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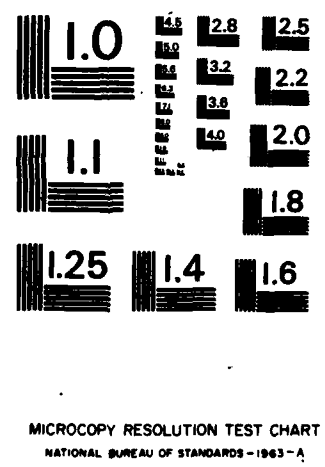
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DOT/FAA/PM-83/27

Program Engineering &
Maintenance Service
Washington, D.C. 20591

Performance of the Collision Avoidance Logic During Preliminary Flight Tests of the Traffic Alert and Collision Avoidance System (TCAS II)

AD-A135 315

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March 1983

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

NOTICE

Technical Report Documentation Page

1. Report No. DOT/FAA/PM-83/27	2. Government Accession No. A135315	3. Recipient's Catalog No.
4. Title and Subtitle Performance of the Collision Avoidance Logic During Preliminary Flight Tests of the Traffic Alert and Collision Avoidance System (TCAS II)		5. Report Date March 1983
		6. Performing Organization Code
7. Author(s) Lillian B. Zarrelli		8. Performing Organization Report No. MTR-82W238
9. Performing Organization Name and Address The MITRE Corporation, Metrek Division, 1820 Dolley Madison Blvd., McLean, VA 22102		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DTFA01-82-C-10003
12. Sponsoring Agency Name and Address Department of Transportation, Federal Aviation Administration, Program Engineering and Maintenance Service, Washington, D.C. 20591		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency Code APM-330
15. Supplementary Notes		

16. Abstract

Flight tests of a prototype Traffic Alert and Collision Avoidance System (TCAS II) were conducted by the FAA Technical Center between August and October 1981. One purpose of the flight tests was to verify the effectiveness of the TCAS logic in generating safe separation. Eighty-three planned encounters were flown during the test program. In addition, 14 low approaches, which resulted in the display of seven resolution advisories, were made into Washington National and Chicago O'Hare Airports. Three encounters of opportunity were also recorded. A total of 93 encounters were analyzed for this document.

The primary characteristics used to measure TCAS performance included the timeliness and correctness of the traffic and resolution advisories, and, where appropriate, the vertical separation provided by the system. The advisories generated during the flight tests were timely and were in the correct direction, based on the data at the time of sense selection.

The vertical separation achieved at closest approach for each encounter was analyzed by a fast-time replay capability. With nine exceptions, this vertical separation was greater than or equal to the system threshold. In three of the exceptions, separation was reduced due to significant pilot delay in responding to the advisory; however the TCAS logic performed properly. Two exceptions produced only slightly less than the system's separation threshold. Logic enhancements added subsequent to the flights were found to successfully resolve these encounters. In the remaining four exceptions, abrupt intruder leveloff maneuvers foiled the TCAS sense selection logic, resulting in reduced separation. Subsequent to the flight tests, logic modifications were added which alert the pilot in the event that an unsafe intruder maneuver occurs after an advisory has already been displayed. However, protecting against sudden intruder maneuvers remains an inherent system limitation.

17. Key Words TCAS, Resolution Advisory, Traffic Advisory, Collision Avoidance		18. Distribution Statement Document is available to the public through the National Technical Information Service, Springfield, VA 22161.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 76	22. Price

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METRIC CONVERSION FACTORS

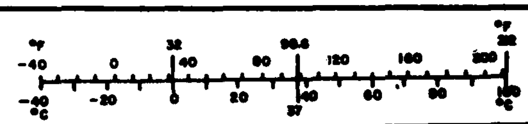
Approximate Conversions to Metric Measures

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

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

Approximate Conversions from Metric Measures

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



ACKNOWLEDGEMENTS

The author would like to thank the staff at the FAA Technical Center for all of their assistance and cooperation in providing the flight test tapes and documentation. The author would also like to thank Dr. William Niedringhaus of MITRE for providing the updated TCAS logic in fast-time simulation, Mr. David Lubkowski for updating the software for processing the TCAS flight test tapes, and Mr. Michael Prospect for assisting in the data reduction.

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CONCLUSIONS

During the series of seven flight tests evaluated for this report, 93 encounters which resulted in the display of resolution advisories were flown. The following conclusions are based on an analysis of the 83 planned encounters flown at the FAA Technical Center and in Washington, and the 10 unplanned encounters which occurred during flights into Washington and Chicago.

1. The logic coded in the Dalmo Victor TCAS was functioning properly during each of the flight tests. One minor coding error which resulted in a one-second resolution advisory transition near closest approach was discovered at the Technical Center. Separation was not affected.

2. Each of the encounters analyzed resulted in timely resolution advisories. There were no late advisories due to design or surveillance problems.

3. The advisory sense selected was appropriate for all encounters based on the data at the time of sense selection. On five occasions, the advisory called for altitude crossing, but the pilots chose not to respond. Four of these scenarios were intentional 'fake-outs' in which the intruder initiated a vertical maneuver toward the TCAS aircraft and then abruptly levelled off, fooling the TCAS sense selection logic. Logic now exists which alerts the pilot in such an event. For the fifth encounter, the new modified logic would no longer select an altitude crossing.

4. For those encounters in which the pilot responded, the vertical separation at closest approach was greater than or equal to the ALIM threshold, with five exceptions. Three of the encounters were adversely affected by poor pilot response to the displayed advisory. Timely response in each of these cases would have generated separation greater than or equal to ALIM. The two remaining encounters have been improved with recently implemented logic modifications. Thus, the current logic now provides all encounters with adequate separation.

5. Logic updates recently released have been shown to improve advisory transitioning. In particular, some early transitions to negative advisories which caused a positive-negative-positive sequence have been eliminated.

Also, transitions to and from less restrictive Vertical Speed Limits have been improved. Unnecessary transitions to more severe advisories near closest approach have been eliminated.

6. A few encounters were found involving relatively large range separation at closest approach. Logic modifications have been designed to eliminate some of these unnecessary alerts.

7. The time between the first traffic advisory and the first resolution advisory was near the nominal 15-second value for the majority of encounters. Shorter precursor warning times were experienced only for those encounters involving a sudden large vertical rate maneuver. The logic performed as designed for each encounter.

8. The occurrence of multiple simultaneous traffic advisories was prominent in the terminal areas of Chicago and Washington. As many as six aircraft at one time were present in the Traffic Advisory track file in the Chicago data. (Only three can be displayed at any one time in the Dalmo Victor TCAS.) However, most of these traffic advisories were found to have been generated against aircraft on the ground and are therefore undesirable. A method has recently been tested in simulation which will inhibit traffic advisories against ground traffic. This logic will be implemented for future flight tests.

9. During most of the low approach flights, sensitivity levels were selected manually and the normal sequence of desensitization was not adhered to. As a result, most of the advisories generated during the low approaches were caused by aircraft on the ground. These encounters were therefore not included in the statistical analyses of the database.

10. The logic performed properly for the three unplanned encounters which generated advisories against airborne aircraft.

1. INTRODUCTION AND APPROACH

This document provides an evaluation of the Traffic Alert and Collision Avoidance System (TCAS) logic, as triggered by the planned and unplanned encounters that were a part of the flight tests of the Dalmo Victor prototype equipment. The tests took place primarily at the FAA Technical Center (FAATC), Atlantic City, New Jersey, between 19 August and 16 October 1981, with additional flights flown into Washington National (DCA) and Chicago O'Hare (ORD) airports. Two FAA Boeing 727s and a Convair 580 were equipped with TCAS at various times during the flight tests.

1.1 Scope

The scope of this analysis was to assess the collision avoidance system (CAS) logic. It is tested for appropriateness and timeliness of both the traffic advisories and the resolution advisories, the acceptability of resolution advisory transitions and duration, and ultimately, the performance of the system with respect to the vertical separation provided at closest approach. In addition, emphasis was placed on analyzing any encounter which prompted comments of reluctance on the part of the pilot to respond quickly to any advisory. Angle of arrival data was collected but not assessed for this study.

In all, seven flights were analyzed. The FAA Technical Center provided flight tapes and letter reports that included plots for each encounter and individual data matrices containing information on system parameters. The plots included in this report that are labeled as FAATC data are taken from the FAA letter reports, which provide detailed documentation on each flight and are listed in References 1 through 7.

After a discussion of the data bases used for this study and a review of the pertinent characteristics of the TCAS logic, the individual encounters are examined both as to the advisory sequences found in the tests and as to how modifications to the logic would change them.

1.2 Method of Data Analysis

Data was recorded on the Dalmo Victor system's nine-track cassette tape and processed through a data reduction package. The basic data reduction package, available at both the Technical Center and MITRE, stores scan-by-scan information of the positions of each aircraft in a permanent reusable file.

In order to analyze the encounters recorded onboard the TCAS flights, a scanning program is first used to locate messages on the tapes that indicate an advisory display. A directory of the advisories, the associated system times and record numbers, and the track numbers of the intruder aircraft is produced.

After locating each encounter on the tapes, another program is used to create the permanent encounter data base. Tracked range and altitude information on the TCAS and intruder aircraft are extracted on a scan-by-scan basis. Table 1-1 outlines the contents of each scan record in the encounter data base. (A glossary is provided in Appendix A.)

Each encounter can then be replayed through the TCAS fast-time simulation to produce plots of the aircraft tracks, the CAS logic variables and advisory sequences. One of the most important benefits of the data reduction capability is that logic modifications can be readily evaluated with actual flight test data. As quickly as undesirable logic characteristics are found and improvements or enhancements are made, they can be verified by this replay capability. This tool is used extensively throughout the document.

In addition to the basic data reduction process available at the Technical Center, capabilities exist at MITRE to transform a scan-by-scan encounter data base into a permanent summary data base organized as a single record per encounter. The summary data base contains information about the position of each aircraft at the instant the first resolution advisory is displayed. In addition, the data base contains information about equipages, sensitivity levels, flight phase, computed time differences between traffic advisories and resolution advisories, horizontal and vertical closest approach, aural alarms, simultaneous traffic advisories, escape rate and response times and other useful data. Table 1-2 outlines the contents of the summary data base.

Another very important future input to the data bases will be the observer's comments. Pertinent subjective information regarding each encounter will be manually entered into the encounter data base and automatically processed for input to the summary data base. No observer's logs were available from this phase of testing.

To complete the data reduction process, statistical data is compiled via the Statistical Analysis System (SAS). The SAS package uses the summary data base and can output histograms, scatter plots, and the like on all or part of the data. These

TABLE 1-1
ENCOUNTER DATA BASE

Scan-By-Scan Data For Each Encounter On Tape

OWN AIRCRAFT:	INTRUDER AIRCRAFT:
MODE-S ID	ID (MODE-S, Track)
Altitude	Altitude
Altitude Rate	Altitude Rate
Radar Altimeter Trip Setting	Range
Year/Mo/Day/Hr/Sec	Range Rate
Current Resolution Advisory	Bearing
Aural Alarm Indicator	Bearing Rate
Sensitivity Level	Sensitivity Level
Multiple Aircraft Indicator	Equipage

Logic Variables

Hit Counter
TRTRU
VMD

Other Encounter Information:

Number of Simultaneous Traffic Advisories
Traffic Advisory IDs
Gear Flap Status*
Phase of Flight*
Location*
Visibility*
Visual Acquisition of Intruder Indicator
Pilot Response to RA Indicator
Pilot Response Time
Intruder Aircraft Type
Planned vs. Unplanned Encounter Indicator
Deviation From Assigned Altitude Indicator
Altitude Cross Indicator

* at the time of the Resolution Advisory

TABLE 1-2
SUMMARY DATA BASE

- o Single Entry Per Encounter

  Tape Identification
  Encounter Number
  Logic Version
  Sensitivity Level
  Time of Day
  Own MODE-S ID
  Own Altitude*
  Own Altitude Rate*
  Intruder ID (MODE-S, Track)
  Intruder Altitude*
  Intruder Altitude Rate*
  Intruder Bearing*
  Intruder Bearing Rate*
  Relative Range*
  Relative Range Rate*
  Intruder Equipage
  Intruder Sensitivity Level
  Planned/Unplanned Encounter Flag
  Phase of Flight
  Location
  Problem Encounter Indicator
  Multiple Aircraft Encounter Indicator
  Duration of Multiple Aircraft Encounter
  Altitude Crossing Indicator
  Actual RA Sense Indicator
  Desired RA Sense Indicator
  Sequence of Resolution Advisories
  Time of First Traffic Advisory
  Time of First Resolution Advisory
  Time from Traffic Advisory to Visual Acquisition
  Time from Traffic Advisory to Resolution Advisory
  Time from Resolution Advisory to Closest Approach
  Separation at Closest Approach (Vertical)
  Separation at Closest Approach (Horizontal)
  Time of Closest Approach
  Pilot Response Indicator
  Time From Resolution Advisory to Response
  Escape Rate
  Amount of Altitude Deviation
  Maximum Number of Simultaneous Traffic Advisories
  Average Number of Simultaneous Traffic Advisories
  Number of Aural Alarms

---

* at first Resolution Advisory

SAS summaries are used as a tool to assess the overall performance of the TCAS logic as well as to identify specific logic problems. The complete data reduction process is shown in Figure 1-1. Reference 8 describes the data reduction software in detail.

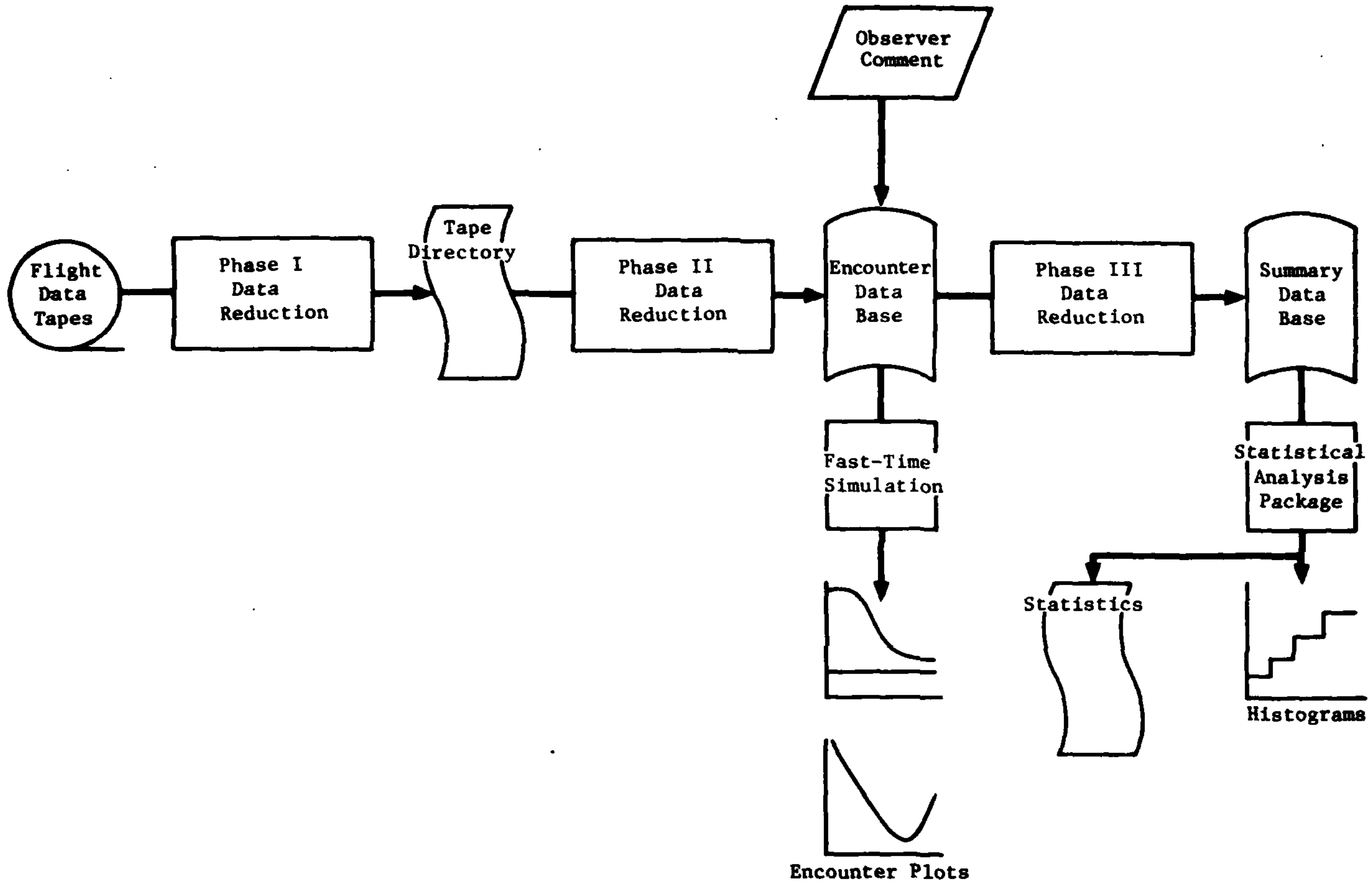


FIGURE 1-1
DATA REDUCTION CAPABILITIES

2. USE OF ENCOUNTER PLOTS TO ANALYZE TCAS LOGIC

2.1 Evolution of the Logic

The tracking, threat detection, and resolution logic which was coded into the Dalmo Victor prototype unit consisted of the October 1980 BCAS logic listed in Reference 9 plus logic updates included in the MITRE letters listed in References 10 through 15.

A number of modifications to the logic have been designed and tested since these flights were made. These modifications will be shown to improve protection performance, or to improve resolution advisory selection and transition sequences. In order to verify the TCAS logic during each stage of its development, updated versions of the logic have been programmed in a fast-time simulation. Data from the flight test tapes is input to the simulation to produce encounter plots with advisories generated by the updated logic. These advisories are then compared with those generated by the onboard unit. Any discrepancies are resolved and improvements are noted. All of the flight test encounters which resulted in less separation than the appropriate positive alert threshold (ALIM) were tested against the most recent TCAS logic, listed as Reference 16. Results are detailed in Section 3.

2.2 Encounter Plots Used for Logic Analysis

As each flight test encounter is replayed through the TCAS fast time simulation, a file is output that may be used to plot various aspects of the encounter on a Calcomp plotter. Plots of aircraft altitude, altitude rate, relative altitude, relative range and calculated tau values versus system time may be generated. An example of one such plot is shown in Figure 2-1. This figure actually consists of three separate plots that use the current system time recorded on the tape as the X-axis.

The bottom plot shows the range tau (TAUR) and vertical tau (TAUV) values plotted as the ordinates. The thresholds associated with TAUR and TAUV, TRTHR, and TVTHR, respectively, are shown as dashed lines and their value is printed in the legend.*

The middle plot in Figure 2-1 is a plot of current altitude separation, A, and projected altitude separation, VMD, versus

*The names of all variables are the same as called for in the logic document, Reference 16.

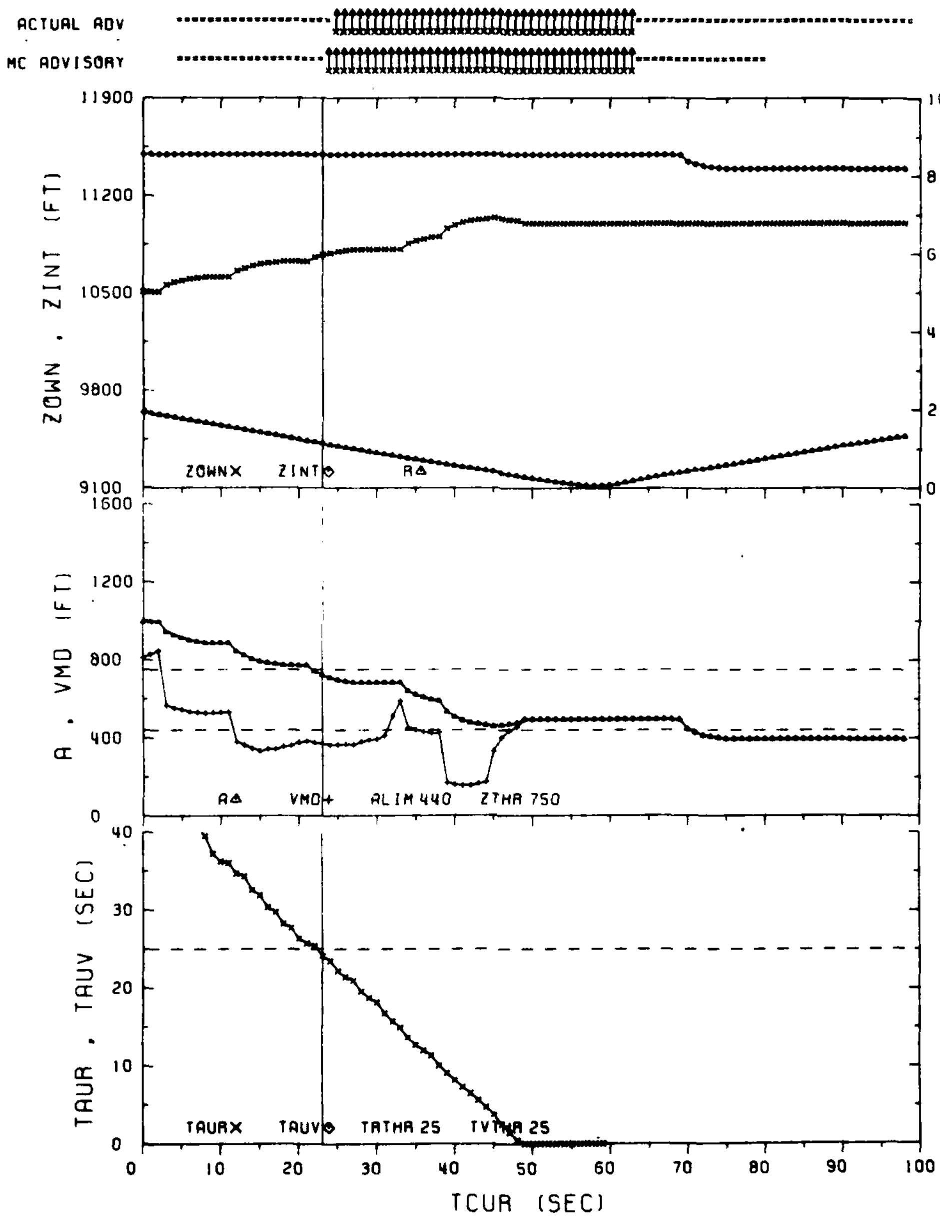


FIGURE 2-1
REPLAY OF 23 SEPTEMBER FLIGHT ENCOUNTER 4

system time. The thresholds for threat detection, ZTHR, and positive/negative advisory selection, ALIM, are both plotted as dashed lines, with their values in the legend.

The plot at the top of Figure 2-1 shows the current altitude of the TCAS aircraft, ZOWN, and of the threat aircraft, ZINT, versus system time. The scale for the altitude plot is on the left vertical axis. The range between the two aircraft, R, is also plotted. The scale for R, in nmi, is on the right vertical axis.

Two advisory lines appear above the plots. The top line represents the actual advisories generated onboard the TCAS aircraft during the flight. The second line represents the advisories generated by the TCAS simulation. A vertical line is drawn through each plot at the time the first resolution advisory (RA) is given. The RAs are represented by arrows. A list of each advisory representation is shown in Table 2-1. Generally, a traffic advisory (TA) will appear before a resolution advisory. The symbol for a TA also appears in Table 2-1.

The computer generated symbols used to represent advisory sequences on the FAATC plots are slightly different than those generated by MITRE's fast-time simulation. The only inconsistency is in the representation of the Vertical Speed Limit (VSL) advisories of 500 and 2000 fpm. Table 2-2 shows the symbols used for the FAATC plots. Traffic Advisory symbols were not included as part of the FAATC plots, however, they do appear on the fast-time replay plots.

2.3 Example of a Typical Resolution

The encounter depicted in Figure 2-1 is a typical tailchase geometry which was flown on 23 September. The top plot in the figure shows the intruder aircraft level at 11500 feet MSL. The TCAS aircraft was overtaking the intruder, and was climbing at approximately 600 fpm from 10,500 feet MSL.

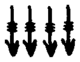
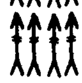
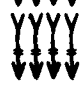
The first advisory displayed to the TCAS aircraft was a traffic advisory. This is indicated by the "equal" signs in the advisory line. Twenty seconds later, as TAUR crossed the TRTHR threshold, a range "hit" was declared by the detection logic. An altitude "hit" was simultaneously declared because A was less than ZTHR.

Once the detection criteria were satisfied, the resolution logic modeled the flight paths of both the TCAS and the threat aircraft to determine the effectiveness of the climb and descend senses. For this encounter, a descend sense was predicted to provide better separation. The logic then chose the advisory

TABLE 2-1
ADVISORY SYMBOLS FOR TCAS LOGIC PLOTS

SYMBOL	ADVISORY RESPRESENTED
	DON'T DESCEND
	LIMIT DESCENT TO 500 fpm
	LIMIT DESCENT TO 1000 fpm
	LIMIT DESCENT TO 2000 fpm
	CLIMB
	DON'T CLIMB
	LIMIT CLIMB TO 500 fpm
	LIMIT CLIMB to 1000 fpm
	LIMIT CLIMB to 2000 fpm
	DESCEND
	TCAS ABORT
	INTRUDER ON GROUND
	TRAFFIC ADVISORY

TABLE 2-2
ADVISORY SYMBOLS FOR FAATC PLOTS

SYMBOL	ADVISORY REPRESENTED
	DON'T DESCEND
	LIMIT DESCENT TO 500 fpm
	LIMIT DESCENT TO 1000 fpm
	LIMIT DESCENT TO 2000 fpm
	CLIMB
	DON'T CLIMB
	LIMIT CLIMB TO 500 fpm
	LIMIT CLIMB TO 1000 fpm
	LIMIT CLIMB TO 2000 fpm
	DESCEND
	MAINTAIN 500 fpm CLIMB
	MAINTAIN 1000 fpm CLIMB
	MAINTAIN 2000 fpm CLIMB
	MAINTAIN 500 fpm DESCENT
	MAINTAIN 1000 fpm DESCENT
	MAINTAIN 2000 fpm DESCENT

which was predicted to provide ALIM separation based on modeled vertical rates. A negative advisory, DON'T CLIMB was selected for this encounter.

In response to the displayed advisory, the TCAS aircraft levelled off at approximately 11,000 feet MSL, 494 feet below the threat. Horizontal closest approach was less than .1 nmi.

For this particular planned encounter, the resolution advisory sequence displayed during the flight test is almost identical to that generated by the fast-time simulation. The difference is that the updated logic displays the advisory one second earlier. This is because there is no longer a two-out-of-three "hit" requirement. Advisories are now selected as soon as the threat criteria are met for the first time. In addition, the traffic advisory was displayed a number of seconds longer during the flight test than in simulation. The reason is that the logic flown during the flight test used a time-out feature to end traffic advisory display whereas the new logic uses a divergence test. The advisories generated for this encounter were timely, effective, and in the correct direction.

3. THE FLIGHT TEST ENCOUNTERS

The FAATC flight tests included both TCAS-equipped and unequipped intruders in single and in multiple encounters. This document was intended to evaluate the TCAS logic against only unequipped intruders. In all, seven flights were evaluated. Table 3-1 describes the date, location, and number of encounters flown.

Resolution advisories were generated in 93 encounters. The majority of the flights consisted of planned encounters flown at the FAA Technical Center and in Washington. This report focuses on these 83 planned encounters. The planned encounters included a number of geometries. Both level and vertically accelerating encounters were flown. Turning and non-turning encounters were flown head-on and at varied crossing angles. Combinations of vertical accelerations and crossing angles were tested. Overall, the scenarios were selected to stress various features of the TCAS unequipped intruder logic.

There were ten unplanned encounters which also generated resolution advisories. These unplanned encounters have been individually evaluated but are not included in the statistical database for the following reasons. Seven of the encounters occurred during low approach flights into the Washington and Chicago terminal areas. In order to see how sensitivity level sequencing affected resolution advisories, a manual override of the normal desensitization sequence was sometimes used. As a result, five of these alerts were generated when proper sensitivity level sequencing was not adhered to. Most of the targets appear to have been aircraft on the ground. In addition, the use of larger detection parameters caused the multiple aircraft logic to be invoked for three of these encounters. These alerts would not normally have been generated so close to the runway. Nevertheless, the Tracking, Detection, and Resolution functions of the logic performed properly.

Two advisories were generated during the low approaches when proper sensitivity level switching was used. These two encounters consisted of only a single report to the TCAS logic followed by nine coasts. It is therefore likely that these tracks are not valid ones. The TCAS logic is designed to detect and resolve conflicts based only on the reports passed to it from surveillance. If the surveillance logic allows tracks to be passed on, TCAS will treat them as valid until they are dropped. Therefore, the logic performed properly for these encounters.

TABLE 3-1
SUMMARY OF FLIGHT TEST ENCOUNTERS

Flight Date	Location	Number of Planned Encounters	Number of Low Approaches	Number of Resolution Advisories Generated on Low Approaches	Other Resolution Advisories Generated as a Result of Unplanned Encounters
8/19/81	FAATC	12			1
8/25/81	FAATC	18			1
9/11/81	FAATC	9			
9/17/81	FAATC	7			
9/23/81	FAATC	21			
9/28/81	Washington	16	4	1	1
9/30/81	Chicago	--	10	6	
TOTAL ENCOUNTERS		83		7	3

The three other unplanned encounters were generated against airborne intruders. In each case the TCAS logic performed properly, and provided traffic and resolution advisories which were timely and effective.

The following sections describe in detail the performance of the TCAS logic during the seven flight tests in FAATC and DCA.

3.1 Overall Logic Performance

Without exception, each of the planned encounters flown were provided with timely resolution advisories. There were no late resolution advisories generated as a result of surveillance or logic deficiencies. The TCAS logic version used in the flight tests worked as intended, providing advisories which were correct with respect to sense (CLIMB, DESCEND) and severity (Vertical Speed Limit (VSL), Vertical Speed Minimum (VSM), Negative, Positive).

One minor logic coding error was identified and corrected by the Technical Center which caused a single inappropriate advisory transition at the end of an encounter. An example appears in Section 3.4.2. While no other errors were found, a few design issues related to advisory severity and transitioning were identified and addressed as a result of flight data analysis. Logic updates have subsequently been made which substantially minimize and smooth advisory transitioning. These updates will be described and individually demonstrated in Section 4.

3.2 Time Between Traffic Advisory and Resolution Advisory

The traffic advisory logic was generally found to provide on the order of 15 to 20 seconds of warning prior to the display of a resolution advisory. Most of the encounters that had less than about nine seconds of warning were alerts against aircraft on or near the ground during low approach flights into terminal areas. These advisories were generated because the logic version flown did not inhibit traffic advisories close to the runway. Section 4.5 describes a logic update which is designed to eliminate advisory display against intruders on the ground.

Figure 3-1 shows the distribution in the precursor warning times for the 83 planned flight test encounters. The 10 unplanned alerts are not included. Each bar segment along the horizontal axis of the graph represents a midpoint of a data segment

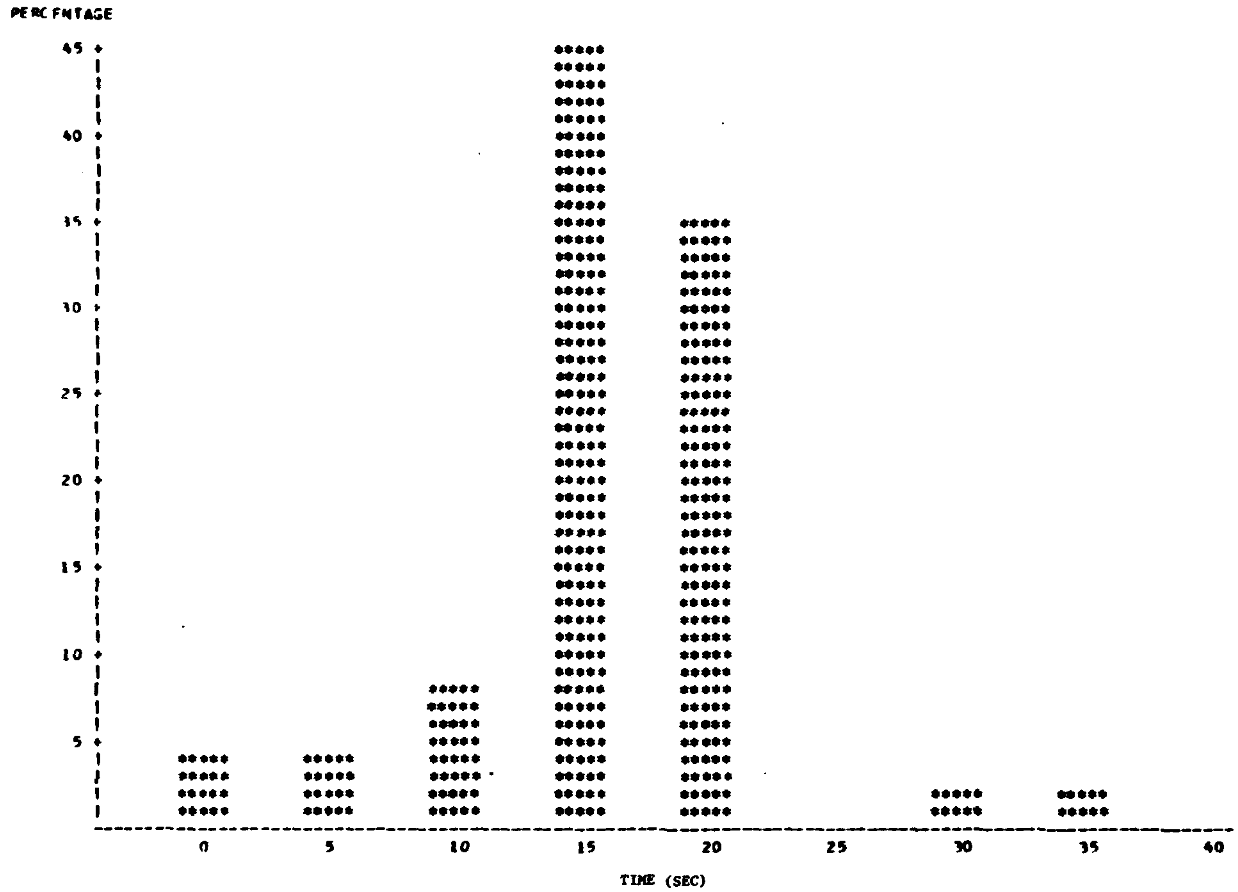


FIGURE 3-1
DISTRIBUTION OF PRECURSOR WARNING TIMES FOR 83 PLANNED ENCOUNTERS

measuring the time between the first TA and the first RA*. For example, approximately 45 percent had precursor warning times between 12.5 and 17.5 seconds. This is shown by the bar labelled 15 seconds. More than 80 percent of the encounters had warning times in the 15 or 20 second ranges. The encounters with warning times less than 12.5 seconds were due to sudden vertical acceleration maneuvers by one of the aircraft.

Tracker lag in responding to vertical accelerations was found to be the cause of these late alerts. When a level aircraft initiates a sudden, high-rate maneuver toward the other aircraft, the computation for time to coaltitude (TAUV) experiences substantial jumps. If the intruder is outside the traffic advisory altitude threshold (ZTHRTA) when the maneuver begins, a number of scans of data are needed before the logic detects a threat.

Figure 3-2 shows the distribution of warning times for the 67 encounters which were not TAUV tripped. When the vertical acceleration encounters are removed, no warning times fall below the 15-second range.

3.3 Time Between Resolution Advisory And Closest Approach

The warning time provided by the TCAS logic from the display of the first resolution advisory to the time of actual closest approach should nominally be equal to the TAU threshold value in the appropriate sensitivity level. The TAU thresholds vary from 20 to 30 seconds against unequipped intruders. There are two occasions, however, when the time between first resolution advisory and closest approach can be less than the TAU threshold. The first occurs when there is a large difference between time to closest approach and time to coaltitude (non-simultaneous horizontal and vertical crossings). The TCAS logic requires that both the range and altitude criteria be met before declaring a threat. Therefore, the range TAU (TAUR) can become quite small before an advisory is displayed if the time to coaltitude (TAUV) is large. There should nevertheless be adequate vertical separation in this scenario.

*The first bar segment represents a range of zero to 2.5 seconds.

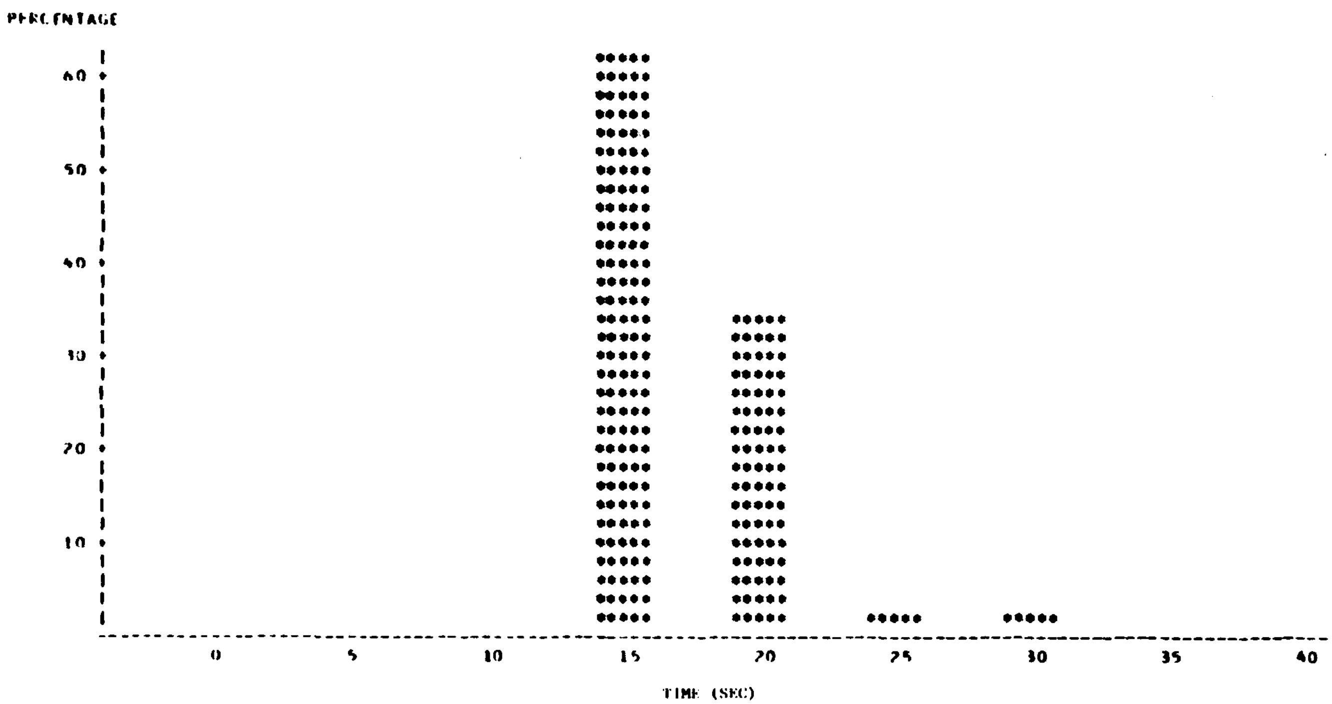


FIGURE 3-2
DISTRIBUTION OF PRECURSOR WARNING TIMES WITH TAUV TRIPPED ENCOUNTERS REMOVED – 67 ENCOUNTERS

The second case occurs when there is a relatively large range miss (e.g., 1.0 to 2.0 nmi) at the point of closest approach. Because TCAS has no horizontal miss distance (HMD) information available, advisories will occasionally be generated when the range criterion is satisfied momentarily, but TAUR does not decrease substantially below the threshold.

In these cases, TAUR is not a very accurate estimate of time to closest approach. Logic has recently been designed to recognize large HMD encounters by evaluating the behavior of TAUR. This logic has been successful in reducing the number of large HMD advisories. An example appears in Section 4.4.

Figure 3-3 shows the distribution of warning time between the first RA and closest approach. Because the closest approach indicates range separation, only the 67 encounters which were triggered by TAUR are included. The TAUV triggered encounters were analyzed separately, and no late alerts were found.

Twenty of the encounters were flown at sensitivity level 4, with the TAU threshold equal to 20 seconds. The remaining encounters were flown at sensitivity level 5, with the TAU threshold equal to 25 seconds. Each encounter was provided warning time of greater than or within about one second of the TAU threshold. Nearly 60 percent of the encounters appear in the range between 22.5 and 27.5 seconds. *No late resolution advisories* were found in the database.

3.4 Vertical Separation At Closest Approach

In assessing the performance of the collision avoidance logic throughout the flight tests, the single most important piece of data which was analyzed was the amount of vertical separation provided at closest point of approach. The TCAS algorithms are designed to provide ALIM feet of separation, unless pilot response or aircraft limitations reduce the separation. ALIM is the threshold of altitude separation used for selecting positive advisories. ALIM varies from 340 to 740 feet to compensate for greater altimetry errors at higher altitudes. Of course pilot response, escape rate, and intruder maneuvers are factors not controlled by the logic, which ultimately can affect separation.

The estimate of vertical separation provided at closest approach is determined from reported altitudes and does not necessarily represent the true separation. Altimetry errors were known to be small and were checked for those planned flights which took place at FAATC and DCA. For flights involving unplanned

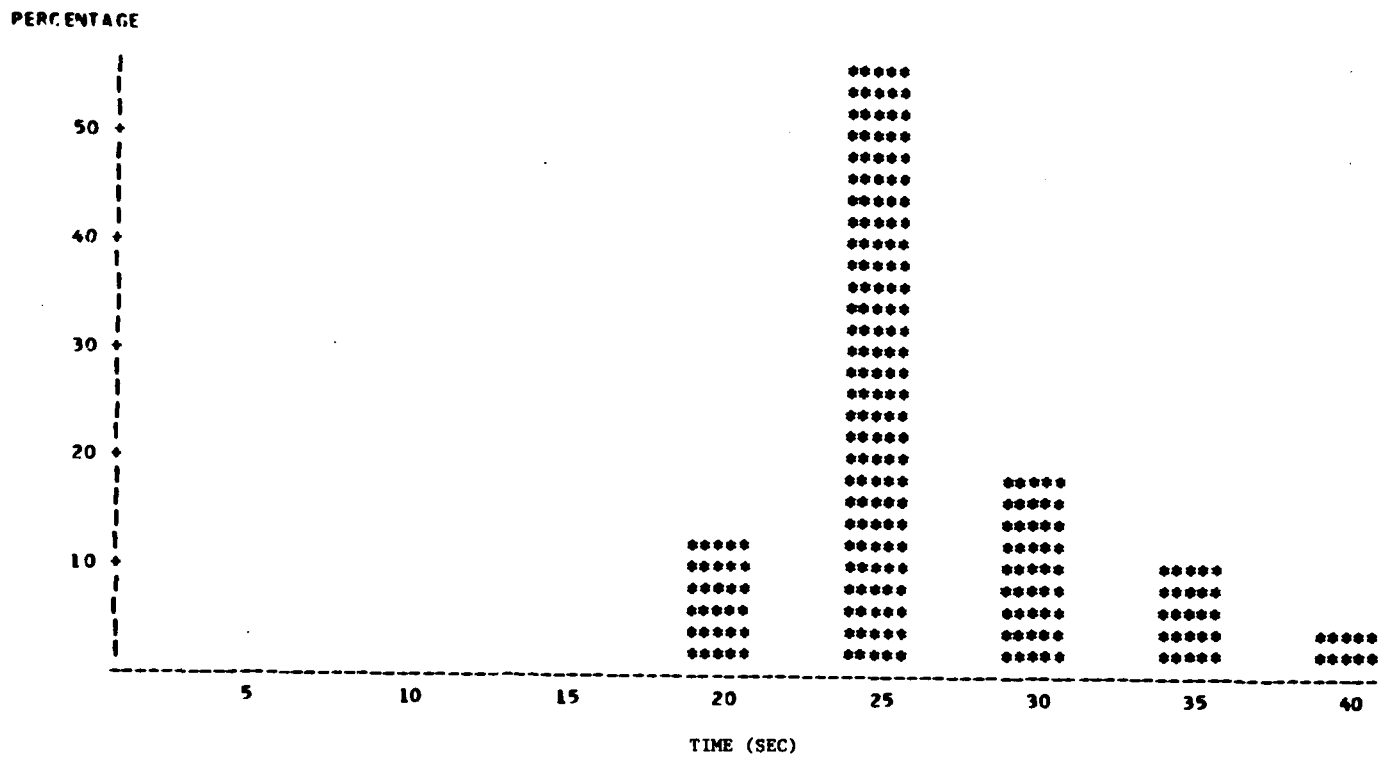


FIGURE 3-3
DISTRIBUTION OF WARNING TIME BETWEEN RA AND CPA FOR 67 ENCOUNTERS

encounters at other airports, altimetry errors are unknown. As a result, true separations may, in some cases, be more or less than indicated by these results.

Figure 3-4 represents the distribution of vertical separations at the closest approach in range. Included in the graph are the 71 planned encounters in which the pilot was instructed to respond to TCAS advisories. During the 12 encounters flown on the first flight, 19 August, the pilots were instructed not to respond to the advisories. Therefore, these encounters were removed prior to plotting. The 12 encounters were level scenarios with 300 feet altitude separations.

More than 95 percent of the encounters were provided with separations of 350 feet or more. One encounter resulted in considerably less than 300 feet of vertical separation. The cause of the poor separation was the lack of pilot response to an advisory which called for altitude crossing. This encounter, which took place on 17 September, is described in the following section.

Figure 3-5 is another representation of the data. Shown is a scatter plot of both the horizontal and vertical separations at closest approach for each of the 71 individual encounters. Each letter on the plot represents the relative separation for one encounter pair. The letter A indicates one encounter pair, the letter B indicates that two encounter pairs had the same separation. Two encounters do not appear because they achieved separation beyond the limits of the plot.

Only five of the encounters achieved vertical separation less than the selected ALIM value. The following sections describe each of these scenarios in detail.

3.4.1 Effects of Delays in Pilot Response

An encounter occurring on 25 August missed the ALIM separation value by about 25 feet. While this is only a marginal loss of separation, the data was analyzed to determine the cause. A pilot delay of 10 seconds was found to have affected performance. At closest approach, the TCAS aircraft had an escape rate of 19 feet per second. A faster pilot response by one or two seconds would have provided the needed ALIM separation. The TCAS logic was working properly. No design flaw is at issue.

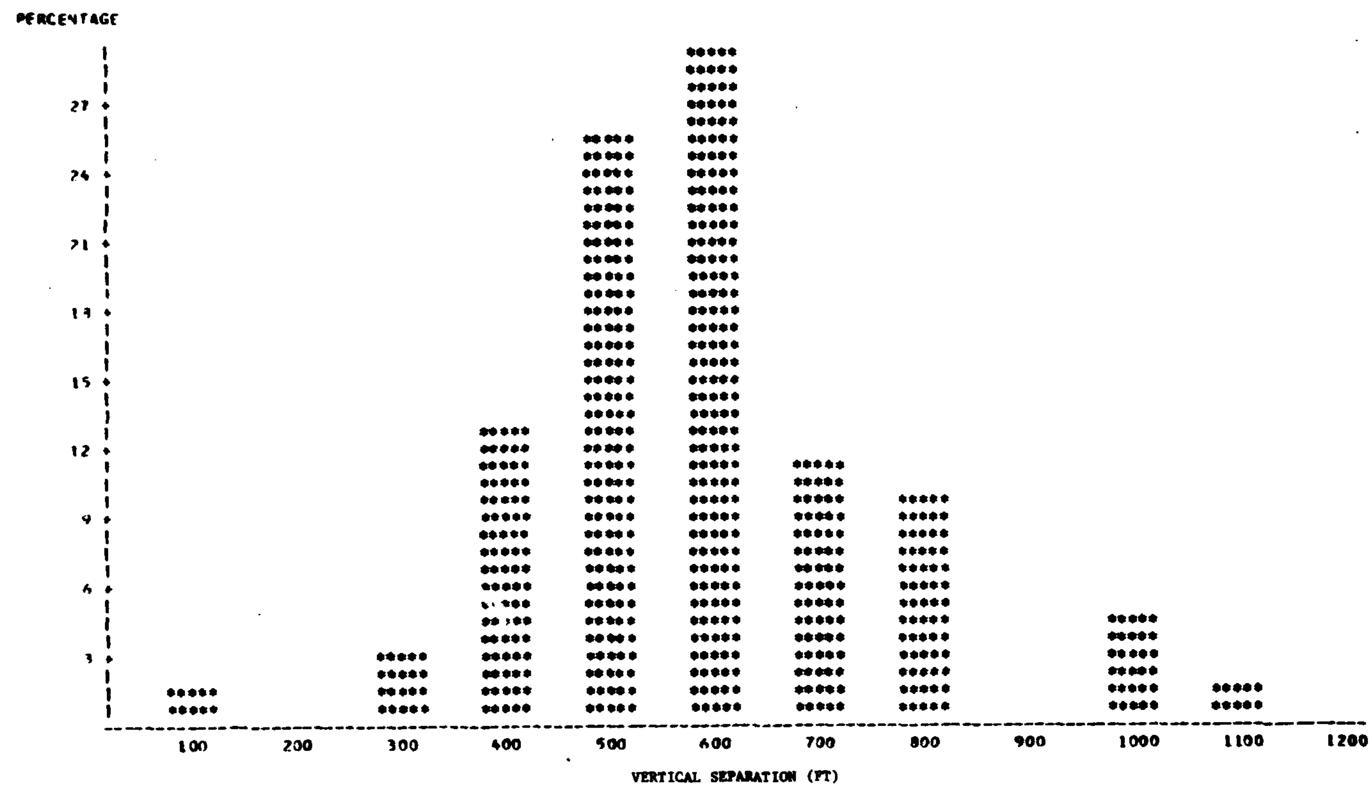


FIGURE 3-4
DISTRIBUTION OF VERTICAL SEPARATION AT CPA WITH 19 AUGUST ENCOUNTERS REMOVED – 71 ENCOUNTERS

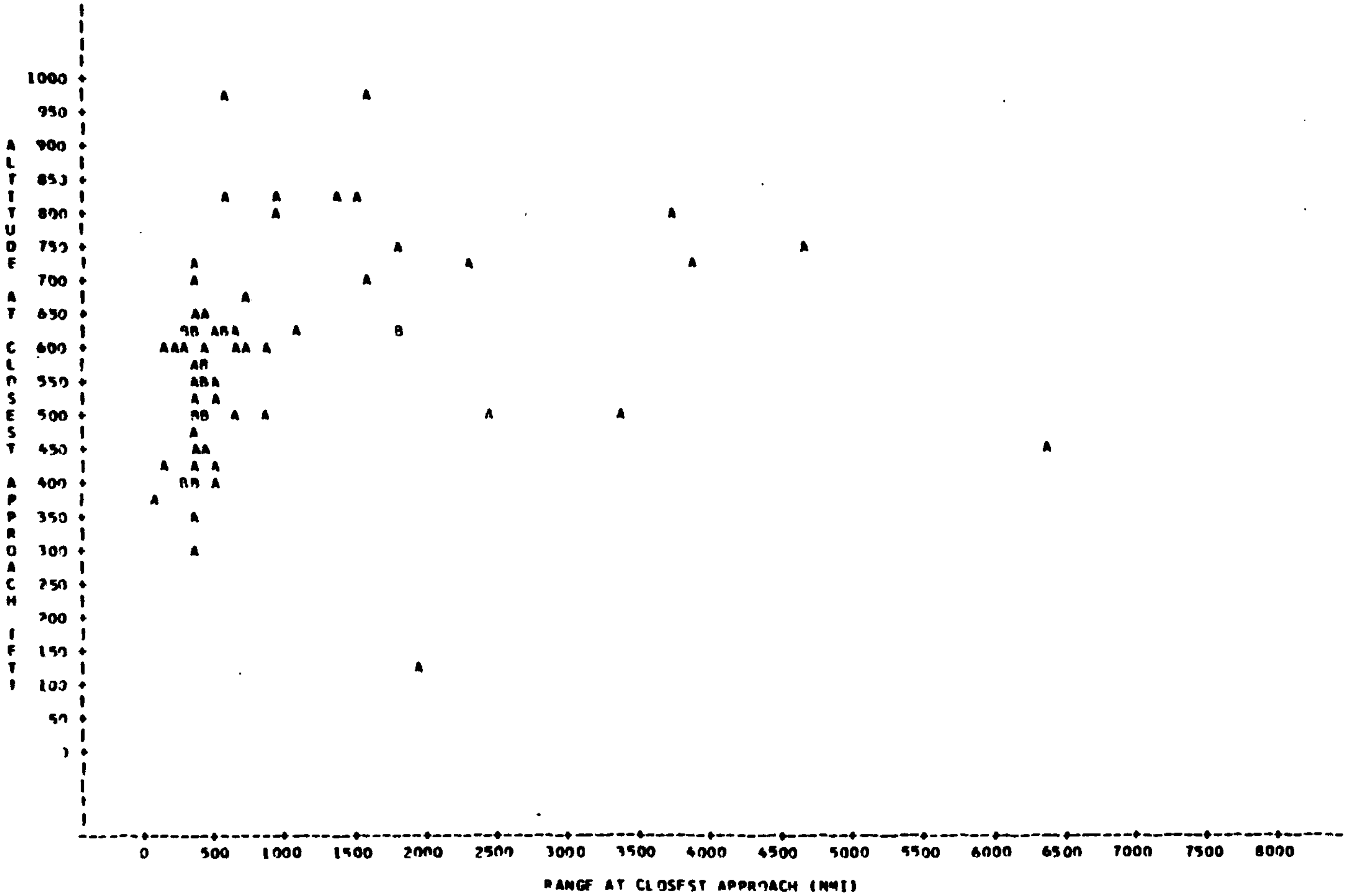


FIGURE 3-5
SCATTER PLOT OF HORIZONTAL AND VERTICAL SEPARATION AT CPA FOR 71 ENCOUNTERS

A second encounter occurring on 25 August provided only 350 feet of separation instead of the 440 foot ALIM threshold. Figure 3-6 (a) shows clearly that the cause lies in the lack of pilot response. Figures 3-6 (a) and (b) show the altitude histories of the TCAS aircraft and the intruder and the computed TAU values plotted against time. A DON'T DESCEND was displayed in the TCAS aircraft at time 58. The altitude plot shows that the pilot continued descending until after the transition to a CLIMB. The TCAS logic again performed as designed for this encounter.

On 17 September, a third encounter resulted in significantly less than ALIM feet in separation. An overly long pilot delay time was again the cause of the decreased separation. However, in this case the pilot delay was due to a reluctance to respond to the display of an altitude crossing advisory.

Figure 3-7 is a plot of this encounter. The TCAS aircraft was level at 11,300 feet. The intruder was climbing from an altitude of 10,000 feet at a rate of about 1300 fpm. The TCAS sense selection logic was invoked at time 60, when TAUR fell below the TRTHR threshold. At this time, a DESCEND was projected to provide better separation than a CLIMB. Had the pilot responded within a few seconds of advisory display, separation equal to ALIM would, in fact, have been provided. However, the pilot delayed 19 seconds before responding. At that time the advisory could no longer provide ALIM feet of separation, yet the DESCEND advisory was followed. Another line has been drawn on the plot which represents the same descent rate used by the TCAS aircraft, but it has been shifted to the left by 12 seconds. Had the pilot delay actually been seven seconds, separation would have been on the order of 440 feet at point of closest approach instead of 130 feet.

Near the point of closest approach, the DESCEND advisory transitioned for five seconds to a Vertical Speed Minimum (VSM), MAINTAIN 1000 FPM DESCENT. The latest TCAS logic no longer displays VSMs. The positive advisory would continue to be displayed instead. The single scan transition to the DON'T CLIMB at the very end of the encounter occurred as the result of a logic coding error which was later corrected by the Technical Center. At that scan, the intruder is about to be dropped as a threat and separation is not affected.

The TCAS logic performed as designed for this encounter, and timely response would have yielded separation equal to ALIM. However, it is evident that improvements in sense selection

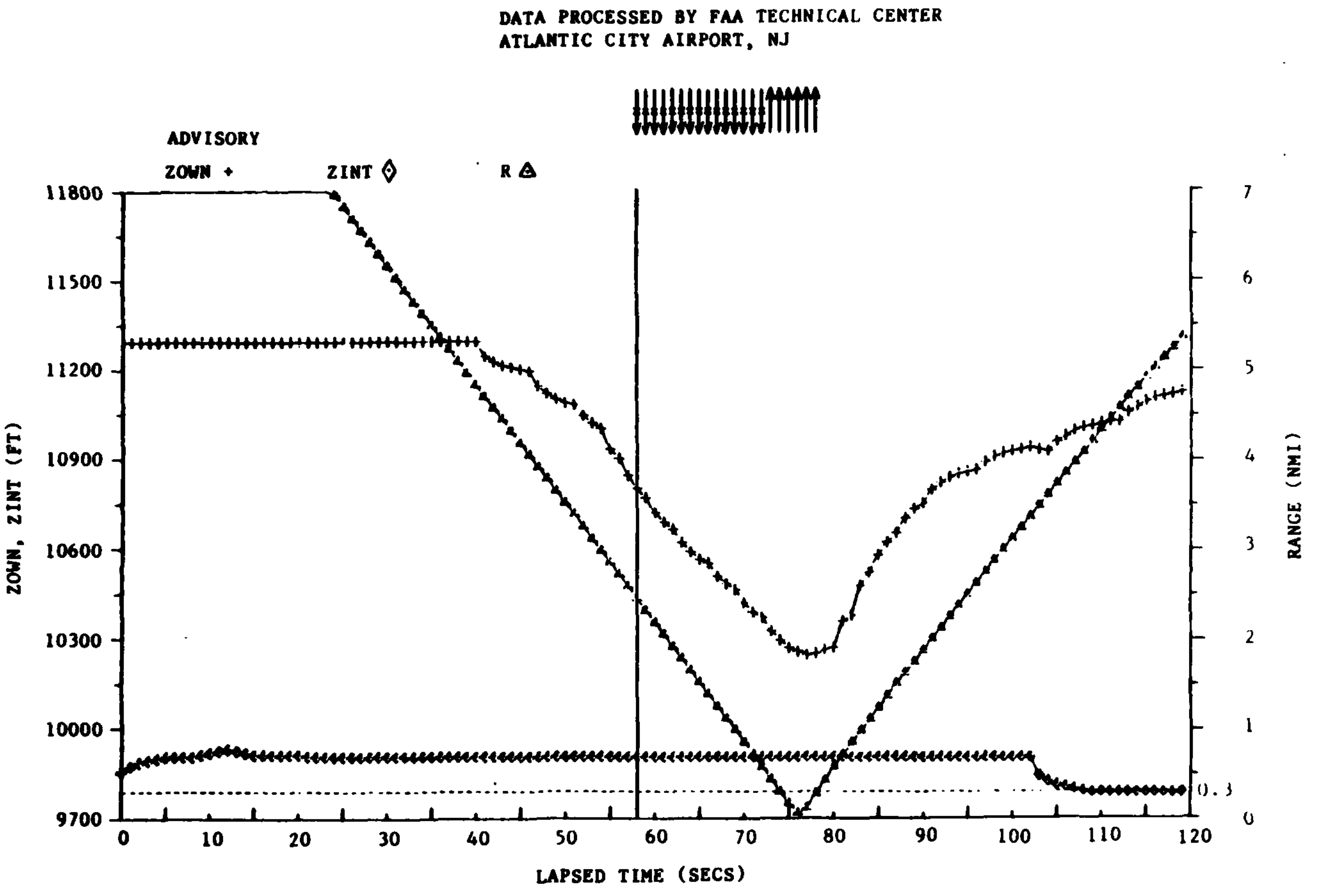


FIGURE 3-6(a)
25 AUGUST FLIGHT ENCOUNTER 17

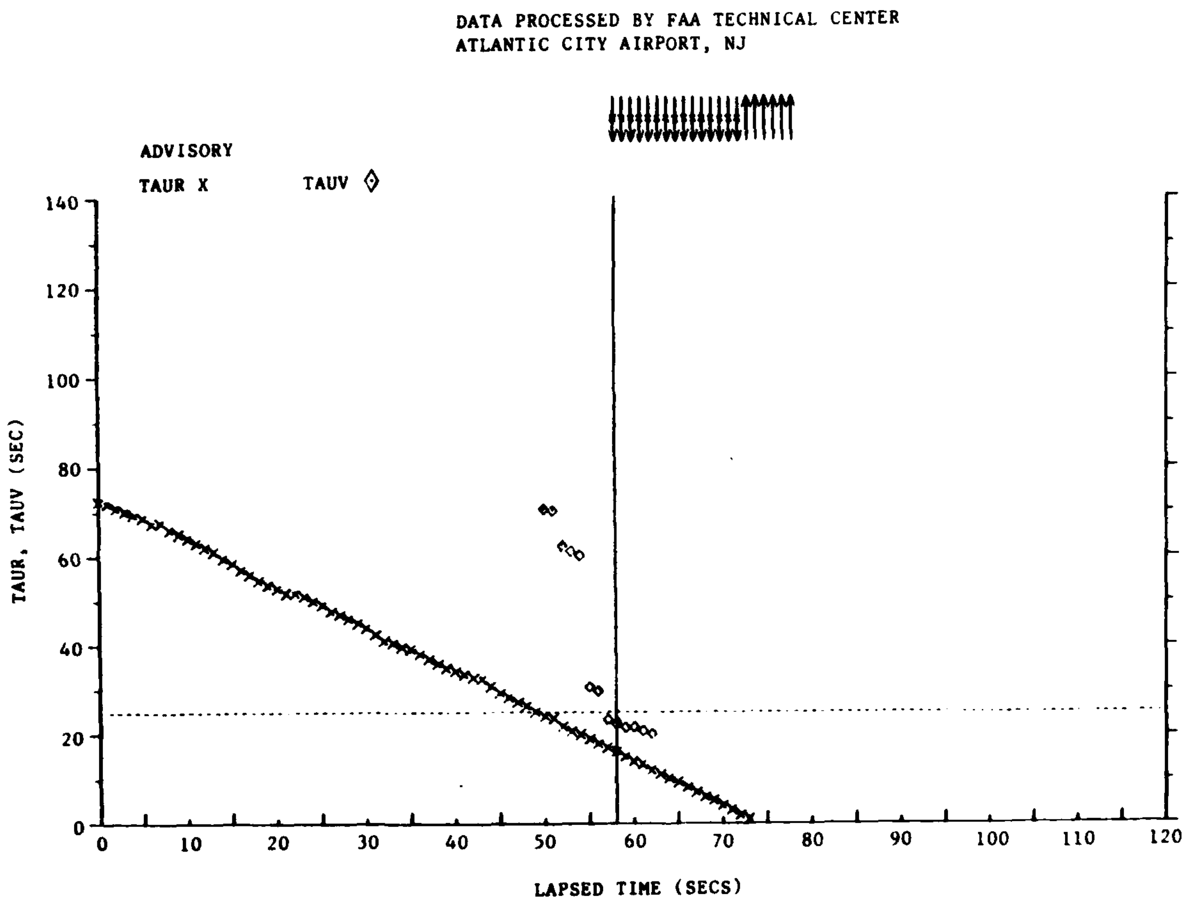


FIGURE 3-6(b)
25 AUGUST FLIGHT ENCOUNTER 17

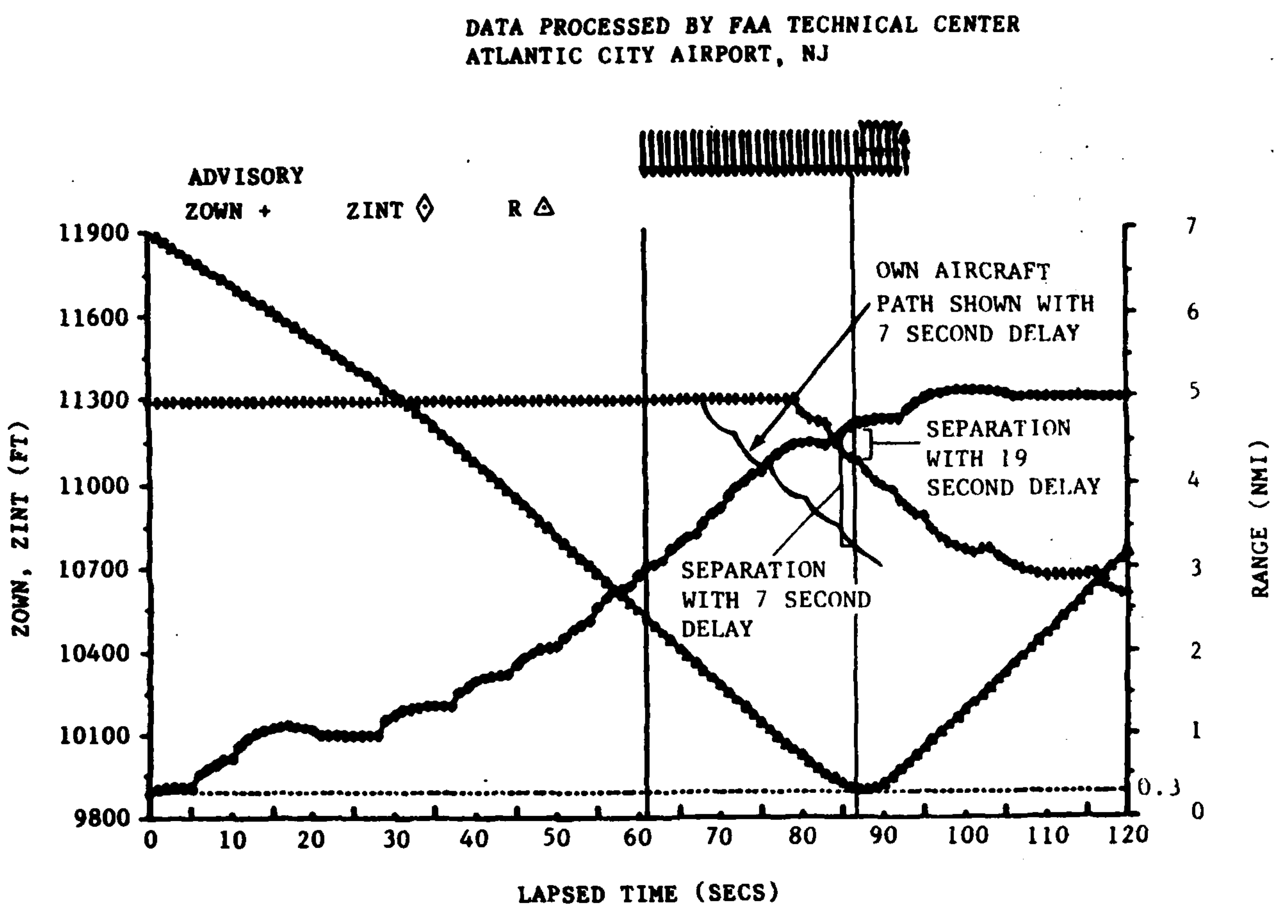


FIGURE 3-7
17 SEPTEMBER FLIGHT ENCOUNTER 4

under certain conditions could be beneficial, particularly considering the reluctance of some pilots to maneuver through the altitude of an intruder. Improvements have, in fact been made which directly effect this encounter. Section 4.2 contains a description of the new logic and shows how this encounter is improved.

3.4.2 Effects of Logic Design

The preceding discussion of three encounters demonstrated the extent to which pilot response can effect TCAS performance. However, the remaining two of the five encounters which produced less than ALIM separation were not affected by pilot response. Rather, the logic design was not conservative enough in the resolution choices.

The first of these encounters took place on 28 September and is shown in Figures 3-8(a), (b) and (c), the altitude, TAU and separation plots. The plots show that the TCAS aircraft and intruder aircraft were separated by only 200 feet near the beginning of the encounter, at scan 25. At scan 60, in response to TAUR dropping below TRTHR, a DESCEND advisory was selected by the logic. Following the initial descent response by the TCAS pilot, separation was projected to be greater than ALIM (shown in Figure 3-8(c)) and an advisory transition occurred at about time 72. In response to the DON'T CLIMB advisory, the pilot of the TCAS aircraft leveled off at time 77. As a result, separation at closest approach (time 82) was 300 feet, 40 feet less than ALIM.

Figure 3-9 is a plot showing the same encounter replayed through the fast-time simulation with the most recent logic listed in Reference 15. The advisory displayed by the TCAS during the flight test is indicated by 'ACTUAL ADV' on the top line. The advisory generated via the Monte Carlo fast-time simulation is indicated by 'MC ADVISORY' on the second line. In this plot, the positive advisory does not transition to a negative as a result of projected aircraft position. The logic now waits until actual separation, A, exceeds ALIM instead of using the projected separation, VMD. This plot is useful for comparing the effectiveness of the original and the updated advisory sequences. The actual aircraft tracks and computed separations shown on the plot remain just as they were recorded onboard the TCAS unit during the flight test. Therefore, the TCAS aircraft is still shown to level off due to the DON'T CLIMB transition. It is clear, however, that the new advisory sequence will have the effect of prolonging the descend maneuver, thereby increasing separation to greater than 340 feet.

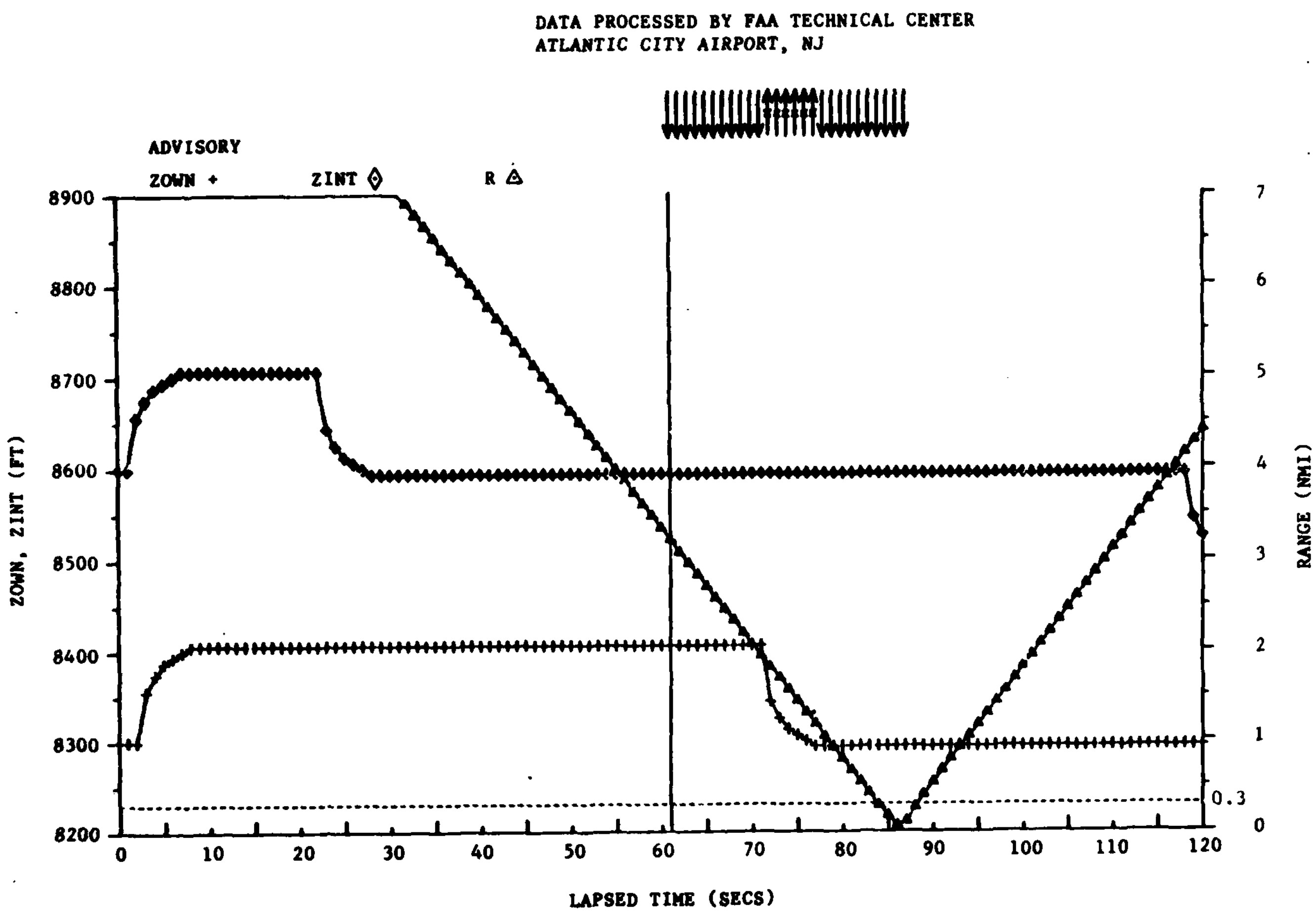


FIGURE 3-8(a)
28 SEPTEMBER FLIGHT ENCOUNTER 9

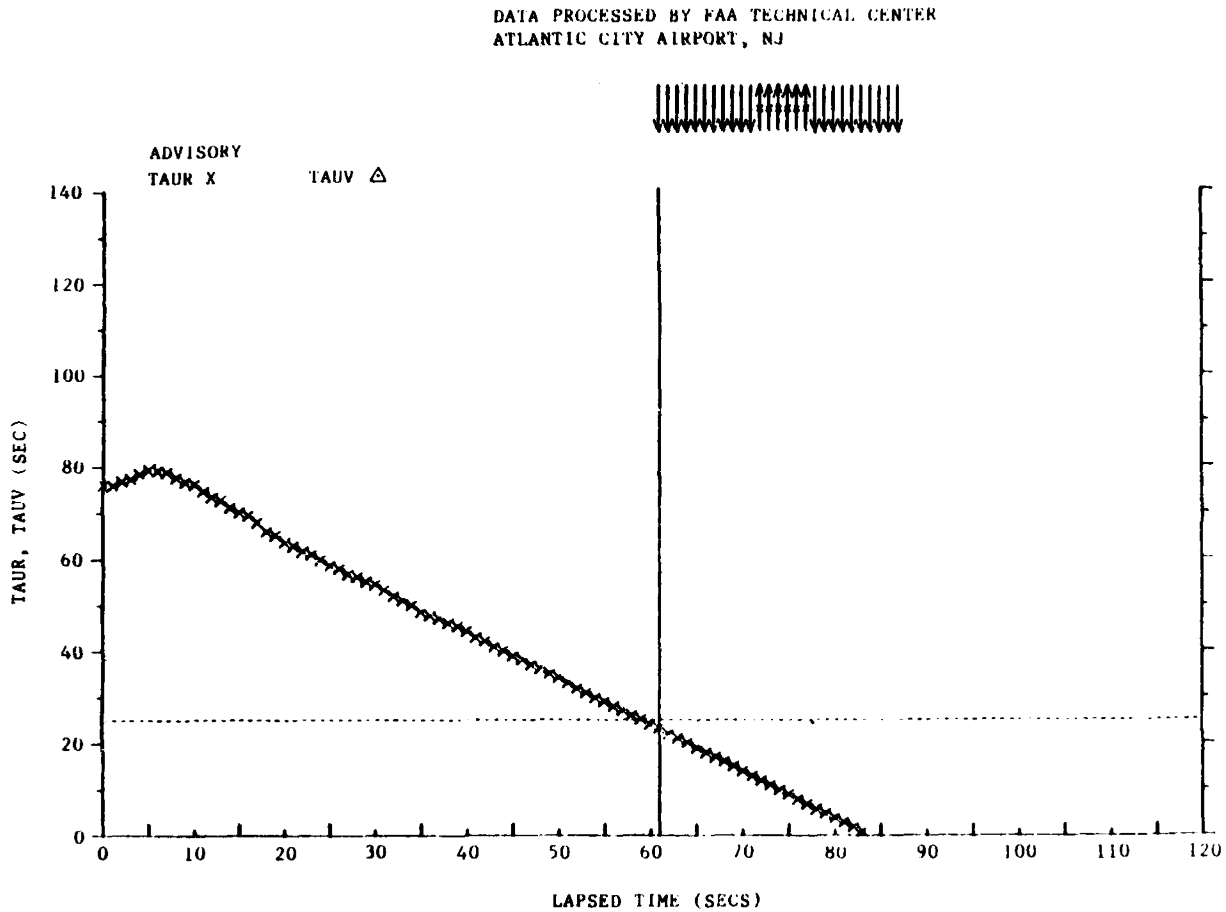


FIGURE 3-8(b)
28 SEPTEMBER FLIGHT ENCOUNTER 9

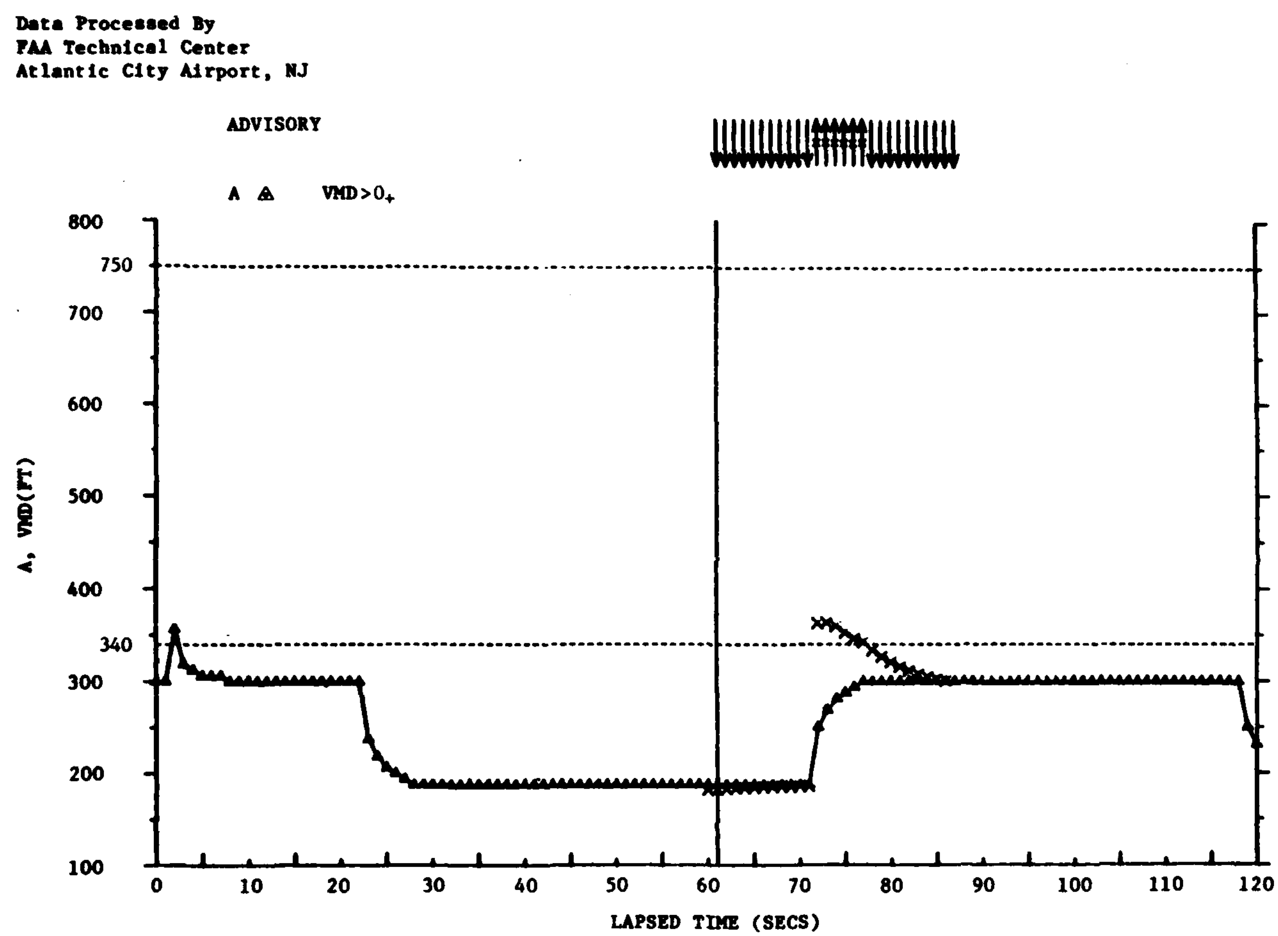


FIGURE 3-8 (C)
28 SEPTEMBER FLIGHT ENCOUNTER 9

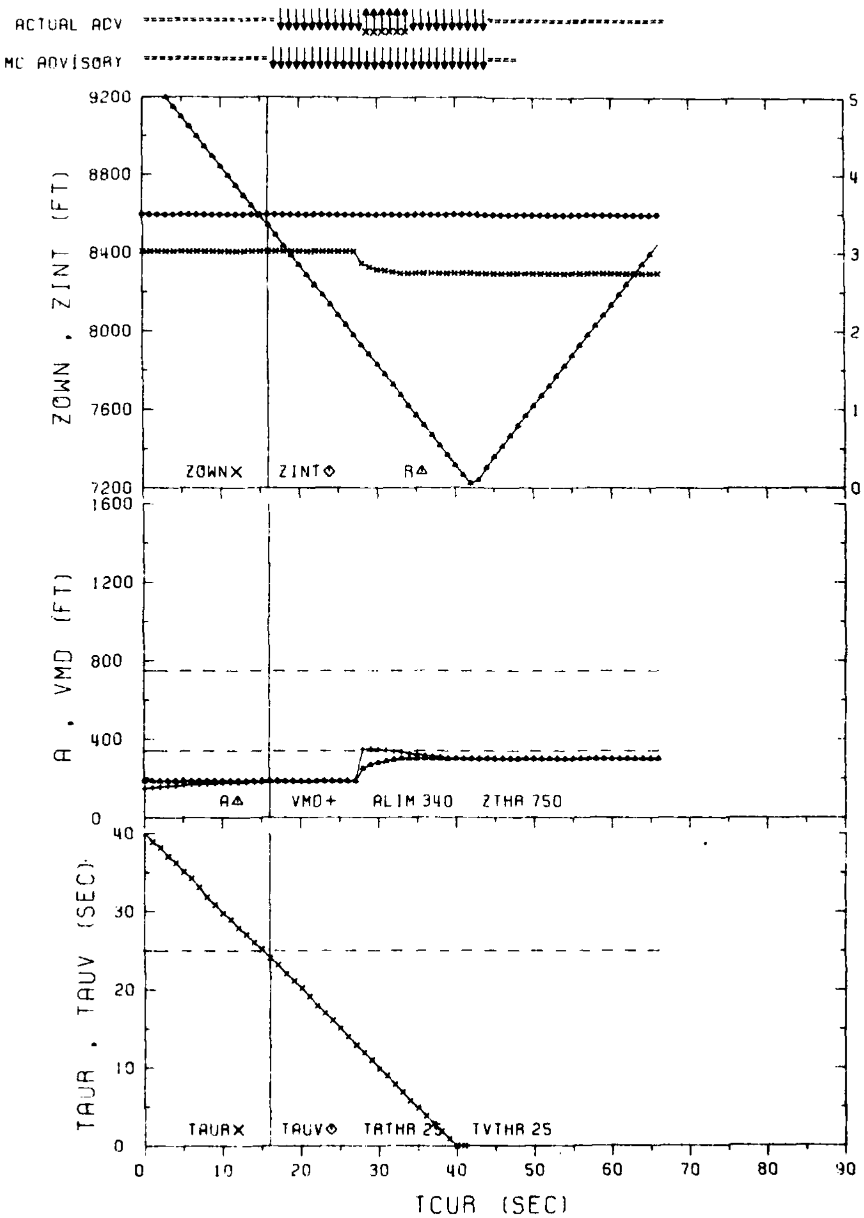


FIGURE 3-9
REPLAY OF 28 SEPTEMBER FLIGHT ENCOUNTER 9

The second encounter which achieved less than ALIM separation occurred on 23 September. Figures 3-10 (a), (b) and (c) are the altitude, TAU, and separation plots for this encounter. Figure 3-10 (a) shows the TCAS aircraft initially separated from the intruder by 1200 feet in altitude. The intruder began climbing at scan 40. At the time of sense selection, the intruder's tracked rate fluctuated around 420 fpm. This rate is less than ILEV, the threshold which determines whether or not an intruder has a rate large enough to trigger the extra warning time logic. This logic allows a positive advisory to be displayed when the projected separation rather than current altitude separation is less than ALIM, thereby providing some additional compensation against a non-level unequipped intruder.

Without the extra warning time logic, a DON'T DESCEND was displayed. When the altitude difference, A, finally crossed ALIM at time 79 (shown in Figure 3-10(c)), the advisory transitioned to a positive CLIMB. However, closest approach occurred only three seconds later. The separation achieved was 381 feet instead of 440 feet.

Recent logic changes have been implemented which improve this particular scenario as well as others. The TCAS logic still uses the ILEV threshold to distinguish between near-level intruders and those with a vertical rate. However, whereas the logic used to wait until current separation fell below ALIM before displaying a positive advisory against near-level intruders, the new logic models projected separation at each scan to determine the strength of the advisory needed. When a posted advisory is determined to no longer provide ALIM feet of separation, the logic selects the next strongest advisory that does.

Figure 3-11 shows this same encounter replayed through the fast-time simulation with the new logic. A positive CLIMB is displayed as the first advisory rather than the DON'T DESCEND. As a result, earlier maneuvering by the TCAS aircraft would have generated adequate separation.

In summary, five of the planned encounters in which the pilots responded to advisories resulted in separation less than ALIM. Only two of these encounters were effected by the design of the advisory selection logic. Both of these encounters have been satisfactorily resolved by recent logic updates. The other three encounters were hampered by lack of timely pilot response to the displayed advisories.

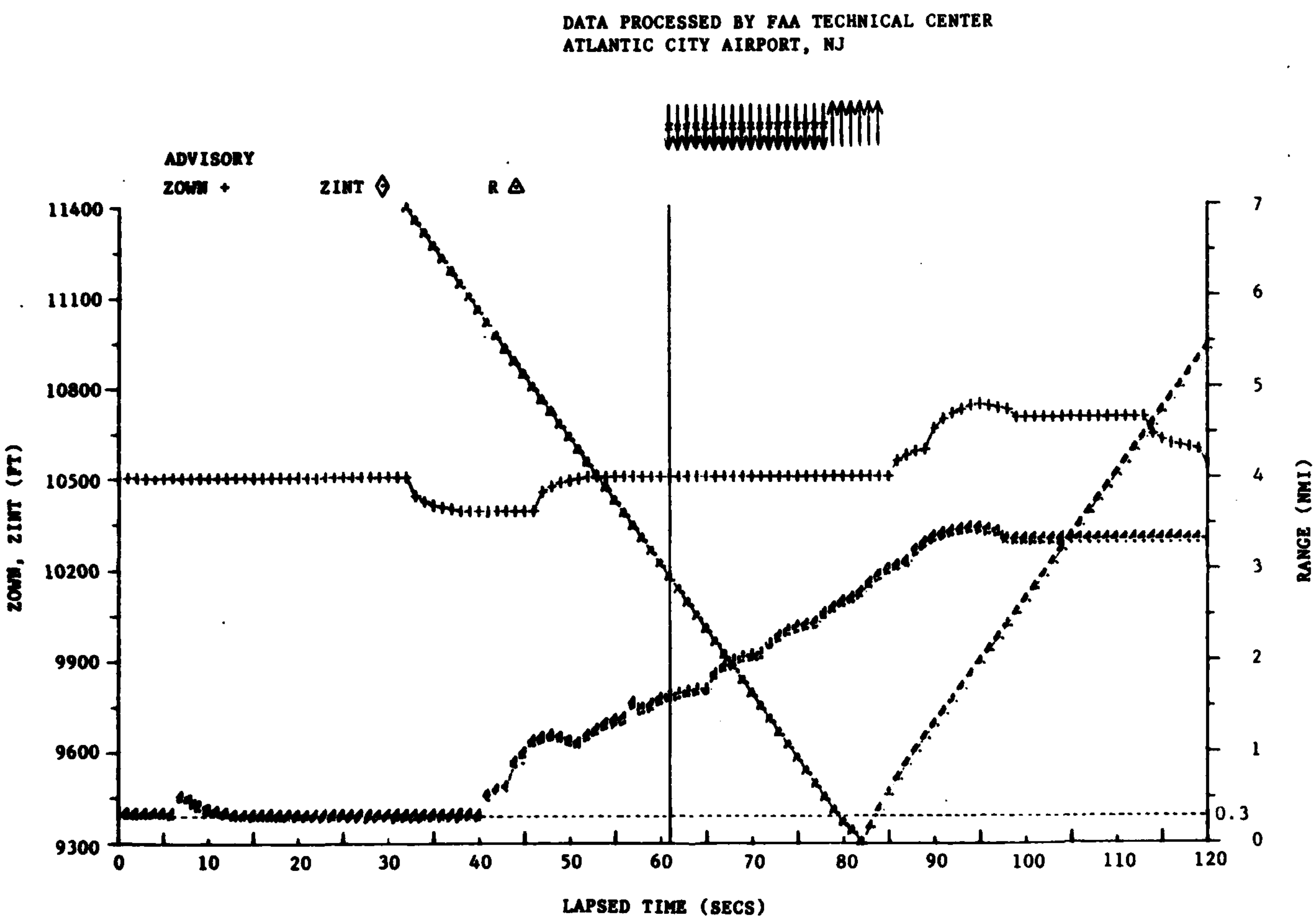


FIGURE 3-10(a)
23 SEPTEMBER FLIGHT ENCOUNTER 19

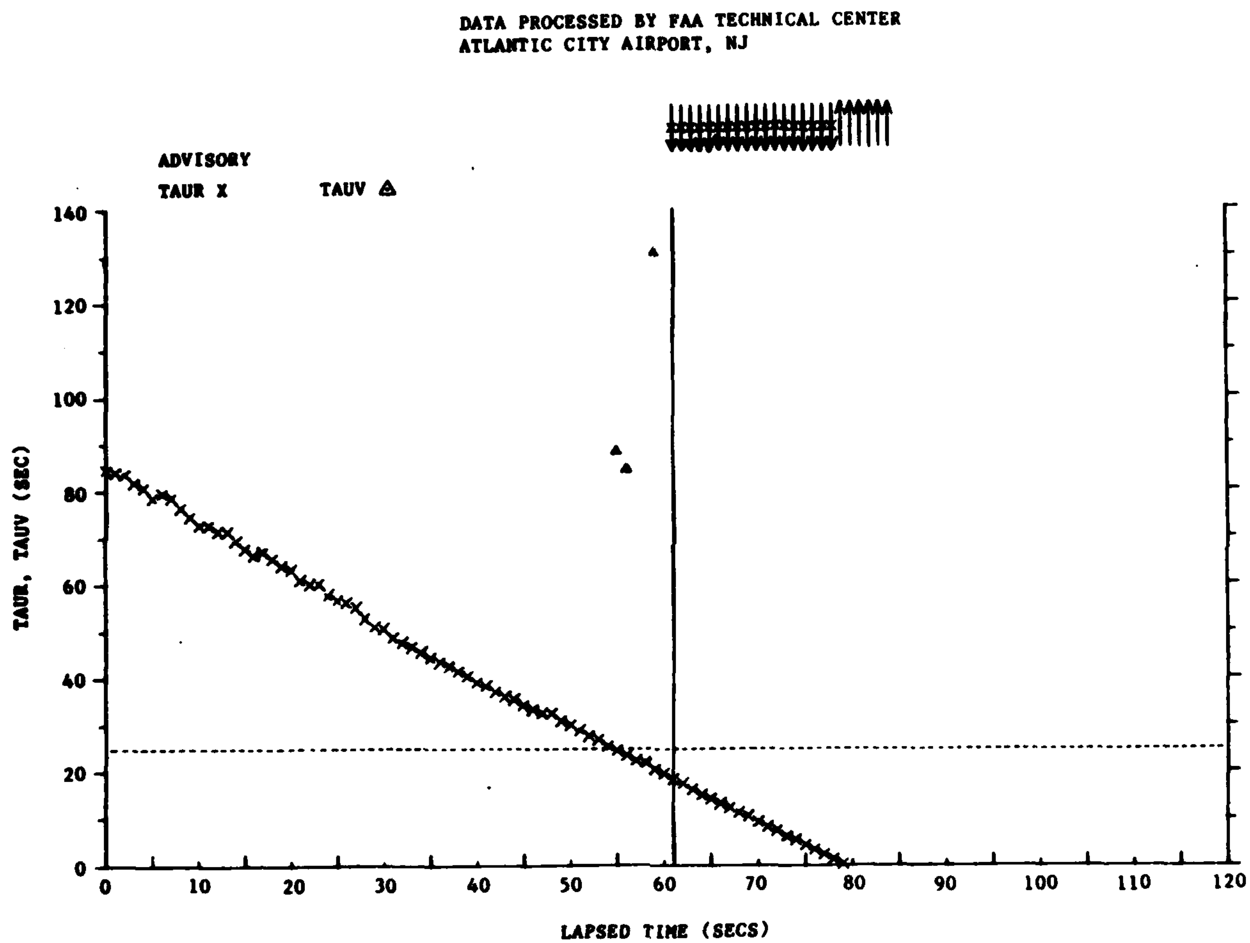


FIGURE 3-10(b)
23 SEPTEMBER FLIGHT ENCOUNTER 19

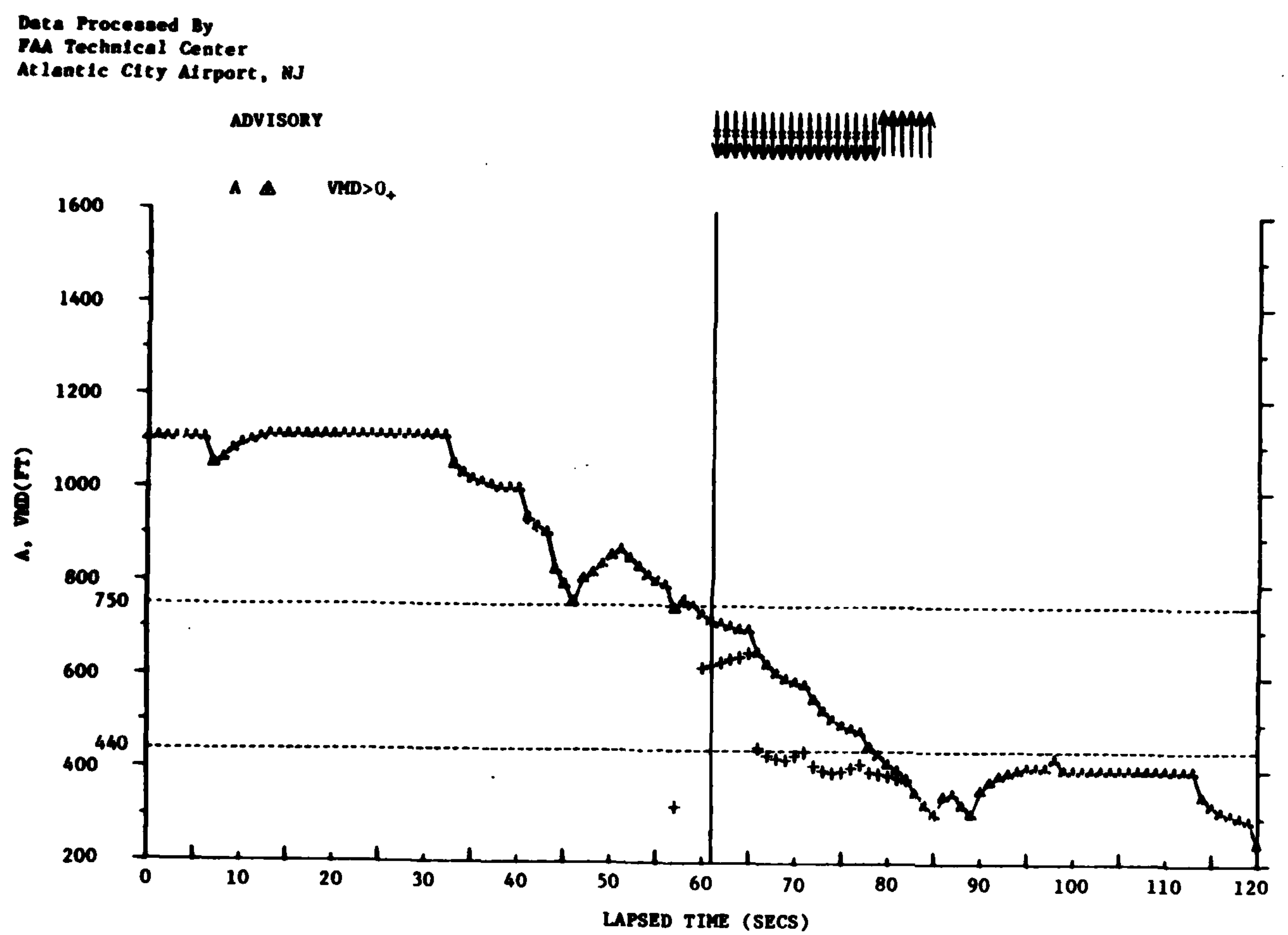


FIGURE 3-10 (C)
23 SEPTEMBER FLIGHT ENCOUNTER 19

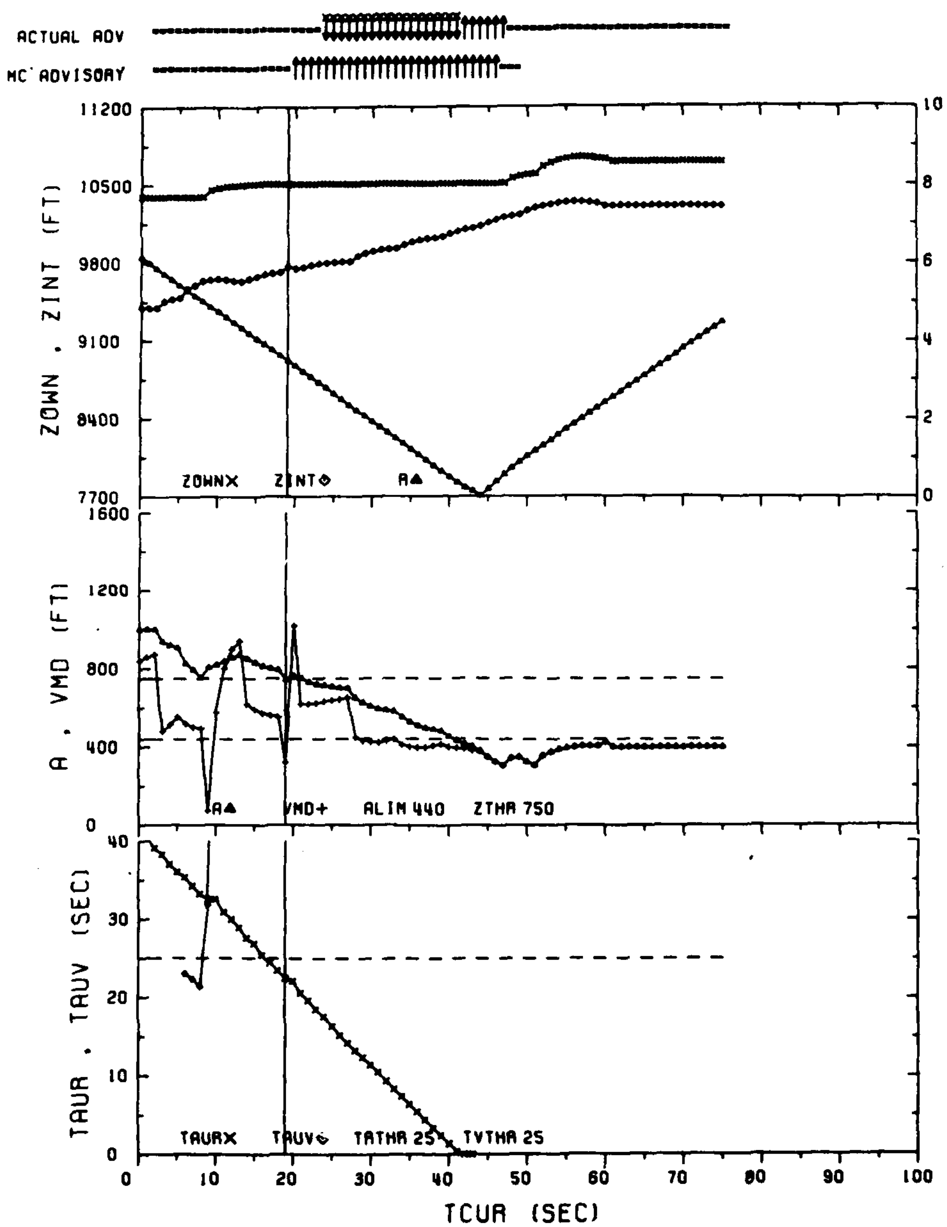


FIGURE 3-11
REPLAY OF 23 SEPTEMBER FLIGHT ENCOUNTER 19

3.5 Fake-Out Maneuvers

In the 83 planned encounters flown, five resolution advisories were displayed which called for the TCAS aircraft to cross through the altitude of the intruder at some time prior to the closest approach in range. One of these encounters, which took place on 17 September, was described in Section 3.4.1. The logic performed as designed in this encounter and would have generated the required separation if the pilot response had been adequate.

Sometimes an altitude crossing advisory is the safest choice against an unequipped intruder with an established vertical rate. However, when separation is projected to be best achieved by maneuvering through the altitude of the intruder, an intruder leveloff becomes a potential hazard. The four other altitude crossing encounters, flown on 25 August, were intentional 'fake-out' maneuvers designed to stress the TCAS sense selection logic. The advisories would not have generated adequate separation if followed. In fact, the pilots did not respond to these four advisories. Plots of these encounters are provided in Appendix B.

The 'fake-out' scenario begins with an intruder in a high rate vertical maneuver toward the TCAS aircraft. The intruder then levels off suddenly during the critical interval in which the logic is selecting or has selected the resolution advisory sense. The resolution logic models the separations achieved with both a CLIMB sense and a DESCEND sense and selects the best maneuver based on projected positions of the TCAS and intruder aircraft. Once selected and displayed to the pilot, the sense is not changed during the remainder of the encounter.

Not all leveloff scenarios 'fake-out' the TCAS logic. In fact, four other similar encounters were flown on 25 August which displayed advisories in the direction away from the intruder. Plots of these encounters are also included in Appendix B. The 'fake-out' condition only occurs when the initial sense choice is opposite that which would have been selected after the leveloff. The TCAS and intruder's vertical rates, the time of the leveloff, and the altitude separations are the variables which, in the right combination, define a 'fake-out'.

Since the structure of the airspace often allows aircraft to fly at altitudes 500 or 1000 feet apart, leveloffs are not unusual. Thus, the possibility exists that an intruder will 'fake-out' the TCAS. Logic has been designed to alert the pilot in the event that a TCAS displayed advisory is no longer effective in resolving the conflict. This logic is described and demonstrated in the following section.

4. EVALUATION OF LOGIC UPDATES

The previous section described each of the flight test encounters which produced less than ALIM separation. Two encounters were shown to be resolved with recent logic updates. A number of other logic modifications implemented and tested since the flight tests have been shown to improve separation or improve advisory transitions.

4.1 Advisory Evaluation Logic

The scenario of greatest concern is the 'fake-out' maneuver, in which the intruder can fool TCAS into selecting the wrong sense. A logic has been designed which detects that the TCAS advisory currently displayed can no longer provide adequate separation and alerts the pilot to the situation. The 'Advisory Evaluation' logic is called whenever TCAS selects the strongest possible advisory in its selected sense. Projected separation is computed at every subsequent scan. If the displayed advisory is predicted to provide less than 100 feet vertical separation, the advisory evaluation flag is set and the information is displayed to the pilot. The cause may be a sudden maneuver by the threat, a late track acquisition, or failure of the TCAS aircraft to respond promptly to a displayed RA. The advisory evaluation logic has been carefully tested to ensure that false alarms are minimized.

Figures 4-1 (a) and (b) show a 25 August flight which resulted in a fake-out maneuver. The scenario began with the intruder level at 11400 feet outside ZTHR. At scan 60 the intruder began a descent in excess of 4000 fpm toward the TCAS aircraft which was level at 9400 feet. Based on the tracked vertical rate and current altitude of the intruder at scan 70, the TCAS logic projected that a CLIMB advisory would achieve the best separation. The intruder was modeled to pass safely below the TCAS aircraft. The climb advisory was valid until scan 85, when the intruder began a sudden leveloff maneuver. The TCAS logic flown during the flight tests had no capability to alert the pilot that the displayed advisory was no longer correct.

The unanticipated maneuver by an unequipped intruder has always been recognized as a problem for a collision avoidance system. The new advisory evaluation logic provides the pilot with some additional information in such an event. Figure 4-2 shows the same encounter replayed through the fast-time simulation. While the logic still selects a CLIMB against the descending intruder,

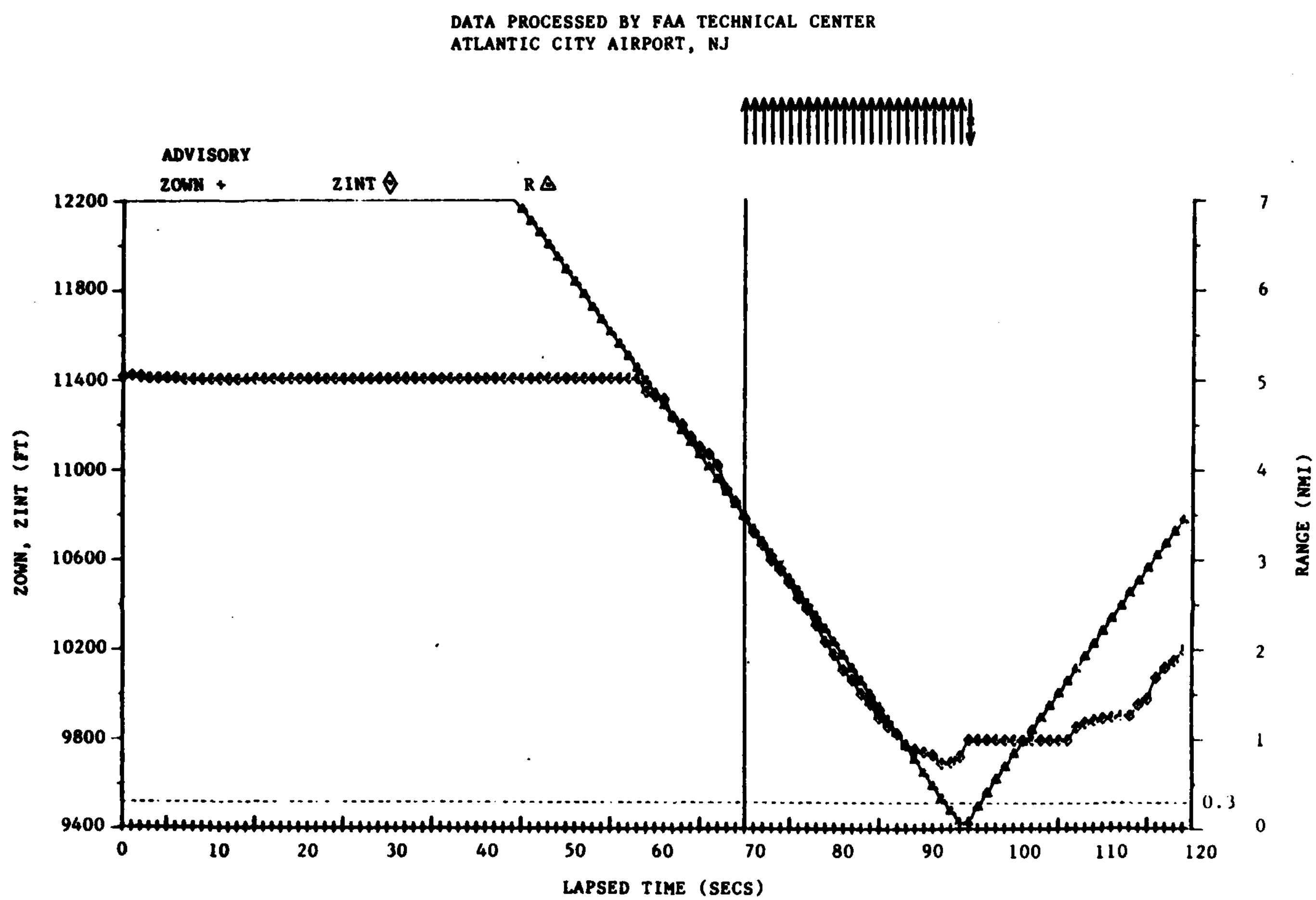


FIGURE 4-1(a)
25 AUGUST FLIGHT ENCOUNTER 10

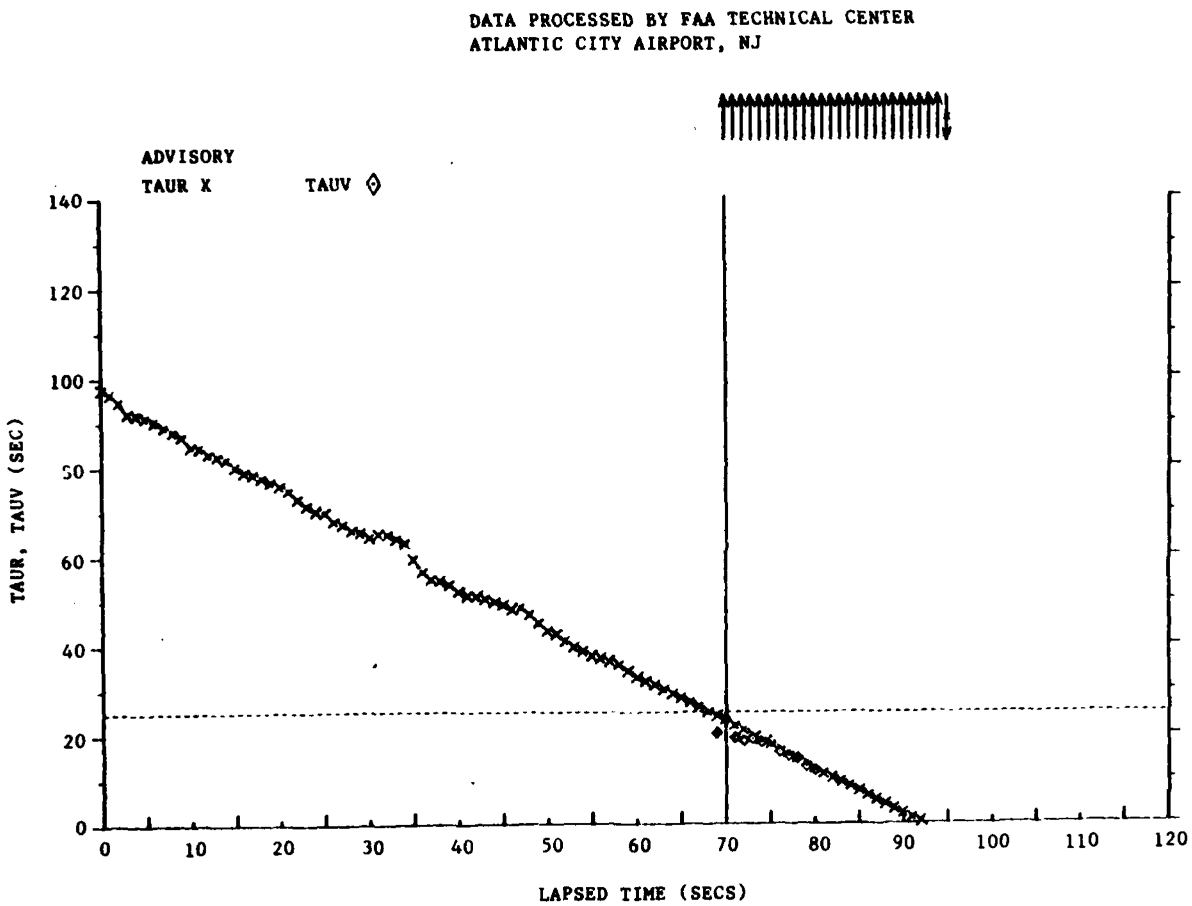


FIGURE 4-1(b)
25 AUGUST FLIGHT ENCOUNTER 10

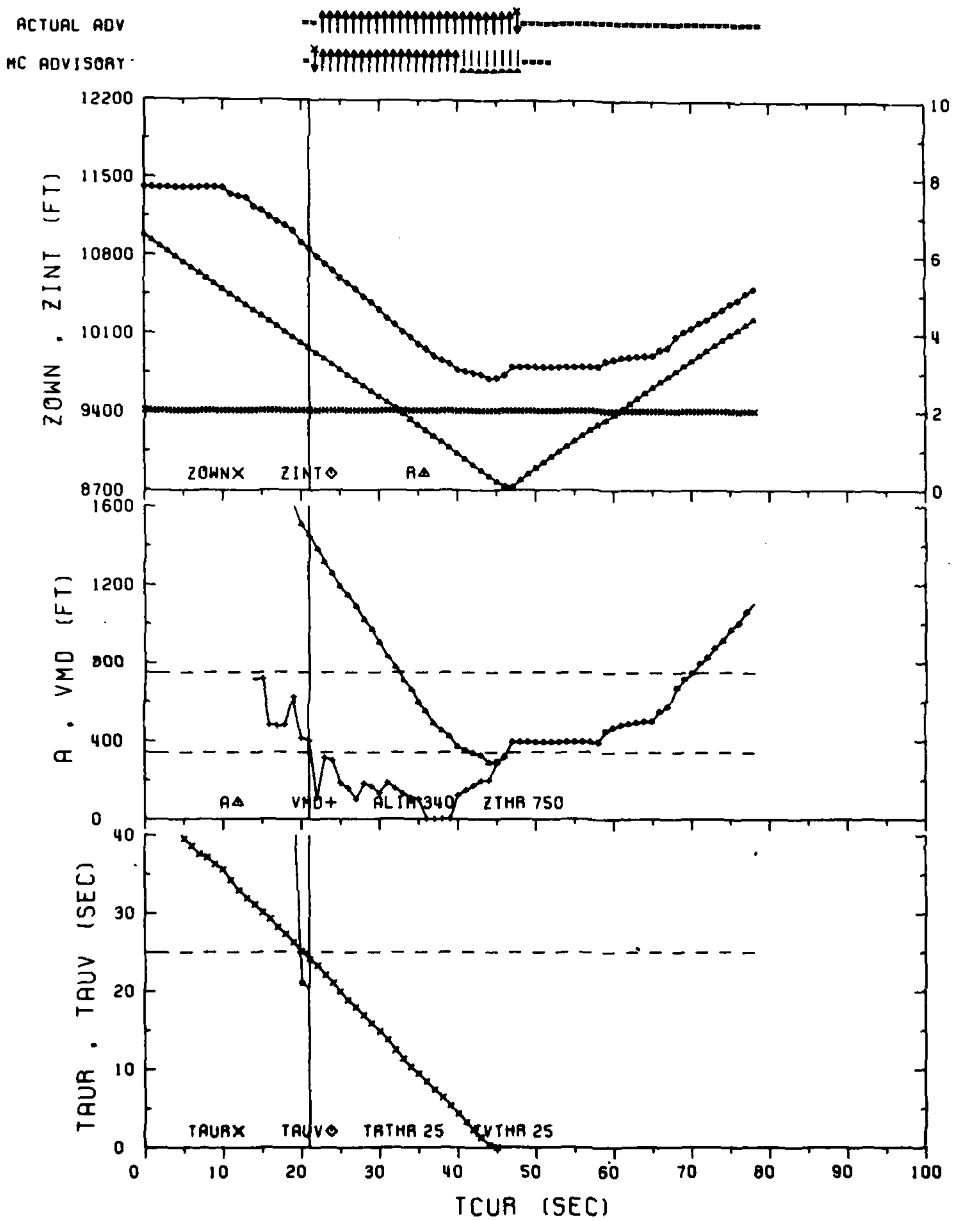


FIGURE 4-2
REPLAY OF 25 AUGUST FLIGHT ENCOUNTER 10

it is quick to recognize the leveloff maneuver and displays a TCAS Abort condition to the pilot, seen at scan 42. This particular encounter is a worst-case scenario because the remaining time-to-go is short, only about 8 seconds.

4.2 The Critical Interval Logic

Another logic design improvement recently made provides increased protection in slow closing rate scenarios. The new logic defines the beginning and end points of a critical interval, the period of time during which horizontal separation is minimal. Normally the beginning and end points differ by only a second or two, and the critical interval collapses virtually to a single point, TRTRU. However, in cases such as the tail chase scenario, horizontal separation may be minimal for a long interval of time. Vertical separation is critical throughout the entire interval. The sense providing best separation at time TRTRU may be inferior and/or inadequate early in the critical interval. The beginning of the interval represents an estimate of the projected time for the TCAS aircraft to penetrate a sphere of radius 1500 feet about the intruder.

An altitude-crossing encounter was described in Section 3.4.1 which resulted in separation less than ALIM. The reason for poor separation was the lack of timely pilot response to the advisory. The pilot was in fact reluctant to cross the intruder's altitude. When this encounter was replayed through the fast-time simulation, however, the updated TCAS logic selected an advisory which did not call for an altitude crossing. This is a result of the critical interval logic.

The logic used during the flight test computed the projected separation at TRTRU for both a climb and descend. A descent was projected to provide greater protection, although in this case, the difference between the two was relatively small. The new logic compares separation over a critical interval rather than only at TRTRU. The critical interval computed for this encounter is three seconds. Therefore, the projected separation at TRTRU minus three seconds is computed for both a climb and descend. A climb is now projected to provide better separation than a descend by at least 100 feet. The new logic selects the climb sense as the most effective in providing safe separation throughout the critical interval during which horizontal separation is minimal.

Figure 4-3 shows the replayed encounter. Since the true aircraft tracks are used in the simulation, the TCAS aircraft did not respond to the CLIMB. As a result, the advisory evaluation logic displayed a TCAS abort condition, seen at scan 59. Separation was projected to be less than 100 feet at closest approach. In fact, separation was just 131 feet. The advisory evaluation logic not only detects sudden intruder maneuvers, it also detects failure of the TCAS aircraft to respond to displayed advisories.

4.3 Advisory Transition Improvements

Several flight test encounters revealed interrupted advisory transition sequences due to vertical tracking or logic inconsistencies. While these encounters did not suffer from poor resolution, the logic design was evaluated in an effort to improve advisory transitions. Recent logic updates have provided significant improvement to advisory sequences.

Figures 4-4 (a), (b) and (c) are plots of an encounter flown on 28 September. The advisory line shows an eight-second interval during which the DON'T CLIMB advisory was interrupted before reappearing. The interruption in display sequence was due to perturbations in tracked altitude rates, which affected the computation of vertical separation at closest approach (VMD), shown in Figure 4-4(c). When the altitude rate perturbations are large, VMD experiences large jumps which temporarily exceed ZTHR. In the logic flown, the intruder was no longer declared a threat and the advisory was dropped. When the tracked rates stabilized, VMD again fell below ZTHR and the advisory reappeared. These relative-altitude rate perturbations can occur either as a result of an intruder vertical acceleration, or as a result of a response by the TCAS aircraft to an advisory.

Figure 4-5 is a plot of this encounter replayed through the improved logic. When the same tracked data is used as input, the advisory sequence remains uninterrupted. This is because certain advisory transitions are now based on current altitude separation, A, rather than projected separation, VMD.

A second example of advisory transitioning is shown in Figures 4-6 (a) and (b). This encounter was flown on 23 September. The TCAS aircraft was climbing at a rate of 750 fpm from an altitude of 10,400 feet. The intruder aircraft remained level at 11,500 feet. The advisory sequence displayed by TCAS was a LIMIT CLIMB TO 1000 fpm-LIMIT CLIMB TO 500 fpm-LIMIT CLIMB TO 1000 fpm-DON'T CLIMB-DESCEND.

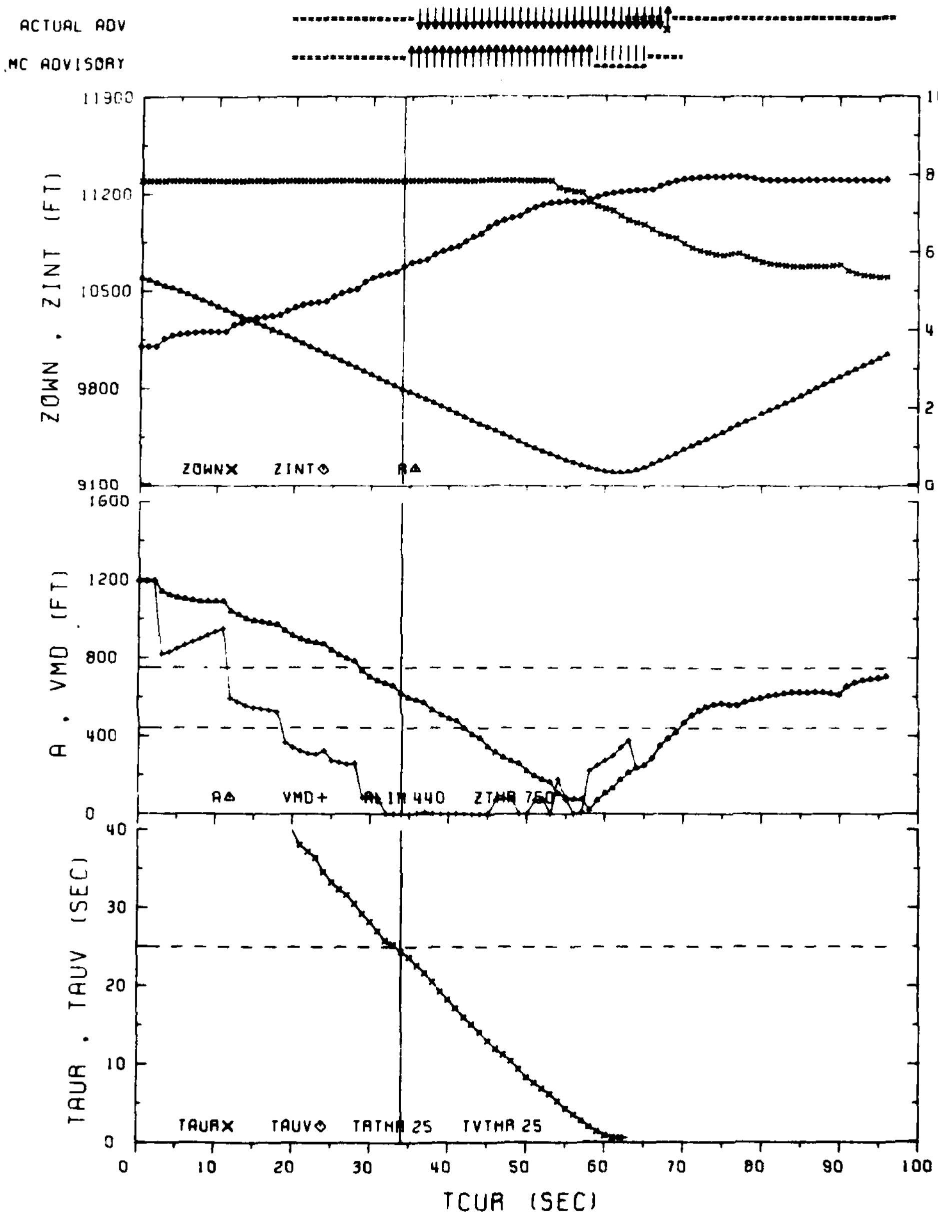


FIGURE 4-3
REPLAY OF 17 SEPTEMBER FLIGHT ENCOUNTER 4

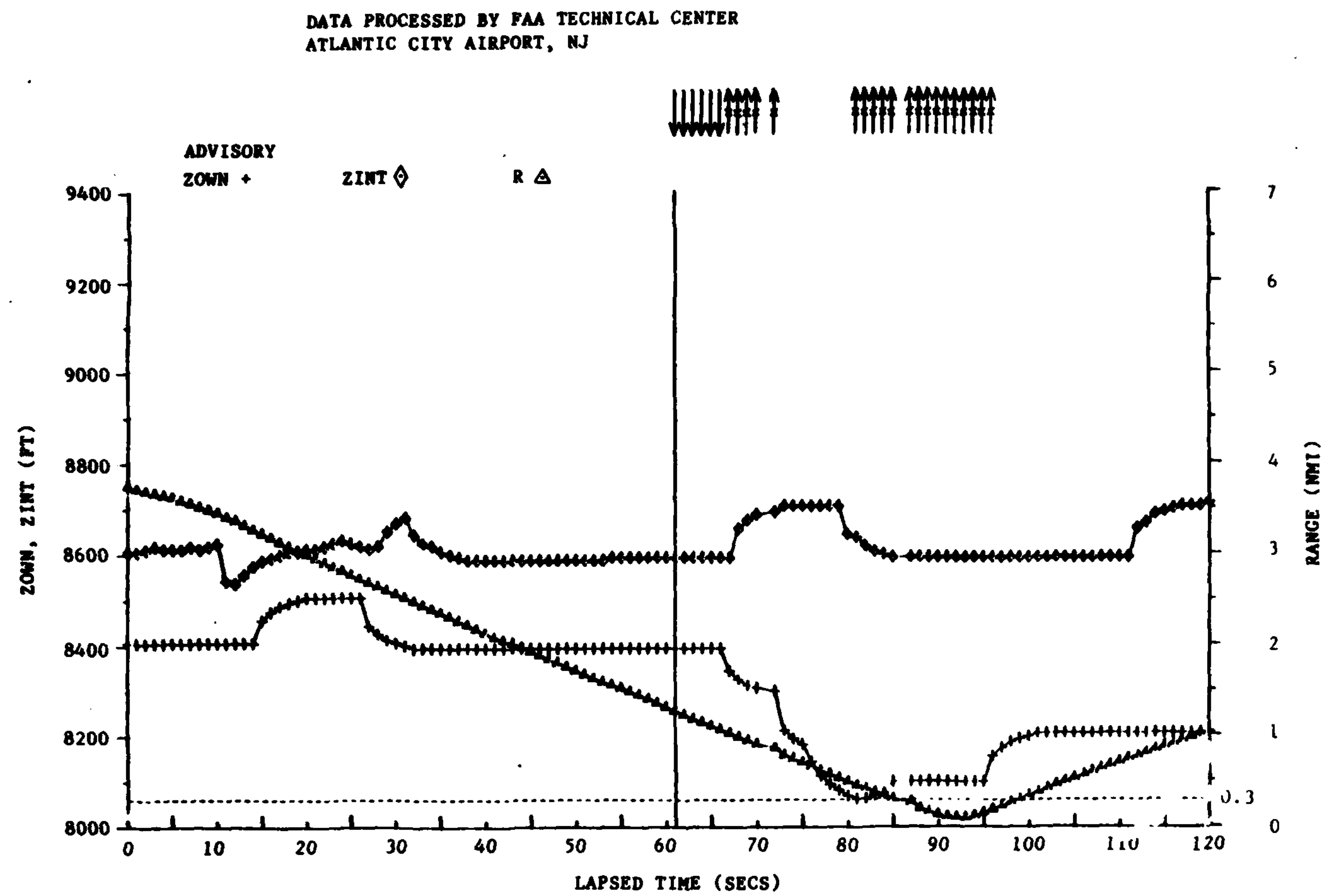


FIGURE 4-4(a)
28 SEPTEMBER FLIGHT ENCOUNTER 4

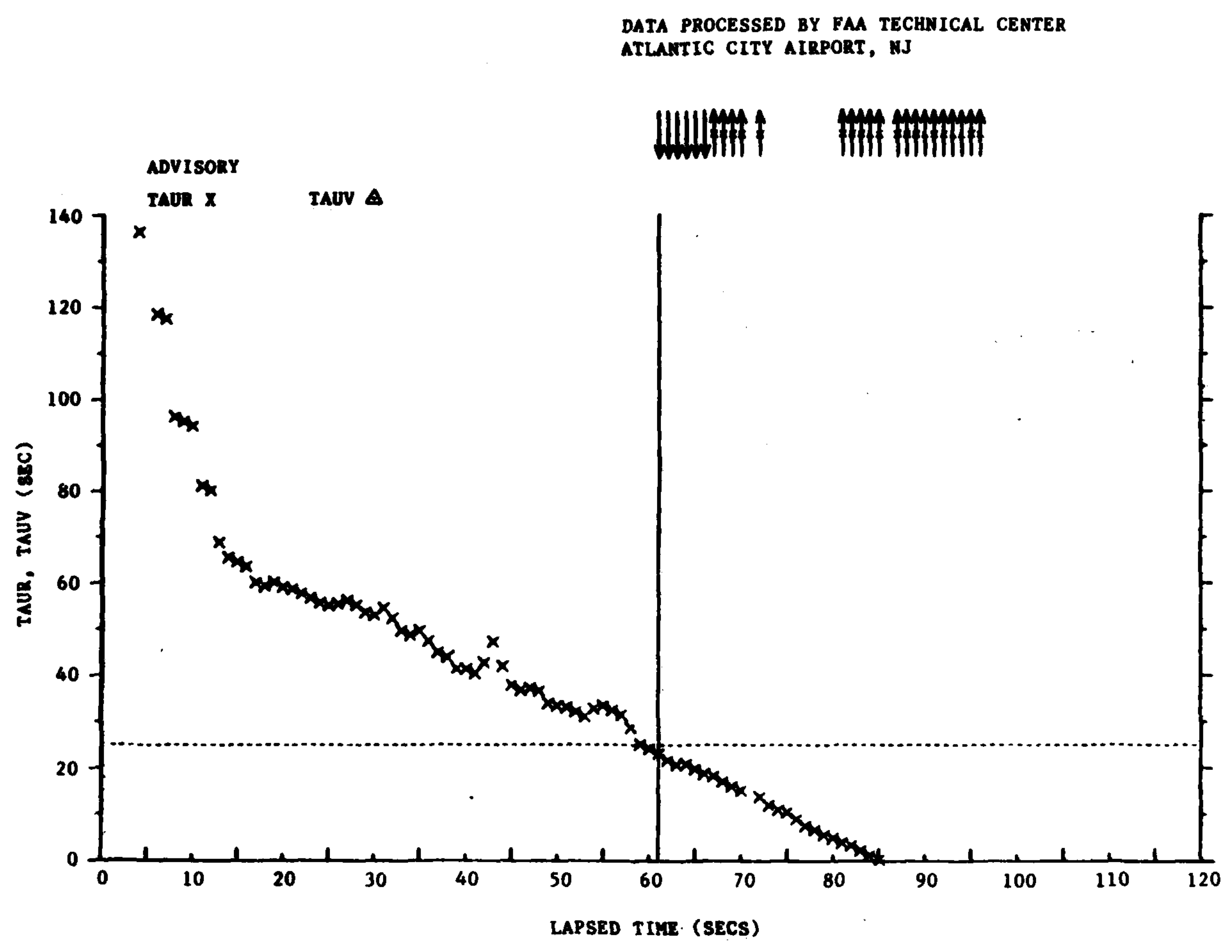


FIGURE 4-4(b)
28 SEPTEMBER FLIGHT ENCOUNTER 4

Data Processed By
FAA Technical Center
Atlantic City Airport, NJ

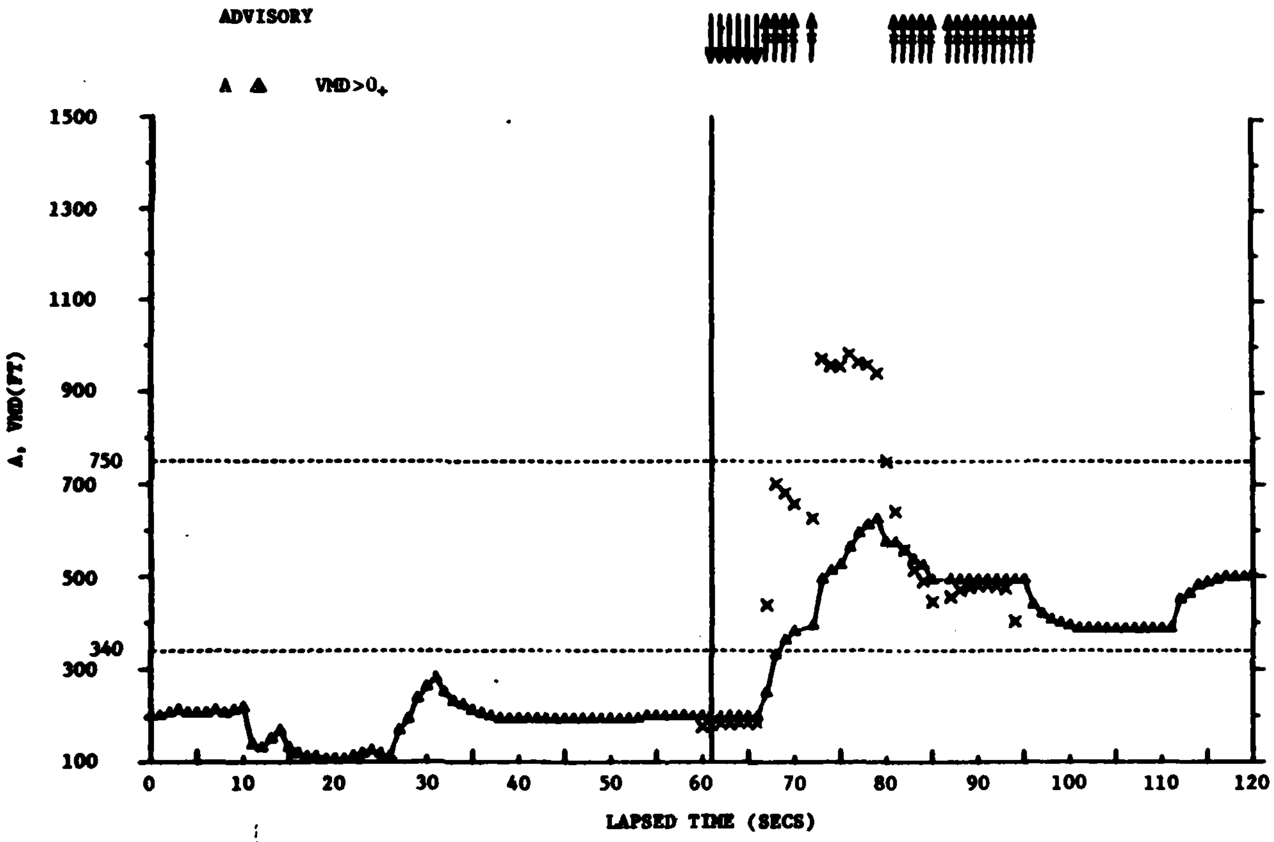


FIGURE 4-4 (C)
28 SEPTEMBER FLIGHT ENCOUNTER 4

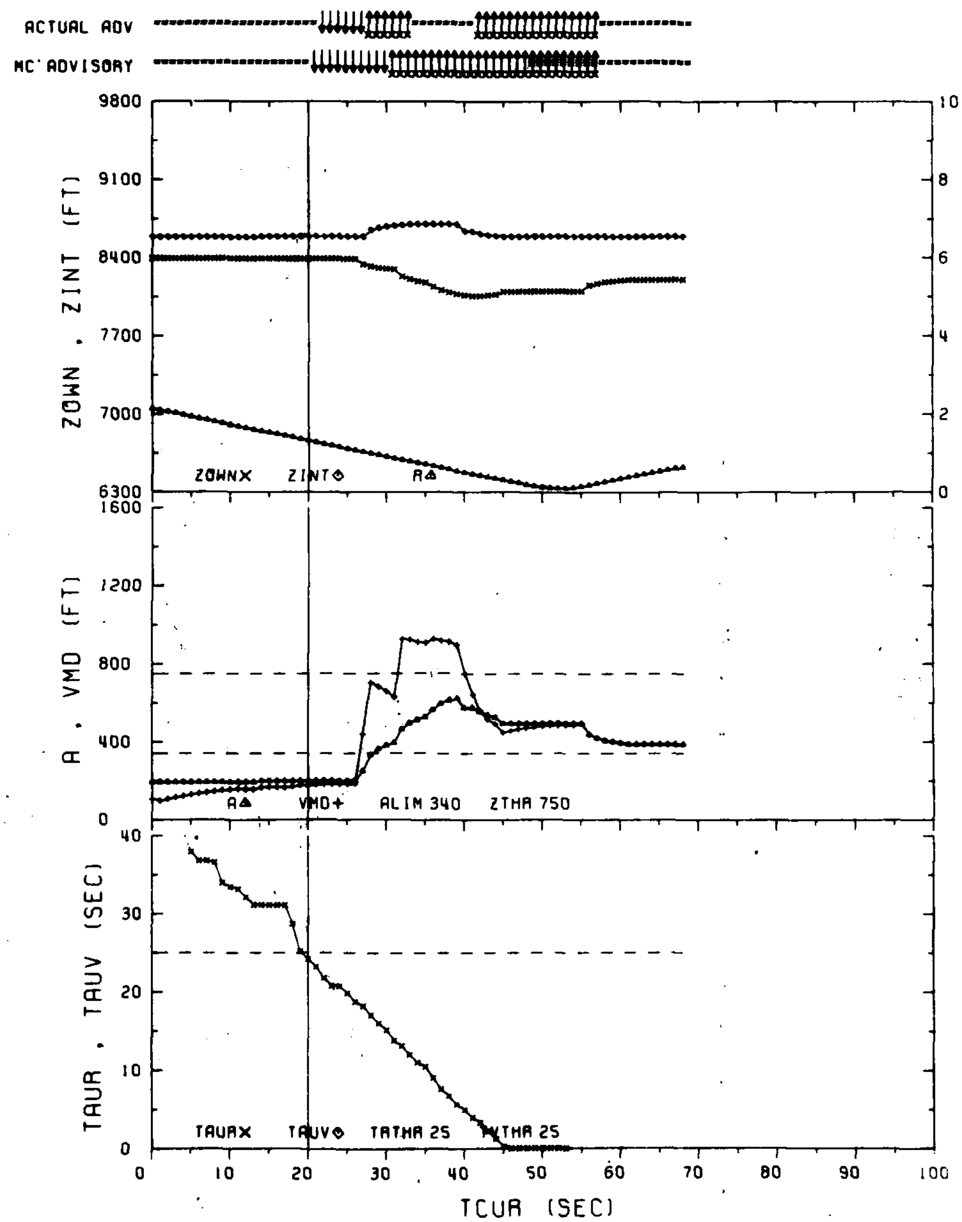


FIGURE 4-5
REPLAY OF 28 SEPTEMBER FLIGHT ENCOUNTER 4

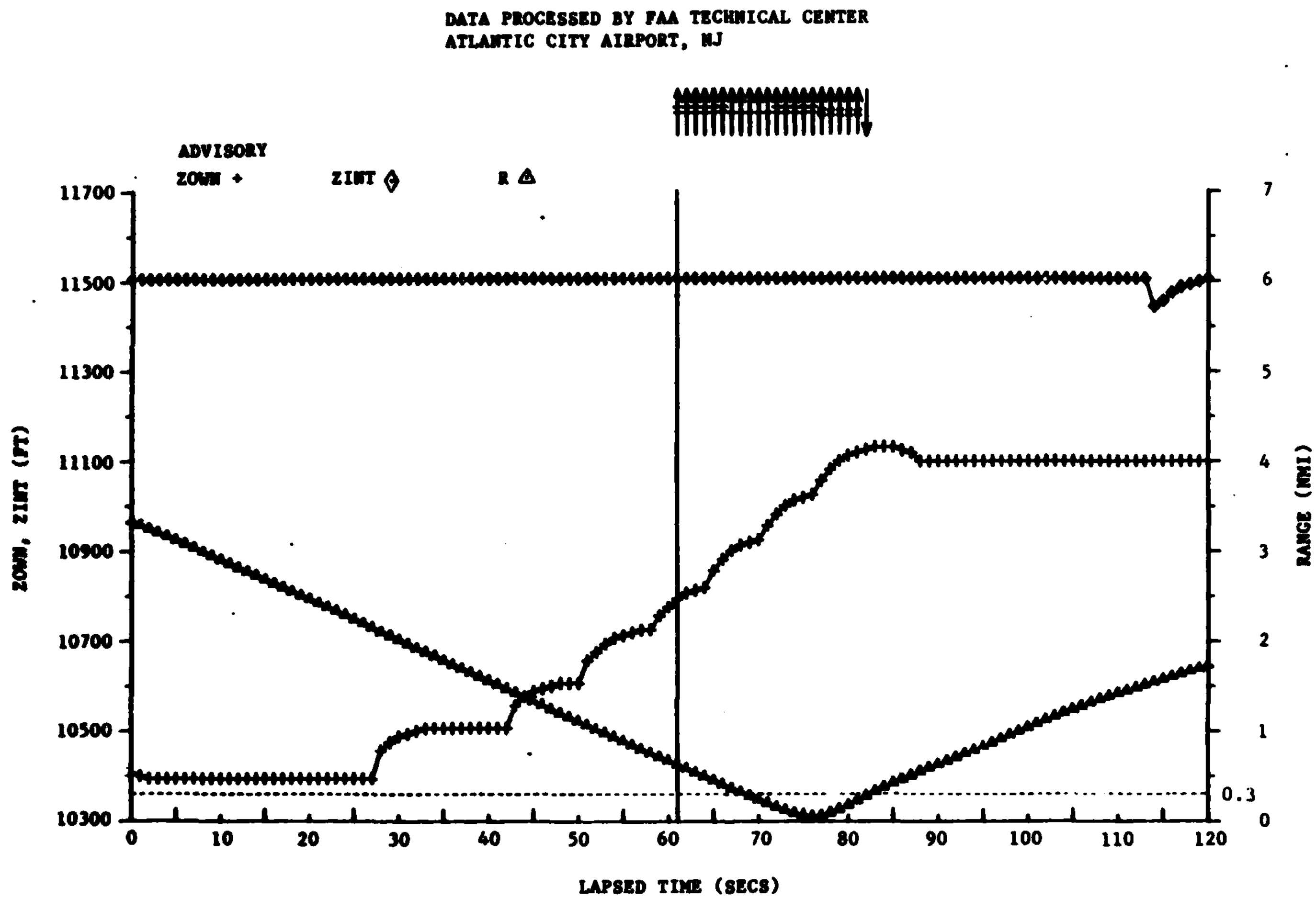


FIGURE 4-6(a)
23 SEPTEMBER FLIGHT ENCOUNTER 3

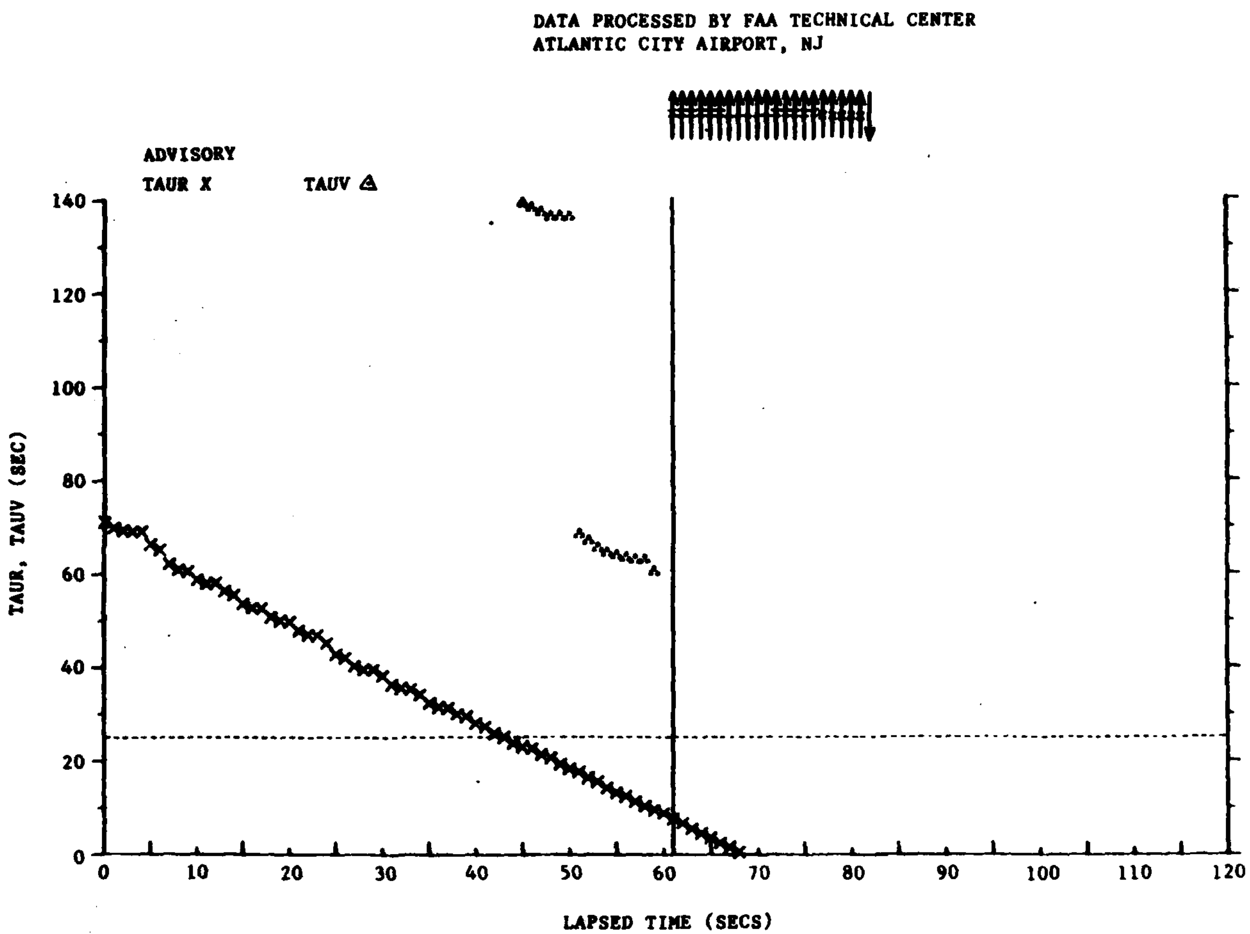


FIGURE 4-6(b)
23 SEPTEMBER FLIGHT ENCOUNTER 3

The transitions between VSLs are mostly due to changes in tracked vertical rates. However, the transitions to the more severe negative and then positive advisories are due to logic design. These transitions were seen in a few other encounters and logic modifications were made to eliminate them. The single scan appearance of the positive advisory was identified by the FAA Technical Center and the logic was corrected prior to the completion of the flight tests. The transition from the VSL to negative is an unnecessary effect of the erratic behavior of TRTRU near closest approach. The TAU variables tend to increase sharply near CPA when there is a horizontal miss. These TAU variables are now inhibited from increasing cycle to cycle, thereby eliminating the transition to a more severe advisory near CPA.

In addition, the logic now continues to display the previous advisory if the time to closest approach is too short for a new advisory to be obeyed. In this way, advisories will not transition simply because the logic detects that separation will fall one foot below ALIM.

Figure 4-7 is a plot of the same encounter replayed through the fast-time simulation. A LIMIT CLIMB TO 1000 fpm was selected to resolve the conflict, and remains displayed throughout the encounter. The actual tracks recorded onboard the TCAS are used to replay the simulation. During the actual flight test encounter, the TCAS pilot maintained a climb rate of 1000 fpm from scan 46 through scan 64, and did not begin to respond to the DON'T CLIMB until after closest approach. In effect, the pilot maneuvered the aircraft in a manner compatible with the new advisory sequence, and vertical separation at closest approach was in excess of ALIM. This new sequence provides a much more stable resolution while still assuring safe separation.

4.4 Elimination of Large Horizontal Miss Encounters

When aircraft are on a collision course, a plot of the true range versus time is linear. When a horizontal miss occurs, the plot of true range versus time is a hyperbola. This effect is due to the behavior of true tau. True tau decreases by less than one second each second when there is a large horizontal miss and typically stops declining and begins rising sharply around 5 to 10 seconds before closest approach. Logic modifications have been made which use this effect to screen unwanted large horizontal miss encounters.

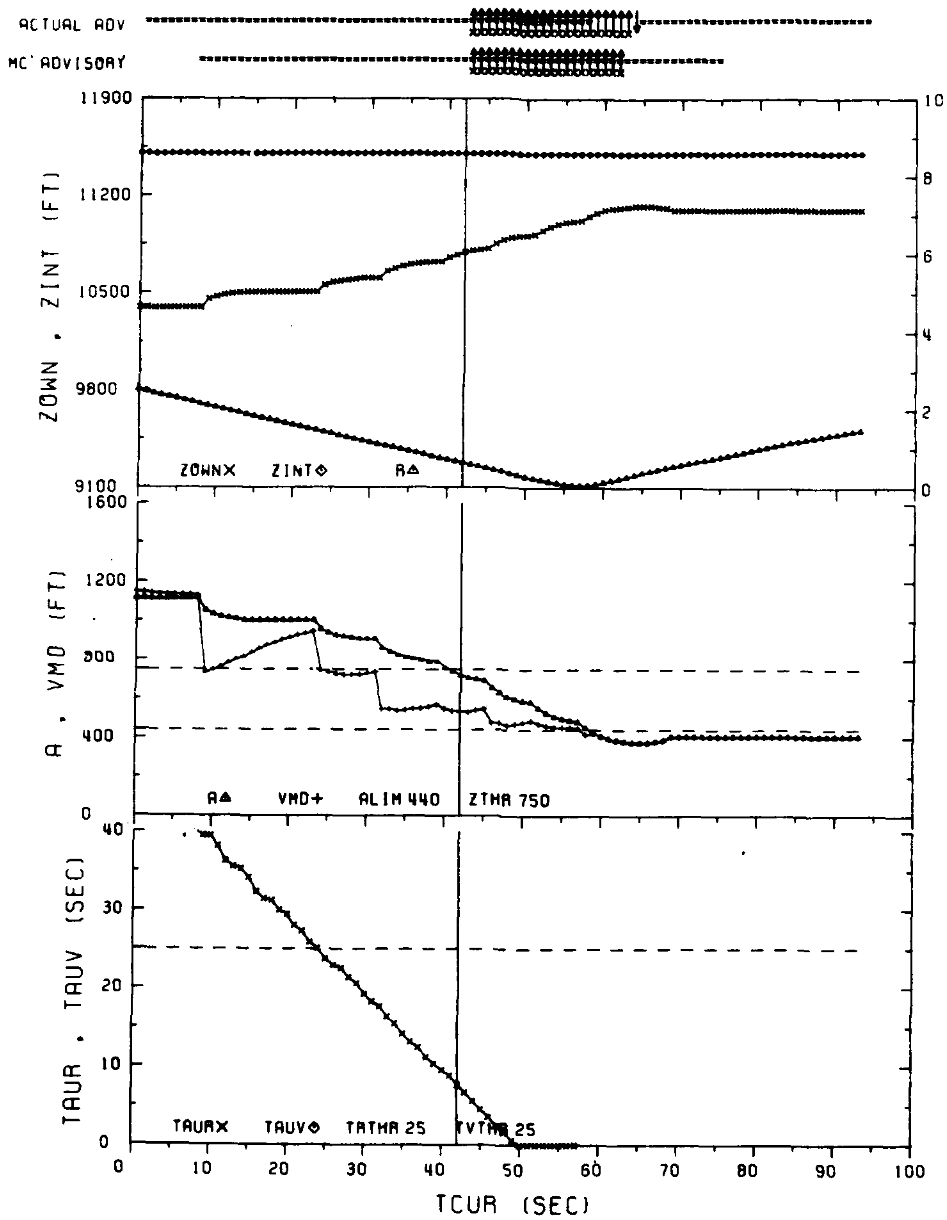


FIGURE 4-7
REPLAY OF 23 SEPTEMBER FLIGHT ENCOUNTER 3

Figure 4-8 is an example of an encounter flown on 11 September which no longer displays a resolution advisory against the intruder. Actual vertical separation in this encounter is about 300 feet, but the closest approach in range is over .8 nmi. During the flight test, the encounter generated a positive DESCEND advisory, to which the TCAS aircraft responded. With nearly a mile in horizontal separation, however, a maneuver by the TCAS aircraft does not seem necessary. The second advisory line shows that the new logic generates only a traffic advisory, no resolution.

4.5 Elimination of Intruders on the Ground

During the low approaches into Washington and Chicago, a number of traffic advisories were displayed against intruders on the airport surface. Several of these advisories occurred simultaneously with as many as six TAs declared at one time. The Dalmo Victor TCAS can only display three TAs at a time. Ground advisories occurred because the TCAS logic does not inhibit TAs in sensitivity level 2. Also, the warning times are quite large for TAs, and therefore detection of ground intruders is likely. As a result of the flight test experience, logic was designed and tested which uses data from both the barometric altimeter and radio altimeter to determine when an intruder is on or near the ground.

Figure 4-9 is a plot of an encounter which occurred on 28 September on approach to Washington National Airport. As the TCAS aircraft descended through 200 feet, a CLIMB advisory was displayed. This only occurred because the sensitivity level was manually set to level 5, as evidenced by the TRTHR threshold of 25 seconds. The sensitivity level normally would be set to level 2 below 500 AGL, by automatic input from the radio altimeter. Resolution advisories are inhibited in level 2, but traffic advisories are displayed. The second advisory line on the plot shows the output from the new logic. The symbol produced by the simulation indicates that the intruder is detected to be on the ground. With this new logic, traffic advisories will not be displayed in the cockpit when the intruder is on or near the ground. This will significantly reduce the incidence of multiple traffic advisories in the terminal area.

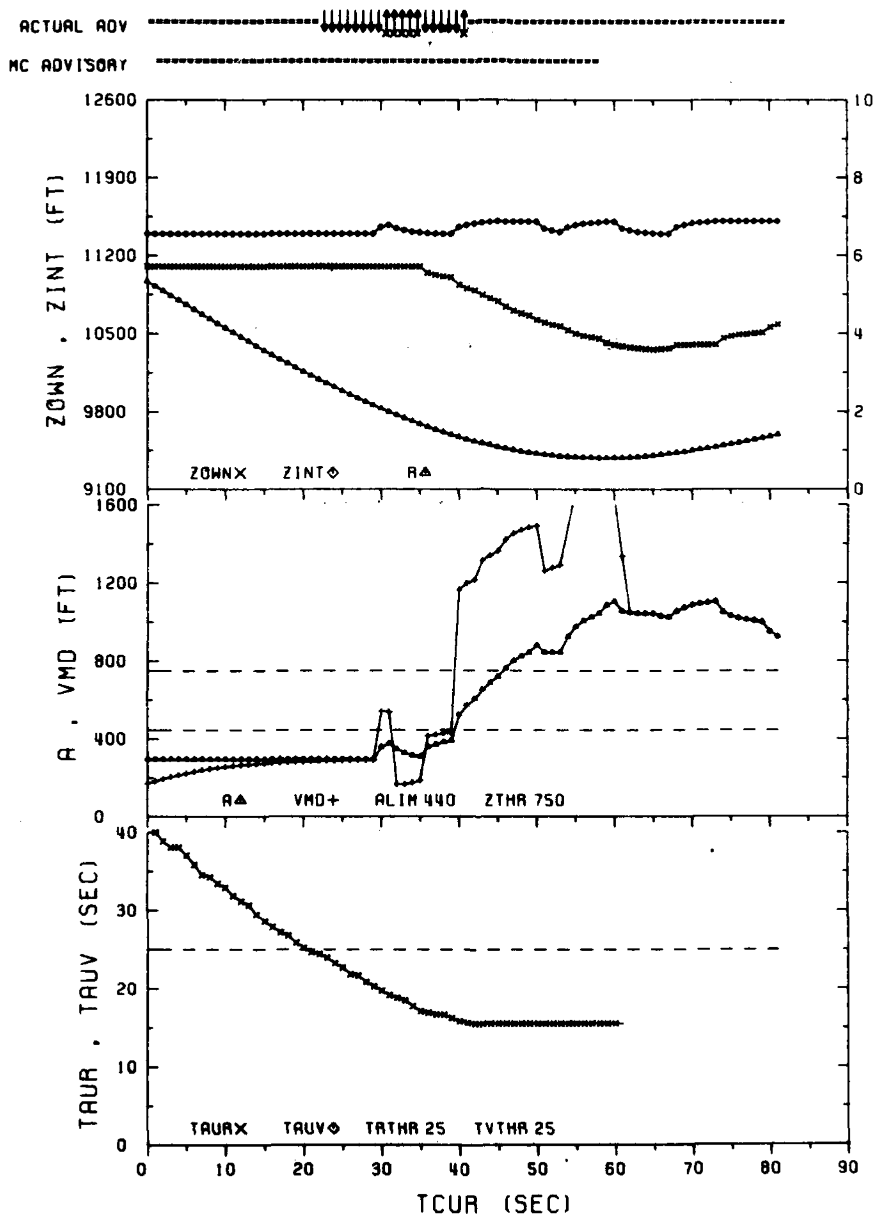


FIGURE 4-8
REPLAY OF 11 SEPTEMBER FLIGHT ENCOUNTER 8

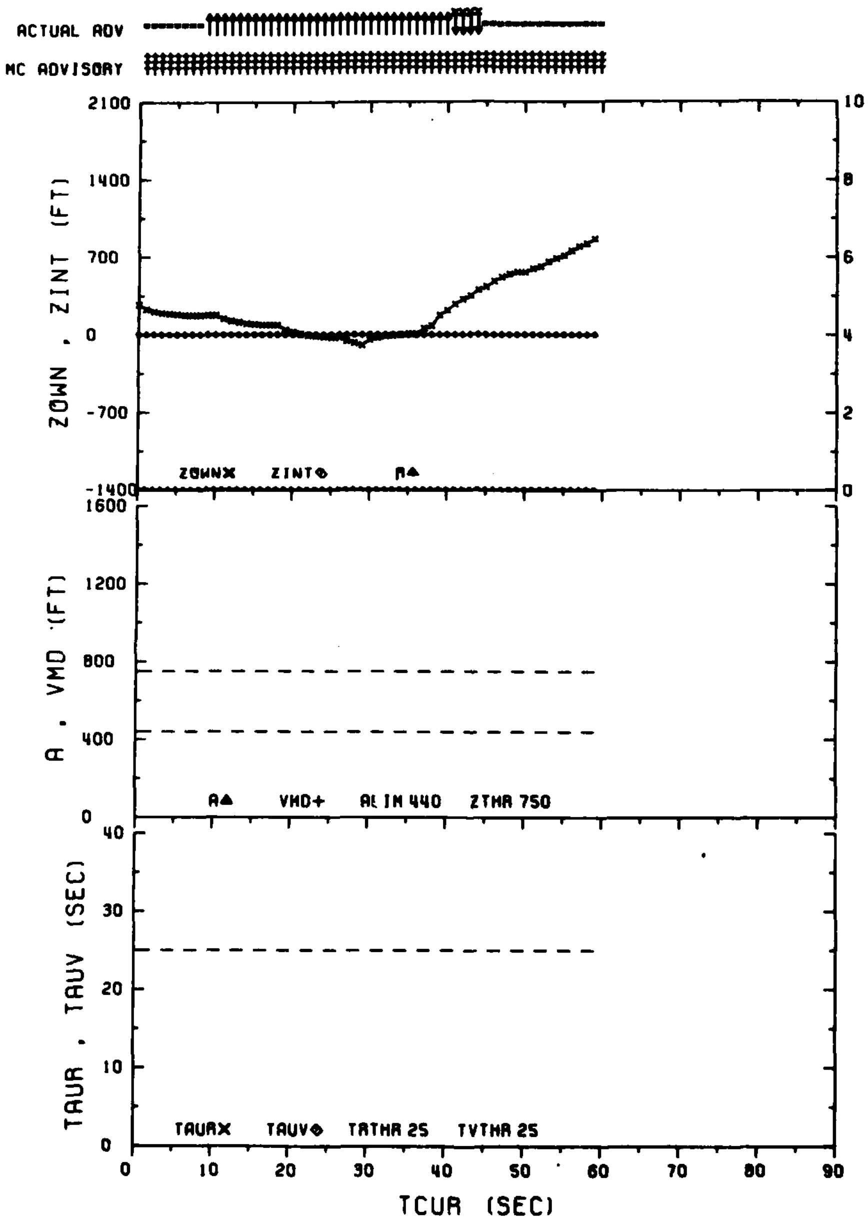


FIGURE 4-9
REPLAY OF 28 SEPTEMBER FLIGHT ENCOUNTER 01

APPENDIX A

GLOSSARY

A	Absolute Value of Relative Altitude
ADOT	Absolute Value of Relative Altitude Rate
ALIM	Positive Advisory Altitude Threshold
DMOD	Incremental Range Protection Volume
R	Tracked Range
RD	Tracked Range Rate
Resolution Advisory	A display indication given to the pilot recommending a maneuver to increase vertical separation relative to an intruding aircraft. Positive, negative, and vertical speed limit (VSL) advisories constitute the resolution advisories.
Sensitivity Level	An instruction given to the TCAS equipment for control of its threat volume.
TAUR	Modified Range Tau (R-DMOD/RD)
TAUV	Altitude Tau (-A/ADOT)
Traffic Advisory	Information given to the pilot pertaining to the position of another aircraft in the immediate vicinity. The information contains no suggested maneuver.
TRTHR	Range Tau Threshold
TRTRU	True Tau
TVTHR	Altitude Tau Threshold
VMD	Vertical Miss Distance at Closest Approach
ZDINT	Intruder Vertical Rate
ZDOWN	Own Vertical Rate
ZINT	Intruder Tracked Altitude
ZOWN	Own Tracked Altitude
ZTHR	Detection Altitude Threshold

APPENDIX B

25 AUGUST LEVELOFF SCENARIOS

Figures B-1 through B-8 show the eight leveloff scenarios flown on 25 August. The geometries of the first four of these encounters caused the TCAS logic to select altitude crossing advisories which would have decreased separation, had the pilots responded. (Figure B-2 was described in detail in Section 4.1.) In each case, the sense selection logic was foiled by the intruder leveloff maneuver. During the fast-time replays of these encounters, shown in Figures B-1 through B-4, the updated TCAS logic recognized the 'fake-out' maneuver and displayed a TCAS Abort condition. The encounter shown in Figure B-1 is unique, however, because when replayed through the latest logic the advisory selected was in the direction away from the intruder (would not have caused an altitude crossing). The advisory was generated one second earlier than in actual flight, and at that scan a DESCEND was projected to provide more separation than a CLIMB; however, this advisory led to a TCAS Abort condition due to tracked rate fluctuations. Scan-by-scan printed output of the flight data shows that the tracked altitude rate of the intruder changed from 3000 fpm at the time of sense selection to 4616 fpm at the time the Abort conditi(: was displayed. The logic predicted that a 1500 fpm descent rate by the TCAS aircraft would not be adequate to resolve the conflict. The intruder's tracked rate began to decrease again within two scans. Since the TCAS logic computes projected separation based on tracked rates, 1600 fpm oscillations can cause the predicted separation to change significantly. The updated TCAS logic contains many new tracking features, including a cycle-by-cycle evaluation of the quality of the tracked rate estimate. While these new features should improve the quality of the vertical rate data input to the logic, it is understood that, in some instances, large perturbations in tracked rates can hinder the effectiveness of the TCAS logic.

The last four leveloff encounters did not cause the logic to select altitude crossing advisories during the flight tests. Figures B-5 through B-8 show the fast-time replays of these encounters. The logic again selected advisories in the direction away from the intruder. However, in Figure B-8, a TCAS Abort is displayed during what appears to be a correct advisory sequence. The cause again lies in tracked vertical rate fluctuations. The intruder's tracked rate increased from 3280 fpm at sense selection to 4762 fpm at the time the Abort condition was displayed. The logic predicted that a 1500 fpm escape rate by the TCAS aircraft was insufficient against an intruder rate in excess of 4600 fpm. The intruder's tracked rate began to decrease again after two scans.

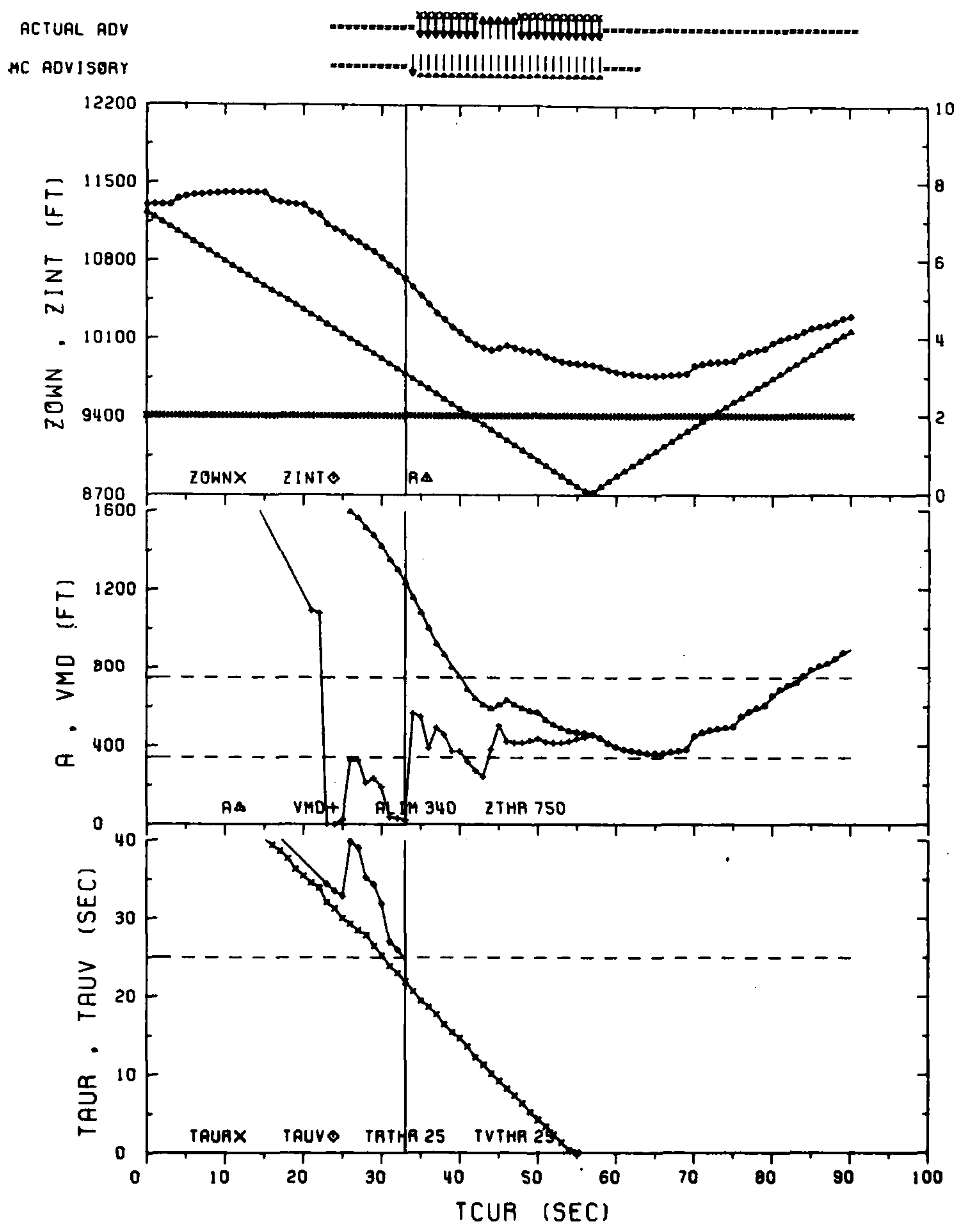


FIGURE B-1
REPLAY OF 25 AUGUST LEVELOFF SCENARIO
ENCOUNTER 9

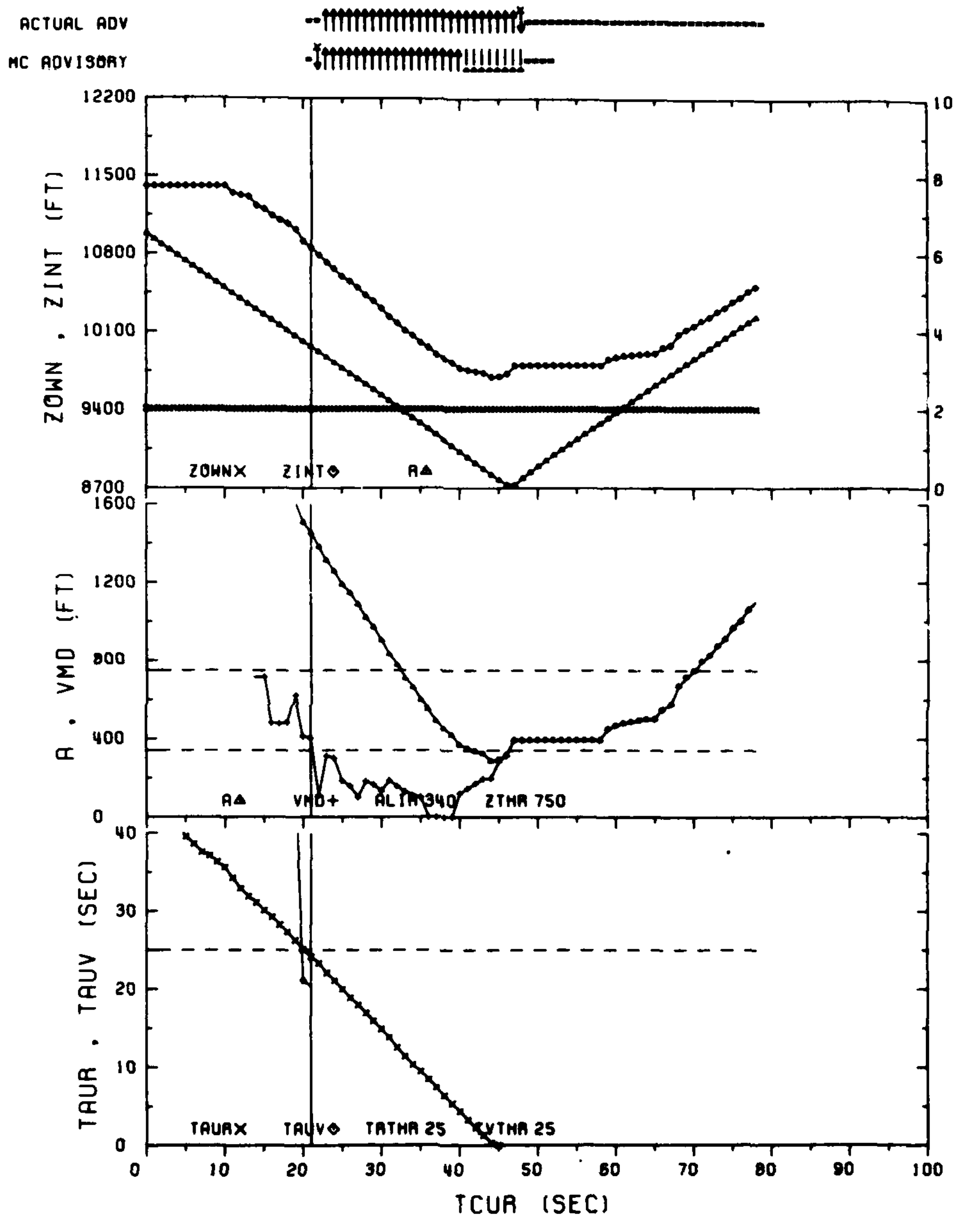


FIGURE B-2
REPLAY OF 25 AUGUST LEVELOFF SCENARIO
ENCOUNTER 10

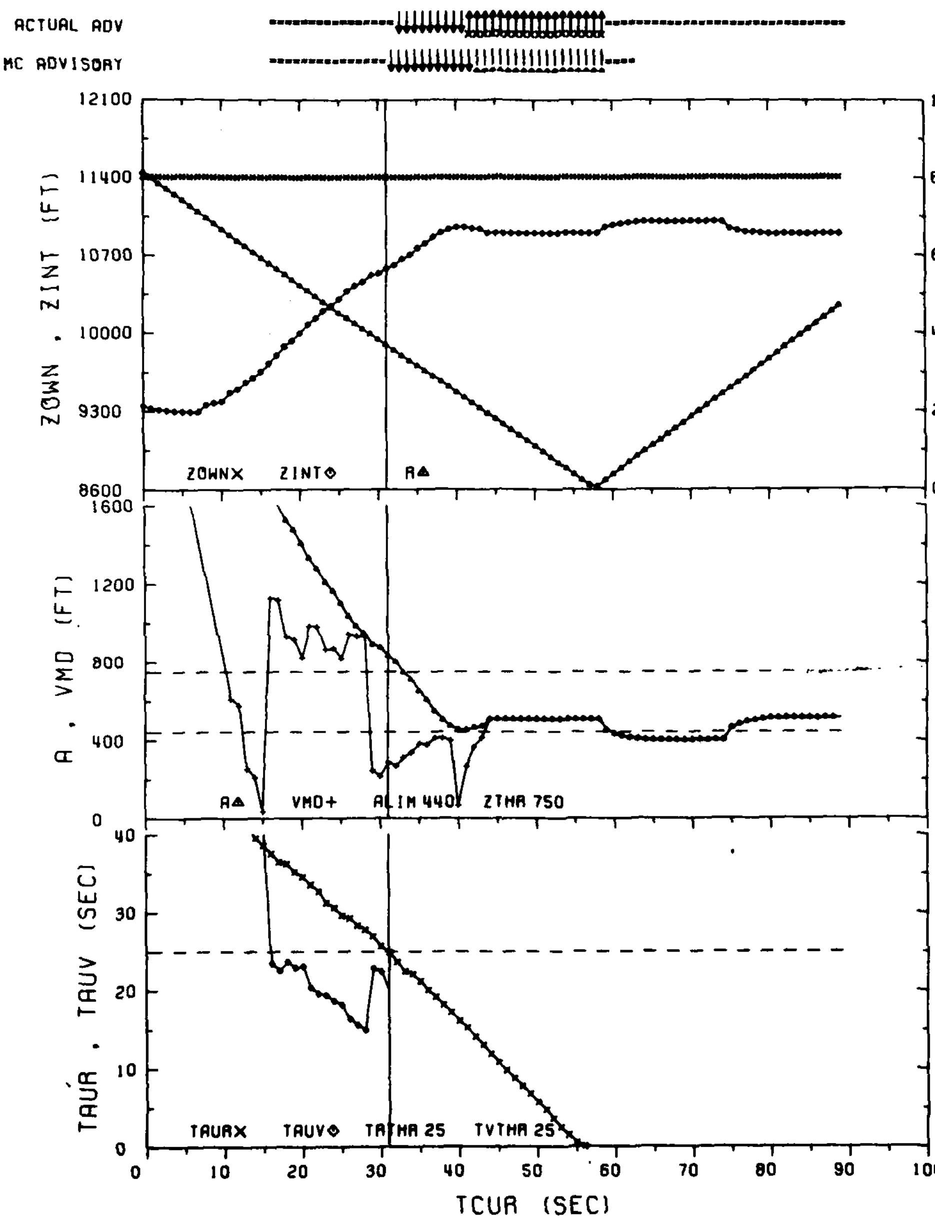


FIGURE B-3
REPLAY OF 25 AUGUST LEVELOFF SCENARIO
ENCOUNTER 14

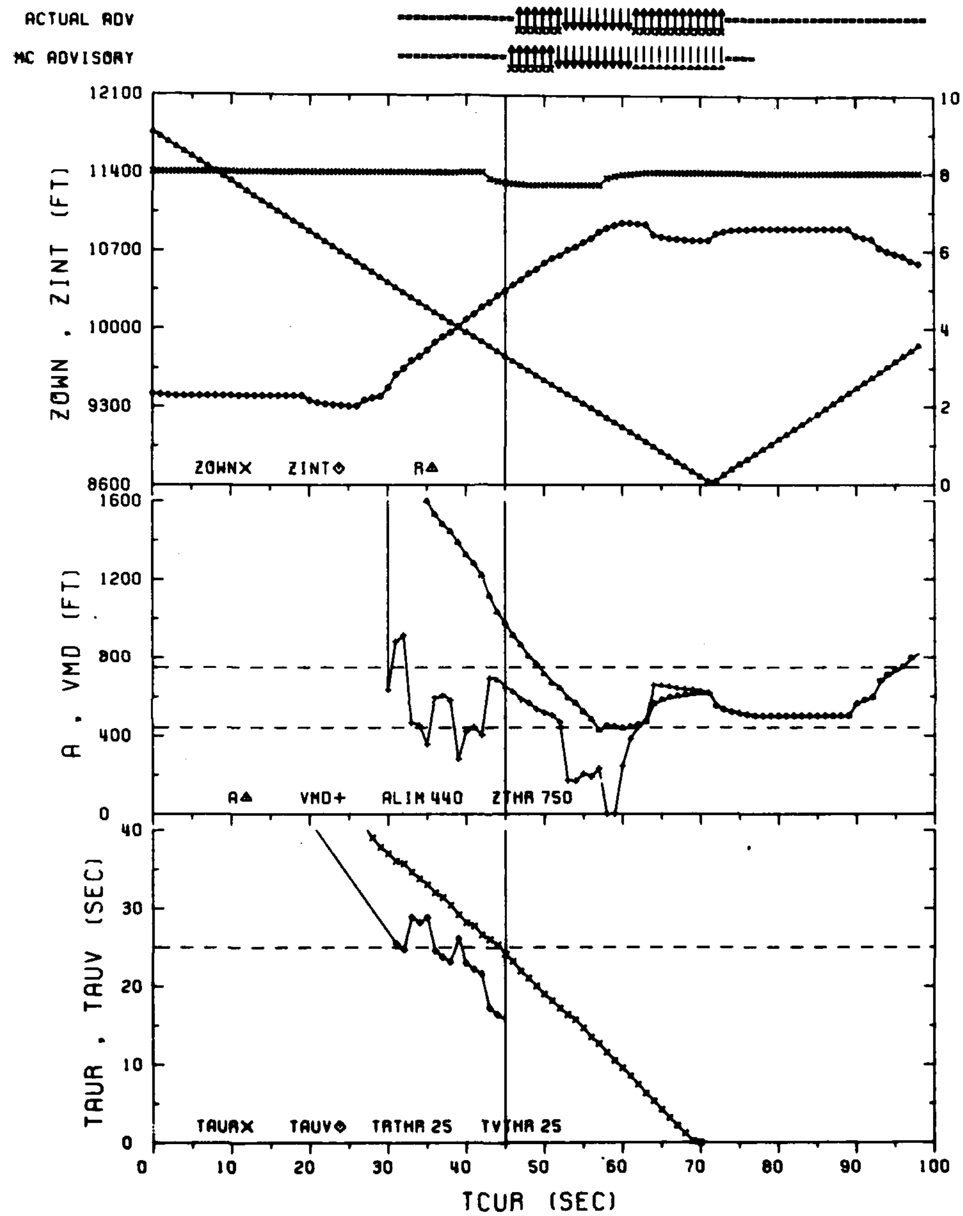


FIGURE B-4
REPLAY OF 26 AUGUST LEVELOFF SCENARIO
ENCOUNTER 15

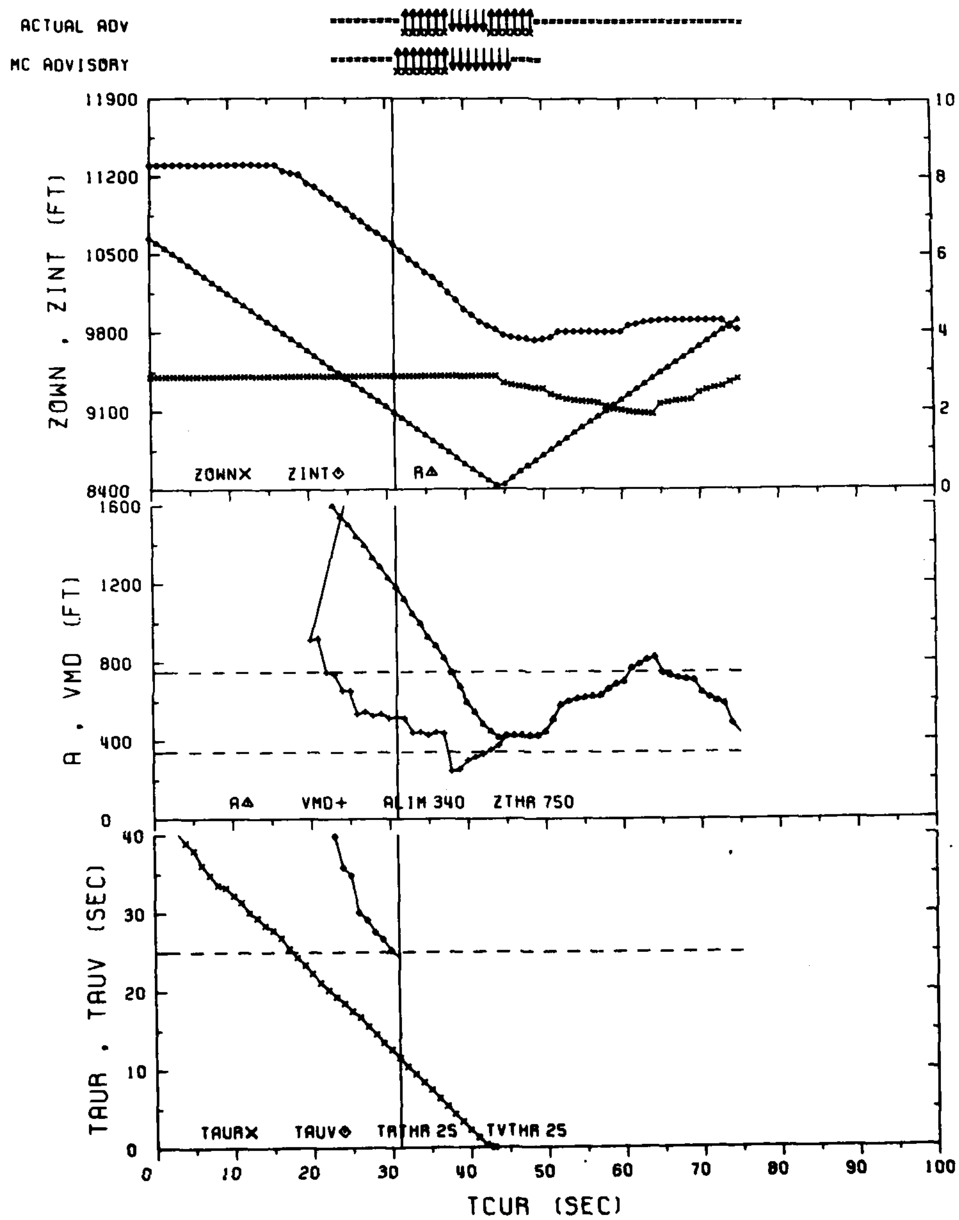


FIGURE B-5
REPLAY OF 25 AUGUST LEVELOFF SCENARIO
ENCOUNTER 12

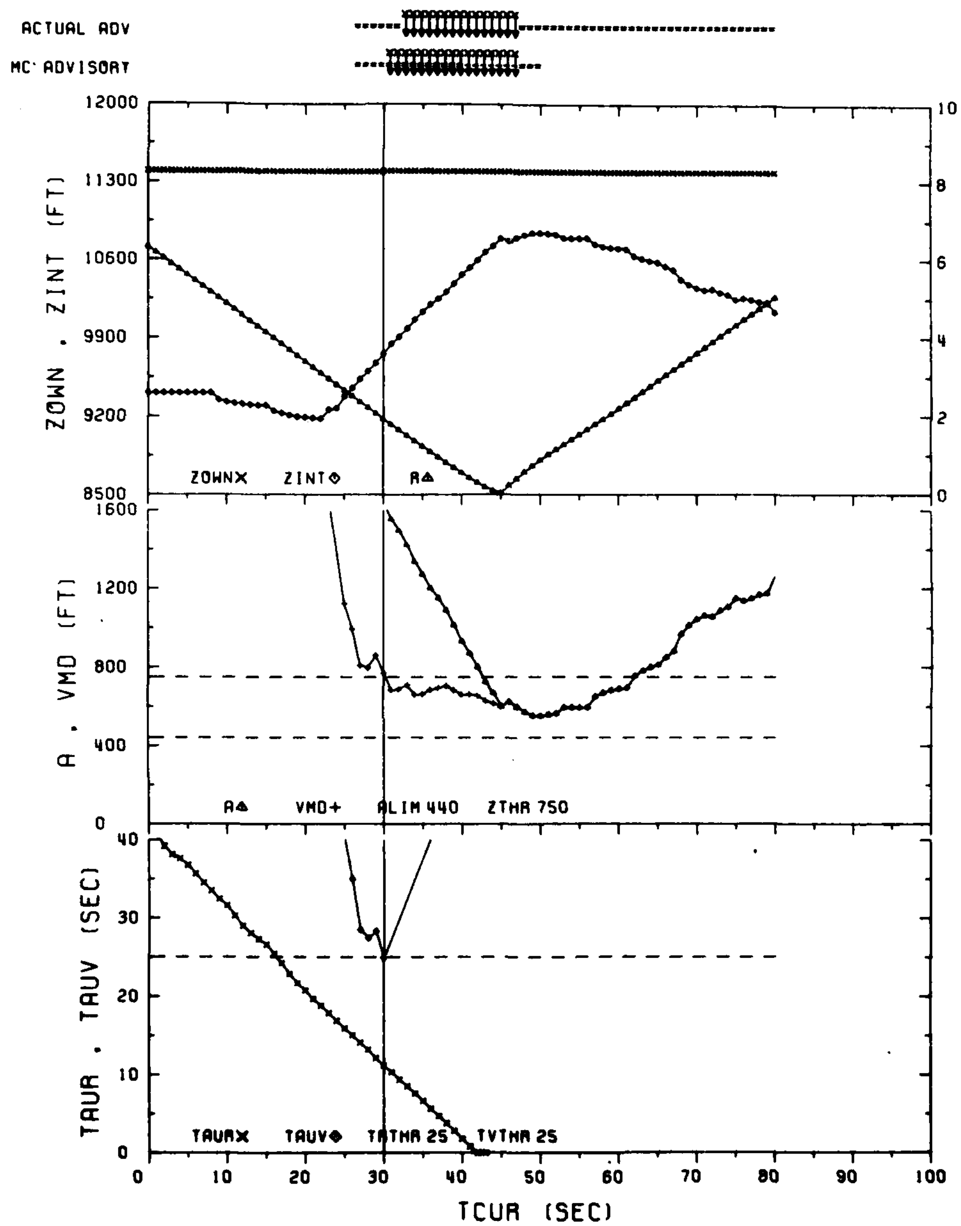


FIGURE B-6
REPLAY OF 25 AUGUST LEVELOFF SCENARIO
ENCOUNTER 13

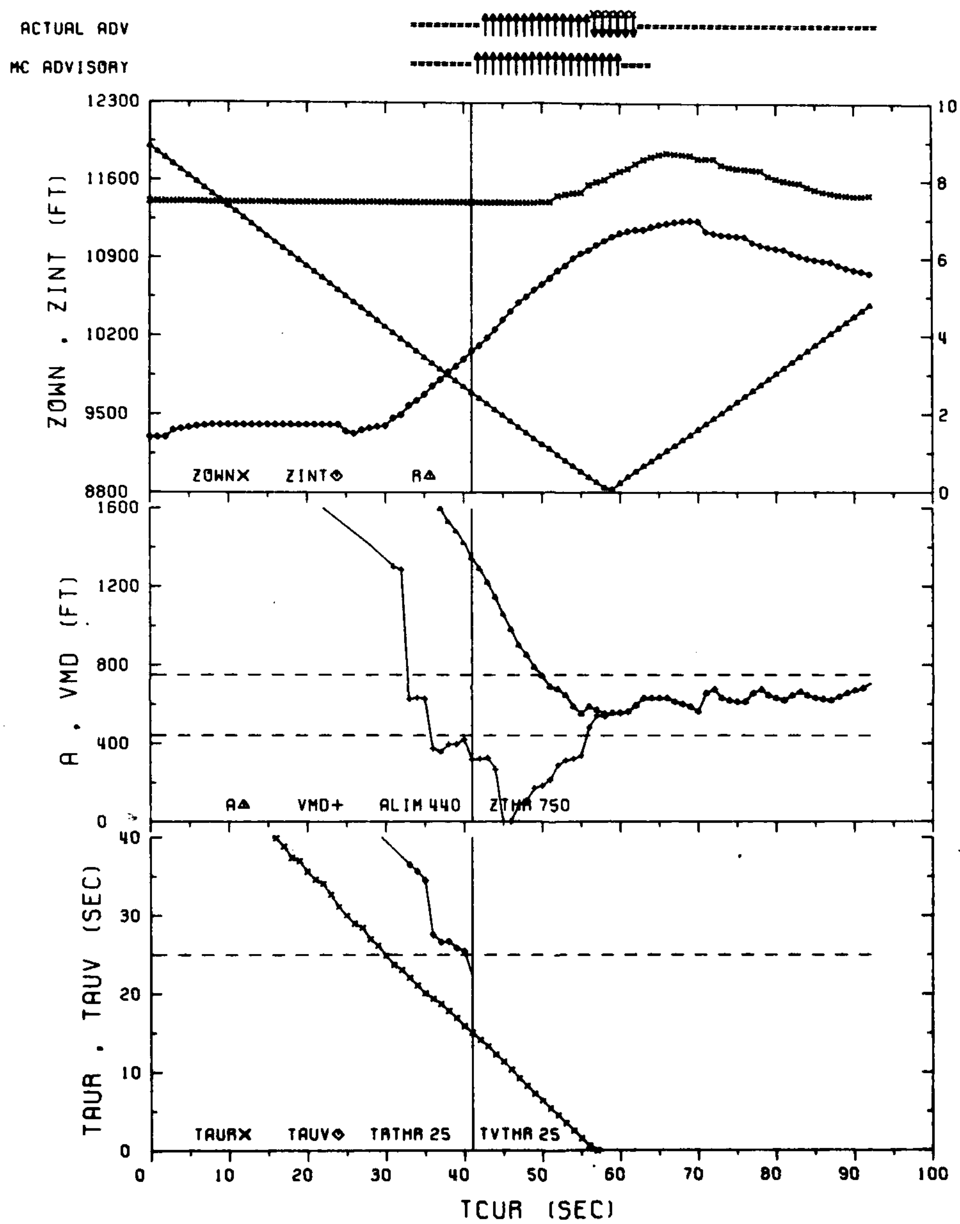


FIGURE B-7
REPLAY OF 25 AUGUST LEVELOFF SCENARIO
ENCOUNTER 16

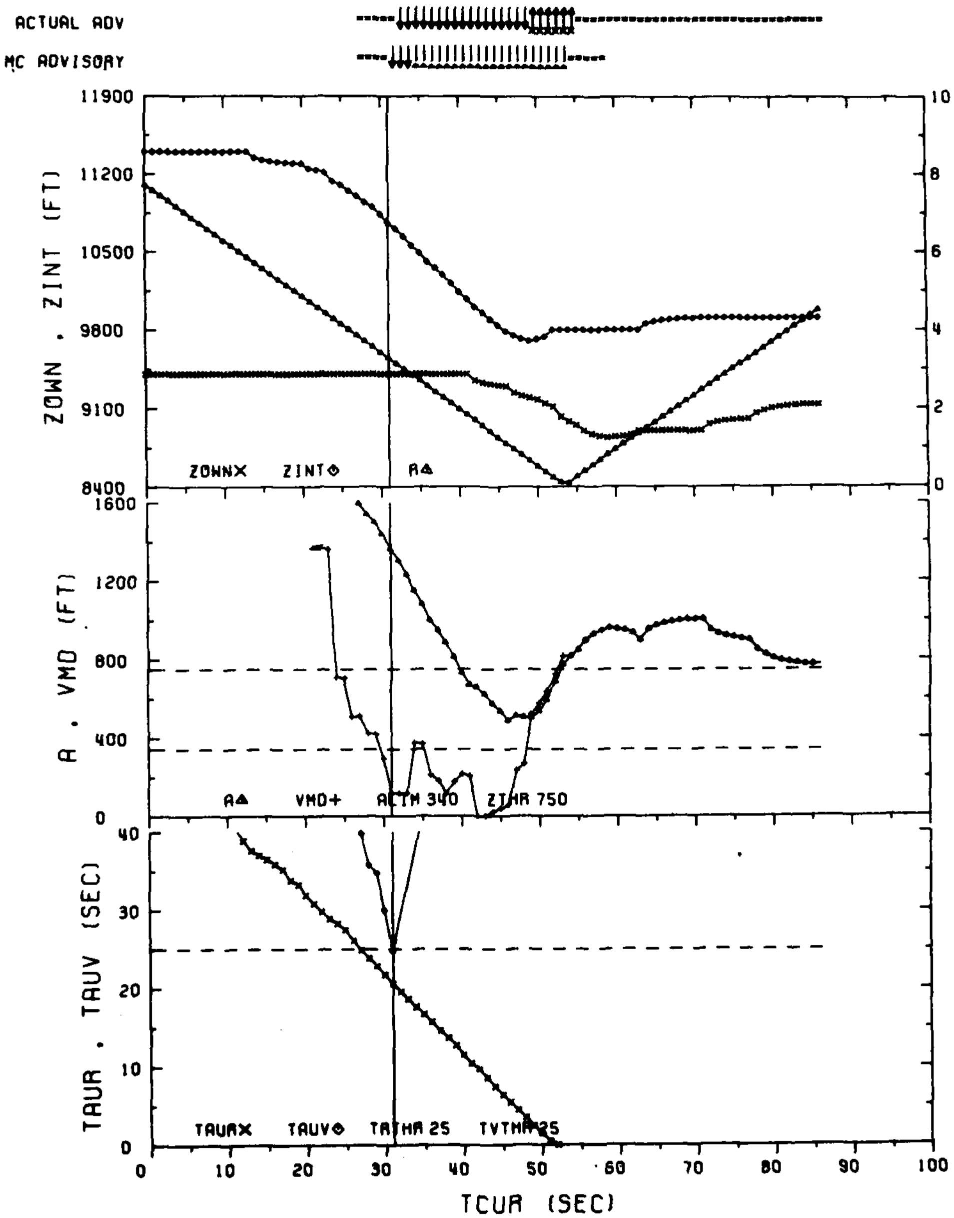


FIGURE B-8
REPLAY OF 25 AUGUST LEVELOFF SCENARIO
ENCOUNTER 11

APPENDIX C

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