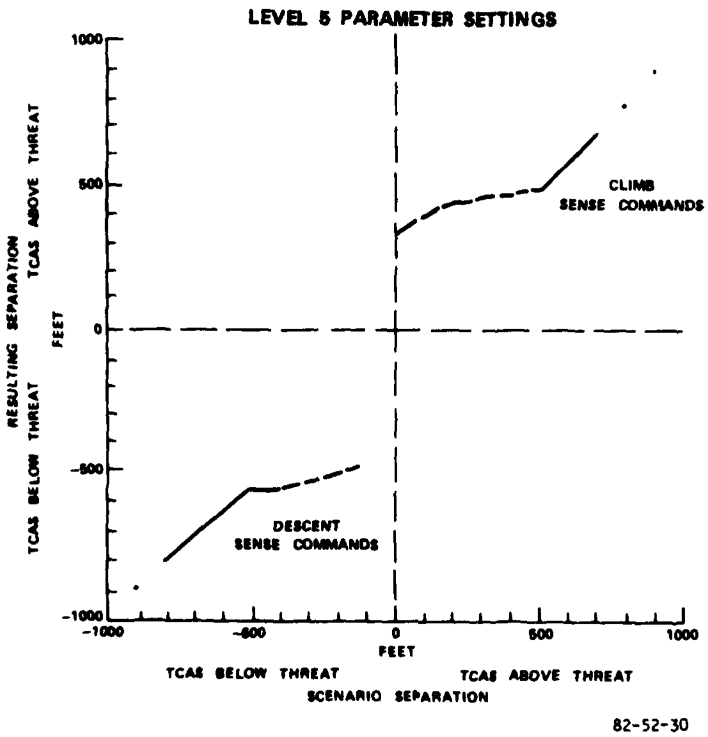


FIGURE 30. RESULTS FOR HORIZONTALLY MANEUVERING DESCENDING INTRUDER

The final example of TCAS performance for horizontal maneuvering threats is presented in figure 31. In this case, the intruder initiates a 3° per second turn 45 seconds prior to CPA. Hence, the intruder completes a 135° turn prior to CPA. This results in horizontal track crossing prior to CPA. The range rate for the encounter in question is initially negative (closure), becomes positive for a short time period (separation) following horizontal track crossing, only to again become negative as the final portion of the turn is completed.

This range rate sequence resulted in secondary positive descent commands for certain values of planned vertical miss distance. A secondary command is a command that occurs after the initial command period has terminated and the intruder is removed from the threat file. This occurred for the cases when TCAS would have passed through the intruder's altitude prior to CPA and would have been below the intruder at CPA. The portions of the intruder's profile which caused the secondary commands are shown in figure 31. The observed results are presented in figure 32. When secondary commands occurred, the TCAS initially received a "do not descend" command. As the range rate became positive, the command was removed permitting the TCAS to resume its descent. Once the range rate again became negative, a descent command occurred. The minimum separation observed was 267 feet.

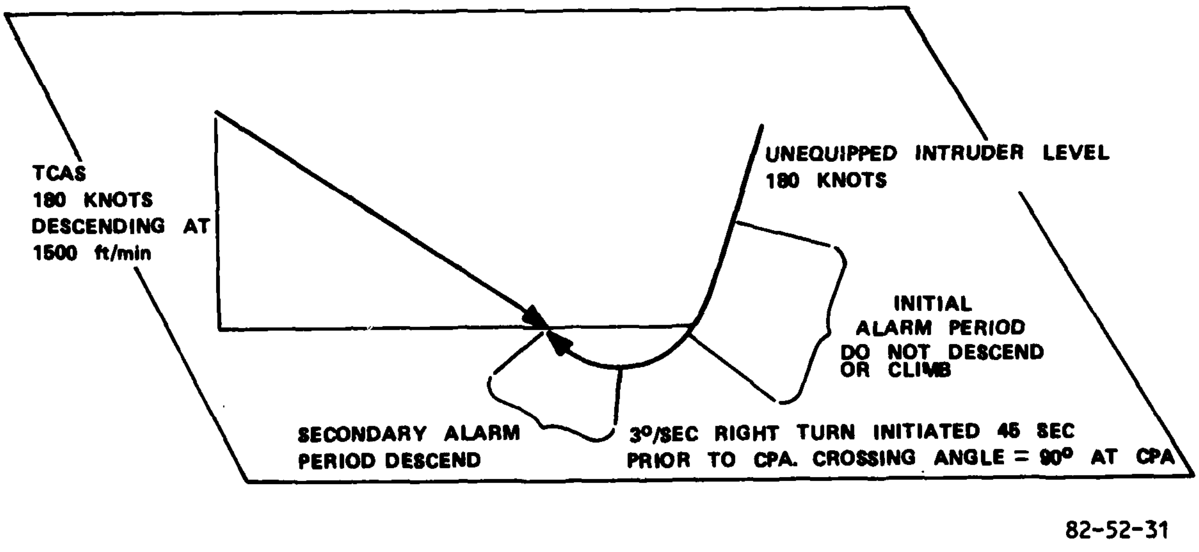


FIGURE 31. SCENARIO INVOLVING A 135° TURN BY THE INTRUDER

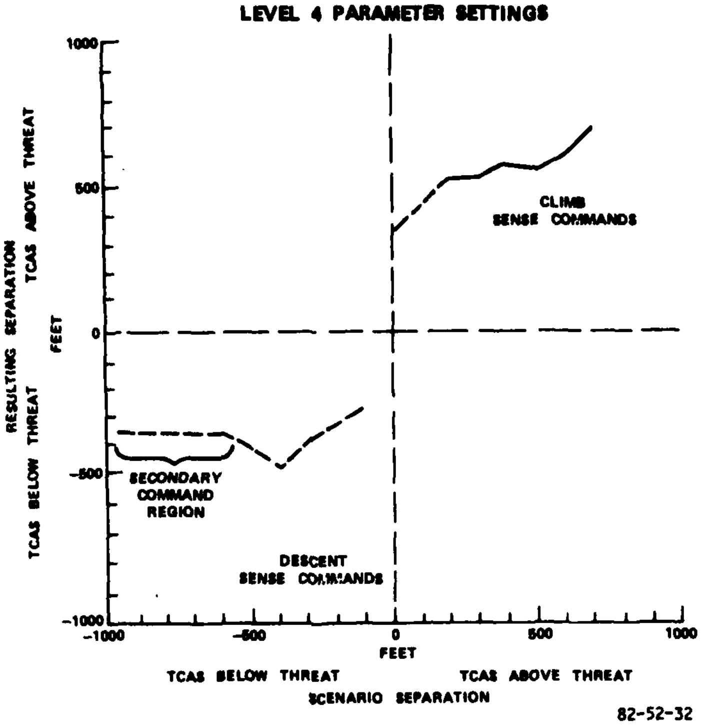


FIGURE 32. RESULTS FOR 135° TURN BY THE INTRUDER

VERTICAL ACCELERATION ENCOUNTERS (FAKE-OUT MANEUVER ENCOUNTERS). This class of encounters is the hardest for TCAS to resolve. The current logic only provides for sense selection (selection of escape maneuver direction) on one logic cycle. Once sense is selected, it cannot change until the encounter is over. The sense is selected on the first logic cycle that the intruder is declared a threat. These rigid sense choice rules can lead to a reduction in separation.

Two conditions cause problems for the TCAS resolution logic. First, sense selection is based upon a 25- to 30-second projection of vertical position. If sense selection occurs during or immediately after a vertical rate change by the intruder, the lag in the vertical rate tracker can induce sufficient error in the rate estimate to result in the wrong sense choice. Considerable research has identified the possibility of incorrect sense choice with previous alpha-beta vertical tracking. Second, the CAS logic ignores (in terms of sense choice) all vertical threat maneuvers that occur after sense selection.

The nonlinear tracker, developed by Lincoln Laboratory, has significantly reduced the probability of incorrect sense choices. The nonlinear tracker is more sophisticated than the alpha-beta tracker. Figure 33 identifies conditions which were simulated to determine the improvement in sense choice with nonlinear tracking.

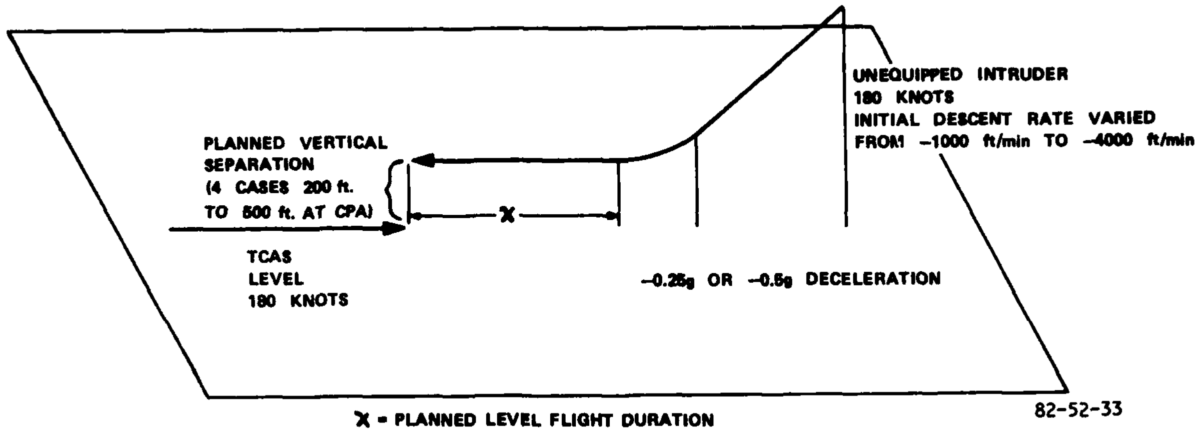


FIGURE 33. GEOMETRIES USED TO DETERMINE SENSE CHOICE IMPROVEMENT (X VARIED 1 to 70 SECONDS)

The sense selection logic ignores vertical rate estimates less than 600 ft/min in magnitude. In these cases, no vertical position projection is made and sense selection is based strictly on relative altitude. For the case in which sense choice occurs during or immediately after the vertical deceleration, wrong sense choice may occur as long as the magnitude of the vertical rate estimate remains above 10 ft/sec. During the period from vertical deceleration onset until the magnitude of the rate estimate is depressed below 10 ft/sec, incorrect sense choices can result if the error in the vertical rate estimate is large enough to offset the planned vertical separation. The number of logic cycles on which incorrect sense choices would have occurred for the stochastic conditions shown in figure 33 were obtained. Tables 5 and 6 compare the number of logic cycles on which incorrect sense choices would have occurred for the nonlinear and alpha-beta tracker.

Table 5 shows that the nonlinear tracker results in fewer incorrect sense choices. The duration of incorrect sense choice periods, that resulted for nonlinear tracking, was less than one-half the duration with alpha-beta tracking. With the faster deceleration (0.5g) in table 6, even more improvement resulted with nonlinear tracking.

While a considerable reduction in occurrences of incorrect sense choice resulted with nonlinear tracking, it must be noted sense choices which maneuver the TCAS toward the level flight intruder can still result. With minimal planned separation

(200 feet), incorrect sense choices can still result in increased vertical separation at CPA. With a 25-second warning time, a nominal response delay, and a 1,500 ft/min escape rate, approximately 300 feet of vertical separation can still be obtained at CPA when the TCAS aircraft climbs through the intruder's altitude. The more dangerous condition detected in simulation (less vertical separation at CPA) occurred when the intruder would have passed 500 feet above TCAS following its vertical deceleration had TCAS not alarmed.

In figure 34, the conditions which were further analyzed are identified. The durations of the level flight portion of the intruder flight path were varied in 1-second increments (i.e., a set of geometries in which only the time of deceleration by the intruder in relationship to CPA is varied were analyzed). For large durations (D > 30 seconds), the nonlinear tracker should have had sufficient time to respond to the transient vertical rate condition. As a result, when the intruder is declared a threat (near 25 seconds prior to CPA), the magnitude of vertical rate should have been depressed below 10 ft/sec and the proper sense choice, descend, should result.

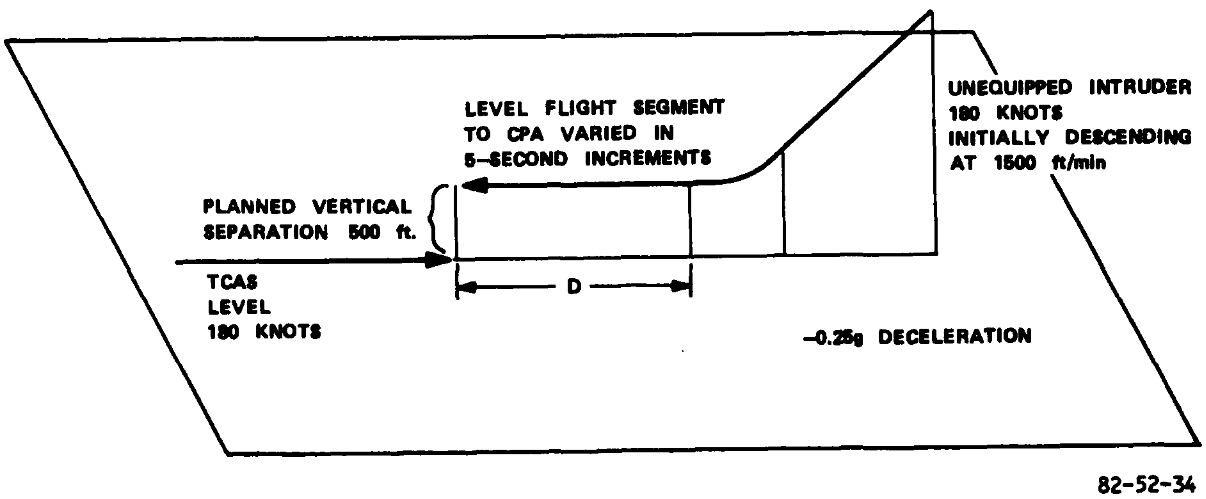


FIGURE 34. GEOMETRIES USED TO IDENTIFY IMPACT OF WRONG SENSE CHOICE ON RESULTING VERTICAL SEPARATION AT CPA

TABLE 5. NUMBER OF LOGIC CYCLES ON WHICH INCORRECT SENSE CHOICE WOULD HAVE RESULTED (-0.25g THREAT ACCELERATION)

Initial Vertical Rate (ft/min)	Planned Vertical Separation at CPA (No TCAS Action) 200 feet N.L.	α-β	300 feet N.L.	α-β	400 feet N.L.	α-β	500 feet N.L.	α-β
-1500	5	9	3	7	4	5	4	5
-1600	5	12	3	10	4	8	4	7
-1700	5	11	4	10	4	8	3	7
-1800	6	11	5	10	4	8	4	7
-1900	5	11	3	10	4	8	4	7
-2000	6	12	4	9	4	8	4	7
-2100	7	11	6	12	6	10	6	10
-2200	7	13	5	11	4	9	4	8
-2300	7	11	5	12	5	10	5	9
-2400	5	12	4	11	4	9	4	8
-2500	7	12	6	12	5	10	4	9
-2600	6	13	5	11	4	10	4	9
-2700	7	13	6	11	4	10	4	9
-2800	7	14	7	14	7	13	7	12
-2900	7	13	5	12	5	10	5	10
-3000	6	14	5	11	5	10	5	9
-3100	7	14	5	12	5	11	4	10
-3200	7	15	5	13	5	12	4	11
-3300	7	15	6	14	6	13	6	12
-3400	5	14	7	13	6	12	6	11
-3500	6	14	7	13	6	12	5	11
-3600	5	14	5	12	5	11	5	10
-3700	7	14	7	13	6	12	6	11
-3800	6	15	6	14	6	13	6	13
-3900	7	14	7	13	6	12	6	11
-4000	7	14	6	14	6	13	6	12

N.L. Nonlinear Tracker
α-β Alpha-Beta Tracker
-0.25g Deceleration

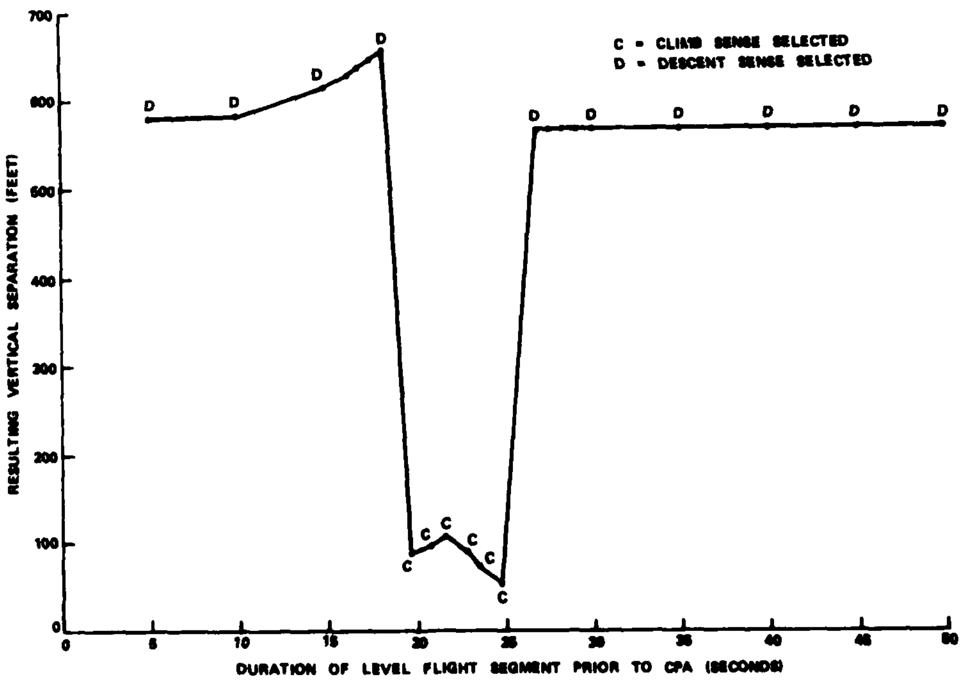
TABLE 6. NUMBER OF LOGIC CYCLES ON WHICH INCORRECT SENSE CHOICE WOULD HAVE RESULTED (0.5g THREAT ACCELERATION)

Initial Critical Rate(ft/min)	Planned Vertical Separation at CPA (No TCAS Action) 200 feet N.L.	α-β	300 feet N.L.	α-β	400 feet N.L.	α-β	500 feet N.L.	α-β
-1500	5	9	3	7	2	5	2	4
-1600	6	12	6	10	5	8	5	7
-1700	6	10	4	10	3	8	3	7
-1800	6	12	5	9	4	7	3	7
-1900	6	11	4	10	3	8	2	6
-2000	6	10	5	10	4	7	3	7
-2100	5	11	4	11	3	9	2	8
-2200	7	12	6	11	5	11	4	6
-2300	5	11	4	12	3	9	2	8
-2400	5	12	5	11	3	11	3	8
-2500	5	12	3	11	2	10	1	8
-2600	5	12	4	11	3	11	2	9
-2700	5	13	3	11	2	10	1	8
-2800	6	13	5	12	4	11	4	9
-2900	5	12	3	11	3	10	2	8
-3000	5	13	4	12	3	11	2	9
-3100	6	14	6	13	5	13	5	10
-3200	5	14	4	13	3	12	3	11
-3300	5	15	6	13	5	13	4	9
-3400	5	14	4	14	3	12	2	11
-3500	5	14	6	13	5	13	4	9
-3600	5	14	4	13	3	12	3	11
-3700	6	14	6	13	5	13	4	11
-3800	6	14	5	13	4	12	3	10
-3900	6	15	6	14	5	13	4	11
-4000	6	15	6	14	5	14	5	12

N.L. Nonlinear Tracker
α-β Alpha-Beta Tracker
-0.5g Deceleration

As the level flight segment is incrementally shortened, the logic cycle on which sense choice is selected falls in the period when the nonlinear tracker has not responded to the transient altitude rate and wrong sense choices result. For the conditions investigated, 1,500 ft/min descent, -0.25g deceleration, and 500 feet planned separation, the incorrect sense choice can occur over a 6-second period. For durations of level flight less than 20 seconds, threat declaration occurs while the threat is still descending at 1,500 ft/min. Although the deceleration follows the sense choice, the proper sense choice, descend, should result. This is true because the vertical projection of the intruder would place it above the TCAS at CPA even without the intruder decelerating (1,500 ft/min = 25 ft/sec, 25 x 20 = 500 feet).

For the analysis, the TCAS aircraft's modeled response was a 5-second nominal delay followed by a 0.25g acceleration to a 1,500 ft/min climb escape rate. The results are presented in figure 35. As anticipated, the proper descent command was selected for level flight durations D $\geq$ 26 seconds. Six incorrect climb sense selections occurred. They occurred for level flight durations between 20 and 25 seconds. Incorrect sense selection resulted during the period the nonlinear tracker had not adjusted to the vertical rate change by the intruder. As a result, the TCAS aircraft responds by climbing toward the now level intruder. The resulting separation at CPA was 51 feet for the 25-second level flight condition. For level flight durations $\leq$ 20 seconds, the appropriate descent command resulted.



82-52-35

FIGURE 35. RESULTING SEPARATION WITH 500 FEET PLANNED VERTICAL SEPARATION AT CPA

This analysis readily justifies the use of nonlinear tracking rather than alpha beta tracking. Investigations to identify at what level vertical rate information should not be used in sense selection are necessary. Currently, the arbitrary value of 600 ft/min is being used. If this value can be increased, the possibility of wrong sense choice would be further reduced. The constraint of not permitting a change in sense of escape maneuver limits the logic's ability to select commands that permit the generation of vertical separation at CPA. This is true when the intruder maneuvers vertically following the selection of escape sense. Other possible methods of improving logic performance are reviewed in reference 4.

Other analyses have shown the problem is not as critical with TCAS equipped threats. While encounter TCAS aircraft may be required to perform escape maneuvers which result in escape through the other aircraft's altitude, inadequate vertical separation at CPA has not been detected. This occurs because of the coordination logic and the fact that both aircraft are maneuvering in a coordinated fashion.

LARGE HORIZONTAL MISS DISTANCES AT CPA ENCOUNTERS.

Problem - Large Overestimation of Time to CPA. The TCAS resolution logic requires the projection of vertical position when either TCAS or the threat is established in a vertical rate maneuver. The projection is based on the pseudo true time to CPA, TRTRU. TRTRU estimates of the time to closest approach are sufficient when the horizontal miss distance is small. However, as the horizontal miss distance increases, the overestimation of time to CPA increases rapidly in the vicinity of CPA.

TRTRU is evaluated as follows:

$$TRTRU = -R/RD$$

If the range is closing, RD < 0

The projected vertical miss distance

$$VMD = RZ + (RZD*MIN(TRTRU, TVPCMD)) \quad (2)$$

where RZ = current measured altitude difference
RZD = current vertical closure rate

TVPCMD is nominally set to 40 seconds. Hence, the maximum projection time is 40 seconds.

When range is increasing, RD > 0,

$$VMD = RZ \quad (3)$$

In a normal scenario, equations (2) and (3) state that prior to CPA, vertical position is based on a TRTRU time projection and after CPA, vertical position projection is set to the current altitude separation. The concept is the appropriate one and would yield good results except for the quality of TRTRU when large horizontal miss distances exist at CPA. When the horizontal miss distance, HMD, is of the same magnitude as DMOD, the tau range modifier, TRTRU, yields very inaccurate estimates of time to CPA in the vicinity of CPA.

Two examples of the divergence of TRTRU from the true time to CPA are shown in figure 36. Both cases represent likely encounter scenarios. Prior to 8 seconds before CPA, TRTRU provides a slight, but nearly constant, overestimation of time to CPA. Closer than 8 seconds, rapid increases in the TRTRU estimate occur. This causes large overestimation of separation at CPA. This impacts command selection and threat detection. The result is a fluctuation in the displayed command. In many cases, the command is removed just prior to CPA because VMD is projected to be so large that the intruder is declared a nonthreat only to reoccur after CPA because VMD is then set to current altitude separation. An even more critical impact can occur in the case of a late detection (near CPA) of a TCAS equipped threat. The large error in the time to CPA results in sense choices which would maneuver aircraft toward each other. However, since little time to respond exists near CPA, wrong sense selection would not necessarily lead to a significant reduction in separation.

Results of Limiting the Overestimation of Time to CPA. It is apparent the addition of techniques to smooth TRTRU in the vicinity of CPA may be desirable. TRTRU is calculated in the HITORM routine. Several possible conditions were analyzed. If the aircraft are diverging in range at a rate greater than the threshold RDTHR, TRTRU will not be used in projecting vertical miss distance. No change is necessary for this condition. To address the remaining cases, an additional variable, TP, which equals the TRTRU calculation on the last logic cycle, was added to the intruder track file. This variable can be initialized to -R/RD in the intruder tracking logic, TRIACT. When separation at a rate greater than RDTHR is not occurring, TRTRU is calculated by HITORM logic. Since TRTRU divergence only occurs near CPA, the range is compared with DMOD following the calculation of TRTRU. If the range is less than DMOD, the slope of the ratio of the difference of TRTRU-TP to TP is checked. If it is greater than 0.5, the increase in TRTRU is determined to be excessive and TRTRU is set to the previous value TP. This change will tend to smooth the projection time when close to CPA. The adjustment of TRTRU is conservative and will not cause prematurely early alarm removal. The threshold value for the slope of the divergence is arbitrary and may have to be reduced. The modification of the HITORM logic is shown in figure 37.

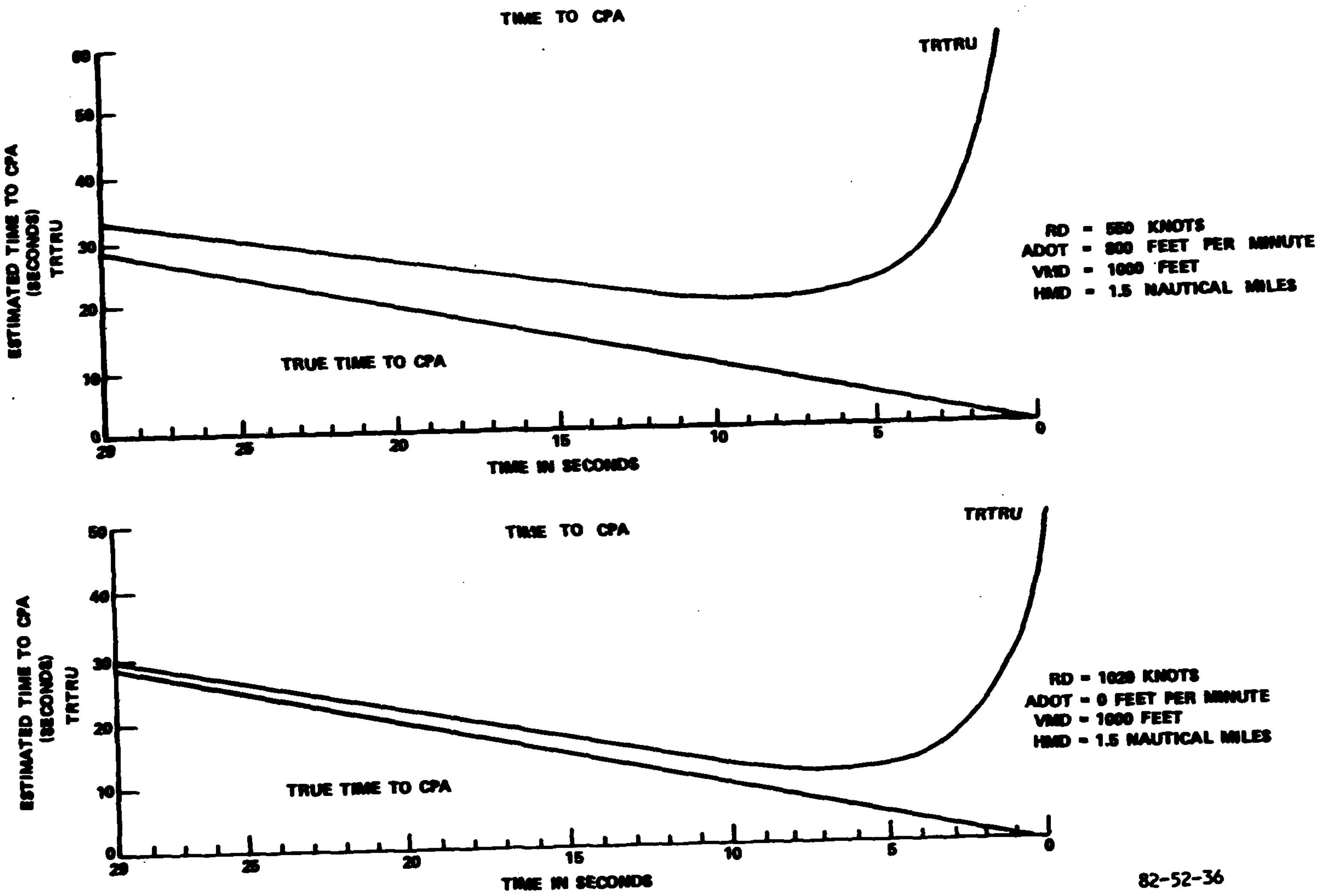
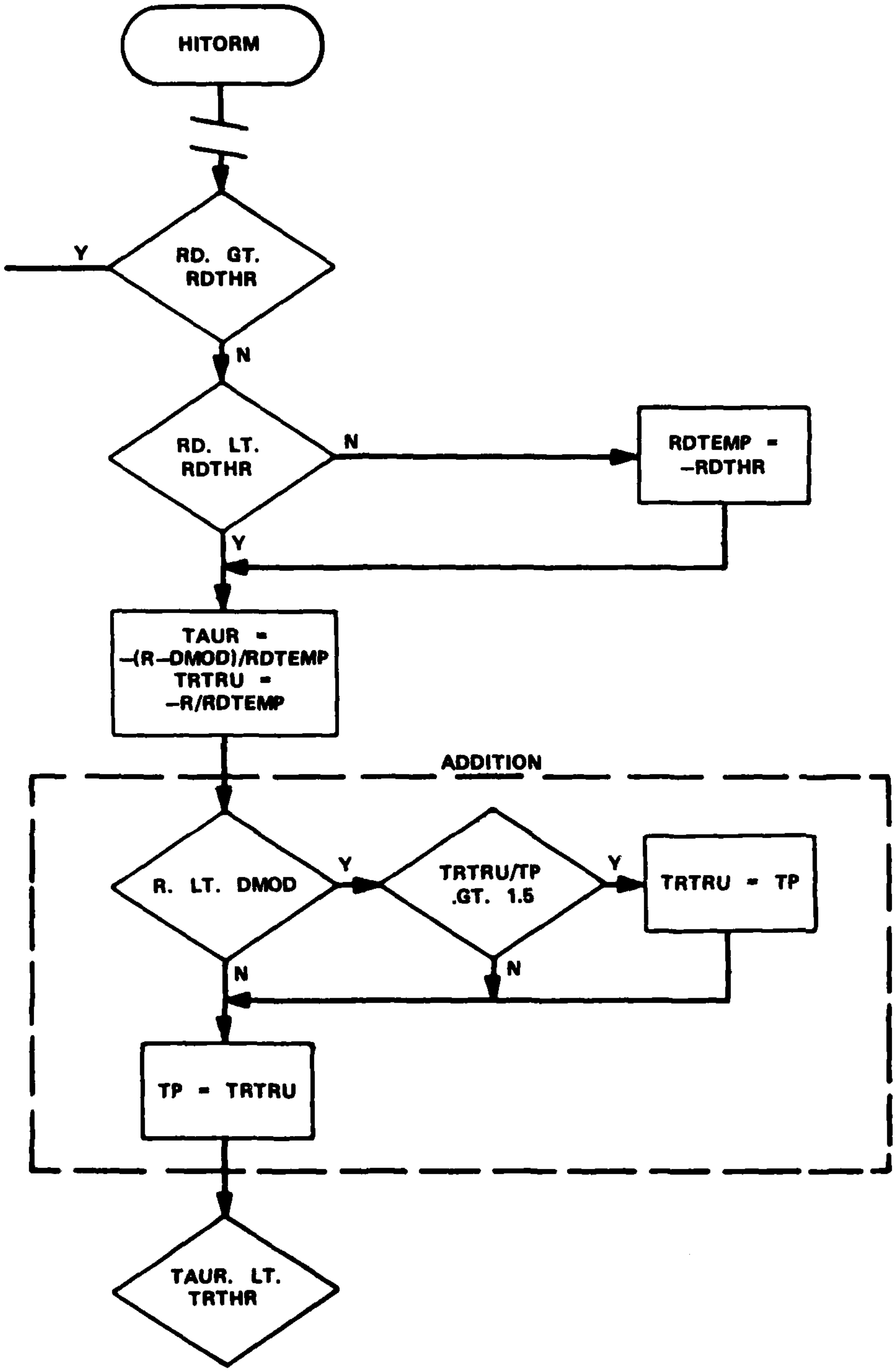


FIGURE 36. TRTRU DIVERGENCE IN THE PRESENCE OF HORIZONTAL MISS DISTANCE AT CPA



(REFERENCE 1 FIGURE 4.4–4A)

82-52-37

FIGURE 37. CHANGES TO HITORM LOGIC

CONCLUSIONS AND RECOMMENDATIONS

GENERAL.

The Traffic Alert and Collision Avoidance System (TCAS) logic when modified as discussed in this report results in generally good performance for unequipped threats. The modifications to the logic as described in the Results section should become permanent additions to the TCAS baseline logic.

When the minimum threat volume parameters are used (performance level 3), less than 300 feet vertical separation at closest point of approach (CPA) is generated for many terminal area encounters. More investigation of the parameter settings for this lowest sensitivity level should be made. An alternative scheme which uses TCAS-sensed intruder density to determine logic sensitivity could be analyzed. Cockpit simulation should be used to determine pilot reaction to the alarms which result during maximum logic desensitization.

The logic that determines maneuver sense selects the sense which generally will result in the greater vertical separation at CPA. Clearly, this is the proper method of resolving threat encounters involving high vertical rate maneuvers. However, in order to maximize the vertical separation at CPA, the TCAS resolution may require the TCAS aircraft to cross the vertical track of the intruder (pass through coaltitude condition) well before CPA. Cockpit simulation or live flight testing should be used to identify additional information pilots may require so they accept resolutions which require vertical track crossing.

Several specific conclusions and recommendations concerning constituent parts of the TCAS logic can be made based on the analysis in the report.

TRACKING LOGIC.

The surveillance tracking system uses a different time constant to drop track than the intruder tracking logic. This can result in track splitting and multiple intruder tracks for the same intruder. The time constants in the surveillance tracking logic and intruder tracking logic should be matched.

The nonlinear tracker has significantly reduced the occurrence of incorrect sense choices. The settling time of the nonlinear tracker following vertical accelerations has been reduced one-half to one-third of the settling time of the previous alpha-beta tracker. Simulation and flight testing have detected minor problems with nonlinear tracking which should be corrected. Cyclic transitions across a Mode C boundary due to flight technical error induces a nonzero vertical rate estimate. This nonzero rate estimate lasts indefinitely. Methods such as that described in figure 5 of this report should be analyzed so that the rate estimates can be reinitialized to 0 ft/sec.

Following periods of missing altitude reports, the nonlinear tracker induces spikes in the rate estimates if the Mode C changed during the missing report period. The current nonlinear tracker updates the rate estimate following a missing data period in the same manner as it does following no missing reports. Additional logic is required to smooth the rate estimates following missing data periods.

The logic permits own altitude tracking to use inputs from the air data computer rather than the larger quantized Mode C data. The current tracker has not been tested for inputs that are not quantized at 100 feet. The finer quantization of the own altitude will improve the own altitude position and rate estimates. However, when a threat is TCAS equipped, it will be making decisions based on the Mode C transponded data. The implications that two different histories of own aircraft's vertical position and rate have on the ability to coordinate resolutions must be investigated.

RESOLUTION LOGIC.

The augmentations to sense choice logic and advisory selection logic in the TCAS baseline logic have improved logic performance when compared to previous revisions of logic. Several steps should be taken to further refine the resolution logic.

VERTICAL DIVERGENCE LOGIC. In an attempt to reduce the positive advisory rate, vertical divergence logic has been added to the TCAS logic. This divergence logic permits an early transition to a vertical speed minimum alarm or a negative advisory. However, during periods of vertical divergence, positive commands are permitted to be removed based on a projected vertical separation at CPA. It is recommended that current relative altitude RZ be used, rather than a projected vertical separation, in determining command severity during periods of vertical divergence.

VERTICAL ACCELERATION. The weakest area of TCAS performance remains the resolution of unequipped threats which accelerate vertically following TCAS resolution. TCAS cannot protect against all accelerations by the threat aircraft. This is especially true of late, high accelerations near CPA. Several alternatives for the possible improvement in TCAS resolution for accelerating threats should be investigated.

Currently, the sense choice logic ignores rate magnitudes of less than 600 ft/min (ZDLVL) on the part of the intruder. In these cases, sense solution is based strictly on current relative altitude. If ZDLVL can be safely increased, resolution can be based on relative position for a wider range of encounter scenarios.

Certain variables within the tracker may be good indicators of vertical rate firmness. If sufficient time remains until CPA, when the threat is initially detected, sense selection could be delayed for a short period when the vertical rate track firmness is low. This would reduce the occurrence of incorrect sense choices which can result during periods of vertical acceleration by the threat.

TCAS can detect the vertical accelerations. When they occur after sense selection, additional information on the threat (relative altitude, altitude rate) could be provided to the pilot. Cockpit simulation and flight testing should be used to determine what additional information may be desired by the pilot. The concept of permitting TCAS to make a second choice following acceleration by the threat to improve performance appears limited.

Analysis described in this report has identical minor resolution difficulties which exist with the use of TRTRU to determine projected vertical position at CPA. This is especially true for encounters where large horizontal miss distance exists at CPA. Methods to smooth the calculated value of TRTRU near CPA, such as the one described in this report, should be analyzed. Based on this analysis, modifications should be made to the resolution logic in an effort to eliminate the problems of vertical projection based on TRTRU.

DISPLAY TIMING. The display timing modifications identified in this report have improved the smoothness of the TCAS advisories being displayed. However, the validity of the display criteria can only be verified through flight testing and cockpit simulation analysis. The same is true for establishing the criteria for an audio alarm.

REFERENCES

1. Grupe, J. A., et al., Active BCAS Detailed Collision Avoidance Algorithms, MTR 80W80, Mitre Corp., October 1980.

2. Adkins, A., et al., Active BCAS Collision Avoidance Logic Evaluation: Vols. 1-4, FAA RD-80-125, January 1981.

3. Andrews, J., An Improved Technique for Altitude Tracking of Aircraft, FAA RD-80-139, January 1980.

4. Billmann, B., Analysis of a Nonlinear Vertical Tracking Method, FAA RD-81-15, October 1981.

5. Spracklin, D., Program Design Specifications for the Fast-Time Encounter Generator, ATCSF 80-005, Computer Sciences Corporation, February 1980.

6. Automatic TCAS Desensitization Near Airports Using On-Board Inputs, Mitre Letter, W46-0845, February 4, 1981.

7. Logic Deficiencies Requiring Early Correction, Mitre Letter, W46-0846, Feburary 9, 1981.

8. Logic Corrections To Active BCAS Logic, Mitre Letter, W46-0865, March 13, 1981.

9. Logic Corrections To Active BCAS Logic, Mitre Letter, W46-0873, March 24, 1981.

10. Changes in TCAS Logic, Mitre Letter, W46-0944, July 16, 1981.

11. Logic Issues and Solutions Critical for Flight Tests, Mitre Letter, W46-0999, October 22, 1981.

GLOSSARY OF TCAS TERMS

A	-	Absolute value of tracked relative altitude of intruder; an element of the intruder track file
ADOT	-	Relative tracked altitude rate (negative values implies vertical closure); an element of the intruder track file
ADIV	-	Thresholds for issuing vertical speed minimum advisories
AD	-	Values taken by ADIV (200, 300, 400, 500 feet)
ALARM	-	Flag For Traffic Advisory Alarm (1=sound alarm)
ALIM	-	Altitude Separation Threshold for Positive Advisories
AL	-	Values taken by ALIM (340, 440, 640, 740 feet)
ATAS	-	Automatic Traffic Advisory Service
ATCRBS	-	Air Traffic Control Radar Beacon System
BCAS	-	Beacon Collision Avoidance System
BCATRES	-	Threshold for deleting nonrefreshed TCAS Maneuver Coordination Register Entries (6 seconds)
BRESP	-	Responsibility Indicator (1=TCAS; 0=TCAS Not Responsible)
BOT (•)	-	Bottom of hysteresis boundary for setting ALIM and ZTHR (0, 9,500, 17,500, 29,500 feet)
CAS	-	Collision Avoidance System
CMDSAV	-	Previous resolution choice with regard to this threat; a threat file entry.
CREFNO	-	Intruder track file entry in surveillance cross reference table; an intruder track file entry.
CREFROW	-	Pointer from track cross reference table to intruder track file row.
DETECT	-	Module name for detection logic
DITF	-	Flag to indicate that terminal threat working list entry already exists for this threat because of intruder track drop due to 10 consecutive missing reports
DMOD	-	Tau distance modifier for resolution (0.075, 0.1, 0.3, 1, 1.3 nmi)

DMODA	-	Tau distance modifier for traffic advisories (0.1, 0.13, 0.2, 0.4, 1.2, 1.6 nmi)
DT	-	Nominal time between track updates (1 second)
DV	-	25-bit Display Vector
HALFSEC	-	Timing Constant (0.5 second)
HITA	-	Flag indicating if intruder meets advisory criteria
HITFLG	-	Flag indicating if intruder meets threat criteria this cycle
HITORM	-	Hit or miss logic module
HMD	-	Horizontal Miss Distance
HSKATF	-	Module which performs housekeeping of the ATCRBS file
HSKBCA	-	Module which performs housekeeping of TCAS structures
HSKRARB	-	Module which performs housekeeping of TCAS portions of the maneuver coordination files
HSKTRF	-	Threat file housekeeping logic
IDINT	-	Intruder's 24-bit DABS ID (0 if ATCRBS); an element of the intruder track file.
IND (•)	-	A function which transforms a pilot selected performance level into a logic performance level
INDEX	-	Performance level index used to select parameters (0 to 7)
INITRAN	-	Flag used to determine interrogation status
ITF	-	Intruder track file
INTMDUP	-	Module which updates the operational status of own TCAS
ITROW	-	Intruder's row number in intruder track file
KHIT	-	Hit counter used to define a threat (0 to 4); an element of the intruder track file
KSMOOTH	-	Logic module used to form the working list of threats based on KHIT status
LAYER	-	Index for hysteresis boundary constants for ALIM, ADIV, and ZTHR (1 to 4)
LDV	-	25-Bit Vector. Mirror image of display vector on last logic cycle.

MACSET - Logic module which sets multiple threat flag

MAP (•) - Function which generates a negative complement of the OWNTENT array

MTOW - Own multiple threat indicator in threat file

NEWTA - Flag indicating display status of traffic advisory

NOTRANZ - No Mode C transition tracking logic

OLDPOI - Pointer passed to maneuver coordination file deletion logic identifying bit to be reset in the maneuver coordination file

OPFLG - Flag indicating functional status of own TCAS

OPTR - Pointer passed to maneuver coordination register addition logic identifying bit to be set in register

OWNTENT - Own aircraft's maneuver intention due to a particular threat (12-bit vector)

P_i - Nonlinear Tracking Constants (i=1, 2, ..., 14)

PERMTENT - Maneuver intent due to threat i. An element of the threat file (12-bit vector)

POOWRAR - Pointer from threat file entry to own resolution advisory for this threat in the maneuver coordination file (1 to 14)

POTHRAR - Pointer from threat file entry to threat's resolution advisory in maneuver coordination file (1 to 14)

POSVSL - VSM logic module

PTR - Pointer in housekeeping logic identifying bit to be reset in maneuver coordination file

Q - Quantization Constant in nonlinear tracker (100 feet)

R - Tracked range to intruder; an element of the intruder track file

RA - Resolution advisory

RAMDUP - Module which determines if TCAS can generate advisories

RAMODE - Flag indicating if BCAS can generate advisories

RARBUS - Flag indicating Maneuver Coordination Register is busy (locked)

RARDEL	-	Maneuver Coordination File Deletion Logic Module
RD	-	Range rate of the intruder; an element of the intruder track file
RDTHR	-	Range rate threshold for determining threat status (0.00167 nmi/sec)
RDTHRTA	-	Range rate threshold for determining traffic advisory status (0.00167 nmi/sec)
RESA	-	Flag indicating this traffic advisory file entry has an active resolution
RESCOOR	-	Resolution and coordination logic module
RESP	-	Flag indicating system resolution responsibility
RR	-	Reported Range of Intruder
RTHRTA	-	Range threshold for meeting traffic advisory criteria (0.25 to 2.0 nmi)
RZ	-	Intruder's relative altitude; an element of the intruder track file
RZD	-	Intruder's relative altitude rate; an element of the intruder track file
SELADV	-	The logic module which selects the resolution advisory to be displayed
SETPRM	-	The logic module which sets the performance level dependent detection parameters
STATUS	-	Status of working list entry (new, continuing, terminal)
TAF	-	Traffic advisory file
TAFLG	-	Flag indicating traffic advisory criteria are met
TALARM	-	Flag indicating to sound audio alarm
TAROW	-	Pointer from TAF to intruder track file position for this intruder
TATLIM	-	Maximum amount of time a traffic advisory may be displayed without being refreshed (30 seconds)
TAUR	-	Time to closest approach with DMOD clearance
TAURTA	-	Time to closest approach with DMODA clearance
TCMD	-	Timer for last change to this threat's resolution; a threat file entry.

TCUR - TCAS executive clock time

TDATAI - Time of latest intruder track file update; an element of the intruder track file

TDROP - Limit of time without a report to drop a track (10 seconds)

TERM - Terminal Threat Status

TFROW - Pointer from threat file to entry in intruder track file for this threat; a threat file entry

THFIL - Threat File

TLOCK - Time the Maneuver Coordination Register was last locked

TLRCMD - Time of last refresh by own TCAS for this threat; a threat file entry

TLOCAL - Local recalculation of predicted time to closest approach used to compute vertical miss distance

TMIN - Minimum command display time (4.5 seconds)

TOP(•) - Top of hysteresis boundary for ALIM, ADIV, and ZTHR (10,500; 18,500; 30,500; 10^5 feet)

TP - Variable used to smooth TRTRU in vicinity of CPA

TRACKZ - Executive Module for Nonlinear Tracker

TRAFADV - Executive Module for Traffic Advisory Logic

TRAFCOR - Module to correlate traffic advisories with TCAS resolution advisories

TRAFDET - Traffic Advisory Detection Logic

TRAFDIS - Traffic Advisory Display Logic

TREPT - Time of last data report; an element of the intruder track

TRFNEMO - Module which creates new threat file entries

TRFUPDO - Module used to update threat file entries

TRIACT - Intruder Tracking Logic

TROACT - Own Tracking Logic

TRTRU - Range/range rate (-R/RD); an element of the intruder track file

TTHLRCM - Last refresh by threat of its advisory; an element of the threat file

TUNLOCK	-	Maximum time the Maneuver Coordination Register may be locked (0.1 second)
TVPCMD	-	Maximum prediction time for computing vertical miss distance (35 to 48 seconds)
VMD	-	Vertical miss distance; an element of the intruder track file
VMD_i	-	Threshold for issuing vertical speed limit advisories (8.33, 16.67, 33.33 ft/sec)
VSL	-	Vertical speed limit advisory
VSM	-	Vertical speed minimum advisory
WLROW	-	Pointer from working list to threat's position in intruder track file
WTROW	-	Pointer from working list to threat's position in threat file
WINDOW	-	Number of simultaneous traffic advisories which can be displayed
ZD	-	Current vertical rate of aircraft to be modeled
ZDINT	-	Tracked vertical rate of intruder; an element of the intruder track file
ZDLVL	-	Vertical rate below which current altitude is used in sense determination (10 ft/sec)
ZDOWN	-	Tracked own aircraft vertical rate
ZDTHR	-	Threshold for detecting vertical divergence (1 ft/sec)
ZFLG	-	Flag indicating presence of altitude information in this track update
ZI(•)	-	Tracking data storage entries I=1,2,...,10
ZINT	-	Intruder tracked altitude
ZM	-	Measured altitude
ZOWN	-	Own tracked altitude
ZP	-	Predicted own aircraft's vertical position
ZT(•)	-	Values taken on by ZTHR (750, 850, 950 feet)
ZTHR	-	Vertical threshold criteria for threat detection (750 to 950 feet)