DOT/FAA/PM-87/14

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

Traffic Alert and Collision Avoidance System

TCAS-III

Allied-Signal
Bendix Communications Division
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April 1987

Final Report

U.S. Department of Transportation
Federal Aviation Administration

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/PM-87/14	AD-A184565	

4. Title and Subtitle	5. Report Date
TRAFFIC ALERT COLLISION AVOIDANCE SYSTEM (TCAS III) FINAL ENGINEERING REPORT	APRIL 1987
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
E.A. Hecht, J.E. Reed	BCD-TR-157
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Allied-Signal Bendix Communications Division 1300 E. Joppa Road Baltimore, Maryland 21204	
	11. Contract or Grant No.
	DTFA01-82-C-10019
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
U.S. Department of Transportation Federal Aviation Administration Program Engineering and Maintenance Service Washington, D.C. 20591	Final Report
	14. Sponsoring Agency Code
	APM-330

15. Supplementary Notes

16. Abstract

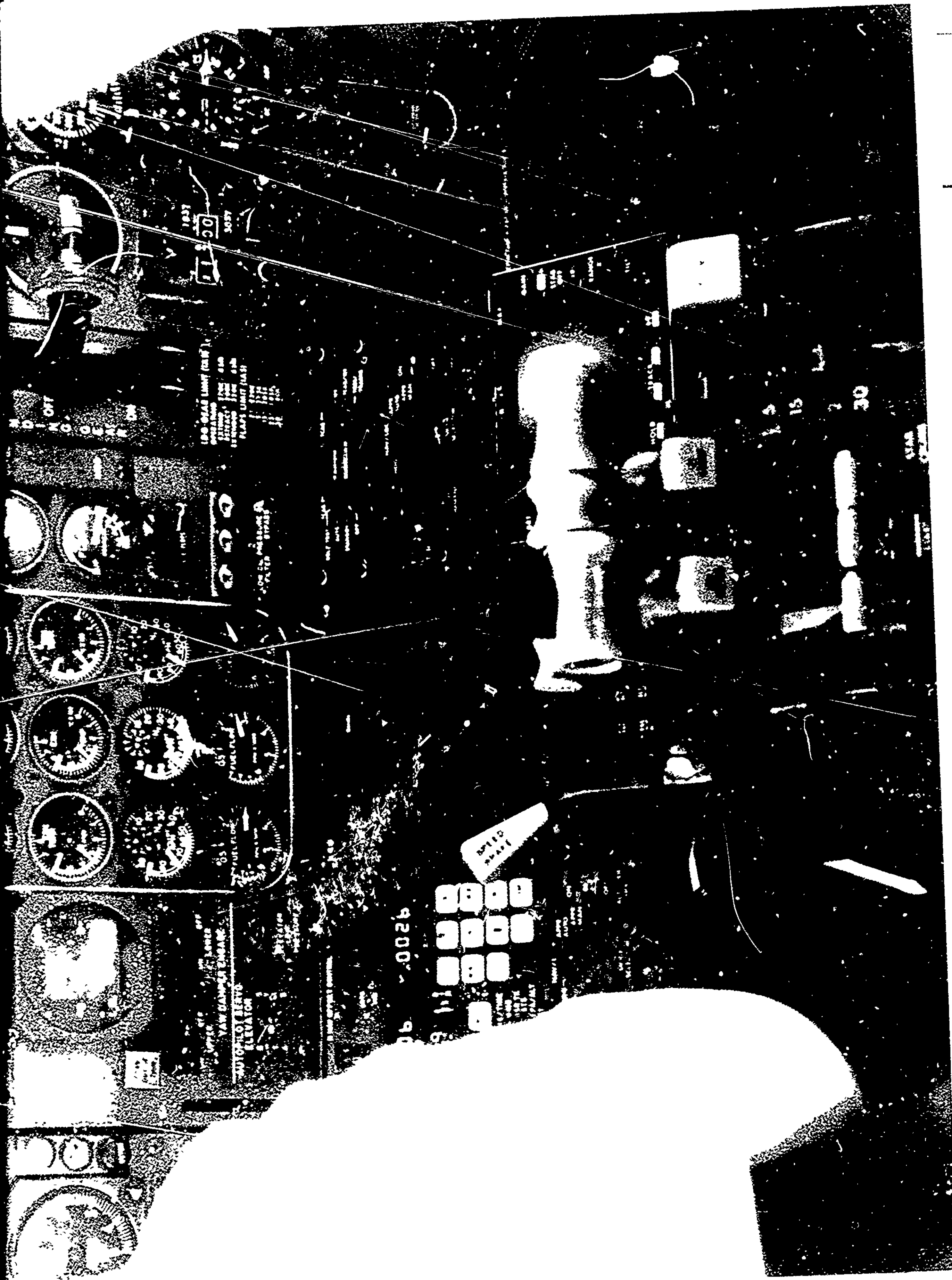
The Task-1 contract on TCAS-II produced a system concept and a Design Specification that show the 743 Aircraft L. A. Basin Model with peak densities well in excess of 0.4 aircraft per square nautical mile can be met. This Task-2 contract is for the design, construction, and testing of two Enhanced TCAS-II (now called TCAS III) Engineering units.

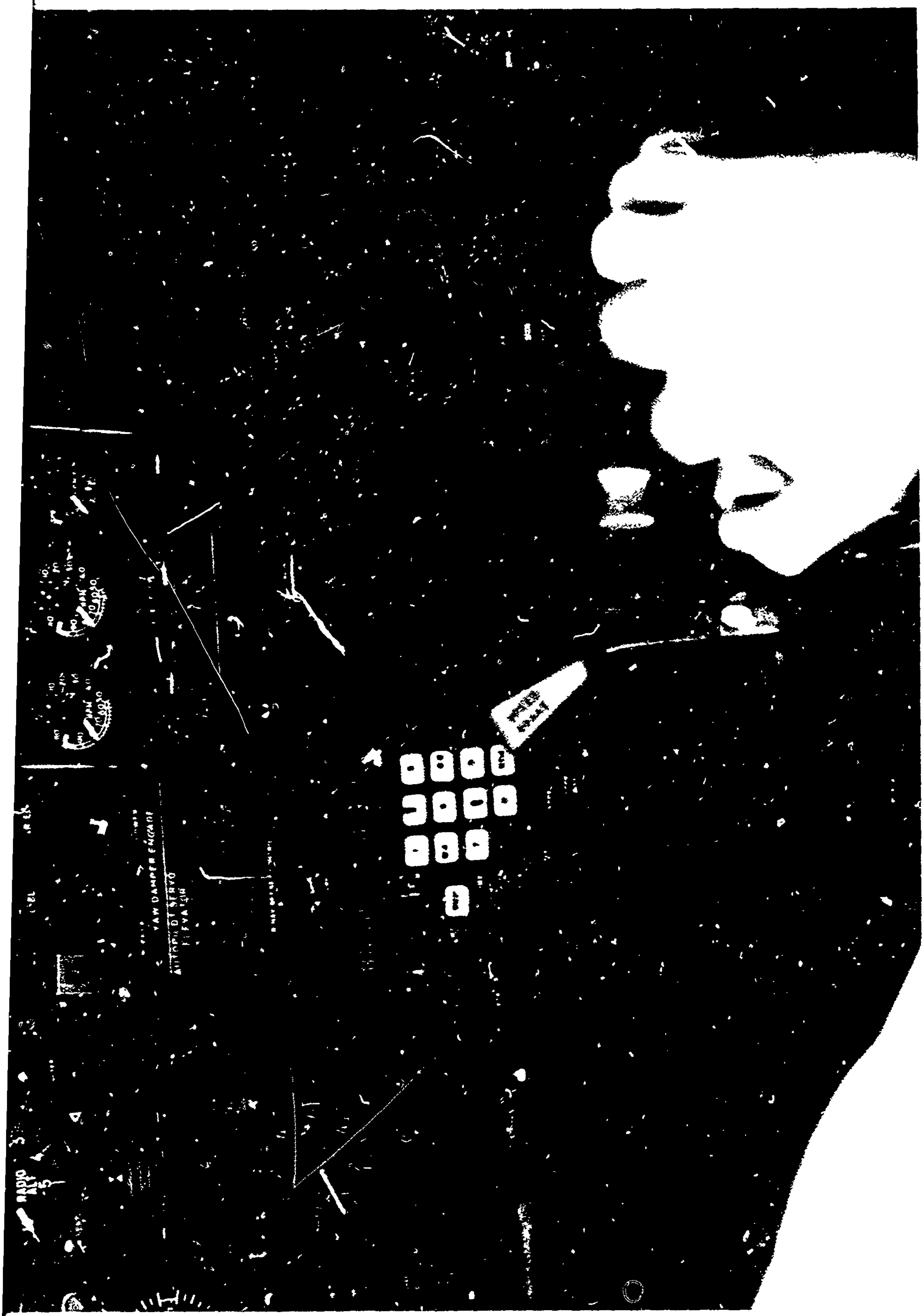
This report contains a description of the TCAS III engineering model and results from various flight tests of the system. System #1 has been installed on the FAA's 727 since 1983. Testing shows that angular accuracies in the order of 1 to 2 degrees are feasible and that Horizontal Resolution Advisories can be given on intruders. System #2 has been delivered to the FAA Technical Center and installed on a Convair 580. Both systems will continue to fly as test beds for TCAS III.

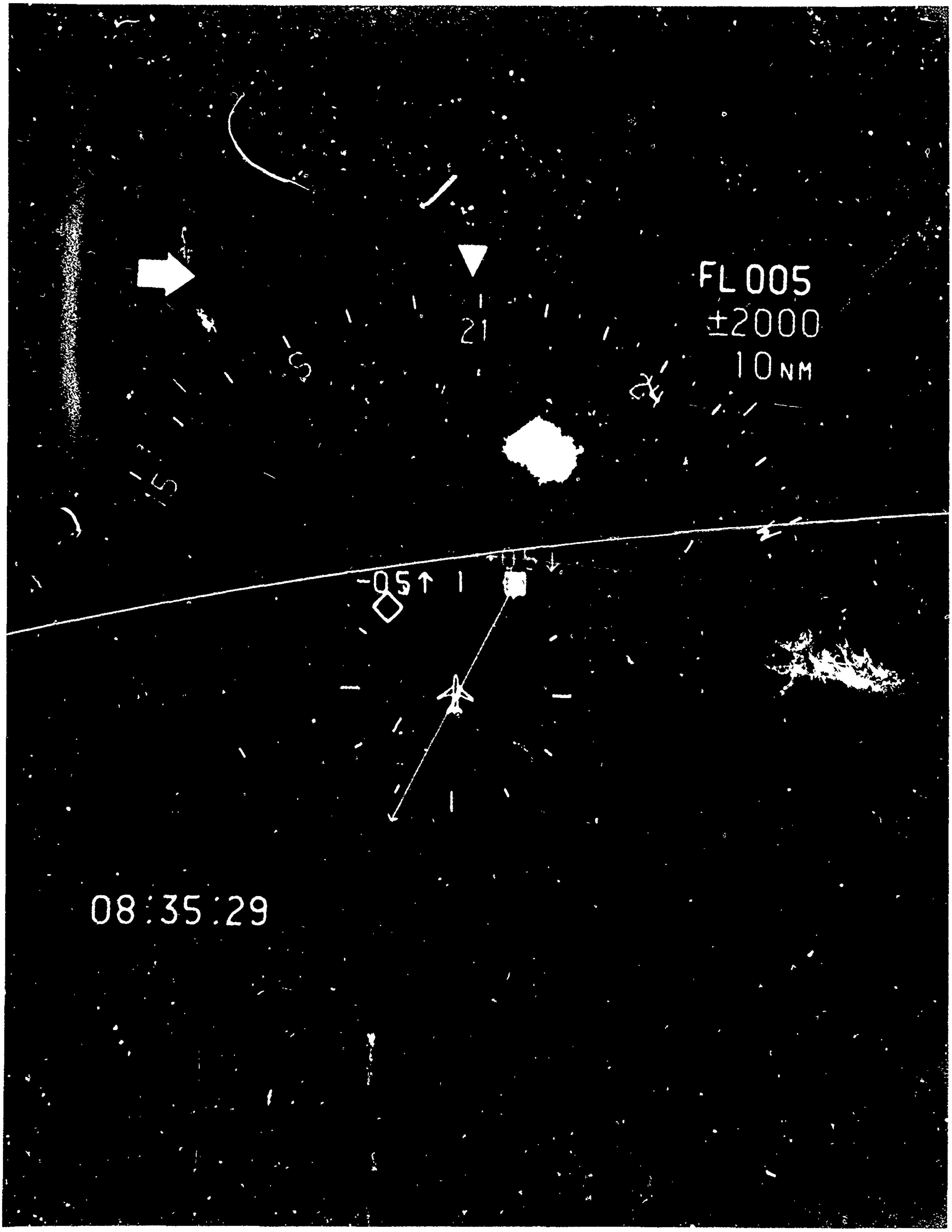
17. Key Words	18. Distribution Statement
Beacon-based Collision Avoidance System, BCAS TCAS-III Traffic Alert Collision Avoidance System	Document is available to the U.S. public through the National Technical Information Service Springfield, Virginia 22161.

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

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



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PREFACE

The three color photographs on the preceding pages show the installation of the TCAS III engineering model cockpit display in the Federal Aviation Administration's test aircraft, a Boeing 727. The display is an Electronic Flight Instrument System (EFIS) display, mounted above the throttle quadrant. The first photograph was taken during a test flight into Dulles International Airport. There is a single target on display; its position relative to the TCAS aircraft is marked by the yellow circle. This target is an actual aircraft that generated a traffic advisory from the TCAS III equipment. The photograph was taken at 11:45:32 when the TCAS aircraft was flying at 1200 feet MSL at 190 degrees heading. The target was approximately 1.5 nautical miles in slant range, -30 degrees relative bearing, and 500 feet below the altitude of the TCAS aircraft.

The second photograph was taken at 11:47:03, just one and one-half minutes later than the first. The TCAS aircraft was on final approach to Dulles at the time. The target shown in the previous photograph has now moved behind the TCAS aircraft and is no longer threatening (as shown by the open diamond symbol) because the traffic advisory aircraft, a small private plane, turned left so it would pass to the left and just below the TCAS 727. The TCAS aircraft continued its approach so the target at 11:47:03 is 4 nautical miles in slant range and 180 degrees relative bearing from the TCAS aircraft. The target's position is displayed with an open diamond with "-01" above the symbol. This means that the target was flying at an altitude 100 feet below the TCAS aircraft. There were four additional targets on the display, all as open diamonds which indicate non-threatening aircraft. Two of the four did not have numbers above the symbol, indicating that those targets had non-altitude encoding transponders. Only the range and bearing of these targets are known.

The third photograph is a close-up of the cockpit display during a simulated test run. The TCAS aircraft was flying at 500 feet at a heading of 210 degrees which was set up by the simulator. In this simulation, there were two targets. The one to the left of the TCAS aircraft is shown as an open diamond. It is not threatening because it is below the threshold used to indicate that it is on the ground and therefore is not considered an airborne intruder at this point. It is flying 500 feet below the TCAS aircraft and ascending as evidenced by the "-05↑" mark by the target symbol. The second target is displayed as a red square; the color and shape of the symbol indicating that the target was determined to be a resolution advisory. This means that the target is threatening and that an advisory is posted on the display for the pilot. In this case, the advisory is "Turn Right", shown as a green arrow pointing to the right in the upper left corner of the display.

For all displayed targets, current relative position is marked by the target symbol. For all targets generating an advisory, 25-second prediction vectors are also displayed. The head of the arrow points to the target's estimated postion in 25 seconds based on current position and rates. A more detailed description of the relative motion display can be found in section 2.7.

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GLOSSARY OF ABBREVIATIONS AND ACRONYMS

A/D	Analog to Digital
ALT	Altitude
ANG	Angle
ARTS	Automated Radar Terminal System
ATC	Air Traffic Control
ATCRBS	Air Traffic Control Radar Beacon System
BCAS	Beacon Collision Avoidance System
CAS	Collision Avoidance System
CL	Climb
CPA	Closest Point of Approach
DABS	Discrete Address Beacon System
dB	Decibel
DEG	Degree
DES	Descend
DMTL	Dynamic Minimum Threshold Level
DP	Data Processor
EFIS	Electronic Flight Instrument System
EL	Elevation
ETEU	Engineering Test Unit
FAA	Federal Aviation Administration
FAATC	FAA Technical Center
FPM	Feet Per Minute
GC	General Correlation
ID	Identification
IFPM	In-Flight Performance Monitor
IP	Interrogator Processor
KTS	Knots
MHz	Megahertz
Mode C	ATCRBS Mode
Mode S	Modified DABS
MSL	Mean Sea Level
MTL	Minimum Threshold Level
nmi	Nautical Mile
NS	Negative Slope
PS	Positive Slope

GLOSSARY
OF
ABBREVIATIONS AND ACRONYMS (Continued)

QV	Quantized Video
RA	Resolution Advisory
RF	Radio Frequency
RSLS	Receiver Side-Lobe Suppression
SBC	Single Board Computer
SEC	Second
SQV	Synchronized Quantized Video
TA	Traffic Advisory
TCAS	Traffic Alert and Collision Avoidance System
TL	Turn Left
TR	Turn Right
W/S	Whisper/Shout
3-D	Three-dimensional

TCAS III FINAL ENGINEERING REPORT

1.0 INTRODUCTION

The TCAS III (Traffic Alert and Collision Avoidance System) was developed by the Bendix Communications Division of the Allied-Signal Corporation under contract to the Federal Aviation Administration, U.S. Department of Transportation. A contract (DTFA01-81-C-10041) for concept development and computer simulation of the TCAS III was awarded in January 1981. This was followed by a contract award (DTFA01-82-C-10019) for the development and test of two Engineering Models in December 1981. This report covers the major features and test results of the TCAS III Engineering Models.

TCAS III assesses possible airborne collision threats by actively interrogating transponder-equipped aircraft using an electronically steered phased array antenna. The accurate bearing measurement of other aircraft allows for horizontal maneuver capability and an accurate relative motion target display in addition to reducing the alarm rate and reducing interference susceptibility. These are the principal features that distinguish the TCAS III from the TCAS II.

The original design of the TCAS III was developed and validated by computer simulation. The computer program logic and a model of the hardware were tested in a Simulation Test Bed that simulated flight through the 1982 Los Angeles Basin traffic environment model. The model has 743 aircraft within an area 120 miles on a side. The results of the Factory Performance Testing showed targets being detected and tracked in high density traffic areas. Approximately 100 targets were successfully tracked within 20 nautical miles of Own aircraft. This level of surveillance activity was maintained through a minute of simulated flight time. During specific tests, conflict situations were successfully detected and reported. Accurate bearing was shown to be most effective in the correlation and association of data. Even in the 743 aircraft case where the peak density of targets is 0.47 aircraft per square nautical mile in the annulus between six and seven miles, tracks were initiated and maintained.

Once the design concept was validated, the fabrication of the two Engineering Models began. The first unit was delivered to the FAA Technical Center in March 1983. It was installed on the FAA's Boeing 727 in May 1983. This first TCAS III Engineering Model was put through a variety of tests - static testing on the ground, flight testing over various terminal areas, orbits, and encounters. In addition, this unit was tested twice in the Los Angeles Basin area for operation in a high density environment. Details on the flight tests can be found in section 4. In September 1984, a modification to the contract was added to focus efforts in several problem areas such as altitude decoding and target splitting. Also, upgrades to the cockpit display and aural advisory capability were identified as priority items. The second TCAS III Engineering Model was delivered to the FAA Technical Center in May 1986. This unit was installed on the FAA's Convair 580 and flown on several test flights. Flight testing of both units will be continuing. Important contract milestones are summarized in Table 1.0-1.

TABLE 1.0-1. TCAS III CONTRACT MILESTONES

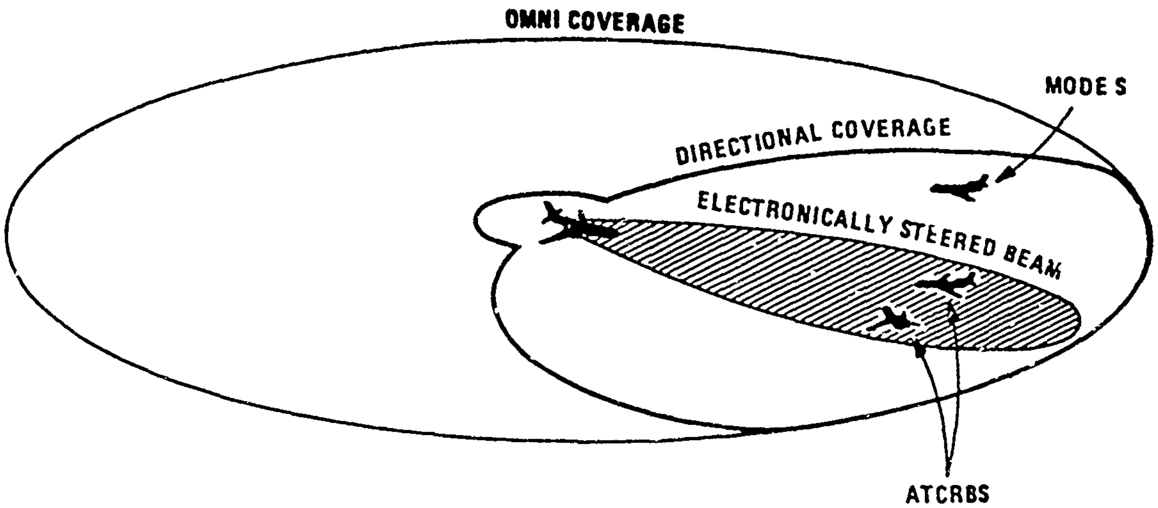
Dec 1981	Contract begins to design, fabricate, and test two Engineering Models.
Dec 1982	Factory Acceptance of first unit.
Mar 1983	Delivery of first unit to FAA Technical Center.
May 1983	Installation of first unit in FAA's Boeing 727. Testing begins.
Dec 1983	Flight testing of first unit with TCAS II logic (vertical maneuvers only) in Los Angeles.
Jan 1984	TCAS III logic installed (vertical and horizontal maneuvers). First flight test with horizontal advisory displayed.
Mar 1984	Flight tests in Atlanta area for high density operation.
Sep 1984	Modification number 0014 to contract.
Feb 1985	Flight tests in Los Angeles Basin.
Oct 1985	Upgrade of cockpit display and aural advisory capability. Demonstrations in Ottawa, Canada.
Apr 1986	Factory Acceptance of second unit.
May 1986	Delivery of second unit to FAA Technical Center. Installation on FAA's Convair 580.

2.0 TCAS III SYSTEM DESCRIPTION

This section gives a brief overview of the TCAS III system and emphasizes the differences of this system versus the TCAS II system.

2.1 TCAS III FEATURES

As shown in Figure 2.1-1, the TCAS III accurately determines the relative position of all ATCRBS and Mode S equipped aircraft operating within its surveillance limits by measuring the relative bearing and range of each aircraft and extracting its encoded altitude from the transponder reply. From these data, the track of each aircraft is generated and its future course projected. This three-dimensional track allows estimates of horizontal miss distance to be made which are used in the evaluation of alternative resolution maneuvers. Through the use of relatively narrow antenna patterns, synthetically narrowed



- NARROW SECTORIZED BEAMS WITH ACCURATE BEARING DATA
- THREAT DRIVEN LOGIC—EFFICIENTLY USES RESOURCES
- MISS DISTANCE FILTERING—REDUCES ALARMS
- POSITION WITH RELATIVE MOTION—EFFECTIVE TRAFFIC ADVISORIES
- HORIZONTAL RESOLUTION—ADDITIONAL MANEUVER OPTIONS

FB-VG-1781

FIGURE 2.1-1. TCAS III FEATURES

sectorized interrogations, and monopulse angle measurements, the TCAS III is able to accomplish its surveillance functions in the highest traffic densities.

The threat driven logic adaptively controls the system to concentrate its operations on collision threats and potential collision threats. It dynamically controls its surveillance parameters (angle, range, power, and transmission rate) to achieve very high surveillance efficiency (in terms of the processing activities used in obtaining the information it needs) and low RF interference to other ATC functions sharing the beacon spectrum.

The accurate bearing measurements of other aircraft is critical for the use of a horizontal maneuver. The results of flight tests show that the design objectives of one to two degrees, one-sigma bearing accuracy in the forward 180 degree azimuth sector has been met. This surveillance capability enables a horizontal maneuver to be safely executed if needed. The track data may also be used to display the relative position and motion of traffic to pilots.

2.2 SURVEILLANCE

TCAS III is designed to operate in traffic densities as high as 0.4 aircraft per square nautical mile (or approximately

32 aircraft within 5 nautical miles of the TCAS III aircraft) with targets having closing speeds of 1200 knots. The design of the system includes not only the necessary hardware but also a surveillance control strategy based upon the use of a dynamic, adaptive, real-time, threat-driven logic, which operates within the same environmental limitations established for the TCAS II.

ATCRBS equipped targets are interrogated using the Mode S format identified as Mode C only All Call (to which Mode C transponders will reply but to which Mode S transponders will not reply). Mode S equipped aircraft are acquired and tracked using their Mode S squitter and replies to discrete interrogations. In both cases, a narrow antenna beam is used which can be instantaneously steered to any bearing angle by the system. For Mode C equipped aircraft, all such targets receiving the interrogation will reply to the Mode C interrogation. This results in some probability that the replies from different transponders will overlap in time and produce what is known as synchronous garble at the TCAS receiver, which makes it difficult to identify and track individual aircraft. To minimize the synchronous garble problem, several provisions are made in the TCAS III.

The most significant of these added provisions is that the normal angular width of the zone in which transponders will reply is "synthetically sharpened" from the free space antenna beamwidth (which is 64 degrees) to 22.5 degrees. Also the angular position of the narrowed sector can be stepped (from one interrogation to another) in increments of 5.625 degrees, a total of 64 equally spaced positions.

Each of these 64 angular positions is visited often enough to ensure a 0.98 probability of detection for any aircraft (traveling at the maximum closing velocity one can anticipate at that bearing) before it can pass through a 10,000 foot detection zone and enter the outer boundary of the TCAS III protected zone, shown in Figure 2.2-1. The outer boundary of the protected zone ensures that the system then has at least 45 seconds remaining before the point of closest approach (assuming a worst case situation). The 45 seconds provides sufficient time to assess the threat, coordinate with the other target if it is also TCAS equipped, select the proper advisory, display the advisory to the pilot and provide him sufficient time to react and then time for the aircraft to accelerate and depart from its original flight trajectory and provide a safe separation distance. The worst case, defined for each bearing angle in terms of the maximum possible relative closing velocity that can exist for two aircraft traveling near Mach 1, results in a protected zone having boundaries as shown in Figure 2.2-1. For the head-on conflict (-1200 knots relative closing velocity), the range at which a target must be detected is significantly greater than it is for the tail chase situation (with a maximum speed differential of -350 knots).

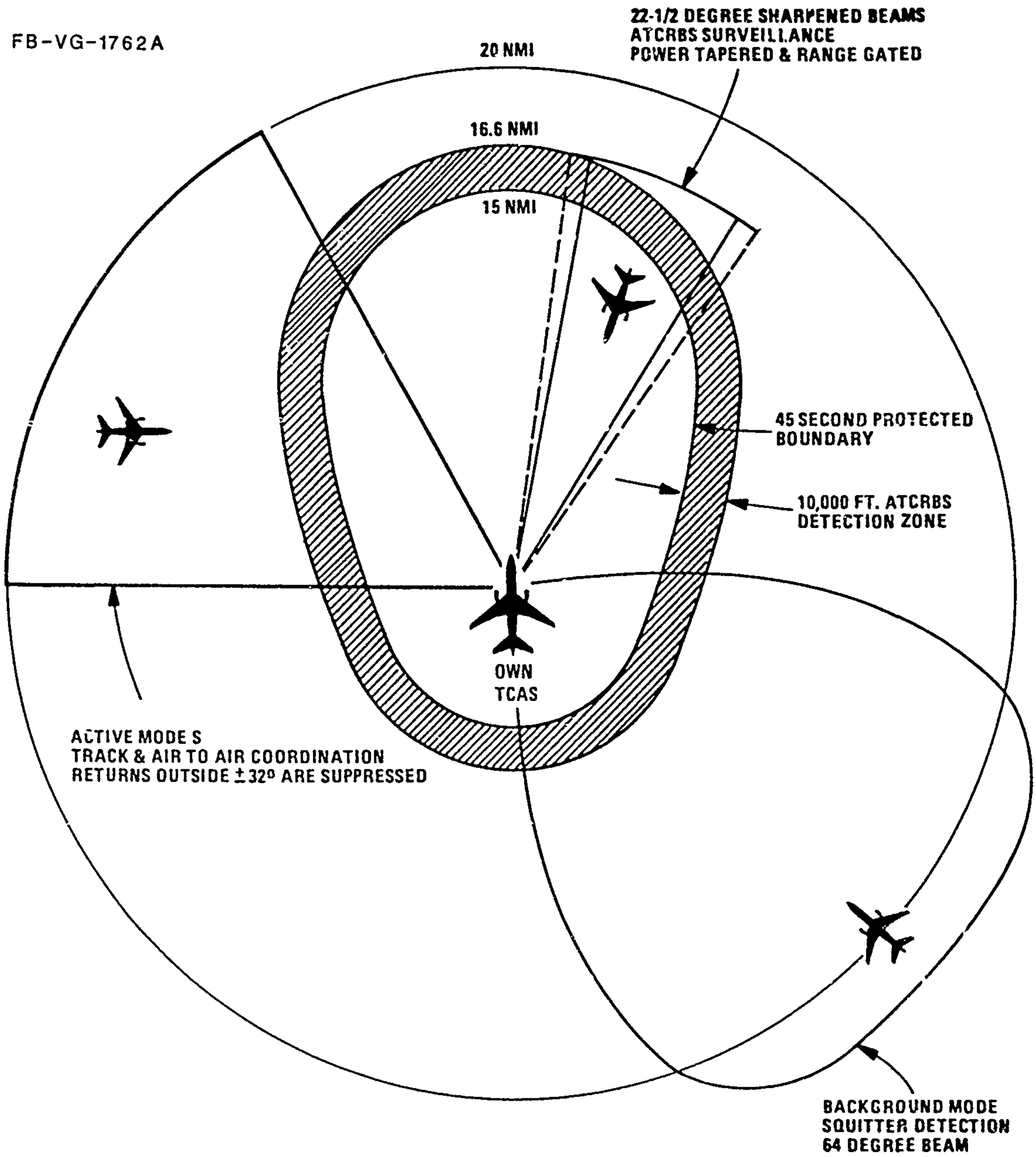


FIGURE 2.2-1. SURVEILLANCE - DYNAMIC THREAT DRIVEN LOGIC

2.3 GARBLE REDUCTION

In a high density traffic environment, the overlapping replies of closely spaced ATCRBS transponders to each interrogation make it difficult for the receiver to detect individual targets. In a density of 0.4 aircraft per square nautical mile, some 32 aircraft lie within 5 nautical miles of range of the TCAS equipped aircraft. Because the duration of each reply is 21 microseconds (or 3.4 nautical miles in range), as many as 26 replies can synchronously overlap at the TCAS receiver if an omnidirectional antenna were used.

As shown in Figure 2.3-1, the most effective mechanism for reducing synchronous garble is to prevent generation of overlapping replies by dividing the space surrounding the interrogator into angular regions using directional antenna radiation patterns. Such patterns are used to limit the angular sector within which transponders are interrogated. Using the 22.5 degree synthetically sharpened pattern for the transmission of interrogations, an effective improvement factor of about 12 to 1 is obtained. (Variations in individual transponder reply thresholds spread the effective beamwidth about 30 percent, thereby reducing the improvement from its theoretical value of 16.) This technique reduces the 26 overlaps that an omnidirectional receiving system would have in a worst case environment to about 2 overlaps, assuming uniformly distributed traffic.

To further reduce the incidence of overlapping replies, a simplified (four-level) form of the whisper-shout technique used in the TCAS II is applied to each 22.5 degree sector that the TCAS III interrogates. Since individual transponders differ somewhat in sensitivity, a low power interrogation transmission will elicit replies from some transponders but not from others. When such a transmission is followed by a S0/P1 suppression pair near the same power level, those transponders replying to the first interrogation will be prevented from replying to successively higher power interrogations. If immediately thereafter a higher power interrogation is transmitted, another group of transponders will reply. In the example shown in Figure 2.3-1, an S0 pulse preceding the P1 pulse by 2 microseconds at 3 dB lower power than the preceding interrogation provides suppression of those transponders which replied to that previous interrogation. This process is repeated four times in each 22.5 degree angular sector in the TCAS III using interrogation power levels separated by 18 dB, 14 dB, 10 dB, and 0 dB, respectively. This produces a net improvement of about 2.5 to 1 in reducing synchronous garble compared to a single high power interrogation.

The total improvement due to the combined use of both sectorized interrogation and four-level whisper-shout is about 30 to 1 in reducing synchronous garble at the receiver terminals. A reply processor is then used, which reliably decodes as many as three overlapping signals, thereby producing a high probability that the TCAS III will resolve individual target replies in high traffic density environments.

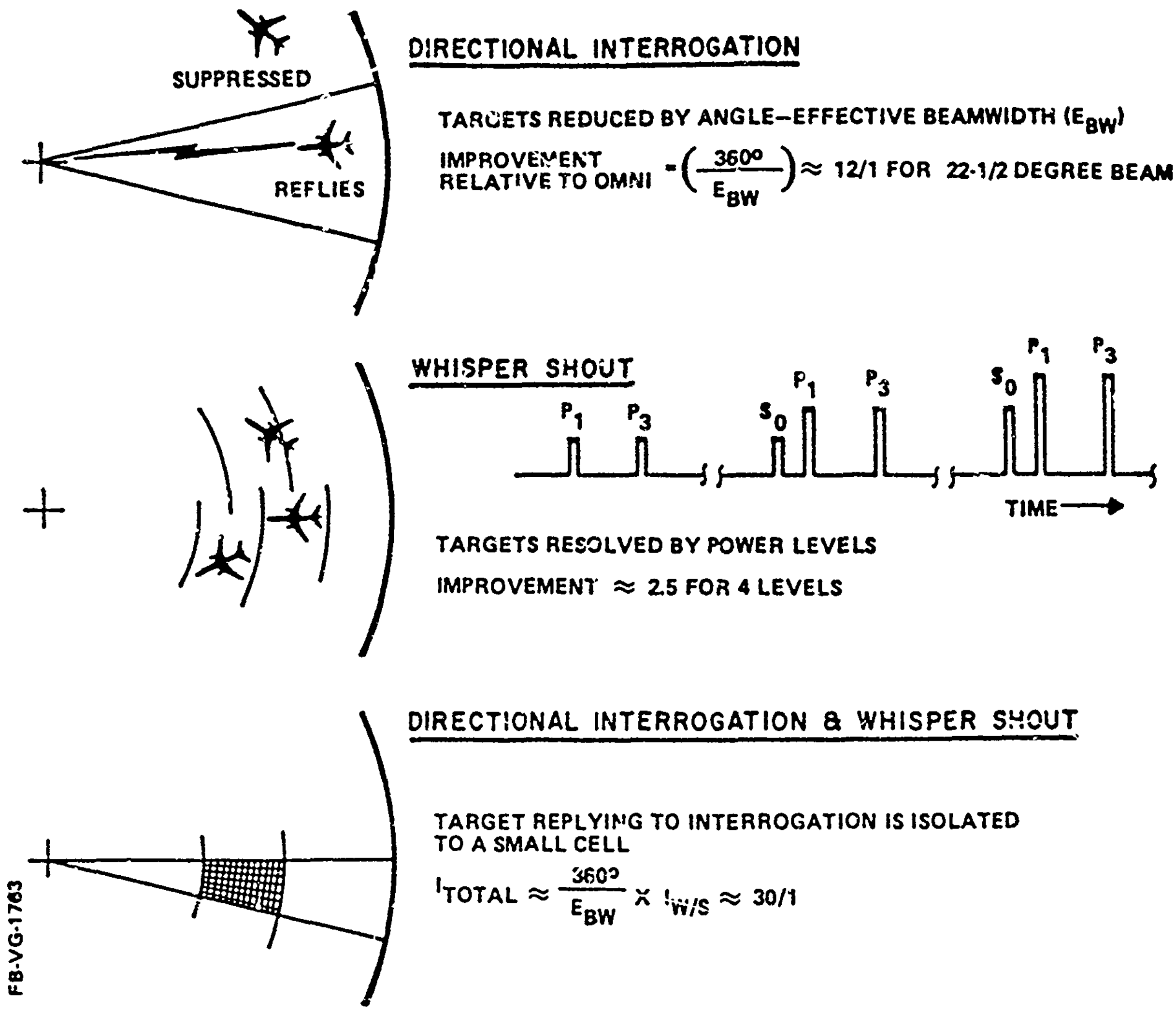


FIGURE 2.3-1. TCAS III REDUCES SYNCHRONOUS GARBLE

2.4 BEAM SHARPENING

The technique used to sharpen the 64 degree 3·dB beamwidth to 22.5 degrees is illustrated in Figure 2.4-1. All ATCRBS transponders include Side Lobe Suppression circuitry. This transponder feature allows comparison of the amplitude of the P1 pulse (which is normally transmitted on a omni-directional antenna) so that it can determine when it is located within the main beam of the interrogator. If it detects the amplitude of the P1 pulse at a substantially higher amplitude than that of the P2 pulse, the transponder will reply provided it receives a P3 pulse at the proper time. If on the other hand P2 is greater than P1, the transponder is caused to "suppress". In this suppression state, the transponder will not respond to any interrogation for a period of about 35 microseconds.

Because TCAS cannot employ a large aperture antenna having the directivity of a ground based interrogator, the technique employed by TCAS III to limit reply zone width uses two specially tailored antenna patterns having the shapes shown in Figure 2.4-1. The P1 and P3 (interrogation) pulses are transmitted on the sum beam, while the P2 (suppression) pulse is transmitted on the difference beam.

A transponder located near the center line (or boresight axis) of the two beams will receive the P2 pulse at considerably lower amplitude than the P1 pulse because it is in the null of the difference pattern. Therefore it will reply. As the transponder moves in bearing away from the sum beam center, the P2 pulse amplitude will increase while that of the P1 decreases until a point is reached where the P2 pulse power exceeds the P1 and the transponder is then suppressed.

Using the antenna patterns shown in Figure 2.4-1, together with an adjustment of the total power in each beam (the sum beam power is reduced about 5 dB from that in the difference beam), a 22.5 degree effective beamwidth is achieved. This width will vary to a small degree with individual transponders due to variations in individual design.

2.5 MONOPULSE MEASUREMENTS AND RECEIVE SIDELOBE SUPPRESSION

The same sum and difference patterns used for transmission are also used on the reception to estimate the bearing angle offset of each target from the antenna boresight axis. This technique is known as monopulse since an angle estimate can be made on a single pulse. It contrasts with existing angle measurement techniques employed by ground ATCRBS interrogators, which require a series of interrogations and replies as the beam traverses the target (hence many pulses) that is then processed to estimate the center point. Monopulse measurements exhibiting 1 to 2 degree standard deviation errors are obtainable with TCAS III. Figure 2.5-1 illustrates the monopulse measurement technique. A monopulse curve, similar to that shown at the lower part of the

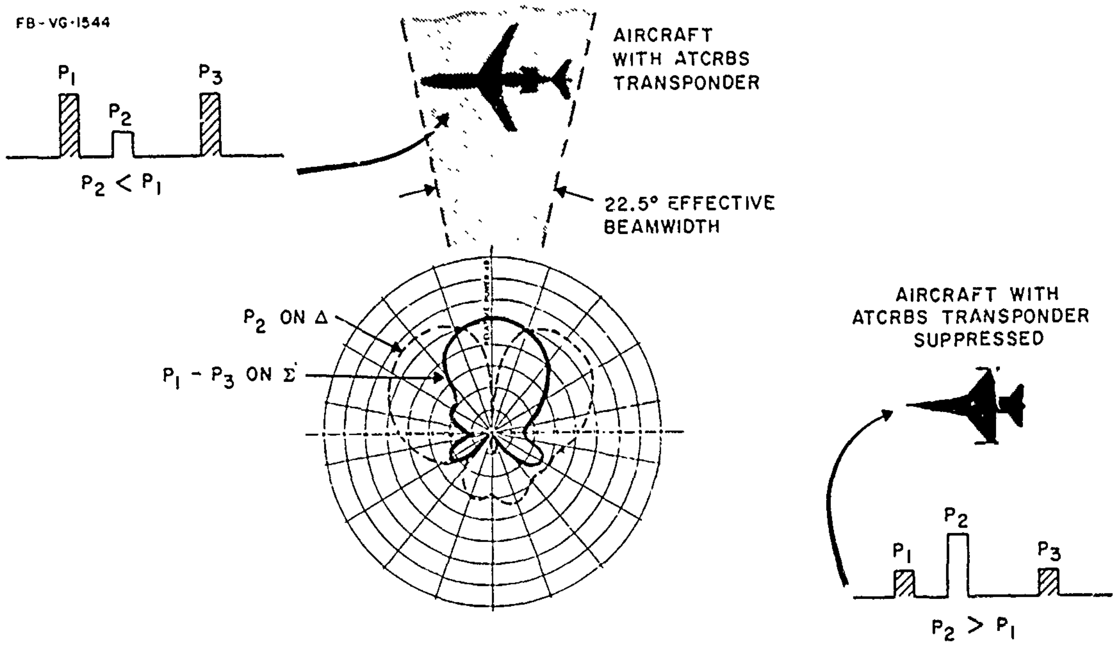


FIGURE 2.4-1. INTERROGATE MODE OF OPERATION

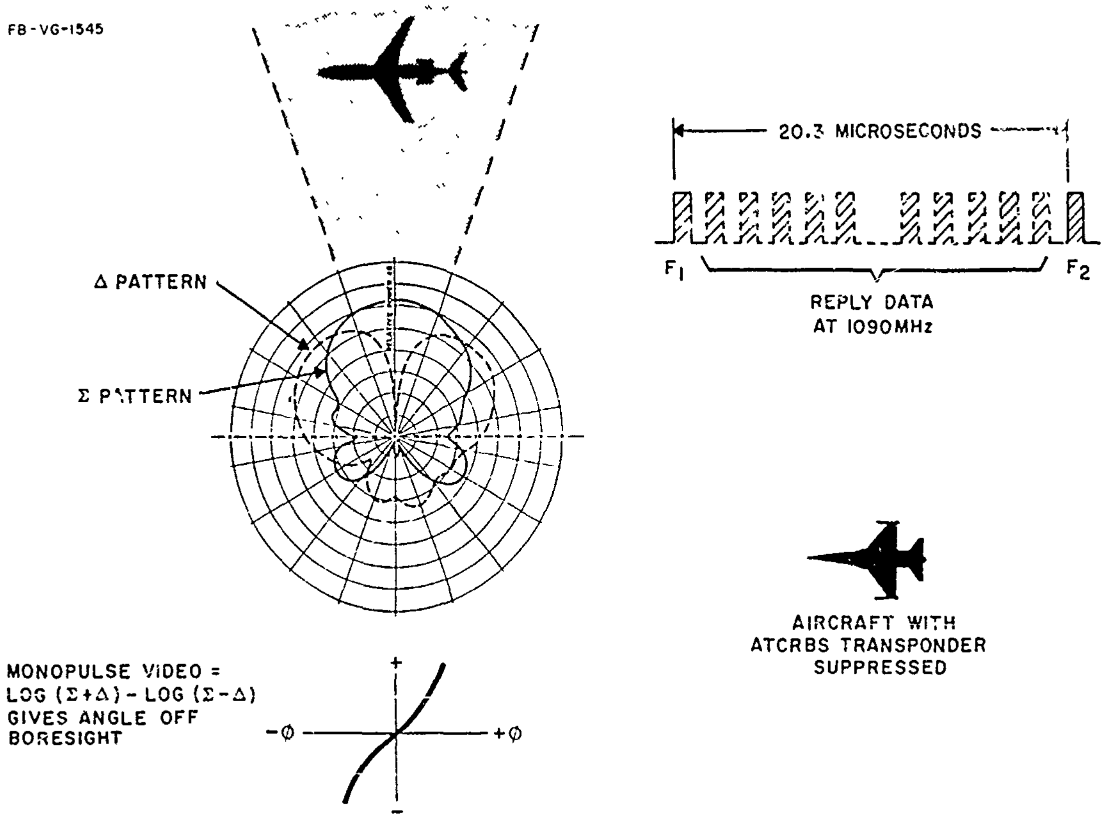


FIGURE 2.5-1. REPLY MODE OF OPERATION

figure, is digitally stored in the data processor for each beam position so that any variations in voltage ratio due to physical differences in antennas are corrected. Each monopulse curve is generated from sum and difference patterns taken at each beam position at 10 degrees elevation. Ten degrees was chosen as an average value between 0 degrees and 20 degrees.

Bearing measurements are made on both ATCRBS and Mode S replies. Measurements are made on each ATCRBS reply using up to four different pulses and the results averaged. If only one pulse is received in the clear (not overlapped by another pulse) whenever a bracket decode is declared, the reply monopulse estimate is made on that one pulse. Sixteen chips from each Mode S reply are averaged to produce the monopulse estimate.

Receive sidelobe suppression (RSLS) is also implemented in TCAS III to eliminate replies (called fruit) appearing from angles outside the beam sector of interest. The circuitry compares the ratio of sum to difference pattern voltages for each pulse. In the sector of interest where the sum pattern exceeds the difference pattern, the ratio has a large positive value. When the bracket pulse voltages exceed the RSLS threshold, a bracket decode is enabled and the reply decoded. Replies from other angles are rejected because the voltage ratio is low. This reduces the amount of fruit that must be processed by a factor of 12.

2.6 STABILIZED COORDINATE SYSTEM

To maintain bearing angle estimates accurate to one degree on intruding aircraft, it is necessary to keep the track file in a north referenced stabilized system. Flight records show that while flying a nominally straight flight path, the test aircraft varies +/- several degrees heading in 20 seconds. Then, to compute an accurate bearing rate in the order of 0.1 to 0.2 degrees per second as needed for a miss distance calculation, Own aircraft's stable reference must be read four times per second.

Measurements made with the directional antenna must be transformed from Own aircraft's coordinate reference frame to the earth stabilized (north reference, locally level) coordinate frame to correct the angle for pitch, roll, and heading. When tracking a target, the interrogation angle is computed by transforming back from the stabilized coordinate to Own aircraft's coordinates. Although these coordinate transformations require considerable computational power, accurate bearing angle estimates cannot be maintained without stabilizing the track file reference frame.

Because a stabilized reference frame is required to retain angle accuracies and aircraft movements are reasonably linear in the local horizontal plane, TCAS III track equations take advantage of the orthogonal stabilized X-Y coordinate frame as shown in Figure 2.6-1. The stabilized coordinate frame is

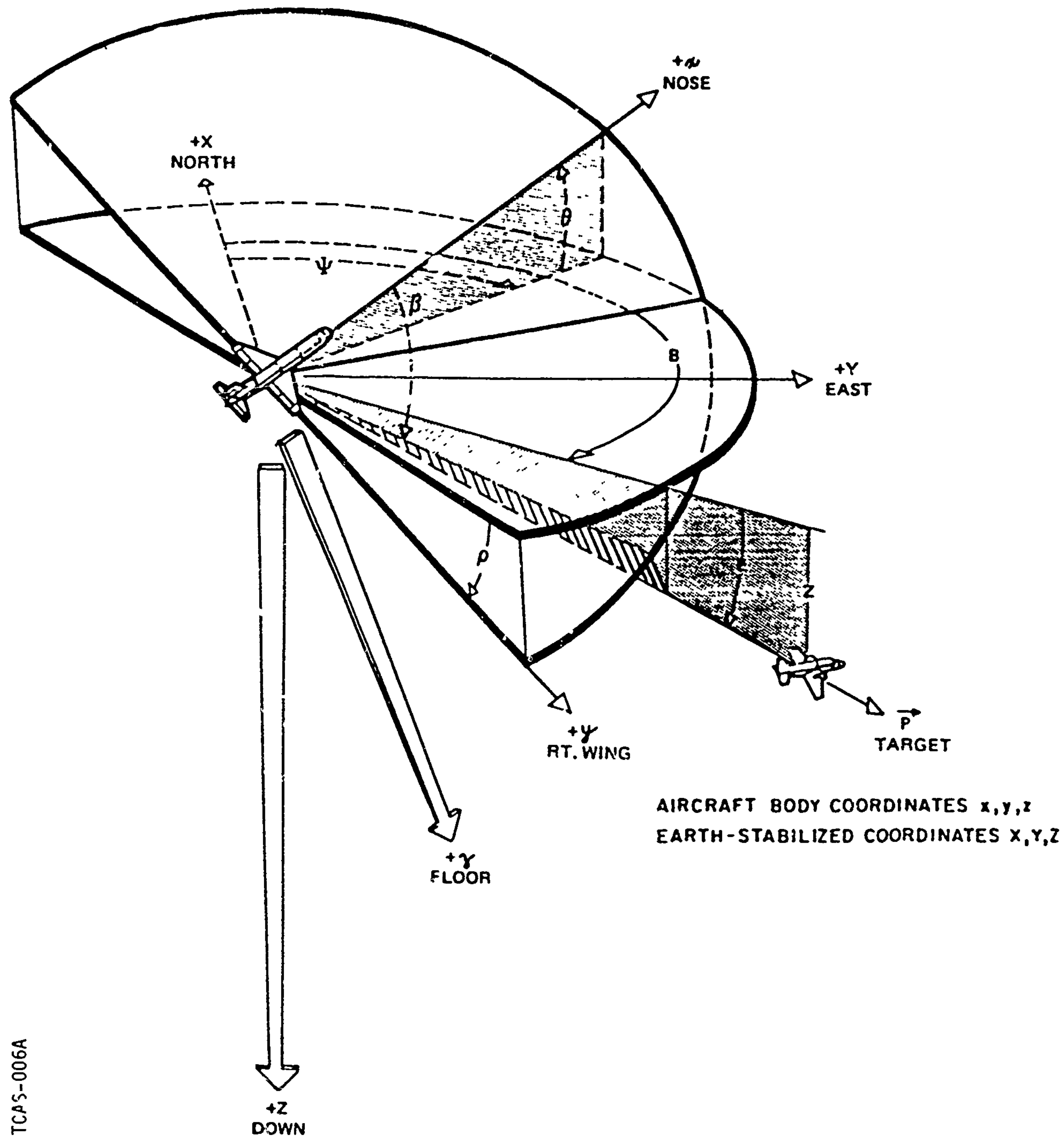


FIGURE 2.6-1. STABILIZED COORDINATE SYSTEM

centered in the TCAS III aircraft with the +X axis pointing north, the +Y axis pointing east, and the +Z axis down. Own aircraft's coordinate system has own aircraft's nose represented by the +x axis, +y axis passing through the right wing, and +z through the floor. In Figure 2.6-1, the remaining parameters are Ψ (own aircraft's heading), ρ (own aircraft's roll), θ (own aircraft's pitch), β (target's bearing in own aircraft's coordinate system), B (target bearing in the earth-stabilized system), and E (target elevation angle in the earth-stabilized system). Measurements are made in range and bearing in the aircraft coordinate because the directional antenna is fixed to the aircraft skin. Vertical tracking is accomplished independently in the Z coordinate using the non-linear tracker developed for the TCAS II by the MITRE Corporation.

2.7 TCAS III RELATIVE MOTION DISPLAY AND AURAL ALARM

The TCAS III relative motion display on the first engineering model was upgraded in October 1985. This cockpit display consists of a modified Electronic Flight Instruments System (EFIS) display and symbol generator. Figure 2.7-1 is an illustration of the cockpit display. It has the following features:

> The location of Own aircraft is designated as an airplane in the center of the display. Own heading is toward the top of the display so all angle positions relative to Own aircraft can be easily discerned.

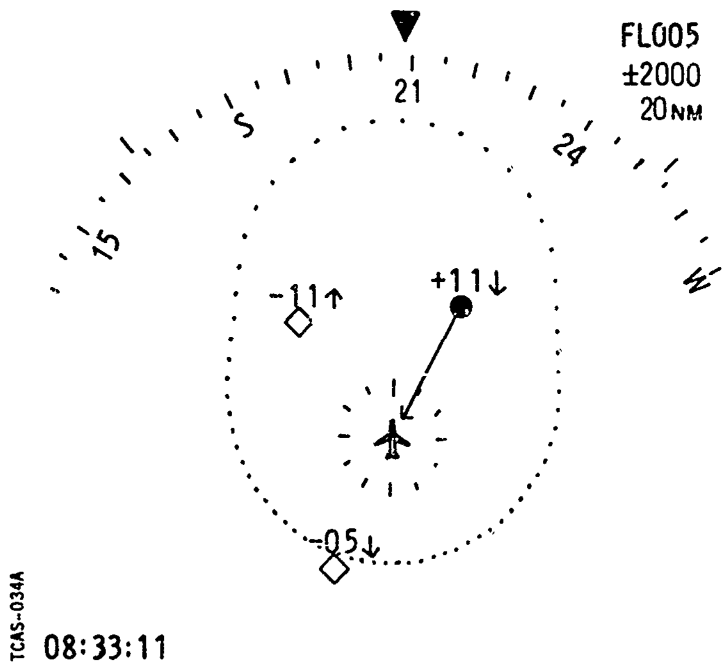


FIGURE 2.7-1. TCAS III COCKPIT DISPLAY

The display range is selectable by the pilot to be 3, 5, 10, 15, 18, or 20 nautical miles. The selected range is given in the upper right corner of the display.

The surveillance range gate is identified by an oval row of dots ranging 16.6 miles directly ahead to 8 miles in the rear.

This boundary represents the maximum range from which an intruder flying 600 knots could reach Own aircraft in 45 seconds plus a 10,000 foot detection zone when Own aircraft is flying at any speed from 600 knots down to 250 knots.

The o'clock positions are always displayed at 4 nautical miles except when the 3 nautical mile range is selected. Four nautical miles is chosen to give the pilot a reference at the range where he should be able to visually locate intruders.

An indication of Own heading is given by the compass arc at the top of the display. The arrow points to Own aircraft's heading. When Own aircraft turns, the compass will turn accordingly. Own aircraft's flight level is displayed in the upper right corner of the display. In Figure 2.7-1, the flight level is 005 or 500 feet and its heading is approximately 210 degrees from magnetic North. Also displayed in the upper right corner is the altitude band within which targets are displayed. In this example, it is ±2000 feet of Own's altitude. This parameter is adjustable by the pilot.

The lower left corner of the display contains the time. This is used for correlation with recorded flight data.

The location of each target symbol indicates the measured range and bearing of the target relative to Own aircraft. The shape and color of each symbol indicates its threat level. The number above the shape gives the target's altitude relative to Own aircraft in hundreds of feet where positive is above Own aircraft. An arrow beside the relative altitude indicates the direction of change of altitude (up indicates increasing). A target with no relative altitude displayed indicates that the target has a non-altitude reporting transponder. A vector is attached to each target that is a Traffic Advisory or Resolution Advisory. The head of the vector indicates the estimated position of the target in 25 seconds based on current range and bearing rates.

(a) An open white diamond indicates a non-threatening target.

(b) A solid white diamond indicates a proximity warning. A target will generate a proximity warning when it comes within four nautical miles in slant range and 1200 feet in relative altitude of Own aircraft.

(c) A solid yellow circle indicates a traffic advisory target. When a target first becomes a traffic advisory, an aural alert is given - the word "Traffic" is repeated two times. This indicates that the target is projected to pass closest point of approach at less than one nautical mile and within 1000 feet relative altitude within 30 seconds.

(d) A solid red square indicates a target that has become a resolution advisory. The recommended manuever is displayed to the pilot.

The Resolution Advisory is shown in the upper left corner of the display as seen in Figure 2.7-2. This area of the display pictorially shows the resolution advisories. When the resolution advisory is first displayed, an aural alert is given - the advisory is repeated three times. If at any time the advisory is changed, the new advisory is repeated three times as well, alerting the pilot of the change.

Figure 2.7-2 shows two targets. One is a resolution advisory that is at 4 nautical miles at 30 degrees relative bearing and 500 feet above Own aircraft and descending. The recommended resolution advisory against this threat is "Turn Right" as shown by the arrow in the upper left corner. The other target is non-threatening, at 4 nautical miles, -30 degrees relative bearing, 500 feet in altitude below Own aircraft, and ascending.

2.8 ALARM REDUCTION

TCAS III has several levels of filtering or target rejection prior to initiating tracks on potential threats. Once a target is in track, it is subjected to threat detection logic tests to assess its potential for collision or near miss.

An important objective of the TCAS III system is to reduce the number of unnecessary alarms while ensuring a high probability of declaring a threat when it exists. To perform the complex data processing required on each threatening target, the number of targets being processed must be minimized.

The most general filter is the limitation of the threat volume by range and interrogation power so replies from aircraft beyond regions of interest are rejected. Next, the interrogation sector of each transmission is limited to an effective 22.5 degree beamwidth. Then, the receive sidelobe suppression (RSLS) circuitry rejects fruit and replies beyond ±13 degrees for ATCRBS and ±32 degrees for Mode S. After a reply is decoded, it may be discarded because it differs in altitude by more than the

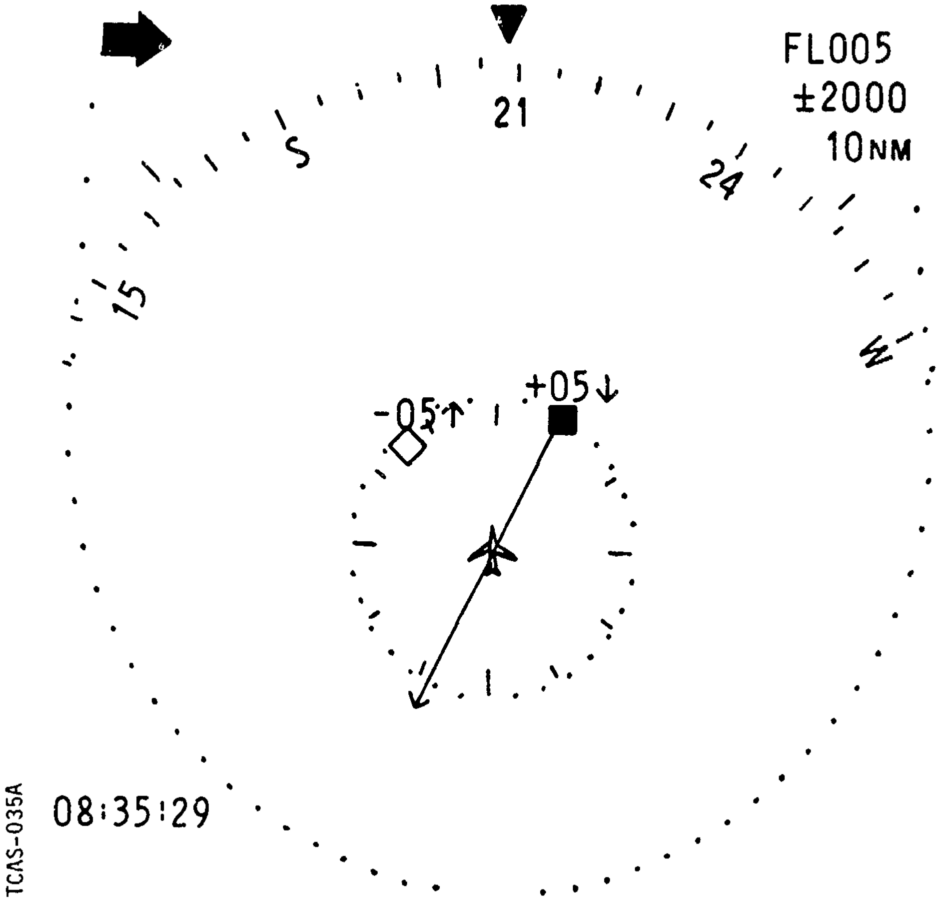


FIGURE 2.7-2. COCKPIT DISPLAY WITH RESOLUTION ADVISORY

threshold (7000 ft). These general or bulk filters in effect reduce the data processing load.

Tracked targets are prevented from causing unnecessary alarms by testing range rate and accurate three-dimensional miss distance against minimum thresholds. Since the determination of a target as non-threatening is the complement of determining it is a threat, this alarm reduction is the negative result of the actions taken to declare a threat.

The TAU criteria, range divided by range rate as shown in Figure 2.8-1, is the best parameter for assessing when a target is a potential threat. It reliably declares threats on every threatening target. However, it indicates many targets are threats when they will pass at a safe distance. Each threat then is tested further for altitude and horizontal separation to eliminate unnecessary alarms.

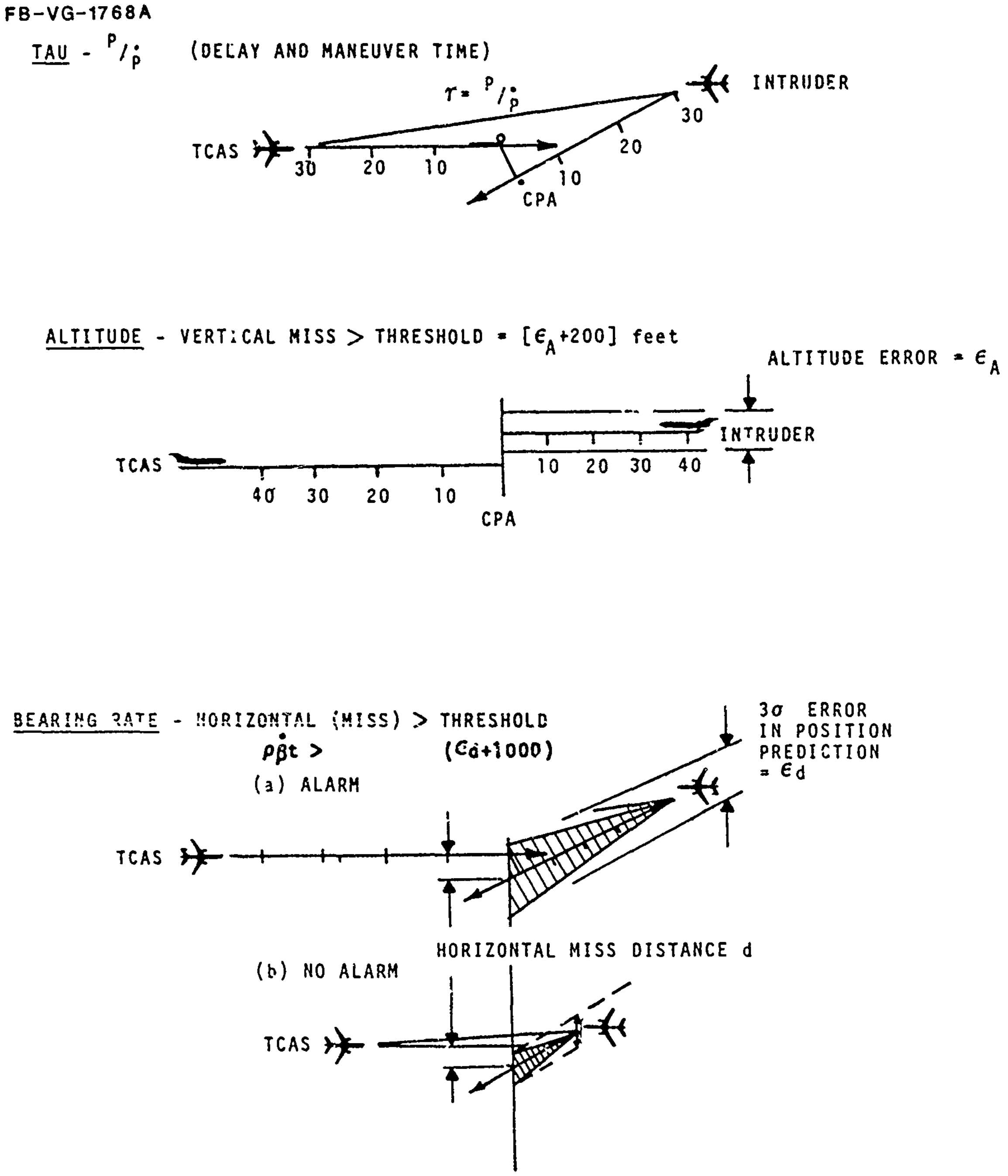


FIGURE 2.8-1. MISS DISTANCE FILTERING

The vertical miss distance is tested next to see whether there is adequate vertical separation at CPA time, where time is determined by the TAU criteria. Graphically, this test is shown in Figure 2.8-1. The vertical separation must be greater than the expected altitude error plus a minimum of 200 feet.

The final test of a potential threat is on horizontal miss distance. The end result of the horizontal miss distance test is to see whether there is safe passage if both aircraft continue on straight courses. Safe passage is miss distance being greater than the three sigma error in computing miss distance plus 1000 feet. As shown in Figure 2.8-1, in (a) an alarm would be given, but in (b) the accuracy of estimating bearing rate is improved and the distance reduced. Even though the time to CPA is reduced, no alarm is needed.

2.9 THREAT DETECTION AND RESOLUTION

The TCAS III Threat Detection and Resolution logic has been developed by the MITRE Corporation. It takes advantage of past Collision Avoidance work and adds new concepts to take advantage of the bearing measurement.

As stated in the discussion of miss distance filtering, the preliminary detection of threats is based upon the predicted time to closest approach, derived by dividing measured range by the range rate estimate. This time test is augmented with an altitude test and a horizontal plane projection to avoid alarms for safe passage. A new concept used in the TCAS III logic replaces the fixed time thresholds with a variable alarm time. An alarm is deferred as long as possible, since most apparent conflicts are safely resolved either by Air Traffic Control or pilot visual procedures. Also, the effects of measurement errors from bearing and altitude rate decrease at smaller ranges. An alert may provide from 10 to 35 seconds of warning time, and is finally given when further delay would cause a standard escape maneuver to provide insufficient separation at the point of closest approach. Figure 2.9-1 shows this concept for vertical and horizontal maneuvers for their potential separation.

Figure 2.9-1 also illustrates the process of evaluating separation by modeling potential maneuvers. Using one-second time intervals, the intruder is projected ahead on an unaccelerated path using the current three-dimensional velocity estimate. Also using the one-second time intervals, Own aircraft's track is projected ahead on a number of different flight paths. Each path simulates a standard response in compliance with a different one of the available advisories. For each of these paths, the point of closest approach may be reached at a different time. When this point is found, the three-dimensional separation and its vertical and horizontal components are stored in a matrix. This is depicted by the middle section of Figure 2.9-1.

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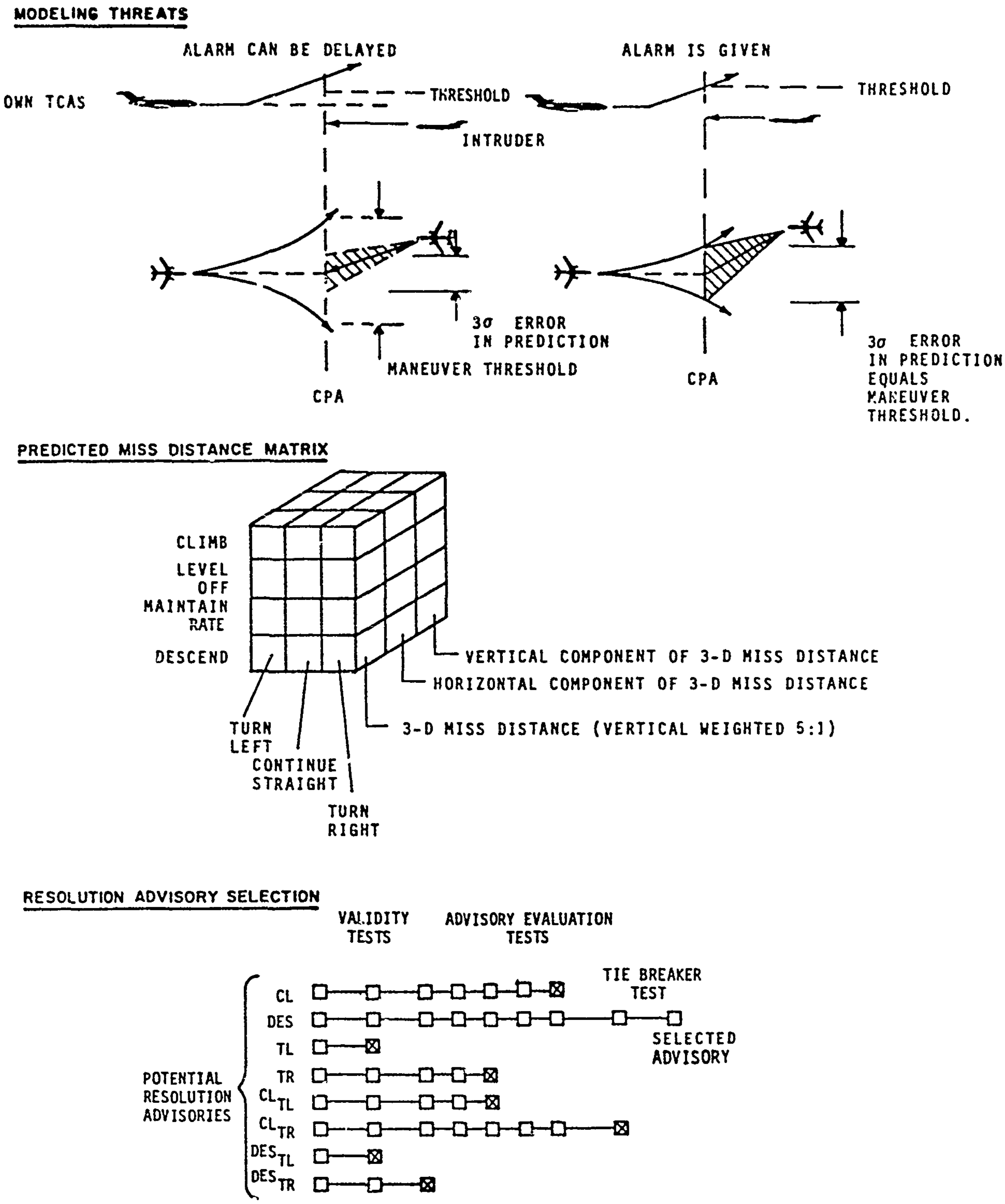

FIGURE 2.9-1. 3-D RESOLUTION ADVISORIES

Choice of the individual Resolution Advisory is made by considering a list of test criteria. Evaluation of these criteria is the means of reducing the list of potential advisories until one choice remains. This method is used because often more than one advisory would provide satisfactory separation, and other considerations take priority over simply maximizing separation. Some examples of the principles motivating these criteria are:

(a) The pilot cannot comply with two contradictory advisories simultaneously, such as "climb" and "descend".

(b) The pilot should not be asked to change the escape maneuver between the vertical and the horizontal plane unless absolutely necessary, and the logic must accomodate typical measurement noise without selecting such changes.

(c) It is preferable to initially display an advisory in a single plane; both a horizontal and a vertical advisory may be given together if the conflict should deteriorate.

(d) An advisory that is compatible with a pre-existing maneuver is preferable to an advisory that would reverse it.

Prior to issuing an advisory, a complementary advisory is coordinated with the intruding aircraft if it is TCAS equipped.

2.10 ENGINEERING TEST UNIT HARDWARE

Figure 2.10-1 is a photograph of one of the TCAS III Engineering Model eight element, directional, electronically steered antennas. It is 14.4 inches in diameter to the outer bolt circle and is 7/8 of an inch high. The top and bottom antennas are identical. Each antenna array also contains a center element which is used by the Mode S transponder. The Engineering Model antenna is curved to fit the 74-inch radius of the 727 fuselage. Although this curvature distorts the pattern slightly from those which would be measured on a flat ground plane, stored monopulse correction curves in the TCAS III processor compensate for the error. Figure 2.10-2 shows the top antenna mounted on the FAA's Boeing 727. The bottom antenna is mounted similarly under the fuselage.

The associated antenna electronics equipment required to steer and shape the patterns is located in a separate package, which is mounted inside of the fuselage near each antenna. This control box interfaces with the TCAS Signal Processor via a 6-bit digital beam steering command and RF connections to the three antenna ports: sum, difference, and omnidirectional. The sum and difference beams, formed by the Beam Forming network, are used for monopulse tracking. The center antenna element is used with

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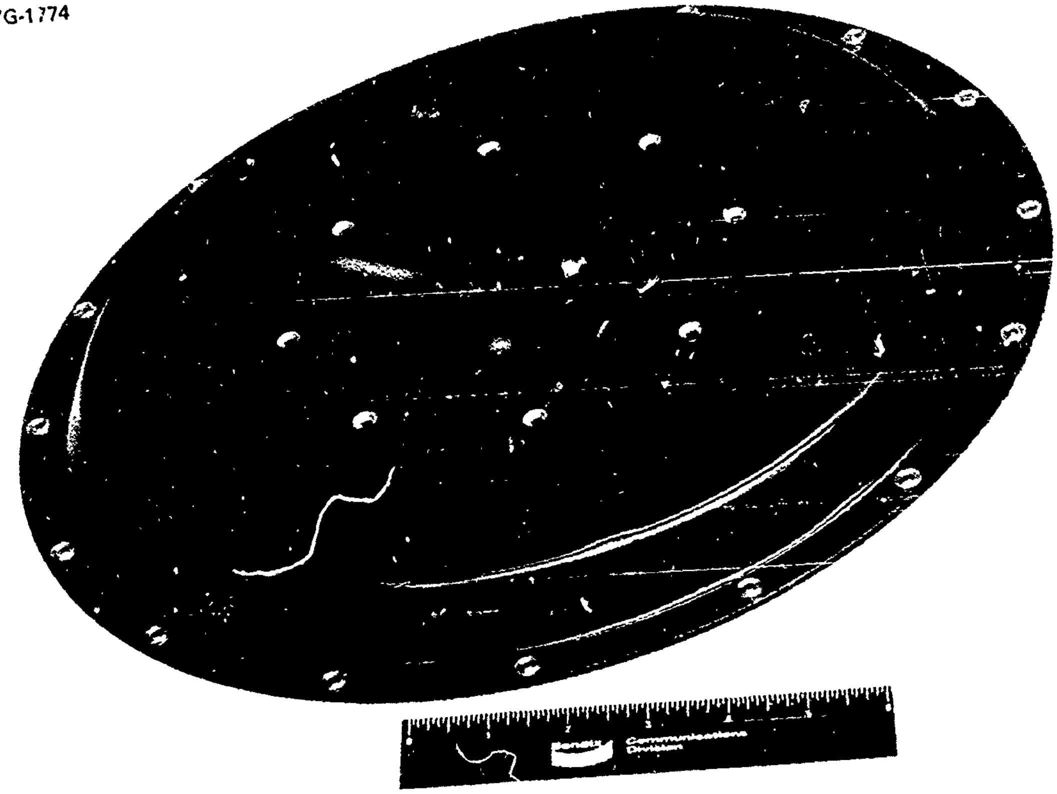

FIGURE 2.10-1. ENGINEERING MODEL DIRECTIONAL ANTENNA

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FIGURE 2.10-2. TCAS III ANTENNA MOUNTED ON FAA'S BOEING 727

the TRU-2B for Mode S transponder functions and air-to-air coordination.

Figure 2.10-3 shows the principal functional blocks or subsystems of the TCAS III Engineering Unit (ETEU). Both the top and bottom mounted antennas are directional. The antenna subsystem also includes all the beam forming and beam steering circuits necessary for directional operation.

The Interrogator RF subsystem includes all the ETEU transmission and reception circuitry. An existing airline quality transponder was modified to serve this function in the Engineering Model. The Mode S transponder is a slightly modified unit from the FAA's DABS Engineering Evaluation program. The Interrogator Processor controls the transmission waveforms, controls the directional antennas, and performs reply signal processing.

The Computer is comprised of four Intel 8086 microprocessors, associated memory banks and power supplies, which share the main TCAS III processing load. It also includes several special purpose circuit boards used in interfacing the ETEU to other aircraft subsystems and performing other special functions. The Computer Programs which it exercises are loaded through the Monitor and Control equipment. These programs include all the tracking algorithms and the logic necessary to determine the existence of a threatening aircraft.

The Monitor and Control subsystem includes instrumentation and display facilities that allow control and ease of changing parameters during flight tests. The display includes a cockpit mounted graphic display of traffic advisory and resolution advisory outputs of the system to the flight crew.

The Own Ship Data interface includes attitude and true North-referenced position data from the on-board Inertial Navigation System. In the TCAS III, it is necessary to make corrections for aircraft attitude to achieve the required system bearing measurement accuracy.

Figure 2.10-4 is a photograph of the TCAS III Engineering Test Unit installed in the FAA's Boeing 727. Rack number 1 on the far left contains the essential TCAS functional equipment while the other three racks contain support and test facilities that would not be provided in an operational application. The top shelf of the first rack mounts the Interrogator (TRA-65A), the Mode S transponder (TRU-2B), and the System Control and Performance Monitor. The second shelf contains the Interrogator Processor Unit and the third shelf the Data Processor Unit which has all the logic needed for threat assessment.

The second rack incorporates peripheral equipment to load the computer (disk drives) and a Microprocessor Development System to be used to maintain or make modifications to the system operating programs. The third rack contains the Traffic Advisory

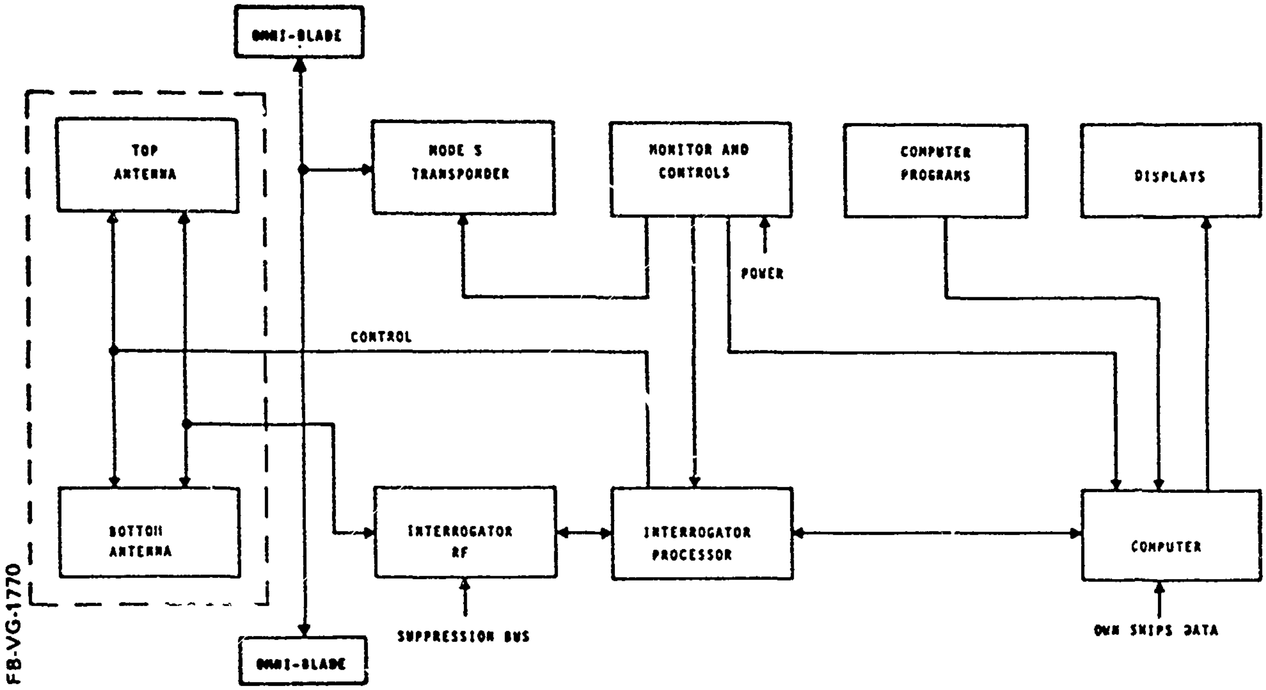


FIGURE 2.10-3. BLOCK DIAGRAM OF TCAS III ENGINEERING MODEL

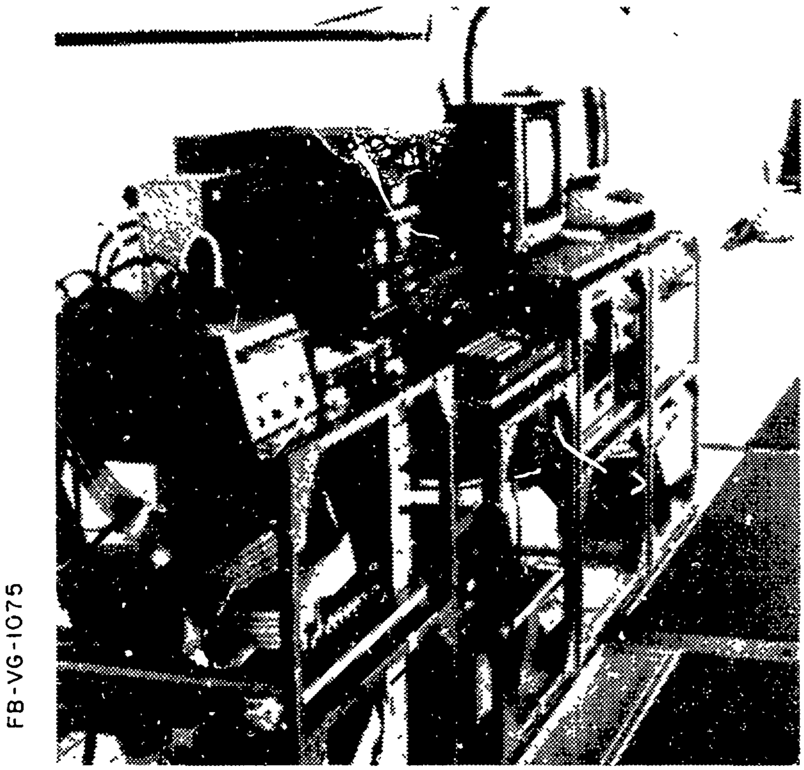


FIGURE 2.10-4. TCAS III ENGINEERING MODEL INSTALLATION ON FAA'S BOEING 727

Display on the top shelf and the Data Extraction and Recording Unit magnetic tape recorder which is used to log data during the flight tests on the second shelf. The fourth rack contains the In-Flight Performance Monitor (IFPM), a small personal computer that has an alphanumeric status display and provides operator interface to the TCAS system.

3.0 TCAS III CONTRACT MODIFICATIONS

While under contract to the FAA, a modification to the contract was added to target several areas that required additional work. This section describes the problem areas and the solutions.

3.1 COCKPIT DISPLAY

The Contractor shall investigate techniques to display the TCAS video output and develop the necessary interface.

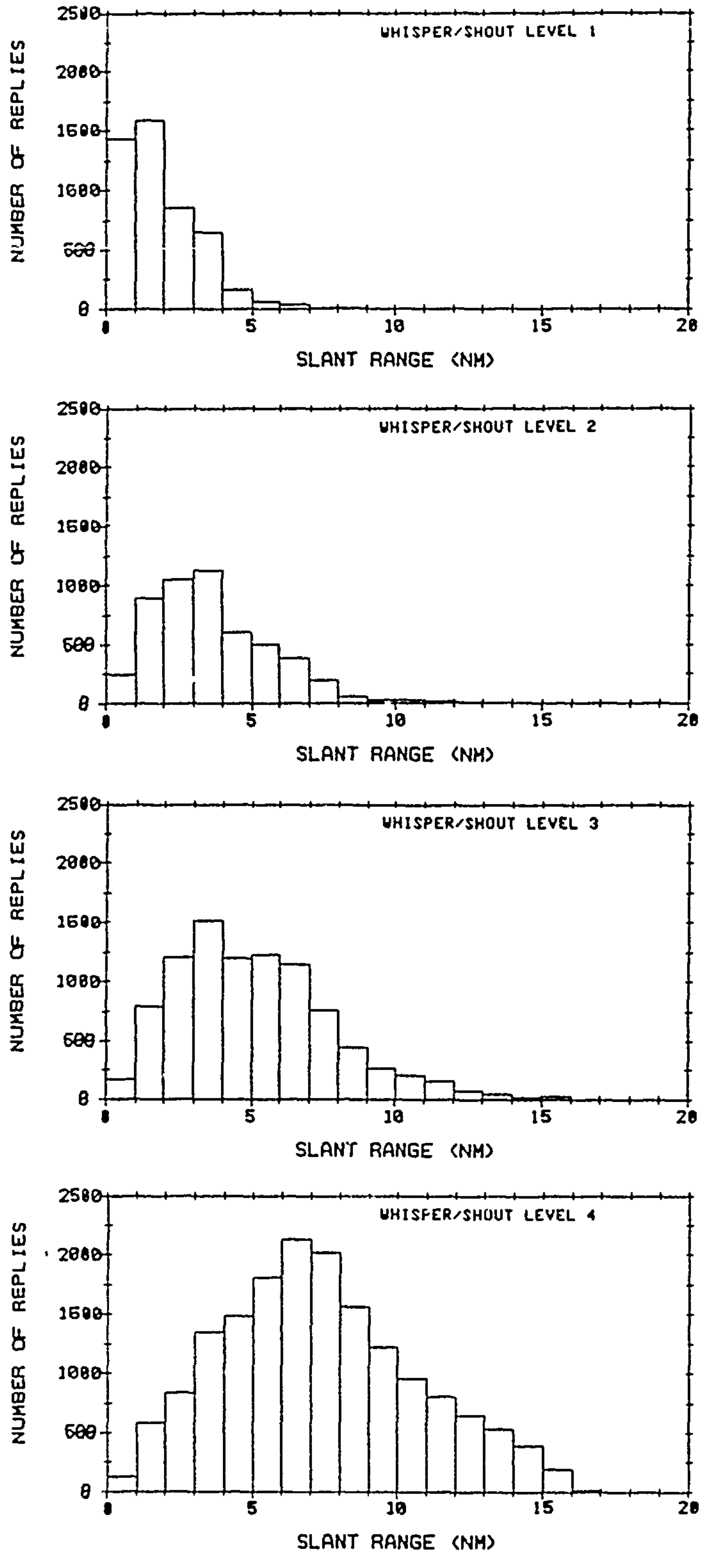
After much investigation, an off-the-shelf Electronic Flight Instruments System (EFIS) display was purchased from Bendix Avionics Division for installation in N-40. The EFIS display is a raster-stroker system that provides superior resolution and brightness. This display system interfaces with the Engineering Test Unit by installing an Intel single board computer (iSBC) in the multibus data processor rack. The iSBC accesses the track file and formats the appropriate data for display and aural advisories. The iSBC forwards the display data to the EFIS symbol generator using a high speed ARINC 429 bus. This display contains all the information found on the IFPM graphic display with the addition of color to indicate threat level and arrows indicating direction of altitude change for every altitude reporting target.

3.2 WHISPER/SHOUT TECHNIQUES

The Contractor shall analyze high density data obtained during flight testing to determine the effectiveness of the whisper/shout levels chosen during simulation. New levels shall be investigated and implemented if warranted.

The whisper/shout performance was analyzed using data recorded during the February 1985 flights in the Los Angeles Basin. A summary of the whisper/shout reply statistics for the February 5th test flight shows that the whisper/shout levels are balanced. The February 3rd A.M. and P.M. flights show almost identical statistics.

Referring to Figure 3.2-1, it is seen that targets at the most dense range (3-4 nautical miles) are almost evenly balanced among the four whisper/shout levels. The whisper/shout interrogation levels of 1 to 4 elicited the following percentage replies:



TCAS-023

FIGURE 3.2-1. THE FOUR-LEVEL WHISPER/SHOUT USED BY ETEU#1 SHOWS EXCELLENT SEPARATION OF TARGETS IN THE L.A. BASIN

Level 1	14 %
Level 2	24 %
Level 3	32 %
Level 4	30 %

If the distribution peaks were estimated from the shape of the curves, the following ranges were observed:

Level 1	1.5 nmi
Level 2	3.5 nmi
Level 3	5.0 nmi
Level 4	6.5 nmi

Figure 3.2-2 shows the whisper/shout level 4 distribution for three power levels transmitted as a function of the range gate range in search and the predicted range in track.

From this summary analysis, the whisper/shout levels appear to be chosen correctly. The data validates the four whisper/shout levels selected by analysis of the 1985 L.A. Basin traffic model early in the contract.

3.3 AUTOMATIC ANTENNA PERFORMANCE MONITORING

The Contractor shall investigate automatic methods of checking antenna performance from an external source and shall implement hardware and/or software to accomplish this.

An antenna pattern check routine was added to the Calibration program to record target reply amplitudes on magnetic tape. The use of an external transponder was required. Data for the sum and difference patterns were gathered separately. A post processing program was written to read the data from magnetic tape and plot it.

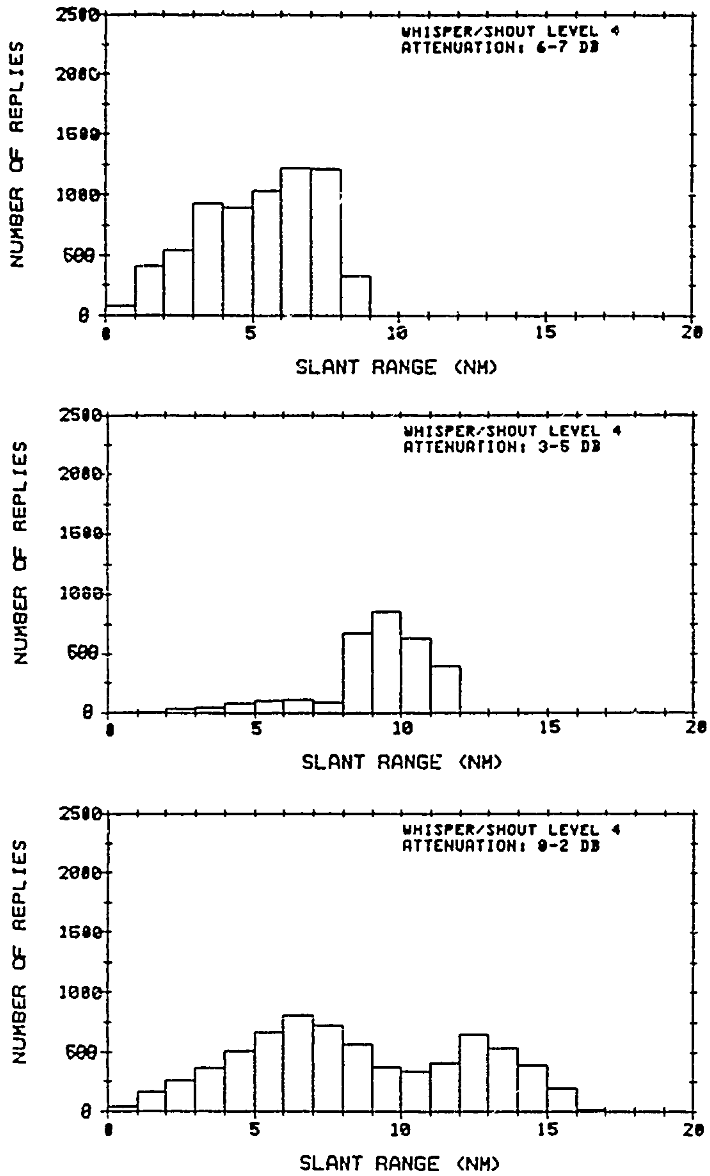
3.4 EFFECTIVE ANTENNA BEAM WIDTH

The Contractor shall analyze a cross-section of transponders interrogated during flight tests to determine effective beam width. Modifications to optimize operation shall be made if warranted.

An attempt was made to analyze data from several flights into Newark, New Jersey. Data tapes from the ARTS-3 radar during the flights were available to provide an absolute reference. The comparison of data between the two sources was found to be insufficient to determine the effective beam width.

3.5 ALTITUDE DECODING ERRORS

The Contractor shall investigate the problem associated with altitude decoding errors and shall incorporate hardware and/or software modifications to minimize the problem. At a minimum, hardware modifications to delay the "in-beam" decision



RANGE	LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4	LEVEL 4A	LEVEL 4B	LEVEL 4C
0- 1	1427	245	169	129	84	5	40
1- 2	1583	886	789	583	411	11	161
2- 3	854	1048	1197	837	544	30	263
3- 4	650	1126	1507	1348	930	45	373
4- 5	161	598	1190	1488	893	83	512
5- 6	63	501	1227	1808	1038	108	662
6- 7	39	382	1138	2128	1211	115	802
7- 8	10	199	752	2017	1210	86	721
8- 9	6	58	443	1566	325	673	566
9-10	1	27	263	1225	0	850	375
10-11	2	25	207	964	0	624	340
11-12	0	20	152	806	0	393	413
12-13	0	8	74	648	0	0	648
13-14	1	0	49	536	0	0	536
14-15	0	0	20	393	0	0	393
15-16	0	1	25	197	0	0	197
16-17	0	0	0	16	0	0	16
17-18	0	0	0	0	0	0	0
18-19	0	0	0	0	0	0	0
19-20	0	0	0	0	0	0	0

TCAS-024

FIGURE 3.2-2. THE SHOUT LEVEL #4 STATISTICS ARE EXTENDED BY COMPUTING THE NUMBER OF REPLIES FROM THE DIFFERENT ATTENUATION LEVELS until after bracket decode has been accomplished, and to include confidence bits for each altitude code pulse, shall be investigated. Software modification to implement a voting scheme using the confidence bits at track initiation shall be explored.

This area was the second highest priority task of the contract modification. Both hardware and software changes were investigated. The hardware changes required modifications to the Interrogator Processor. The first change was to use the sum beam video for decoding. When the equipment was built, the video from the $[(\Sigma + j\Delta) + (\Sigma - j\Delta)]$ monopulse circuitry was used for decoding rather than the sum beam as planned. The hardware was modified to use the sum beam only for bracket detection and altitude decoding. This reduced the interference from fruit, reduced the punch-through and improved the RSLS in-beam circuitry. To incorporate this change, the Analog/Digital card was modified by changing the wire wrap connections. Also the Minimum Threshold Level (MTL), Dynamic Minimum Threshold Level (DMTL), Receiver Side-Lobe Suppression (RSLS), and other thresholds were recalibrated.

The second hardware change was also made to the Interrogator Processor. This modification was to remove the altitude decode pulses from RSLS in-beam filtering. A new board (A4) was designed, so when installed, altitude code bits are not eliminated by the RSLS threshold. This new board permits confidence bit flags to be logged when pulses are in-beam. When the A4 card is removed, operation reverts to its original state, such that all pulses are gated by the RSLS in-beam criteria.

In the process of incorporating the confidence-bit-flag change in the IP, two circuit problems were identified. One resulted from the clocking of the quantized video (QV) and the differential pulse positive slope (PS) prior to qualifying the PS with QV. The 125 nanosecond quantization on each allows up to 250 nanosecond variation between the two pulses. In addition, the PS position changes approximately 100 nanoseconds as the pulse amplitude approaches MTL. Thus the PS relative to the QV changes approximately 350 nanoseconds depending upon clock timing and pulse amplitude.

The second circuit problem was more subtle. Prior to the log amplifiers, the pulse is differentiated to obtain leading and trailing edge pulses. It was also found that high frequency noise generated in the log amplifier can result in extra positive slope declarations.

The combination of noise in the circuit and quantization errors necessitated an investigation into possible hardware changes that would increase the percentage of decodes. Four hardware configurations were analyzed. After testing, it was determined that the analog detection of PS and QV provided the most improvement in the altitude decode performance. This change was installed in the Interrogator Processor of both units.

Another problem with the Interrogator Processor was discovered during flight testing in the Los Angeles Basin. In certain situations, real altitude code pulses were eliminated, causing the non-linear vertical tracker to predict an erroneous altitude rate. The problem was traced to the suppression drive circuit in the TRA-65A. The solution was to add a 470 ohm resistor at the amplifier output of the circuit.

Various software modifications were also investigated to improve the system's altitude decoding capability. The first was an altitude bit voting scheme. After range and bearing correlation, the altitude code of each defruited reply was compared to the three previous replies from the same target and adjusted if it seemed that there were bits in error. The method for determining bits in error was to compare the number of 1's and 0's for each bit over the current reply and the three previous ones. The current reply bit was "voted" to be either a "1" or a "0" depending on the number of occurrences of 1's and 0's from the previous three replies. The "voted" altitude provided the input to the vertical tracker. The flight testing of this algorithm and the analysis of its performance indicated that another algorithm needed to be implemented.

The next algorithm was to implement an alpha-beta tracker for altitude correlation. After range and bearing correlation, a defruited reply is then correlated in altitude to the predicted value output of the alpha-beta tracker. If it is within ±200 feet, the decoded altitude itself (not the output of the alpha-beta tracker) is sent directly into the non-linear vertical tracker for altitude rate estimation. This algorithm along with the hardware modifications described above resulted in a large improvement in the altitude decoding capability of the system.

3.6 ADDITIONAL AURAL ADVISORY CAPABILITY

The Contractor shall investigate schemes to incorporate a low cost digital voice simulator and shall program it to provide aural advisories if warranted.

The additional aural advisory capability was added along with the upgraded cockpit display. The aural alert and voice synthesizer unit is controlled by the same single board computer (iSBC 86/35) that controls the display. Aural advisories are forwarded to the aural alert unit using the iSBC parallel output port. The iSBC identifies each discrete phrase to be spoken to the pilot. Also, the aural advisories were added to the pilot's intercom.

The vocabulary of the aural alert unit consists of the following phrases: Traffic, Climb, Limit Vertical Speed, Descend, Turn Left, Turn Right, Limit Turn, RA Clear, RA Invalid, and Crossover. The unit provides aural alerts when a target becomes a traffic advisory, when a target becomes a resolution advisory, when a resolution advisory changes, when the advisory is finished and when TCAS is unable to resolve the conflict.

3.7 TARGET SPLITTING

The Contractor shall investigate more thoroughly the problem of target splitting (multiple tracks on the same target in range and/or azimuth) and shall incorporate hardware and/or software modifications to minimize the problem.

Target splitting was considered the highest priority item in the contract modification. Investigation into the problem showed that multiple tracks were also generated due to faulty altitude decoding. Improvements in altitude decoding, as described above in section 3.5, provided a reduction in the number of multiple tracks as well.

Even with the improved altitude decoding, there were still a number of target splits. So, a new software module, General Correlation (GC) was added to the operational program. The purpose of this module is to identify multipath, punch-through, and split targets. A multipath target is one that correlates in bearing and altitude with another target, has greater range, the same sign of range rate and a smaller magnitude of range rate than the target. A target that is declared to be multipath is flagged as such in the track file and is not actively updated. The target split test consists of correlation in range, bearing, and altitude. A target that is declared a split is deleted from the track file. Punch-through targets occur when sidelobes of the sum beam "punch-through" (have higher amplitude than) the difference beam at the same azimuth angle. A punch-through target will correlate in range and altitude and will have a lower signal level than the actual target. The punch-through target will be flagged and retained in the track file until it is dropped. Both multipath and punch-through targets are not actively updated in track, do not go through the threat detection and resolution logic, and are not displayed. The installation of this module provided a significant reduction in the number of multiple tracks.

Another software modification implemented was range gating on the bottom antenna. After flights in high density areas such as Atlanta and Los Angeles, it was noticed that a large number of nuisance replies were detected by the bottom antenna. So, a range gate of four nautical miles was placed on the bottom antenna for search only. Active track updates on the bottom antenna however are still performed to full coverage. To compensate for reduced coverage on the bottom antenna, the top antenna now processes replies down to - 5 degrees elevation instead of 0 degrees as was previously set. When Own aircraft is flying above 10,000 feet and at high speeds, the top directional antenna provides sufficient coverage to long ranges. Below 10,000 feet where the maximum relative velocity is 500 knots, the four nautical mile range provides 30 seconds protection. This range gate reduced a large amount of fruit returns and enabled the system to operate reliably in a high density environment. In addition, multipath returns which are usually detected on the bottom antenna due to surface reflections, were also reduced.

An additional source of target splits was found to be caused by Mode S targets. Originally, Mode S targets were correlated by Mode S address only. It was discovered, however, that due to punch-through and/or multipath effects, target replies were being correlated by the ID even though the range and/or bearing was in error. These inputs to the trackers caused erroneous rate and position estimates and very poor Mode S tracking performance. The solution was to subject all Mode S replies to the same range, bearing, and altitude correlation algorithms that apply to all ATCRBS replies. The Mode S address test is still performed for correlation of Mode S replies. This software modification resulted in a significant improvement in Mode S tracking performance.

3.8 HORIZONTAL THREAT DETECTION PROCRAM

The Contractor shall analyze various schemes to improve the efficiency of the horizontal threat detection logic and modifications to accomplish this.

Once the horizontal threat detection and resolution logic was operational in the TCAS, analysis of the efficiency of the algorithms was begun. The most important discovery was that the time involved with modeling the flight paths of the intruder was rather large, especially when there was more than one threat. This prompted MITRE to propose an alternate method for modeling aircraft maneuvers for a revised version of the CAS logic.

3.9 HORIZONTAL THREAT DETECTION AND RESOLUTION LOGIC VALIDATION

The Contractor shall test the horizontal threat detection and resolution logic by simulation (using both real target data obtained in flight tests and simulated targets) to determine its performance for a wide range of scenarios, and shall recommend improvements.

At the request of the MITRE Corporation, certain track file and CAS logic variables were logged on tape to facilitate post processing of flight data for CAS validation. The FAA Technical Center conducted a large number of flight tests that contained a wide variety of scenarios. From the data logged on tape, an estimate of bearing and bearing rate accuracy was compiled. This accuracy translates directly into miss distance accuracy which is essential to the CAS logic algorithms. A large amount of post processing of flight test data was analyzed to determine search and track performance in addition to validation of the threat detection and resolution algorithms. More details on the flight data analysis can be found in section 4.

4.0 FLIGHT TEST DATA

The FAA is in the process of testing TCAS III to validate its ability to reduce unnecessary alarms, to provide relative motion on traffic advisories, and to give appropriate horizontal resolution advisories. The first Engineering Test Unit was installed on the FAA's Boeing 727, N-40, in 1983. So far, the majority of the operational testing has been done using this unit. The major test objective of assuring that the system angular accuracy is sufficient to predict miss distance has been completed. More testing is scheduled to evaluate Version II of the TCAS III logic and the air-to-air coordination.

To measure the antenna angular accuracy, two aircraft were flown in both linear encounters and circular orbits. They were flown from the FAA Technical Center over their instrumented test range. A Convair 580 with a regular ATCRBS transponder on board was used as the target aircraft. The TCAS III installed on N-40 acquired, tracked and logged range time-referenced data on tape for the many encounters and orbits flown. The FAA Technical Center precision tracking radars locked on to the range instrumentation x-band transponders mounted on the test aircraft and provided an accurate position of one aircraft relative to the other as a function of time. After each flight, data from the two separate sources were compared. Because the radar is five to ten times more accurate than the TCAS III, its position estimates are considered to be perfect and all errors are attributed to the TCAS III.

To test operational performance in typical and high density environments and to build a data bank from which performance estimates can be made, the TCAS III has been flown into and over many areas such as Los Angeles, Boston, New York, Atlantic City, Philadelphia, Washington, and Atlanta. In addition, encounters with a target aircraft have also been run in these airspaces to evaluate the effect of traffic density on the TCAS III's ability to track and issue appropriate resolution advisories.

4.1 ANGULAR ACCURACY TESTS

To test the angular accuracy of the TCAS III, the target aircraft was flown in 360 degree orbits about the Engineering Test Unit #1 at elevation angles from -20 degrees to +20 degrees. As previously discussed, the radar data is assumed to be perfect and all the angular error is attributed to the TCAS III. Figure 4.1-1 shows a summary graph of six such orbits.

Bias errors shown at the top of the figure do not impact calculations for a horizontal maneuver because true relative bearing does not appear in the formula for computing miss distance. The effect of such bias errors is to give the pilot a small error in the direction visually searched for a target. Bearing rate is used to calculate horizontal miss distance.

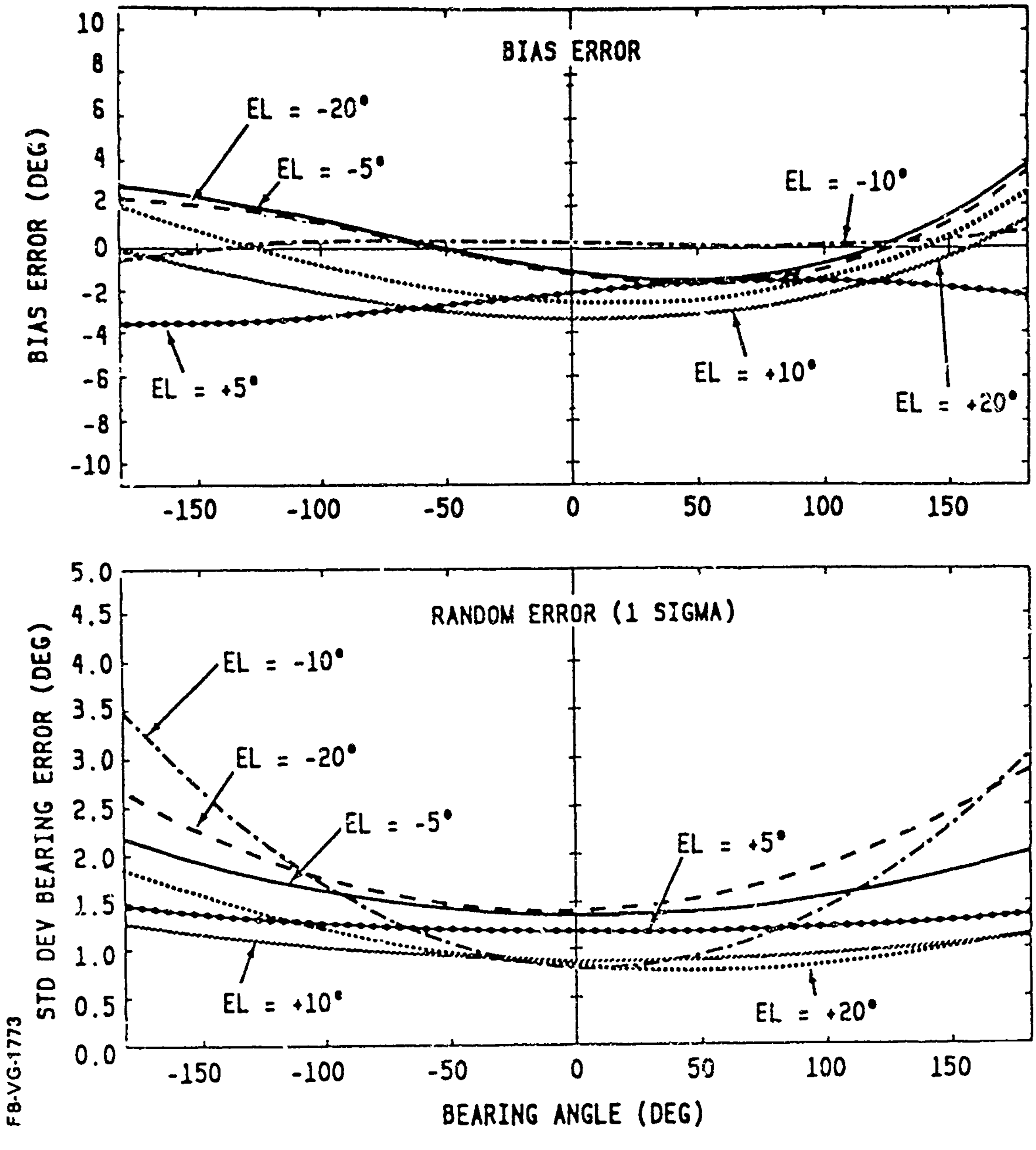


FIGURE 4.1-1. ANGULAR COVERAGE PERFORMANCE

Bearing rate errors are caused by random errors or bias errors that appear as random errors due to changes in bias as the angle changes slightly. In the assessment of angular coverage performance, the combined random errors and changes in bias are observed because errors are computed as the difference between radar measurements (assumed to be correct) and the TCAS III angle measurements. It is seen that these one-sigma random errors are from 1 to 2 degrees near the nose, and in a worst case approach, 3.5 degrees at the tail. It should be noted that the radar data was updated ten times each second and that Own aircraft data was updated only once per second during this test rather than four times per second.

Angular errors over a wide range of elevation angles have been tested several times. In addition to both TCAS and target aircraft flying, such testing includes placing the TCAS III aircraft on the ground near the center of the airport and flying the test aircraft at positive elevation angles. With own aircraft on the ground and a five mile TCAS to target aircraft orbit range, the random error is reduced to one-half the dynamic result that was shown in Figure 4.1-1. The dynamic errors plotted in the figure (assumed to be worst case errors) are still well within the tolerance needed to compute horizontal miss distance for resolution advisories.

4.2 TCAS ENCOUNTER FLIGHTS, FEASIBILITY OF HORIZONTAL MANEUVERS

Encounters between the TCAS III and a target aircraft have been run to evaluate the feasibility of horizontal resolution advisories. In these cases, the encounters were run on the FAA Technical Center instrumented test range with one radar tracking the TCAS III aircraft and the other tracking the target aircraft. The data measured by the TCAS equipment was compared to the data measured by the radar as described in Figure 4.2-1. The encounters were run at different speeds and at different angles to determine errors in miss distance derived on board the TCAS III equipment in real time. In addition, both vertical and horizontal fake-outs were run. The fake-outs are encounters where the target flys a straight and level trajectory, then makes a sudden maneuver in either the vertical or horizontal plane. The data presented in this section are taken from 3 flight tests: December 19, 1983; January 23, 1984; and October 25, 1984.

Figure 4.2-2 is a typical encounter. Although the track was started at a much longer range, only the last 40 seconds before CPA (closest point of approach) are shown on the plots. In this particular encounter, the target aircraft is on a course 90 degrees from the TCAS III. The speeds were approximately 200 knots and the altitude separation at intercept was 300 feet.

The first plot is an x-y presentation of the target track. It indicates the target's position relative to the TCAS aircraft. The next set of plots show the bearing accuracy. Each asterisk

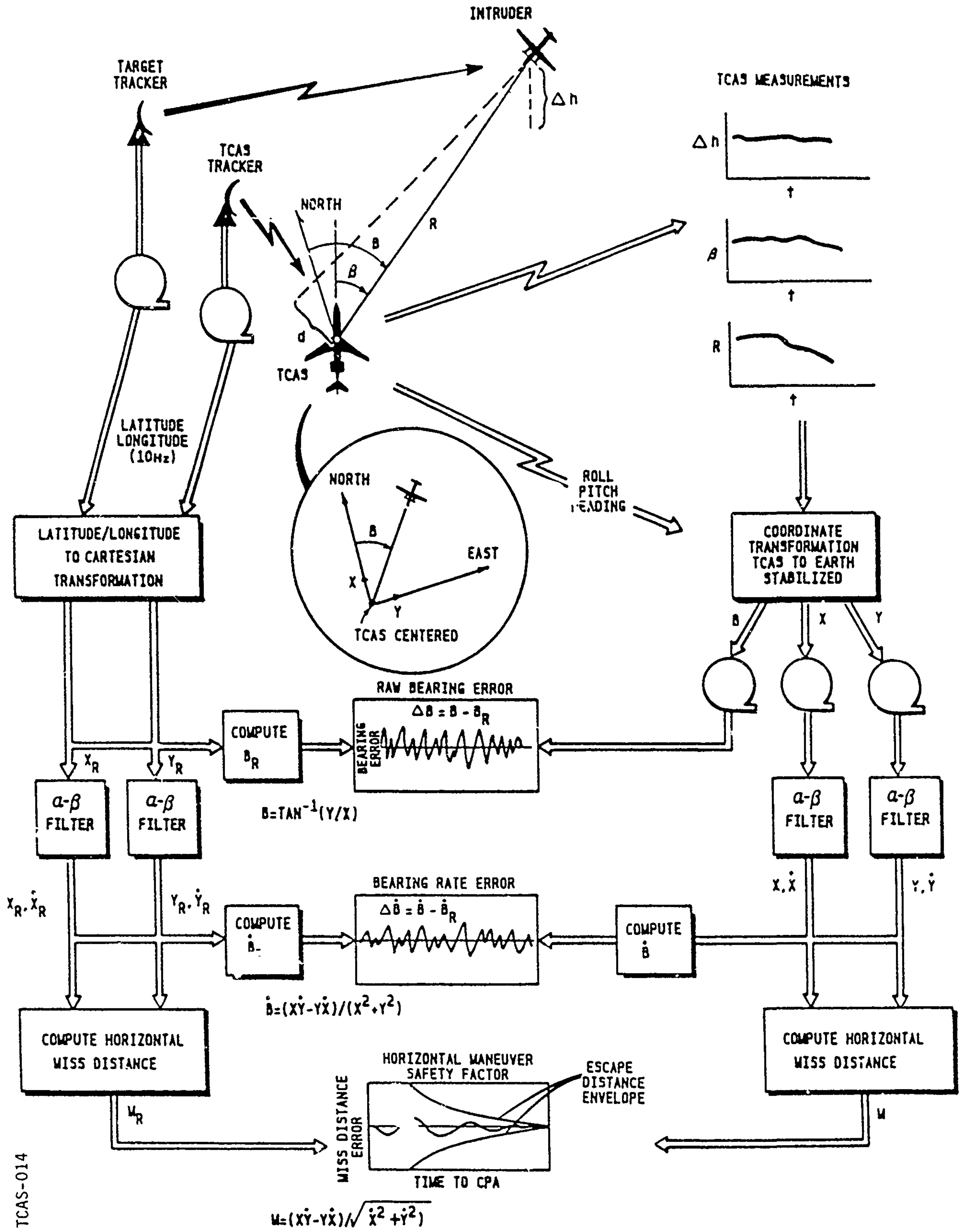
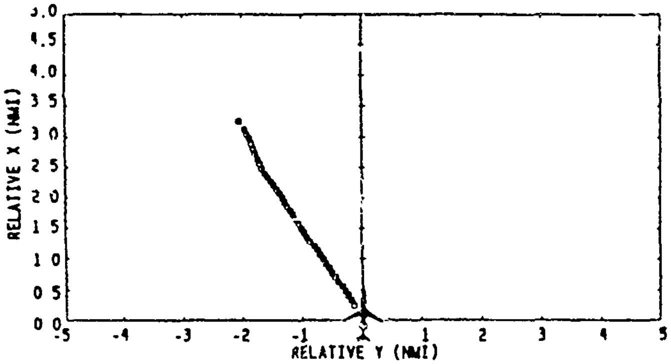


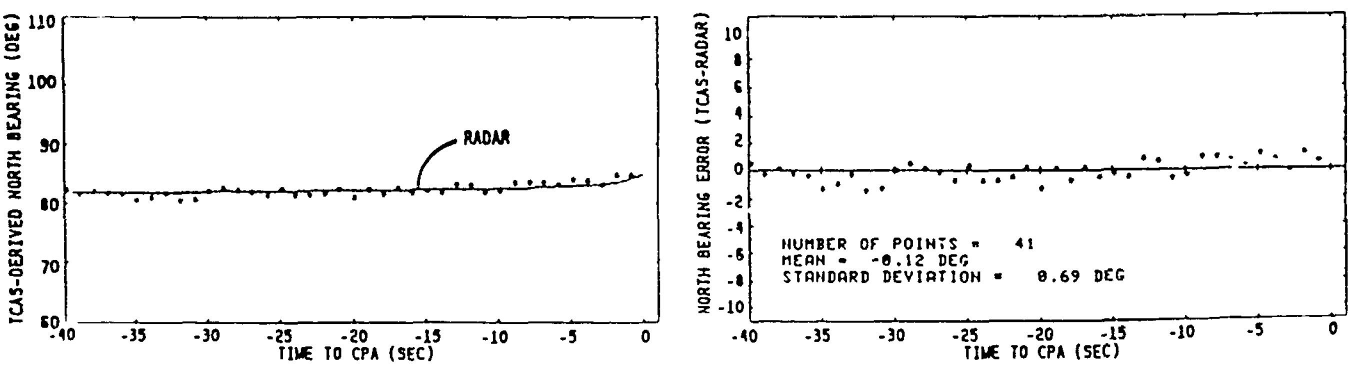
FIGURE 4.2-1. EVALUATION OF TCAS III HORIZONTAL MISS DISTANCE ESTIMATE

TARGET TRACK



TRACK NUMBER: 37
ENCOUNTER DATE: 12/19/83
TIME: 12:24:00
ENCOUNTER ANGLE: 90 DEGREES
OWN: SPEED = 200 KNOTS
ALTITUDE = 4500 FEET
TARGET: SPEED = 200 KNOTS
ALTITUDE = 4800 FEET
SEPARATION: +300 FEET VERT

BEARING ACCURACY



BEARING RATE ACCURACY

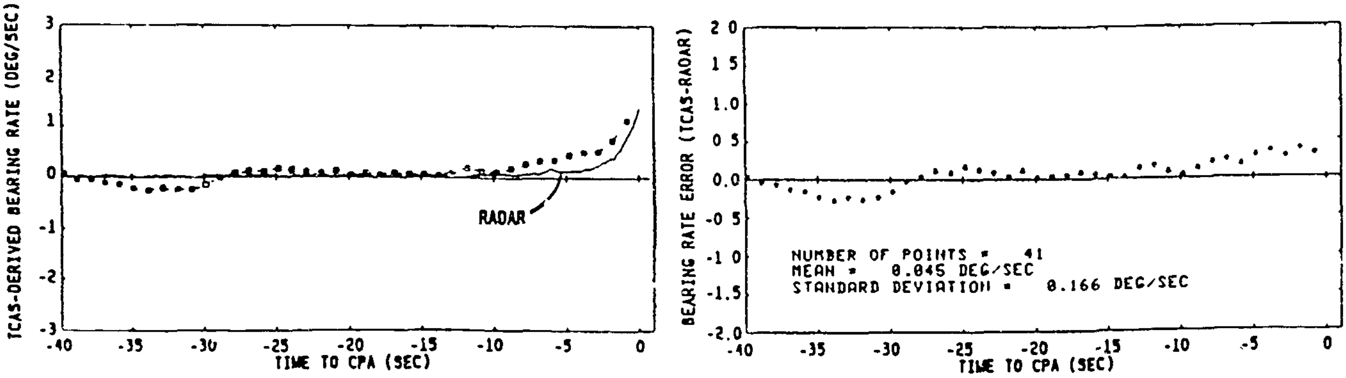


FIGURE 4.2-2. 340-KNOT, 90-DEGREE ENCOUNTER
(SHEET 1 OF 2)

FB-VG-1421

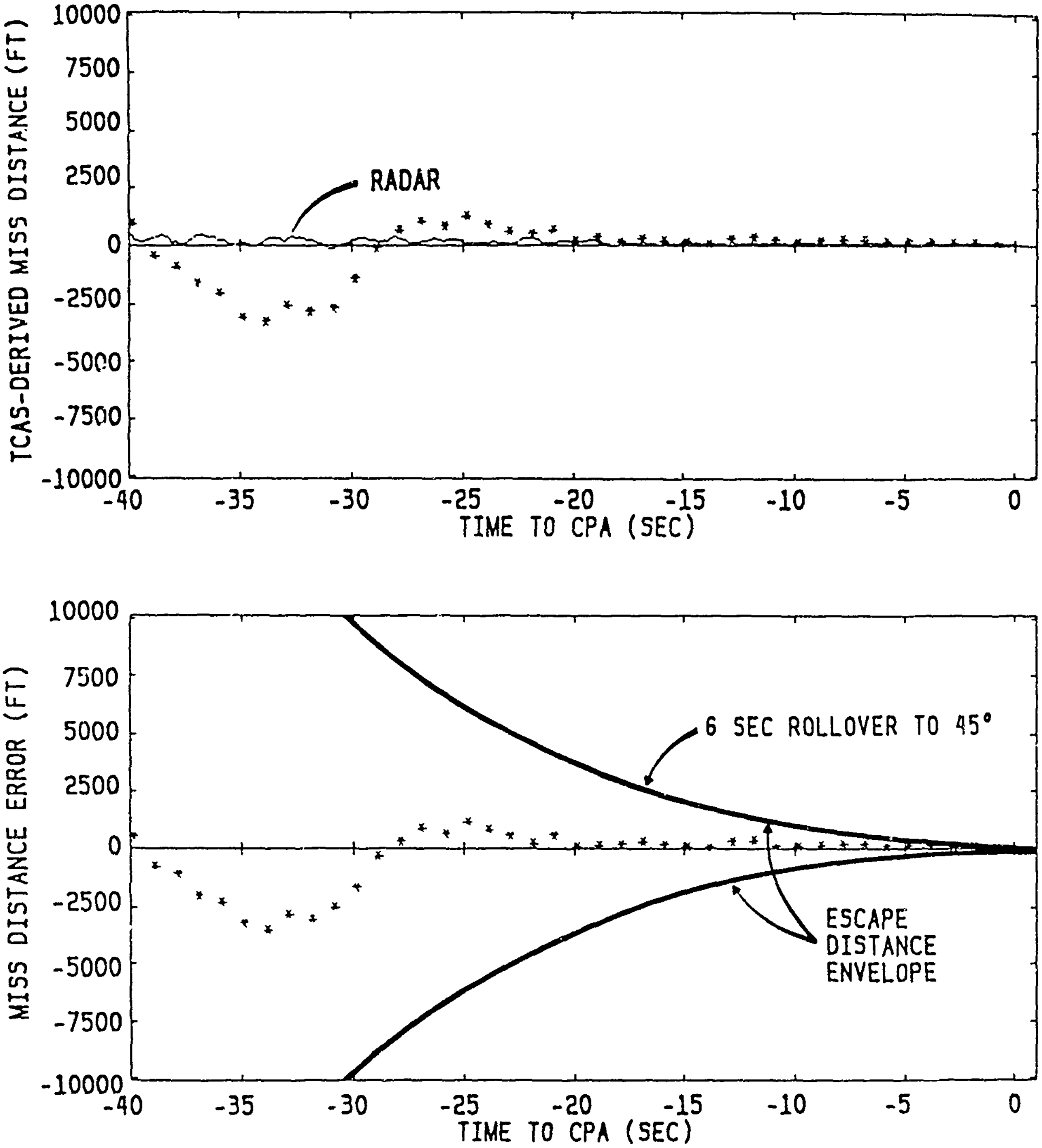


FIGURE 4.2-2. 340-KNOT, 90-DEGREE ENCOUNTER
(SHEET 2 OF 2)

on the TCAS-derived north bearing plot indicates a single bearing measurement made by the TCAS III. The straight line is the bearing derived from the radar measurements. The plot next to the north bearing gives the error between the TCAS-derived and radar-derived measurements. The third set of plots shows the bearing rate accuracy of the TCAS relative to the radars. The importance of these encounter flights is shown in the final set of graphs which compare miss distance derived from TCAS and the radars. On the miss distance error plot, heavy lines are drawn to represent the distance own aircraft can move by executing a coordinated maneuver within 6 seconds of the graphed time to CPA. For example, it is assumed that a traffic advisory has already been given so the pilot is alerted to the fact that traffic exists in the direction indicated. Then, if a horizontal resolution advisory is given at 25 seconds before CPA, the pilot could achieve as much as a 6000-foot or one nautical mile lateral separation should the situation require it.

Some additional examples of different types of encounters are shown on the following pages. Figure 4.2-3 shows an 810 knot, 0 degree closing encounter. Figure 4.2-4 shows a 415 knot closing, 15 degree encounter. The next three encounters are horizontal fake-outs where the aircraft are separated 300 feet in altitude and the encounter begins with aircraft offset horizontally as well. As the encounter progresses, the target crosses directly over TCAS in Figure 4.2-5, crosses in front of TCAS in Figure 4.2-6, and crosses behind TCAS in Figure 4.2-7. These six examples are just a few of the many encounters run at the FAA Technical Center.

The conclusion after these encounters is that warning information given to the pilot prior to a resolution will alert him should an advisory become necessary. However, with the three-dimensional separation modeling, an alarm may be safely delayed to the last possible moment, so that in most cases, the potential conflict will be resolved by ATC procedures or a pilot's normal action. If the conflict persists and a resolution advisory is given, the pilot will respond quickly with emergency type actions. Since the modeling is repeated every second, the resolution advisory is removed as soon as the threat is resolved.

4.3 LOS ANGELES BASIN FLIGHTS

TCAS III was flown in the Los Angeles Basin in February 1985 to assess its performance in a high density aircraft environment. Over the span of five days, the TCAS III Engineering Test Unit logged over 15 hours of flight time and flew in 60 encounters with an FAA target aircraft. The Los Angeles Basin flight tests indicate that TCAS III performs well in all types of environments. It detects targets at the maximum surveillance range and tracks them reliably even in high density areas. It assesses threatening situations and determines the appropriate maneuver to avoid a possible collision. In addition, it provides

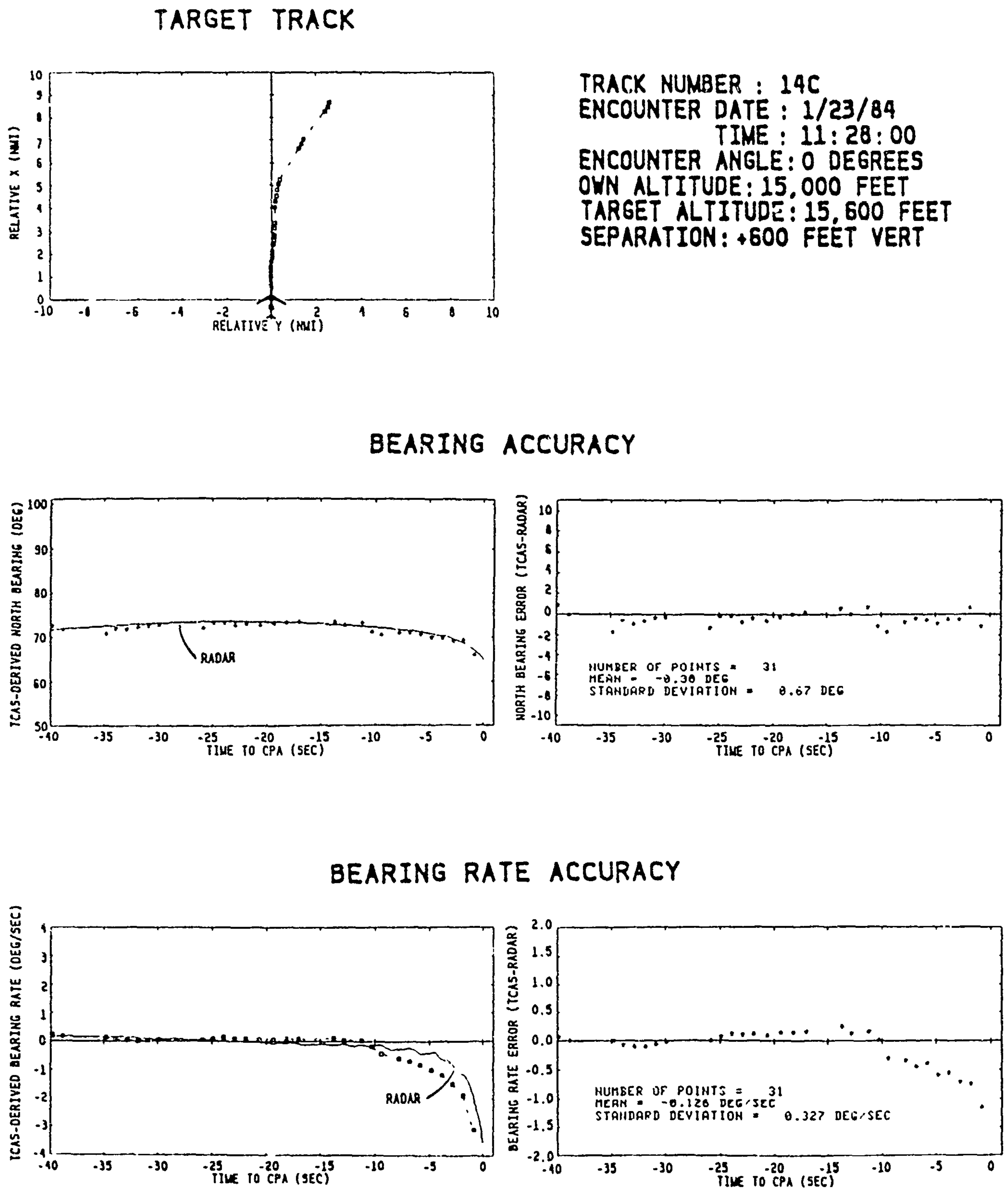


FIGURE 4.2-3. 810-KNOT, HEAD-ON ENCOUNTER
(SHEET 1 OF 2)

FB-VG-1435

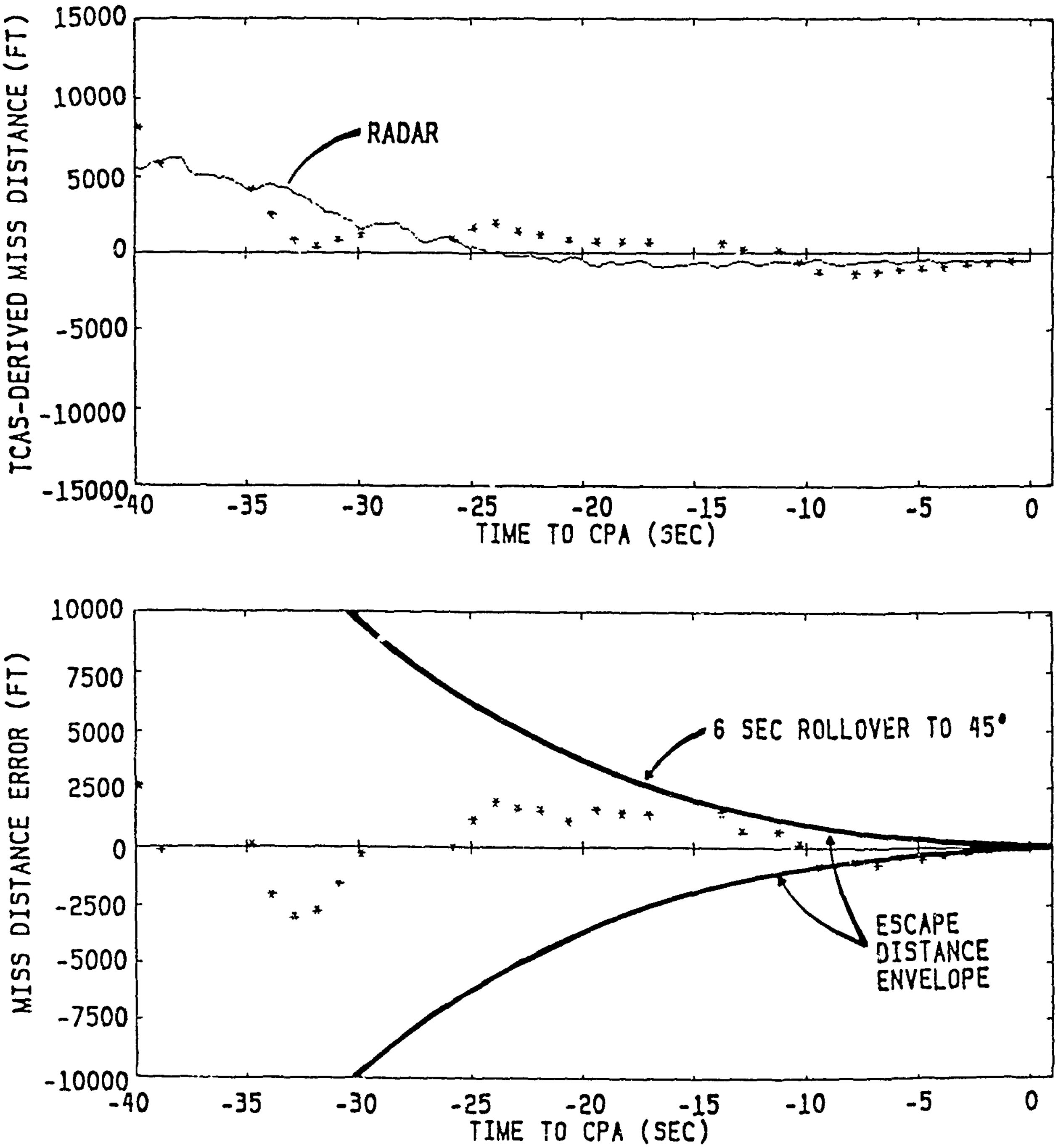


FIGURE 4.2-3. 810-KNOT, HEAD-ON ENCOUNTER
(SHEET 2 OF 2)

FB-VG-1440

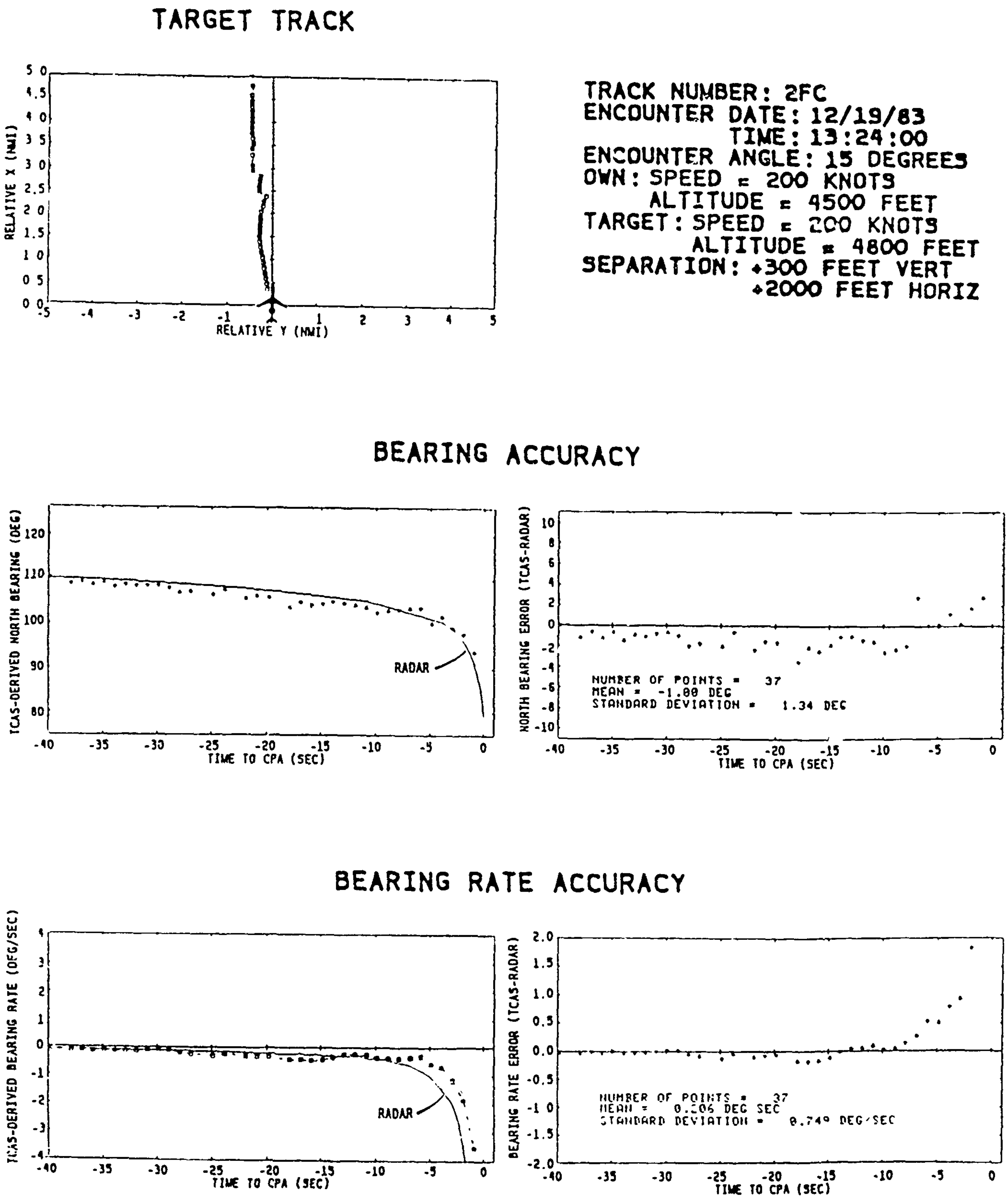


FIGURE 4.2-4. 415-KNOT, 15-DEGREE ENCOUNTER
(SHEET 1 OF 2)

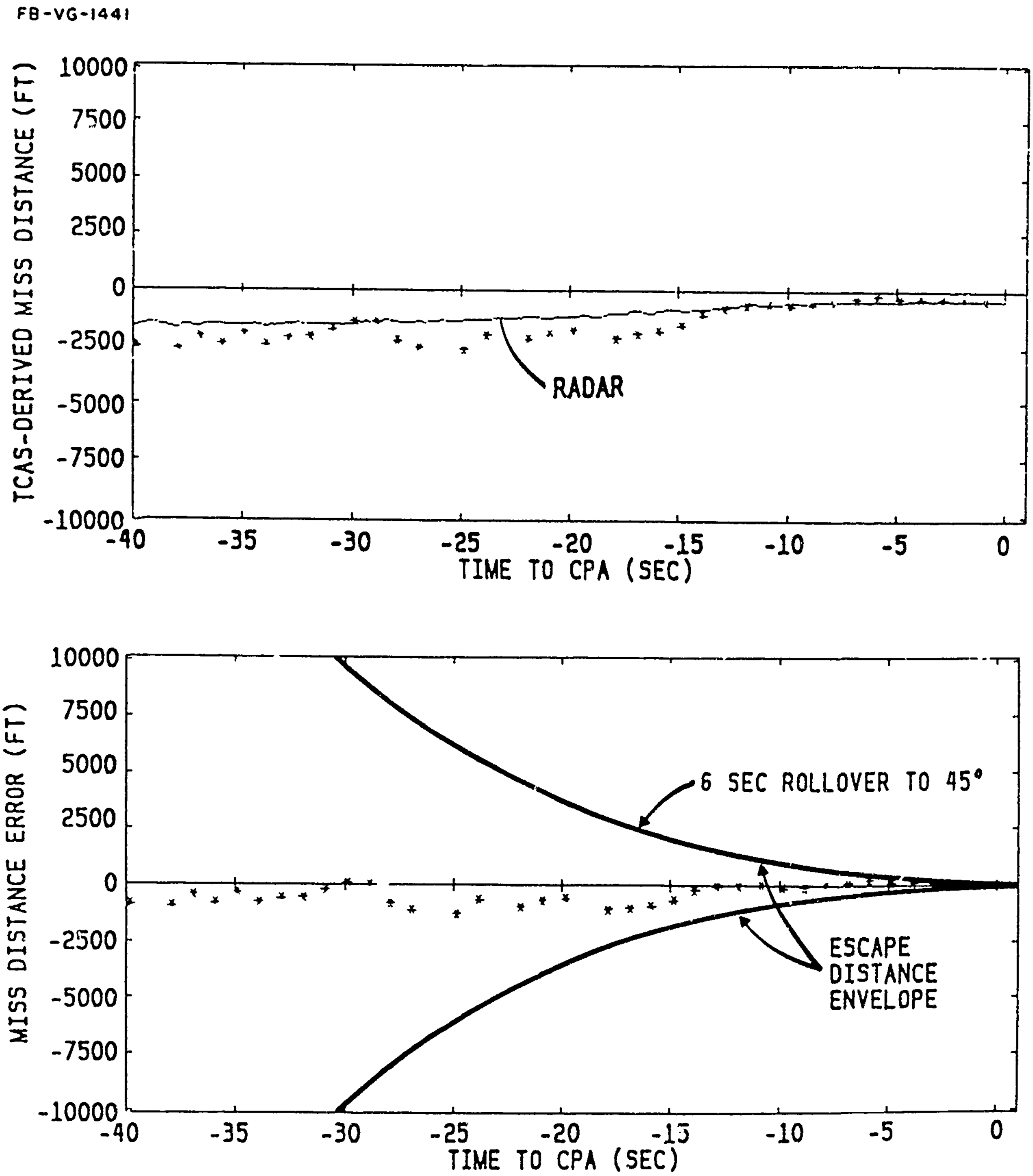
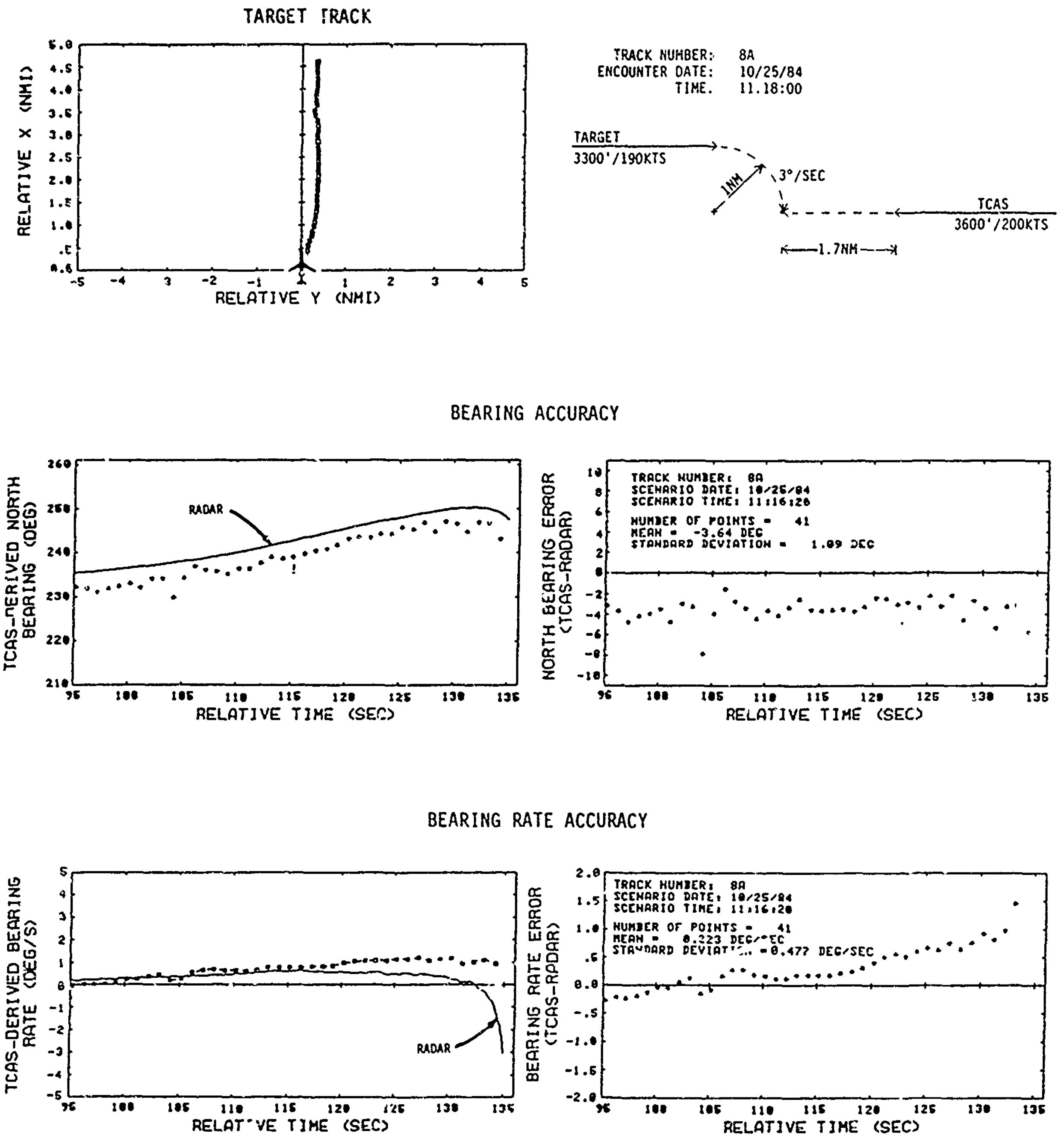
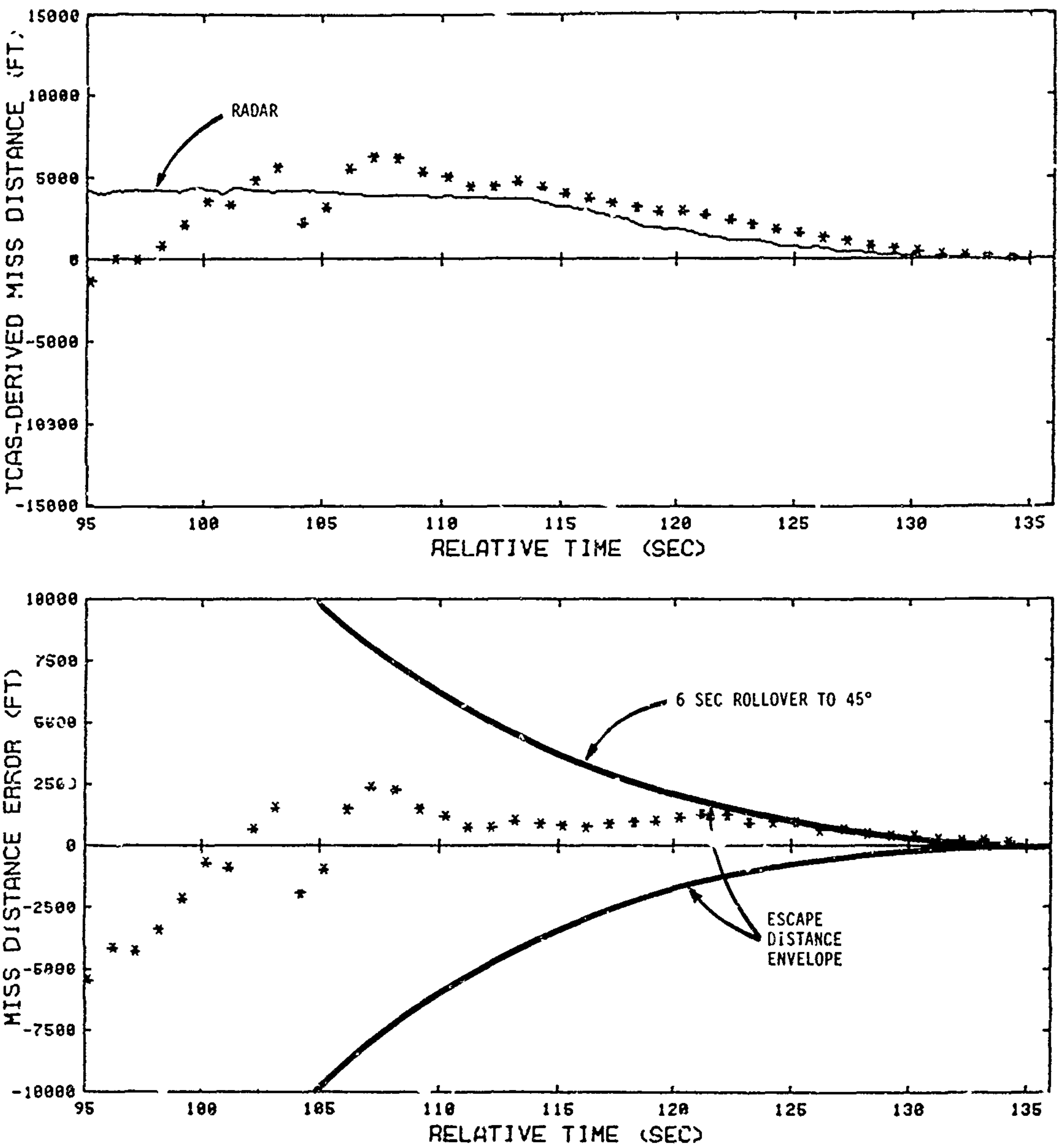


FIGURE 4.2-4. 415-KNOT, 15-DEGREE ENCOUNTER
(SHEET 2 OF 2)



TCAS-025.1

FIGURE 4.2-5. HORIZONTAL FAKEOUT, TARGET CROSSES BELOW TCAS (SHEET 1 OF 2)



TCAS-025.2

FIGURE 4.2-5. HORIZONTAL FAKEOUT, TARGET CROSSES BELOW TCAS (SHEET 2 OF 2)

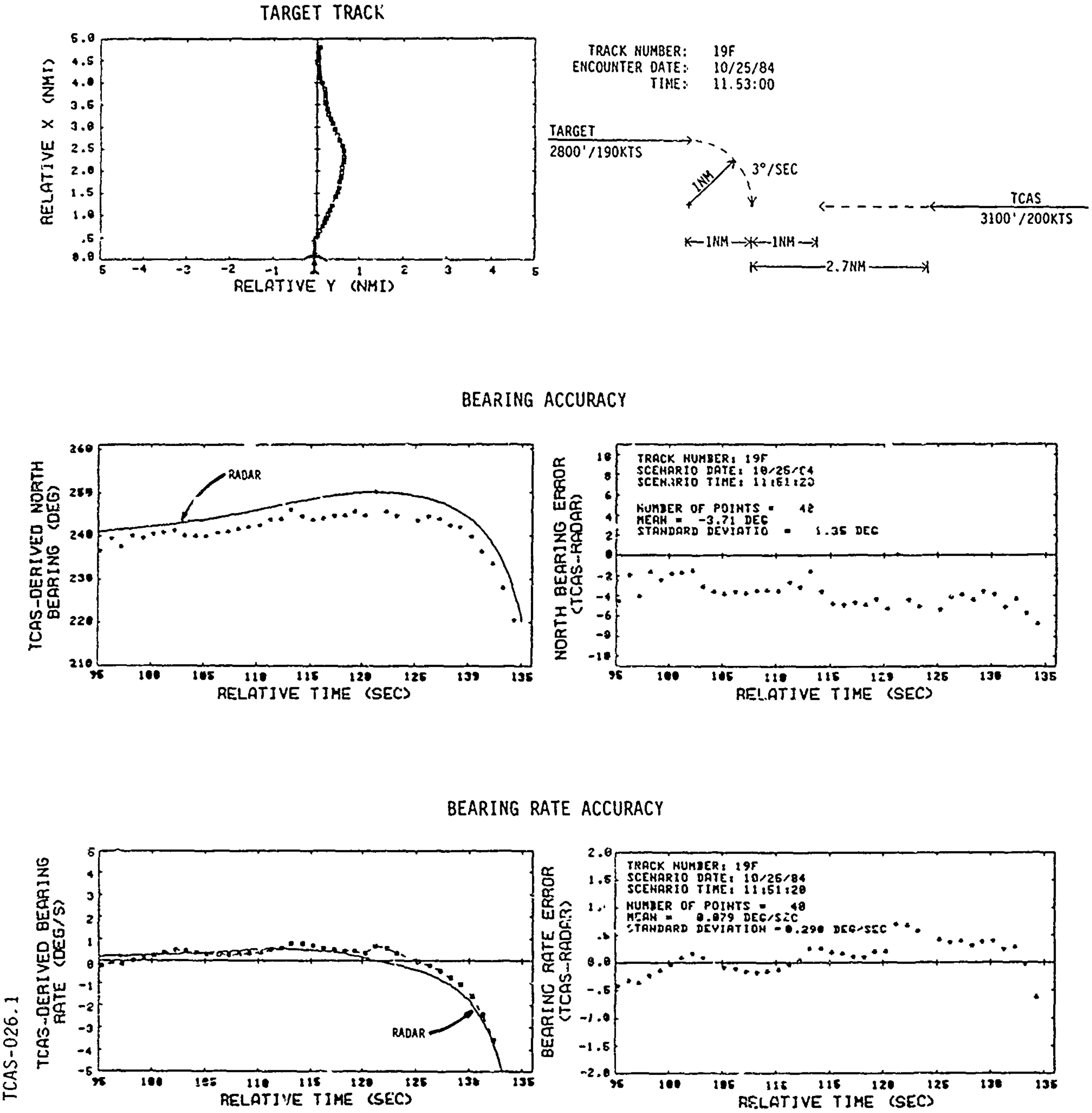


FIGURE 4.2-6. HORIZONTAL FAKEOUT, TARGET CROSSES IN FRONT OF TCAS (SHEET 1 OF 2)

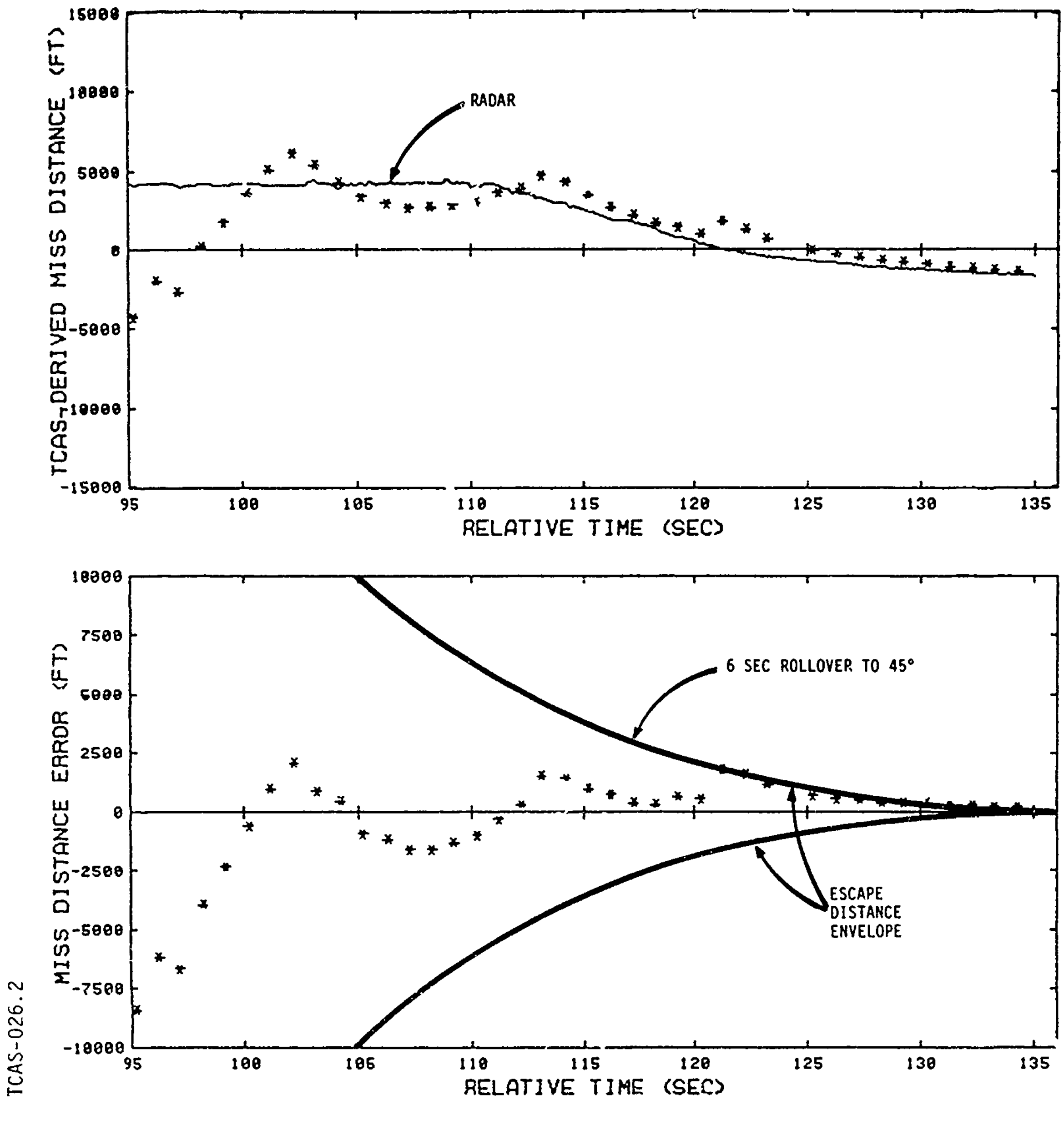


FIGURE 4.2-6. HORIZONTAL FAKEOUT, TARGET CROSSES IN FRONT OF TCAS (SHEET 2 OF 2)

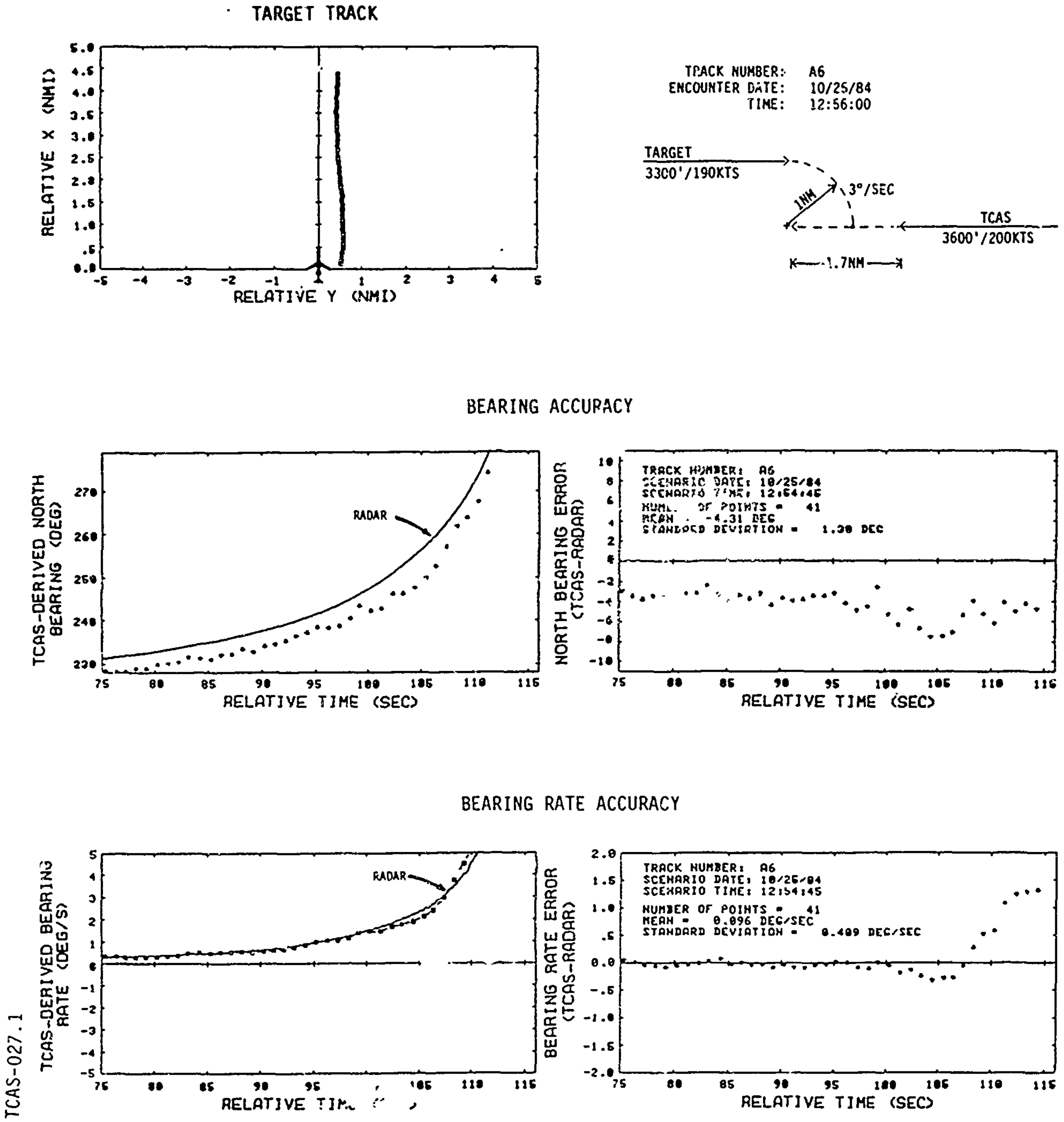


FIGURE 4.2-7. HORIZONTAL FAKEOUT, TARGET CROSSES BEHIND TCAS (SHEET 1 OF 2)

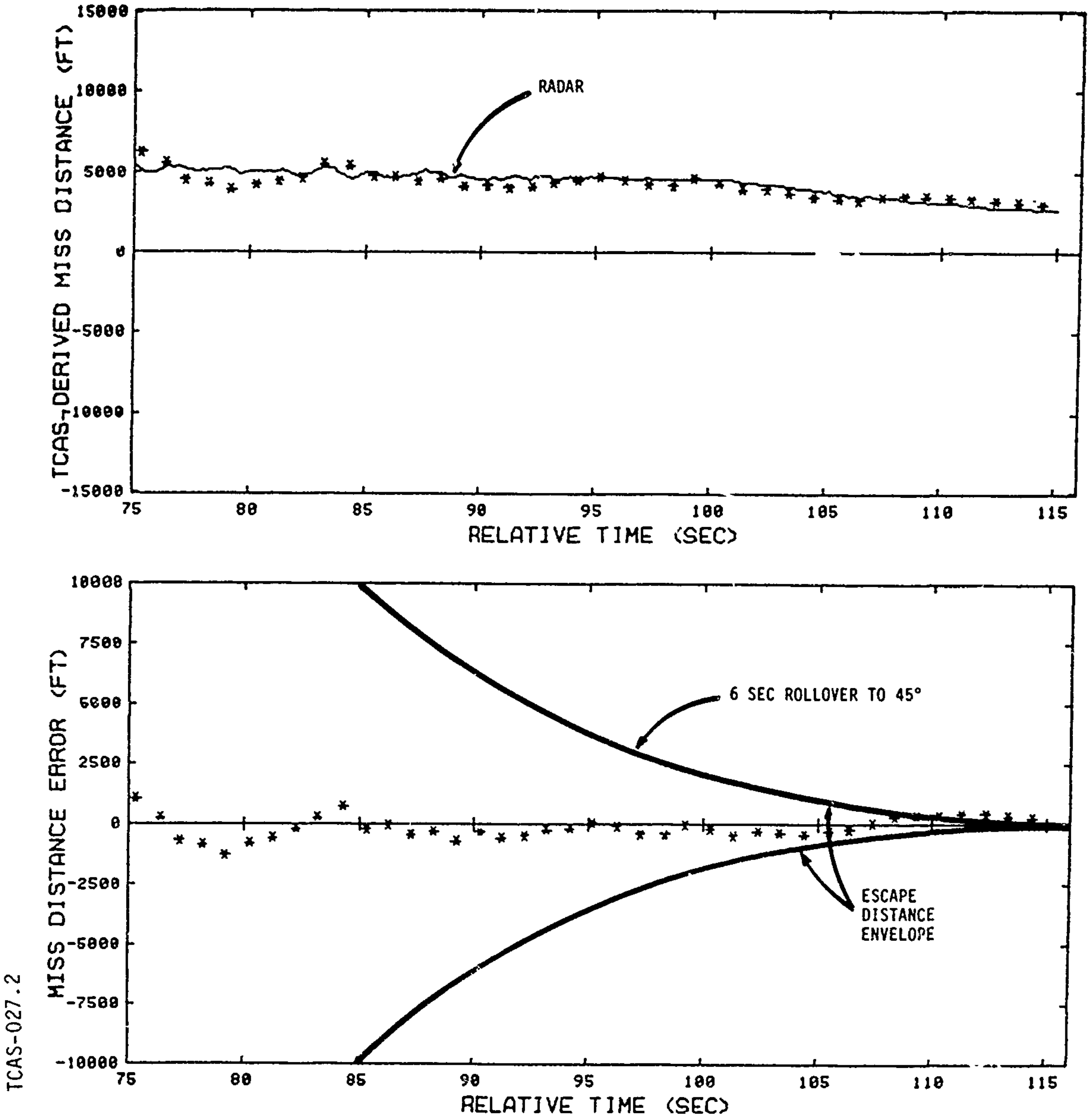


FIGURE 4.2-7. HORIZONTAL FAKEOUT, TARGET CROSSES BEHIND TCAS (SHEET 2 OF 2)

accurate targe relative motion to the pilot on the traffic advisory display.

4.3.1 DENSITY MEASUREMENTS

One of the major reasons the TCAS III equipment was flown in the Los Angeles Basin was to monitor its operation in a high density environment. Density measurements were calculated over a 4-nautical mile circle during each of the 60 encounters. The number of targets under track each second were averaged over 60 seconds during each encounter. Then this average was divided by the area (50.3 nmi) to give the aircraft density per square nautical mile. The highest density during the 60 encounters was 0.155 aircraft per square nautical mile (or 7.8 aircraft over a 4 nmi circle) and the average over all the encounters was 0.08 aircraft per square nautical mile or 4.1 aircraft over the 4 nmi circle. The maximum number of targets under track within a 4 nautical mile circle in any second during the 60 encounters was 13, equivalent to 0.26 aircraft per square nautical mile.

Figure 4.3.1-1 shows two slant range versus time plots. Each is a plot of all target reports received during a 5-minute time interval in the Los Angeles Basin flight tests. The top plot shows a period of average aircraft density while the bottom one is of a higher density environment. Both plots include reports from both altitude reporting and non-altitude reporting transponders. Each asterisk on the plot indicates a received target report at a particular time and slant range. Note that the asterisks are not evenly spaced in time. This is due to the threat-driven surveillance feature of TCAS III in that threatening aircraft are interrogated more often than non-threatening aircraft.

4.3.2 HIGH DENSITY ENCOUNTERS

Aircraft encounters between the TCAS III Engineering Model on the Boeing 727 and an FAA Convair 580 were flown in the Los Angeles Basin area. Representative encounter geometries are shown in Figure 4.3.2-1. Of the 60 total encounters, 9 were head-ons, 6 were 20-degree crossovers, 4 were 45-degree crossovers, 9 were tail-chases, and the remaining 32 were fake-outs. The fake-outs are those encounters where the target aircraft maneuvered in either the vertical or horizontal direction in an attempt to confuse the threat detection and resolution logic. Many of these encounters have already been flown at the FAA's Technical Center in New Jersey, but never in such a high density environment.

Figure 4.3.2-2 shows a typical encounter from the Los Angeles flight tests. This particular encounter is a 20-degree crossover with a 200-foot vertical separation. The plot shows slant range versus time for a 5-minute interval around the encounter. The track of the encounter aircraft is marked on the plot. Also included in the figure are three snapshots of the

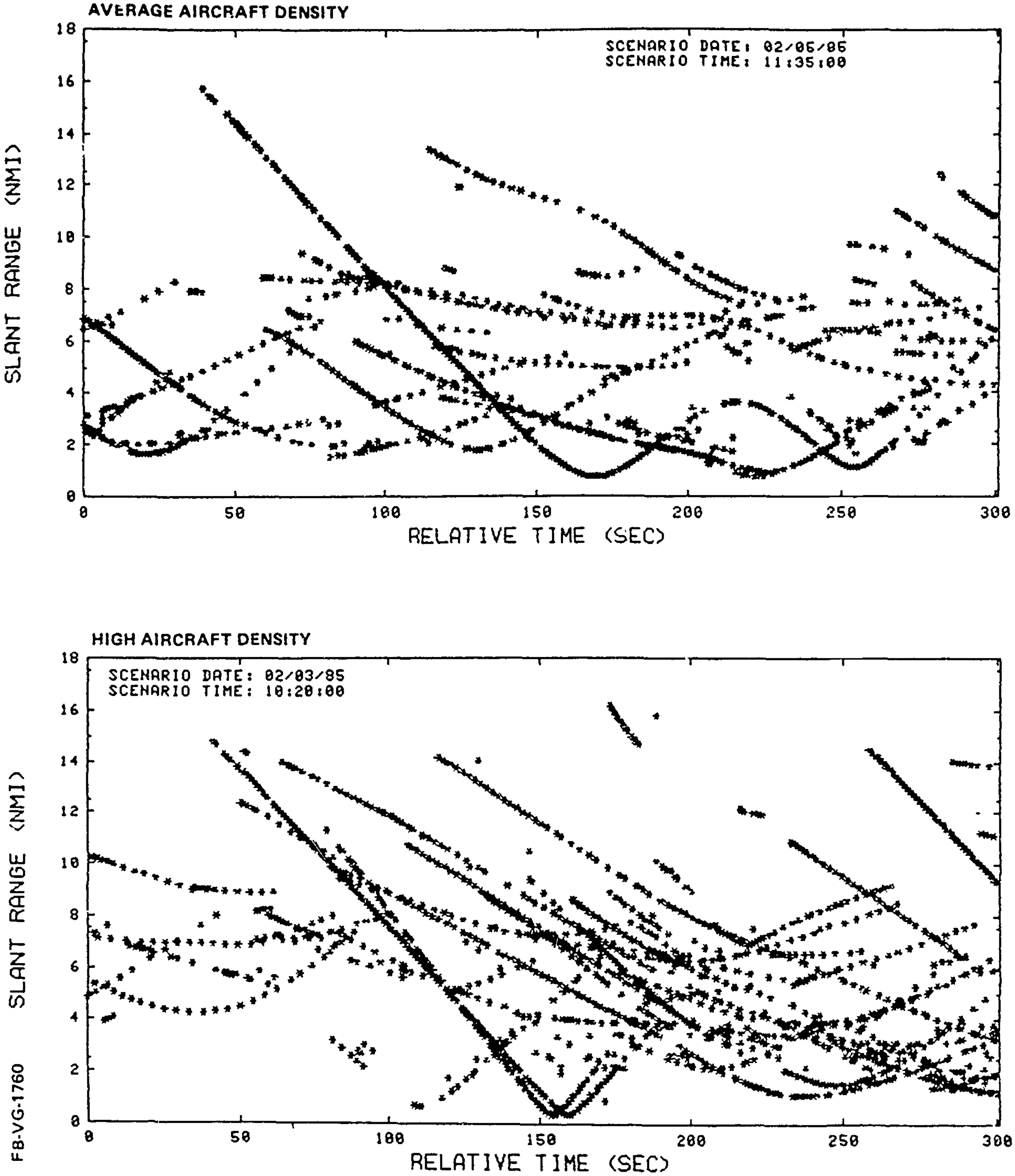


FIGURE 4.3.1-1. TYPICAL RECEIVED TARGET REPORTS, LOS ANGELES FLIGHT TEST

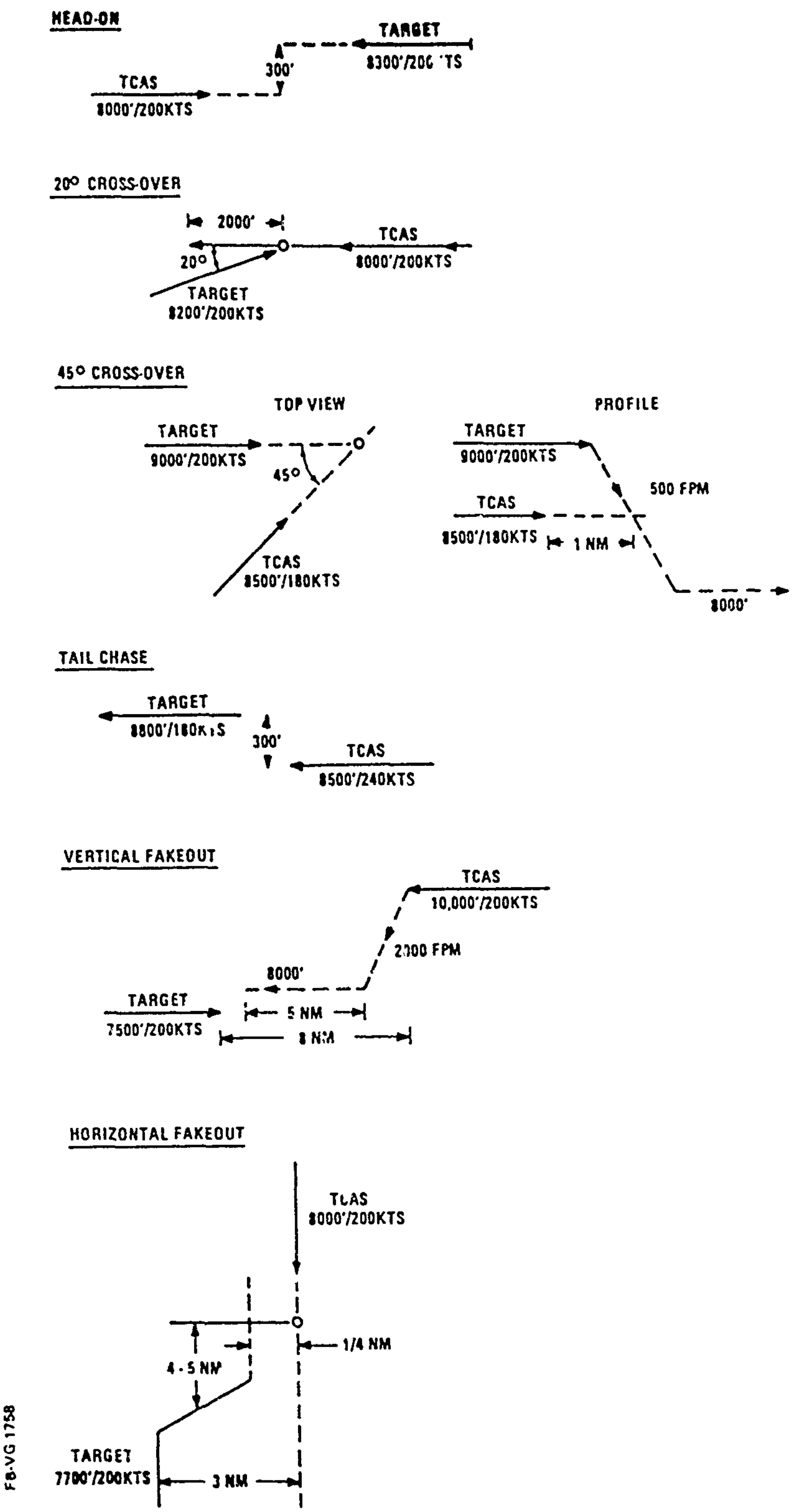
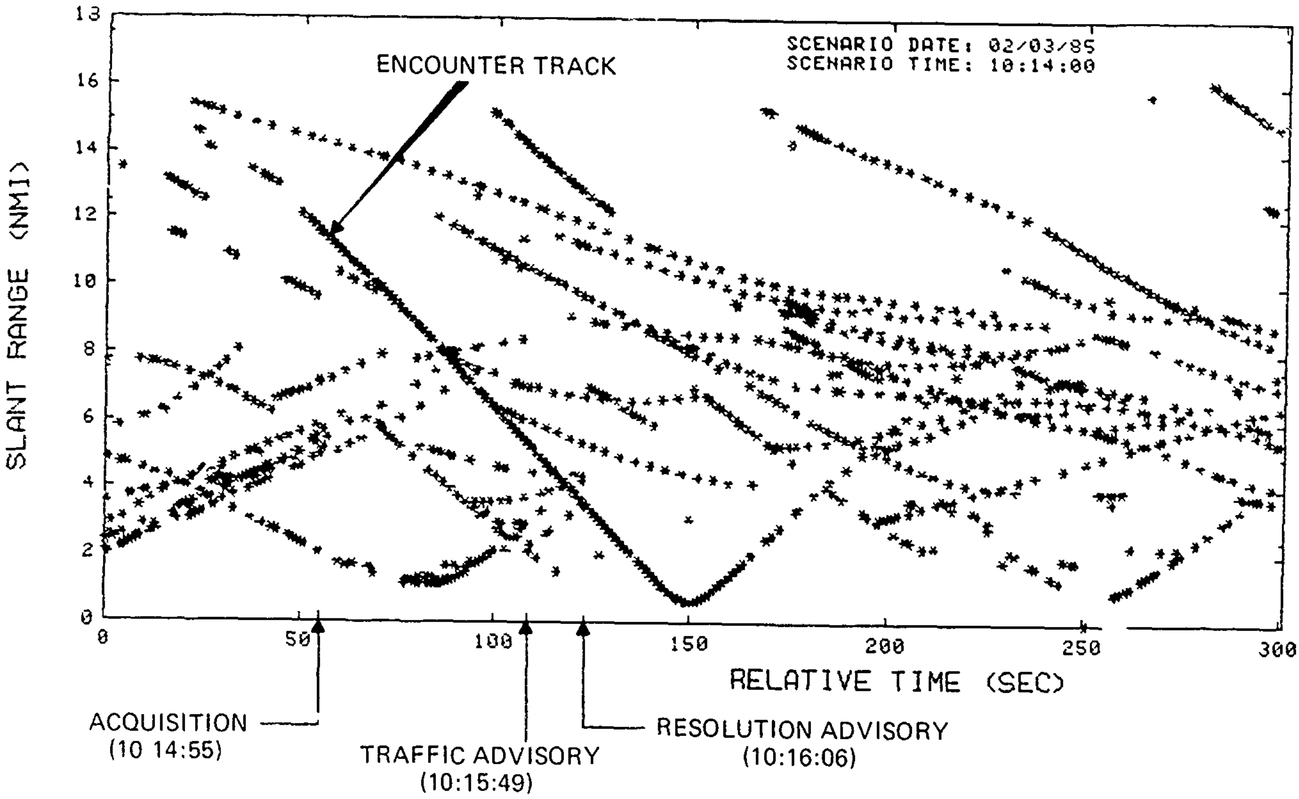


FIGURE 4.3.2-1. AIRCRAFT ENCOUNTER GEOMETRIES

FB-VG-1759.1



ACQUISITION

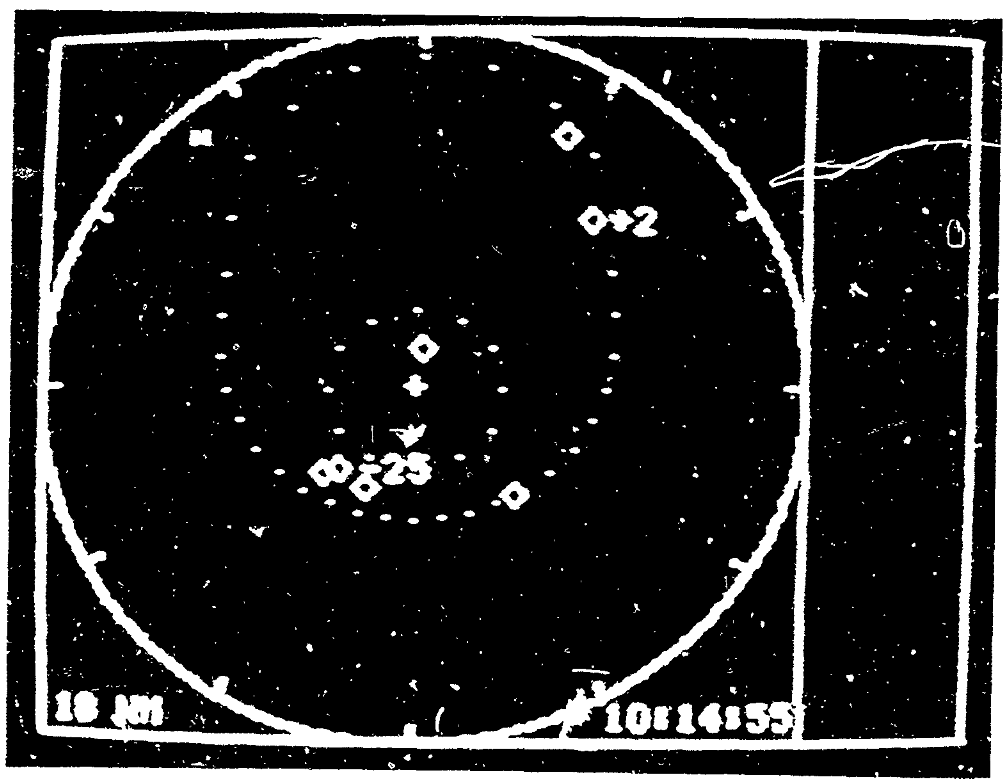
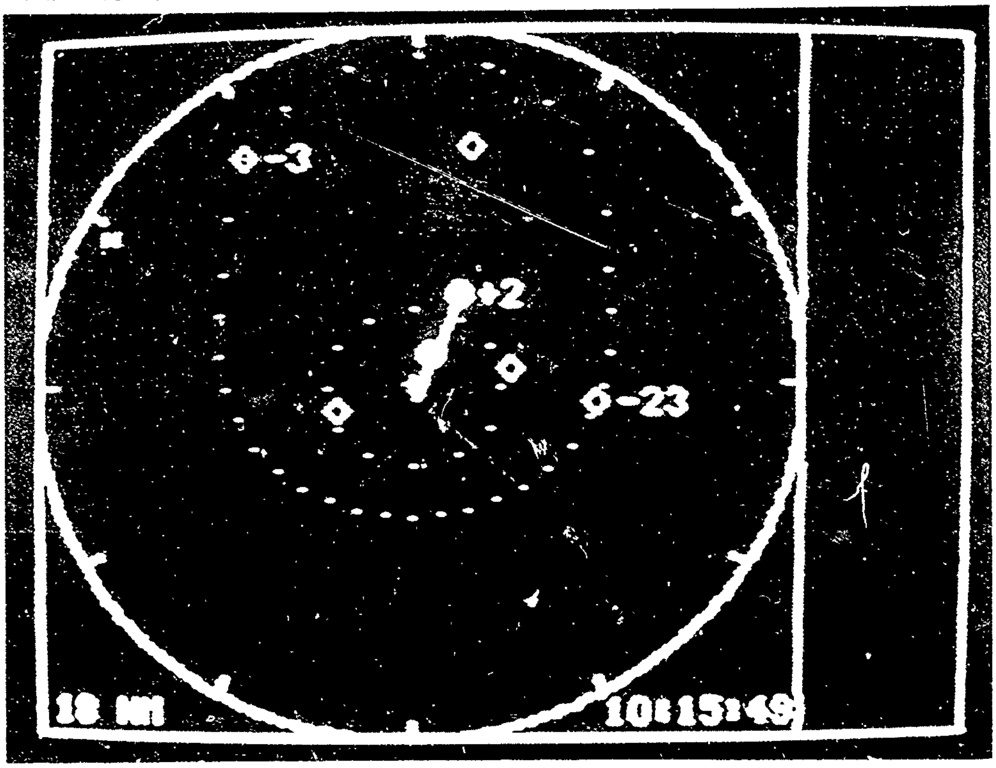


FIGURE 4.3.2-2. TYPICAL ENCOUNTER DISPLAYS, LOS ANGELES FLIGHT TESTS (SHEET 1 OF 2)

TRAFFIC ADVISORY



RESOLUTION ADVISORY

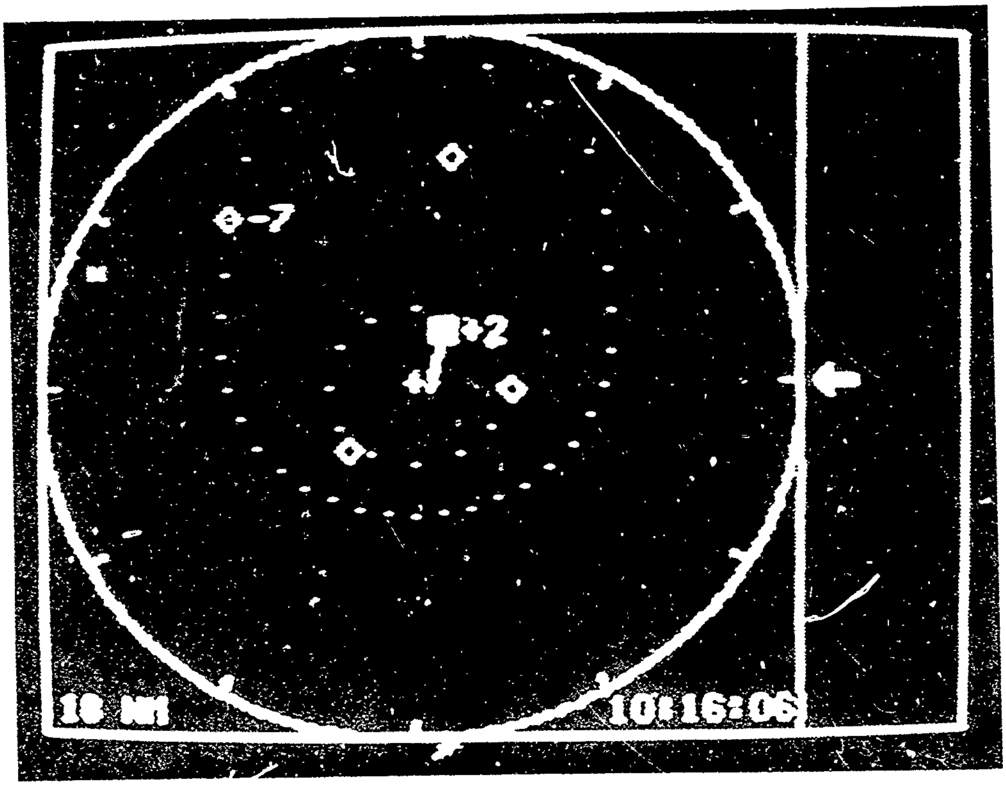
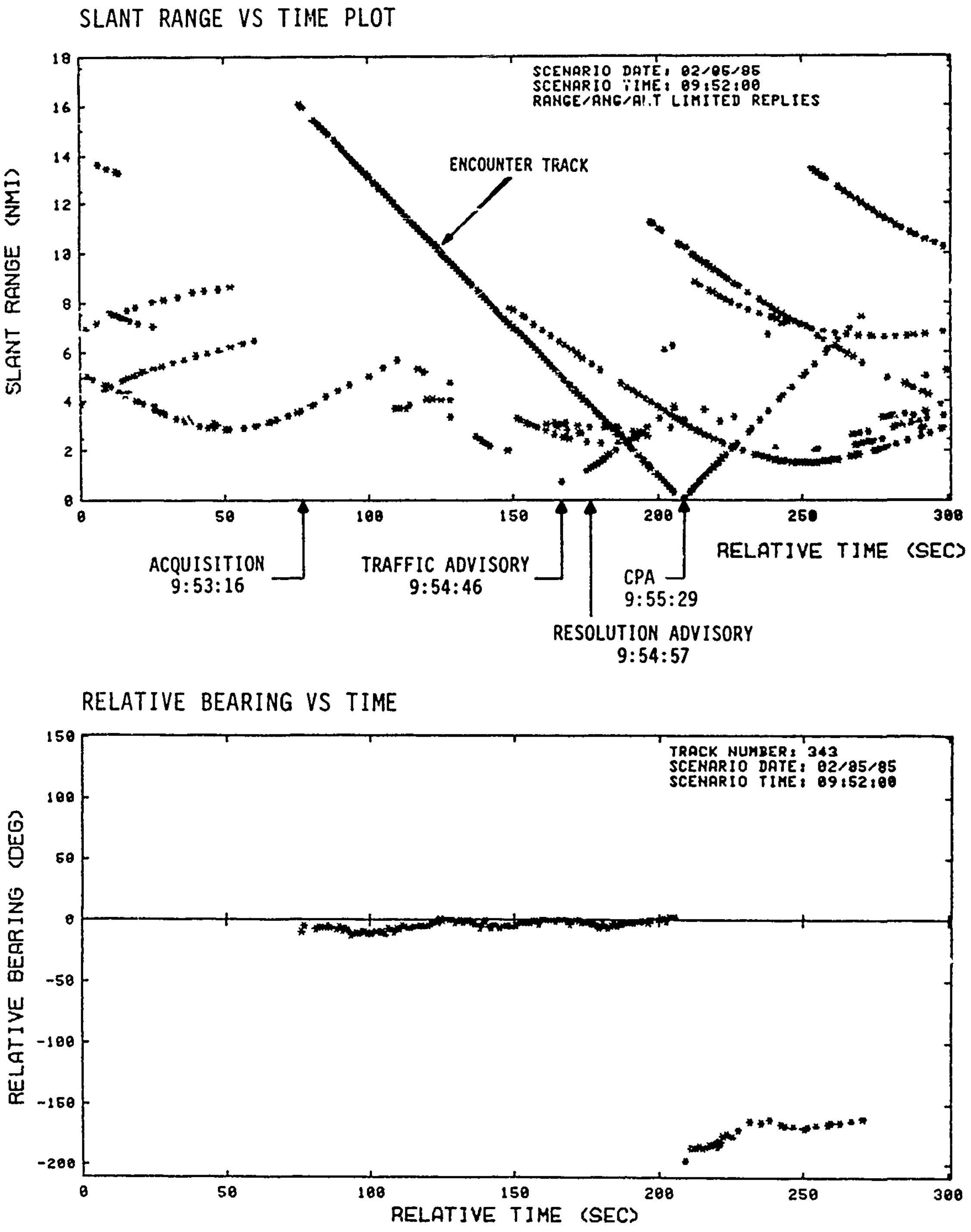


FIGURE 4.3.2-2. TYPICAL ENCOUNTER DISPLAYS, LOS ANGELES FLIGHT TESTS (SHEET 2 OF 2)

traffic advisory and relative motion display during the same encounter. The display shown in this figure is not of the cockpit display as described in section 2.7, but of the display located on rack number 3 along with the rest of the engineering model equipment. This display is of lower resolution than the cockpit display and has slightly different positioning of the resolution advisory and Own aircraft information. The first snapshot is at acquisition. The open diamond symbol shows the position of the target relative to Own aircraft. The target was acquired at 12 nautical miles in slant range with a relative bearing of 40 degrees at 10:14:55. The +2 next to the symbol indicates the relative altitude of the target. In this case, the target is +200 feet above Own aircraft. Target symbols without a relative altitude indicate aircraft whose transponders do not contain Mode C altitude encoding. It became a traffic advisory at 10:15:49 at 5 nautical miles slant range and 24 degrees relative bearing (snapshot 2). Note that a traffic advisory is displayed as a filled-in circle with a 25-second prediction vector attached. The third snapshot is at 10:16:06 when a resolution advisory was generated. The threat is at 3 nautical miles in slant range and 23 degrees in relative bearing. The "Turn Left" advisory is shown to the right of the display. This advisory was also displayed to the pilot on the cockpit display. The average aircraft density during this encounter was 0.066 aircraft over 4 nautical miles.

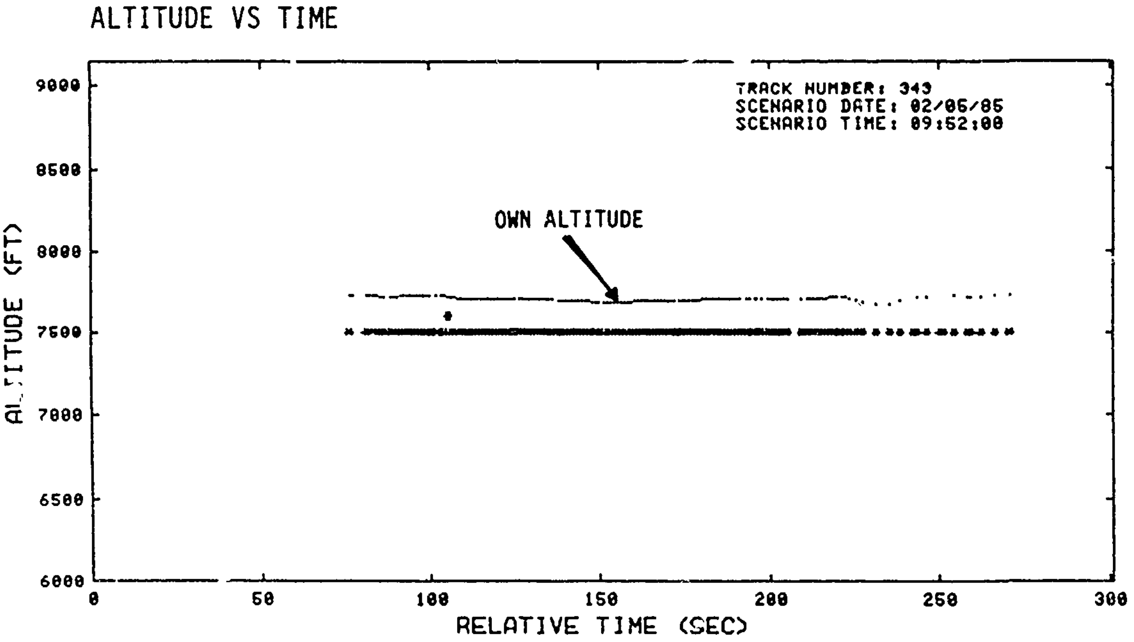
Some additional encounters during the Los Angeles testing are included in the following pages. Figure 4.3.2-3 shows a head-on encounter. The first plot in the figure shows slant range versus time for a 5-minute interval around the encounter. The track of the encounter aircraft is marked on the plot. Acquisition of the target was at 16 nautical miles at 9:53:16, approximately 129 seconds before closest point of approach. It became a traffic advisory at 9:54:46 at 5.1 nautical miles slant range and 359 degrees relative bearing. A resolution advisory of "Climb" was generated at 9:54:57 when the target was at 3.7 nautical miles at 356 degrees. The closest point of approach (CPA) was at 9:55:29 when the target was just 830 feet in slant range and 200 feet below the TCAS aircraft. Average density during the encounter was 0.078 or 3.9 aircraft over 4 nautical miles. The second plot in the figure shows relative bearing versus time. The third plot is the target's altitude with own TCAS's altitude overlaid on the plot. Each asterisk represents a received target report. The last plot in the figure shows the track of the target relative to Own TCAS. In this example, the resolution advisory of "Climb" given to the pilot was not followed.

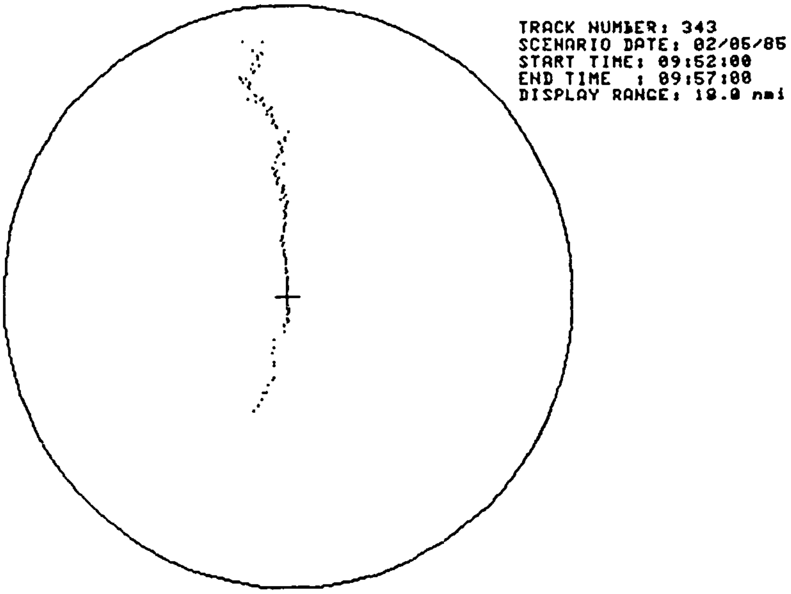
Figure 4.3.2-4 shows a 45-degree encounter. TCAS acquired the target at 15:22:31 at 11.6 nautical miles slant range and 45 degrees relative bearing, 114 seconds before CPA. The target became a traffic advisory at 15:23:32 at 4.7 nautical miles and 21 degrees. It became a resolution advisory at 15:23:56 at 2 nautical miles at 15 degrees. The displayed advisory was "Don't Descend Faster than 1000 FPM" followed by "Don't Descend Faster



TCAS-028.1A

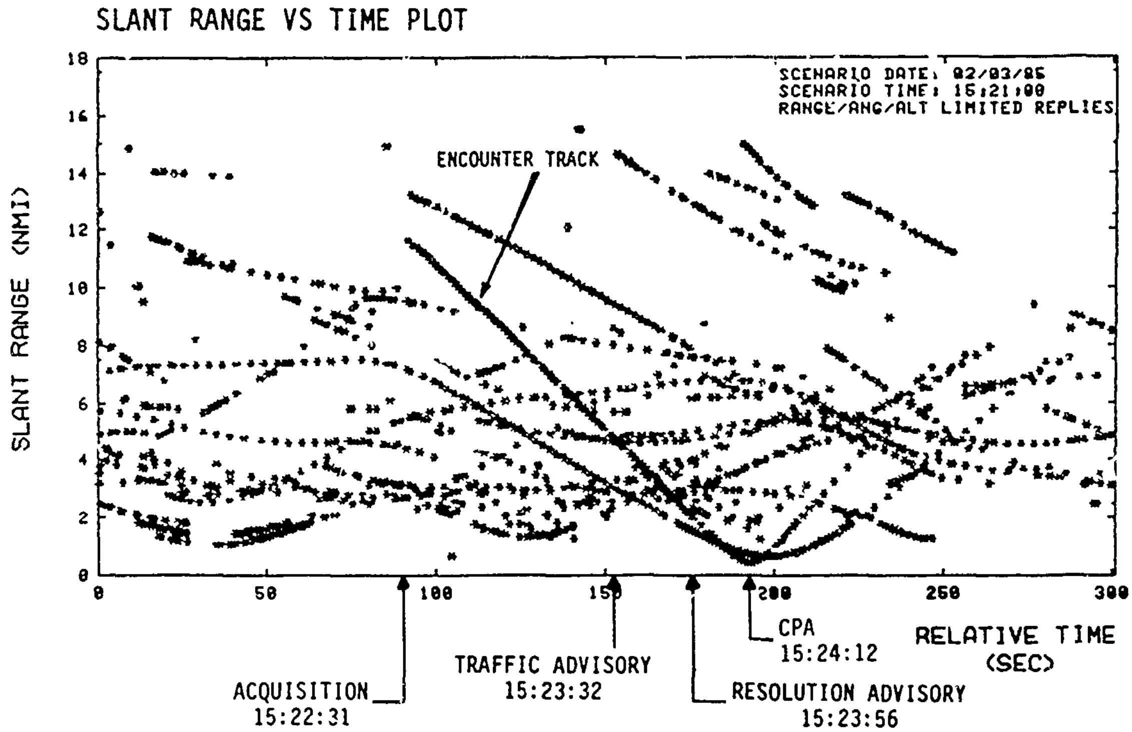
FIGURE 4.3.2-3. HEAD-ON ENCOUNTER
(SHEET 1 OF 2)

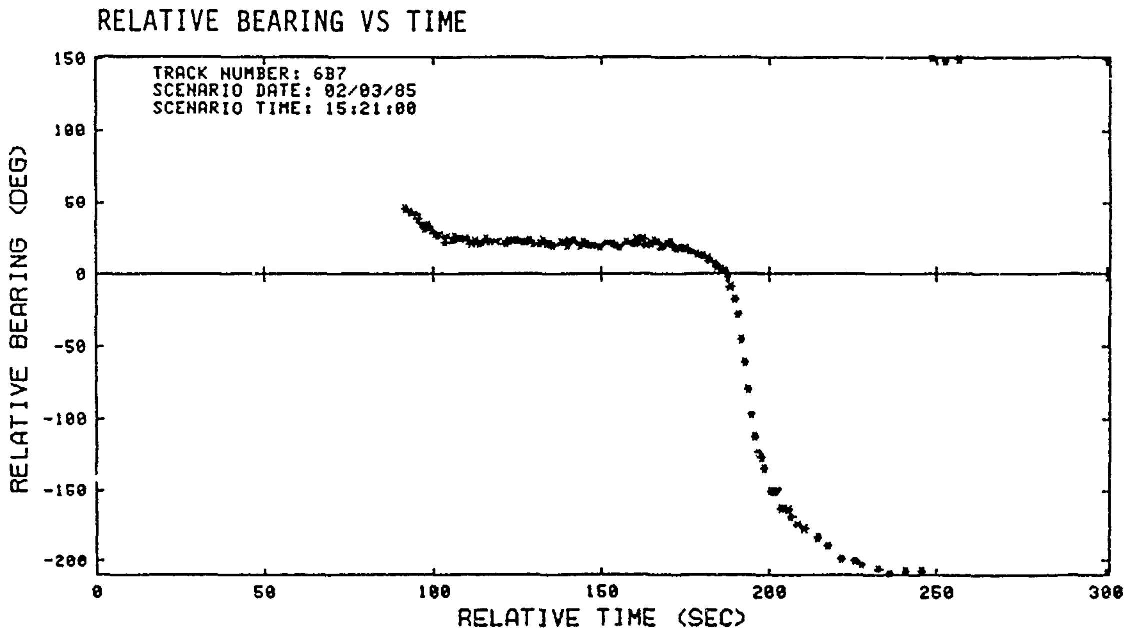




TCAS-028.2A

FIGURE 4.3.2-3. HEAD-ON ENCOUNTER
(SHEET 2 OF 2)

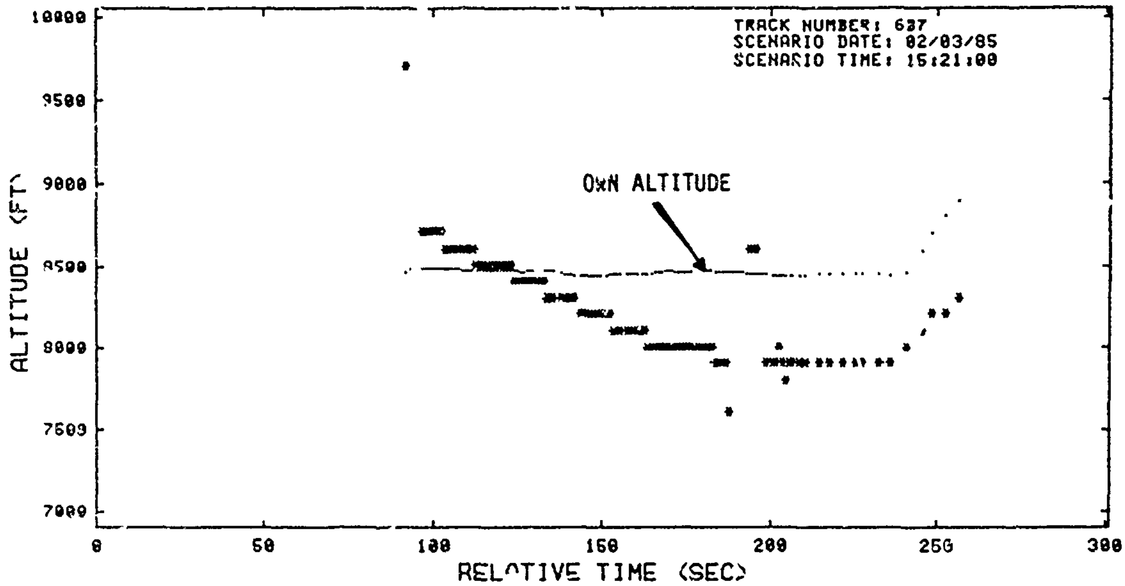


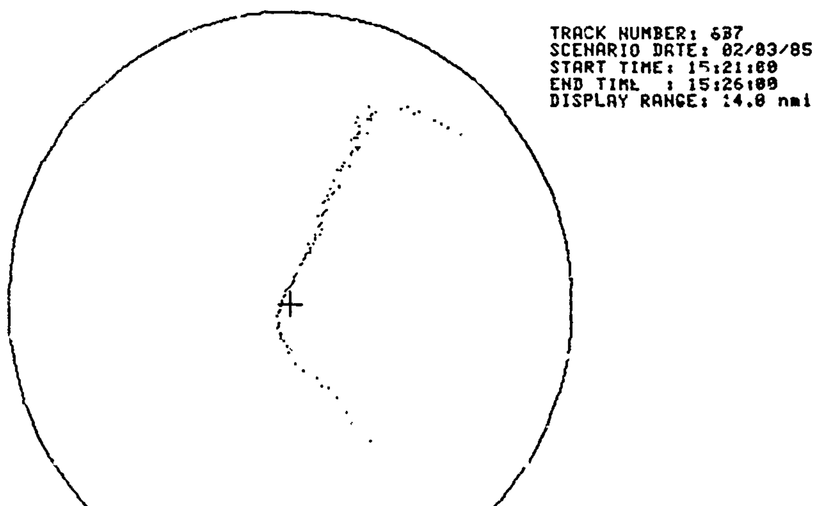


TCAS-029.1A

FIGURE 4.3.2-4. 45-DEGREE ENCOUNTER
(SHEET 1 OF 2)

ALTITUDE VS TIME





TCAS-029.2A

FIGURE 4.3.2-4. 45-DEGREE ENCOUNTER
(SHEET 2 OF 2)

than 2000 FPM". The average density was 0.155 or 7.8 aircraft over a 4 nautical mile circle.

Figure 4.3.2-5 is an example of a vertical fakeout. At acquisition (14:42:32, 122 seconds before CPA), the target was at 15.5 nautical miles slant range, 346 degrees relative bearing, and 1500 feet above Own altitude. During the encounter, the target remained at a constant altitude while Own climbed 1000 fpm and leveled off 600 feet below the target. A traffic advisory was generated at 14:43:52 at 5.3 nautical miles, 1 degree and 1000 feet above Own altitude. The target became a resolution advisory at 14:44:10 at 3 nautical miles, 600 feet above Own aircraft. A "Don't Climb" advisory was displayed.

The last example shown is a horizontal fakeout in Figure 4.3.2-6. The encounter began with the trajectories of the two aircraft spaced 3 nautical miles in the horizontal plane. The target aircraft maneuvered until it was within 1/4 mile. Acquisition was at 10:00:45 at 12.9 nautical miles slant range and 20 degrees relative bearing, 112 seconds before CPA. The target remained 200 feet below Own aircraft during the entire encounter. It became a traffic advisory at 10:02:00 at 4.7 nautical miles and 13 degrees. A resolution advisory of "Turn Left" was generated at 10:02:21 when the target was at 2 nautical miles slant range and 19 degrees relative bearing.

These are just a few examples of the many encounters run in the Los Angeles Basin. The rest of the high density encounters exhibited similar performance. Table 4.3.2-1 gives some summary statistics for all the L.A. encounters. As shown, the target aircraft was acquired with more than sufficient time to track and assess its collision potential before closest point of approach. The average slant range at acquisition is slightly misleading since the TCAS III maximum search range varies as a function of bearing. In the case of a tailchase encounter when the target overtakes the TCAS aircraft, the acquisition range will be small since the closing rate is so low.

4.3.3 TARGETS OF OPPORTUNITY

In addition to the preplanned encounters in the Los Angeles Basin, there were many other aircraft that were tracked by the TCAS. Some of these targets of opportunity generated traffic advisories from the TCAS and some even became resolution advisories. The importance of these targets is the opportunity to analyze the TCAS performance with different transponders. All of the planned encounters were run against a specific aircraft and transponder. So, the statistics generated from these encounters really show performance with a specific transponder. The targets of opportunity provide information about a larger cross-section of aircraft transponders.

On the five days that the TCAS aircraft flew in the L.A. Basin, 34 Mode C targets of opportunity generated traffic

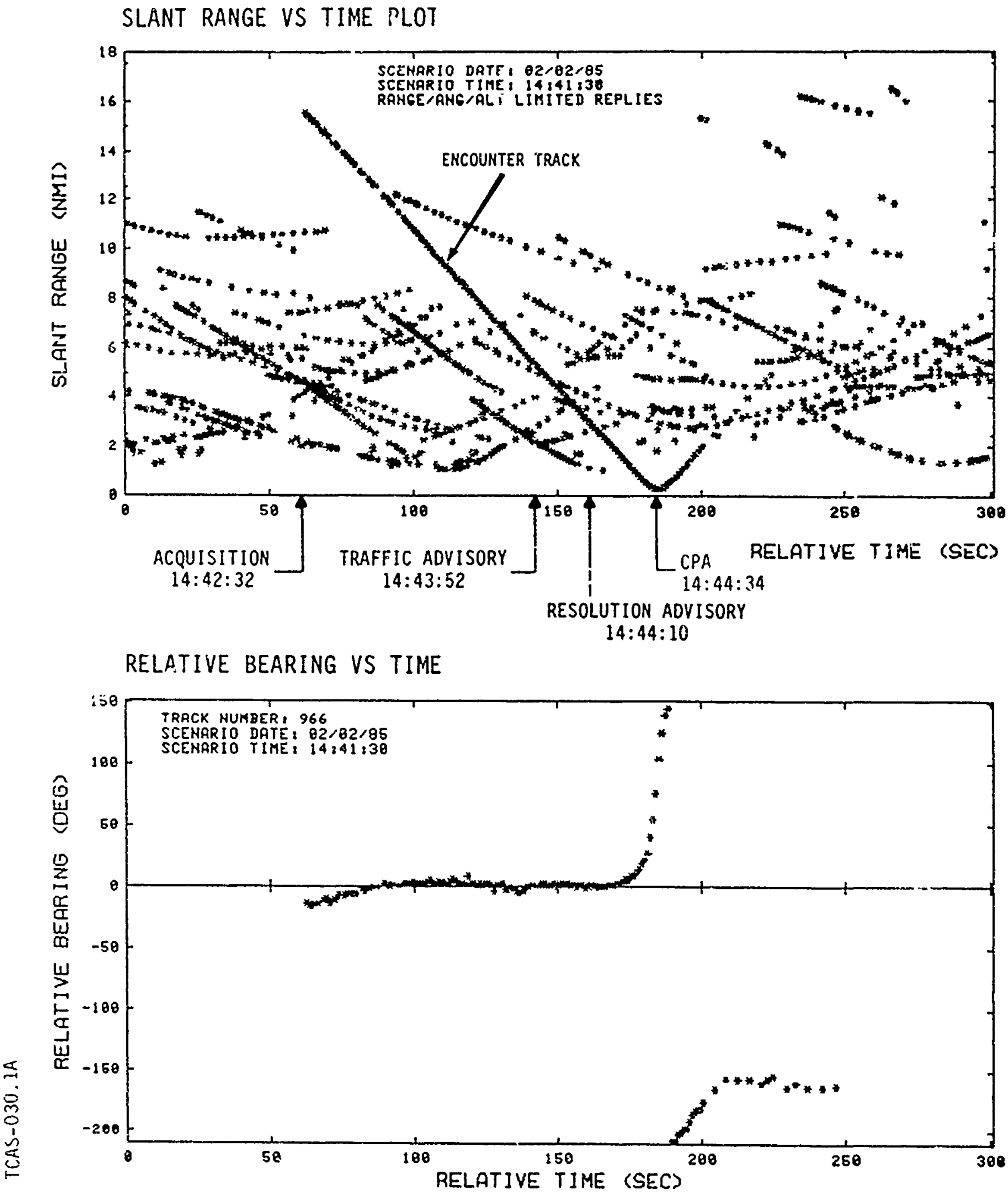
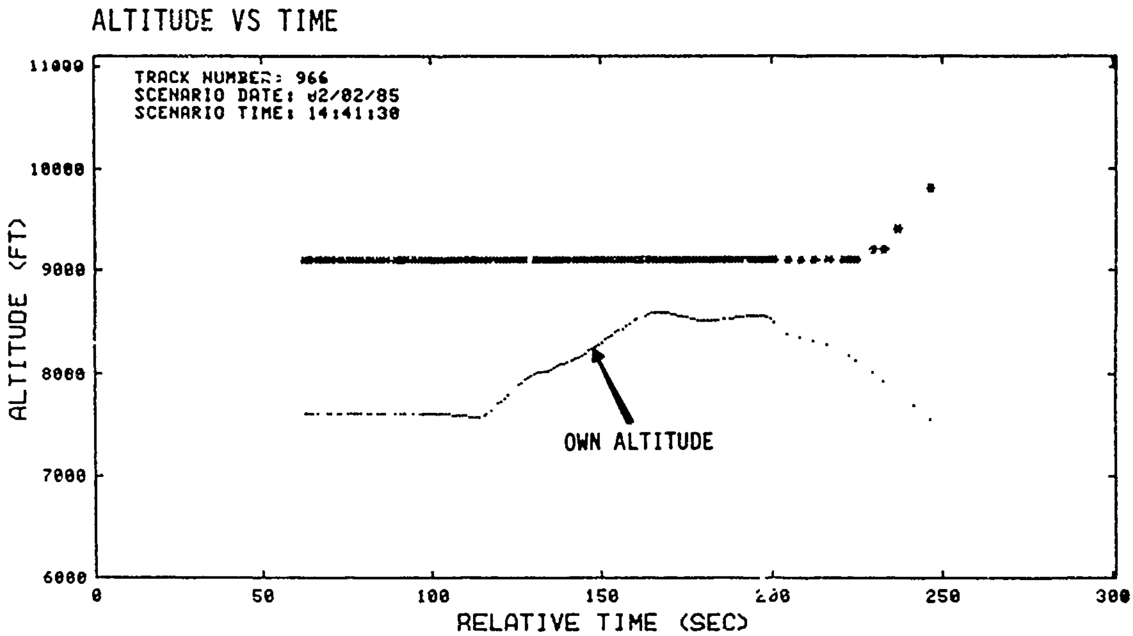
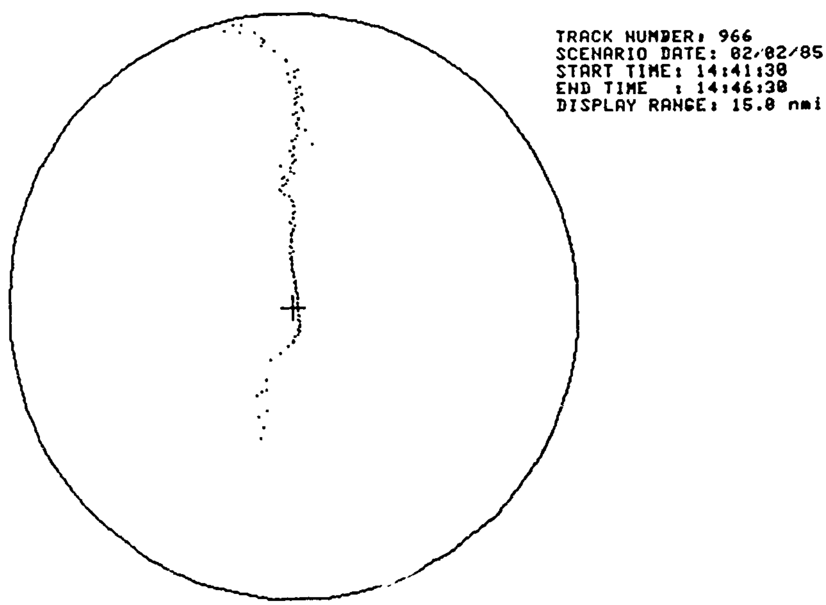


FIGURE 4.3.2-5. VERTICAL FAKEOUT
(SHEFT 1 OF 2)





TCAS-030.2A

FIGURE 4.3.2-5. VERTICAL FAKEOUT
(SHEET 2 OF 2)

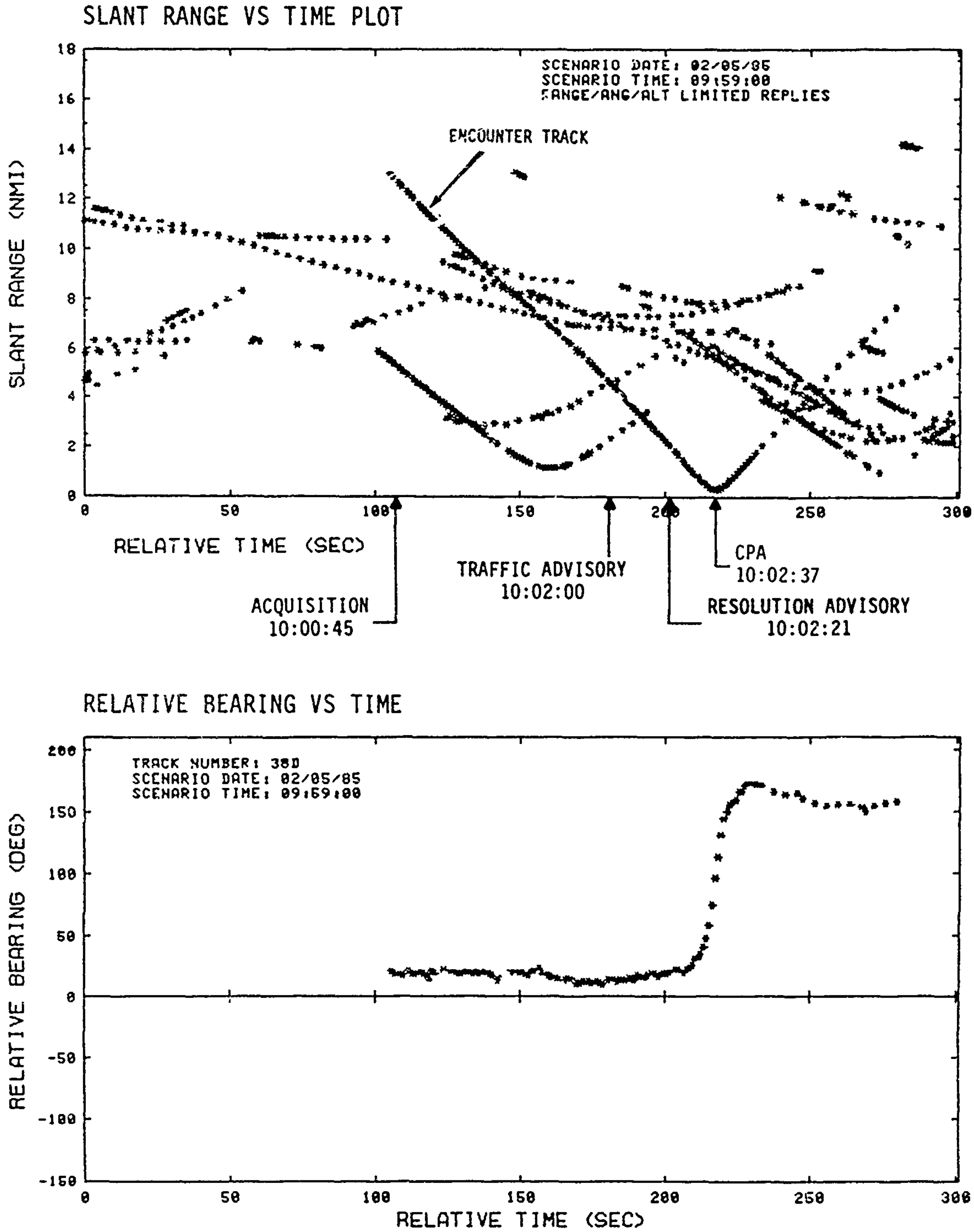


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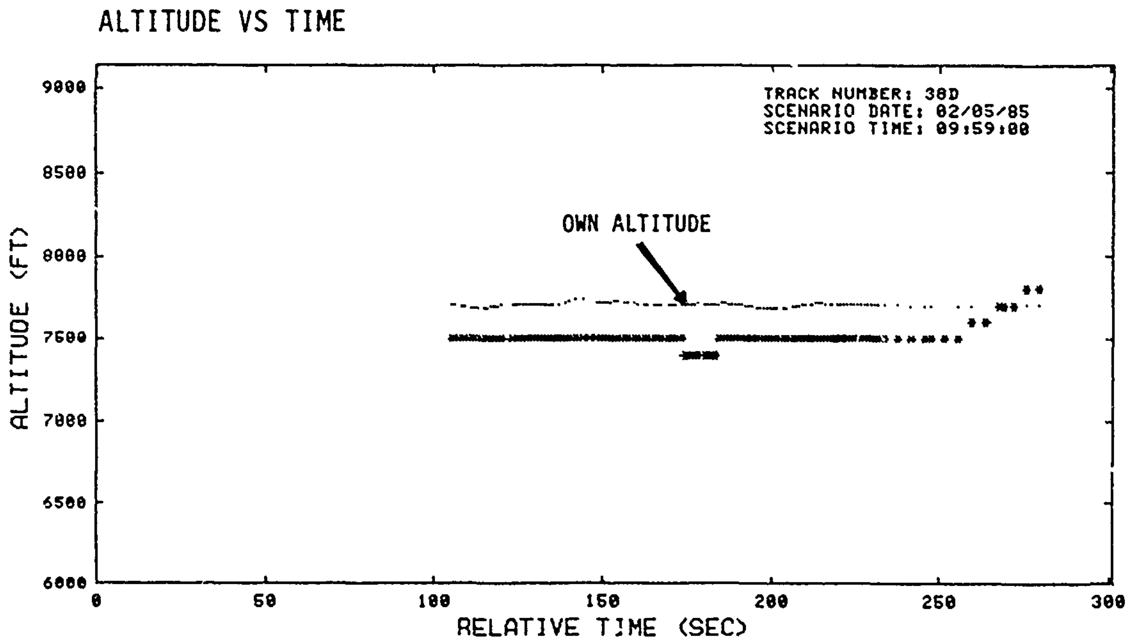
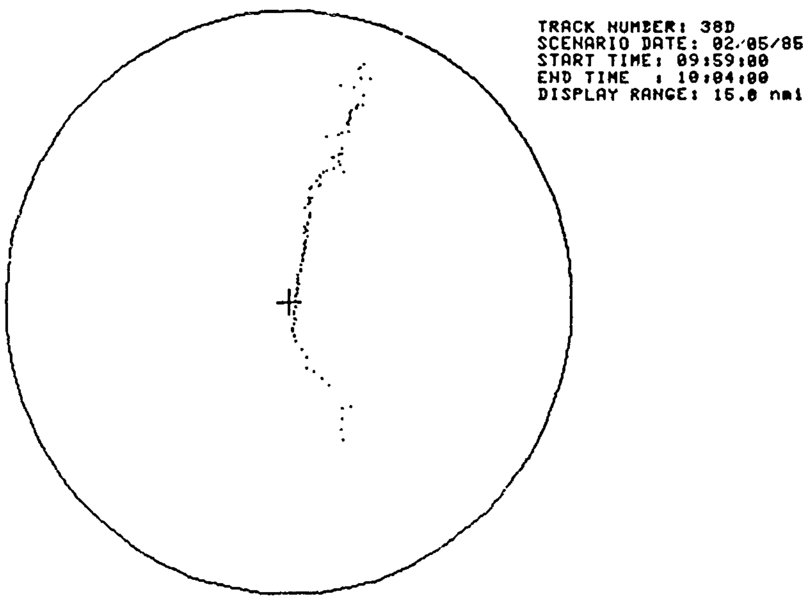
FIGURE 4.3.2-6. HORIZONTAL FAKEOUT
(SHEET 1 OF 2)





TCAS-031.2A

FIGURE 4.3.2-6. HORIZONTAL FAKEOUT
(SHEET 2 OF 2)

TABLE 4.3.2-1. LOS ANGELES BASIN ENCOUNTER STATISTICS

TYPE OF ENCOUNTER	NUMBER	AVERAGE SLANT RANGE AT ACQUISITION(nmi)	AVERAGE SIGNAL LEVEL AT ACQUISITION(dBm	AVERAGE TIME TO CPA AT ACQUISITION(sec)	AVG DURATION OF TRACK(sec)	AVG DURATION OF TRAFFIC ADVISORY(sec)	AVG DURATION OF RESOLUTION ADVISORY(sec)	AVG AIRCRAFT DENSITY OVER 4nm² DURING ENCOUNTER
HEAD-ON	9	13.1	-60	101	166	14.7	29.8	0.068
20° CROSSOVER	6	13.8	-62	107	187	12.8	31.8	0.091
45° CROSSOVER	4	9.3	-61	133	245	32.2	18.5	0.108
TAILCHASE	9	4.7	-53	179	444	11.5	34.4	0.080
VERTICAL FAKEOUTS	20	13.3	-61	104	192	22.7	24.4	0.070
HORIZONTAL FAKEOUTS	12	8.5	-57	159	287	22.5	33.2	0.066

advisories. Of these 34 targets, 7 targets also became resolution advisories. There were also quite a number of non-Mode C targets that generated traffic advisories. However, these targets are of less interest since their altitudes were unknown and they would never become resolution advisories.

Figure 4.3.3-1 is an example of one target of opportunity that generated a resolution advisory from the collision avoidance logic. The first plot is a slant range versus time plot for the five-minute interval around the encounter. The target was acquired at 10:29:52 at 13.5 nautical miles slant range, 8 degrees relative bearing, and 1100 feet above Own altitude. It became a traffic advisory at 10:30:57 at 5.2 nautical miles, 12 degrees relative bearing, and 1000 feet above Own altitude. At 10:31:19, the target generated a resolution advisory at 2.4 nautical miles slant range, 16 degrees relative bearing, and 700 feet above Own altitude. The displayed resolution advisory was "Descend". The closest point of approach occurred at 10:31:37 when the target was just 0.7 nautical miles in slant range and +300 feet above Own aircraft. Average density was 0.1 or 5 aircraft over a 4 nautical mile circle. The second plot in the figure shows the measured relative bearing versus time of the target during the entire track. The third plot indicates the target's absolute altitude with Own's altitude overlaid on the plot. The last plot shows the target's track relative to Own aircraft. Each asterisk indicates a received target report.

A second example is shown in Figure 4.3.3-2. This particular target was acquired at 10:24:16, 136 seconds before closest point of approach, at 12.1 nautical miles, 43 degrees relative bearing, and 1400 feet below Own altitude. A traffic advisory was generated at 10:25:53 at 4.3 nautical miles as the target was just 100 feet above Own altitude. At 10:26:22, the target became a resolution advisory at 1.2 nautical miles, 600 feet above Own altitude. An advisory of "Don't Climb" was displayed. CPA occurred at 0.4 nautical miles at 10:26:32. Average density during the encounter was 0.063, or 3.2 aircraft over a 4 nautical mile circle.

Both of these target encounters are examples of unplanned encounters. The first example occurred while the TCAS aircraft was just flying around the Los Angeles Basin. The second example occurred in the Seal Beach area as the TCAS aircraft was running high density encounters with an FAA target aircraft. In both of these examples plus other cases where advisories were generated by targets of opportunity, TCAS III acquired the target well ahead of CPA, kept a steady track on the target and posted a reasonable advisory against the target.

4.4 PERFORMANCE STATISTICS

The performance of TCAS III can be summarized as shown in Figure 4.4-1. Two types of tracks were considered in this analysis: encounters and targets of opportunity. The encounters

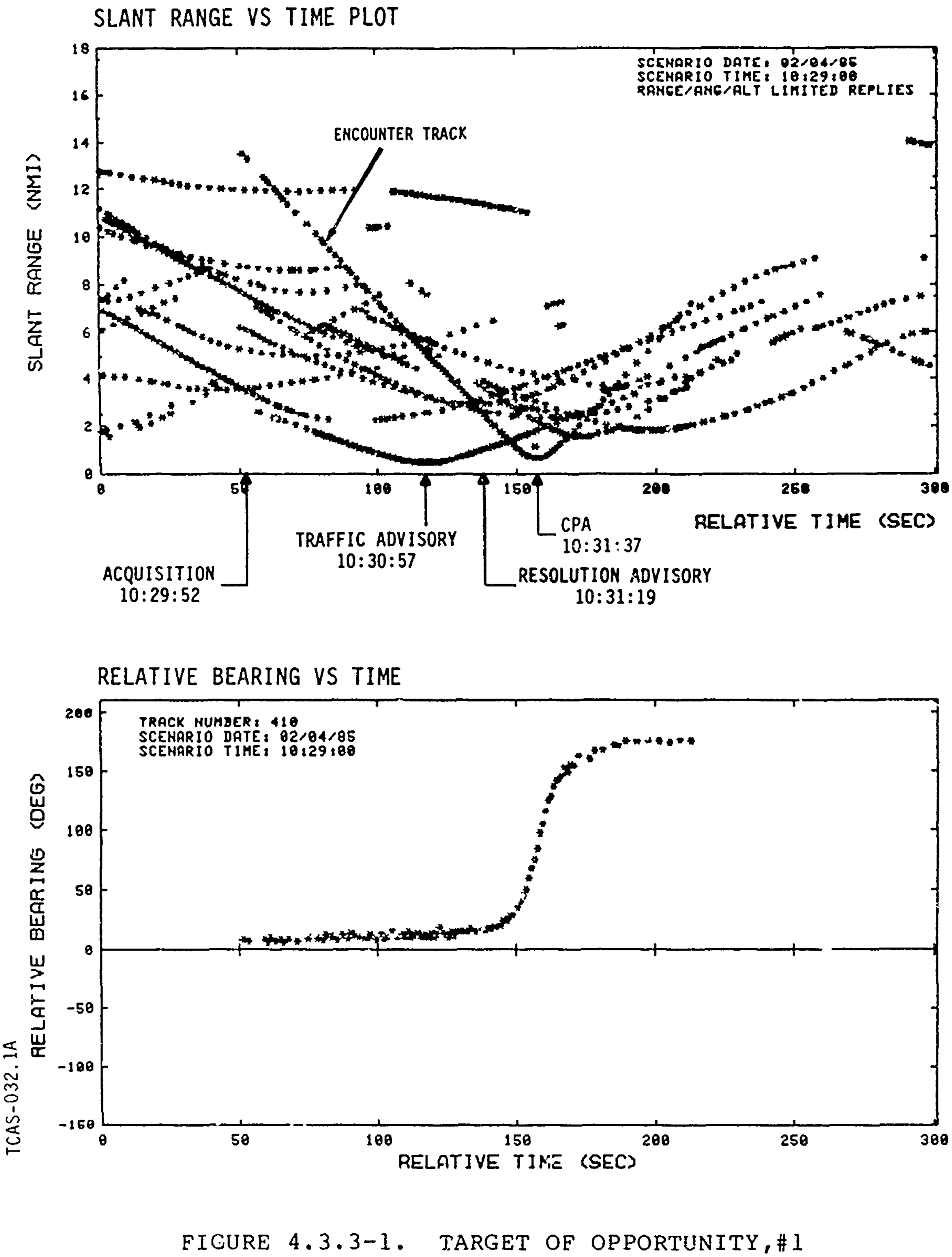
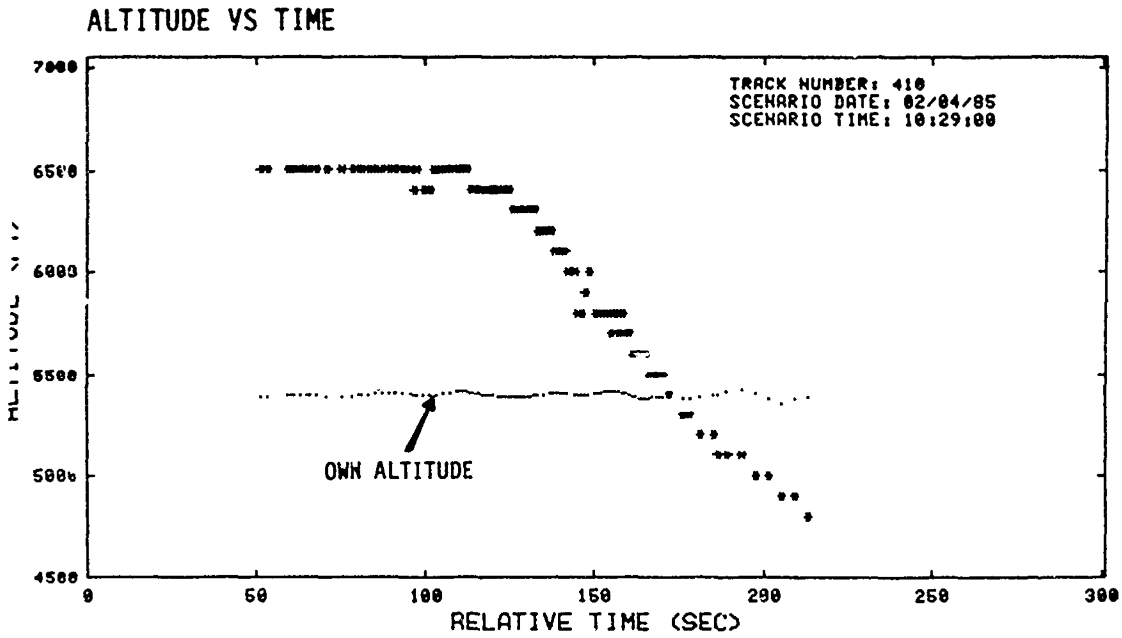
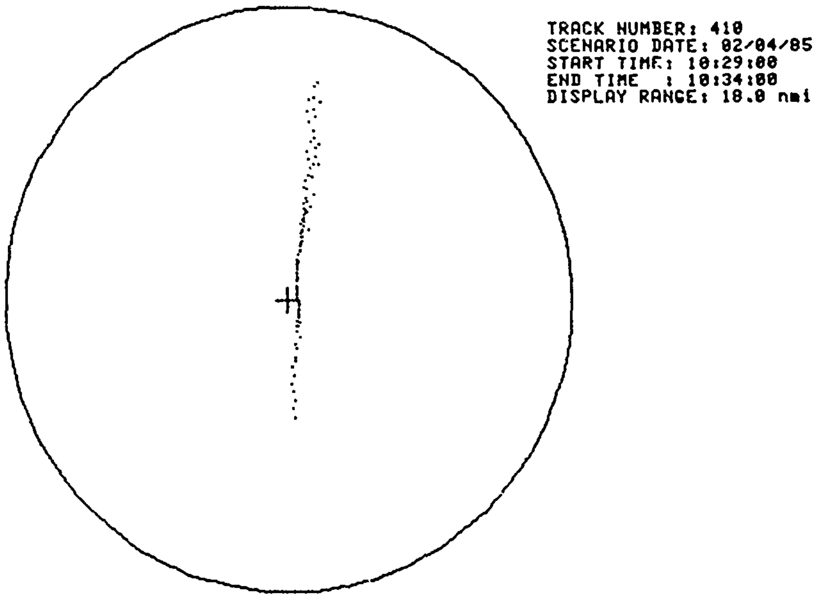


FIGURE 4.3.3-1. TARGET OF OPPORTUNITY,#1
(SHEET 1 OF 2)





TCAS-032.2A

FIGURE 4.3.3-1. TARGET OF OPPORTUNITY, #1
(SHEET 2 OF 2)

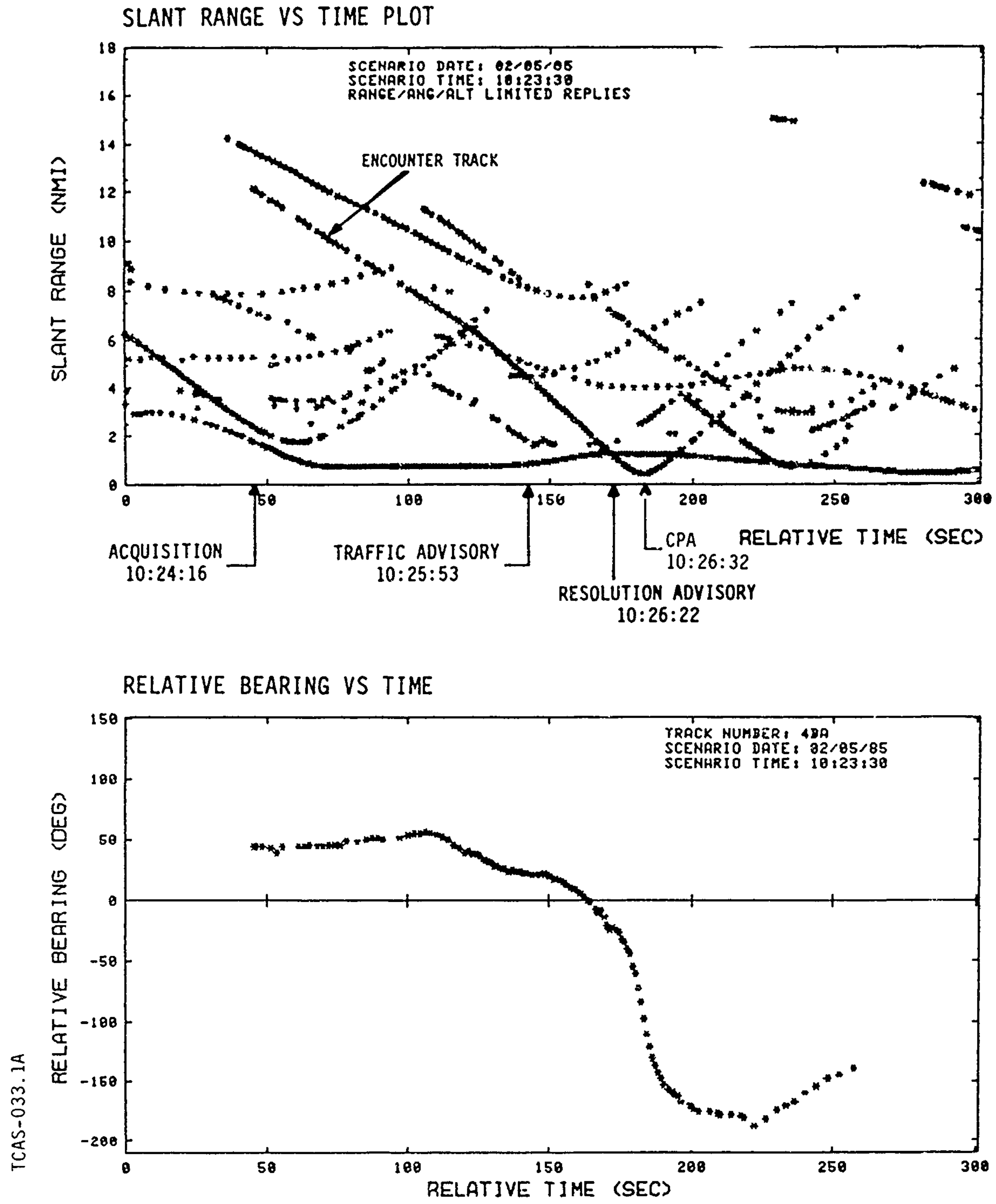
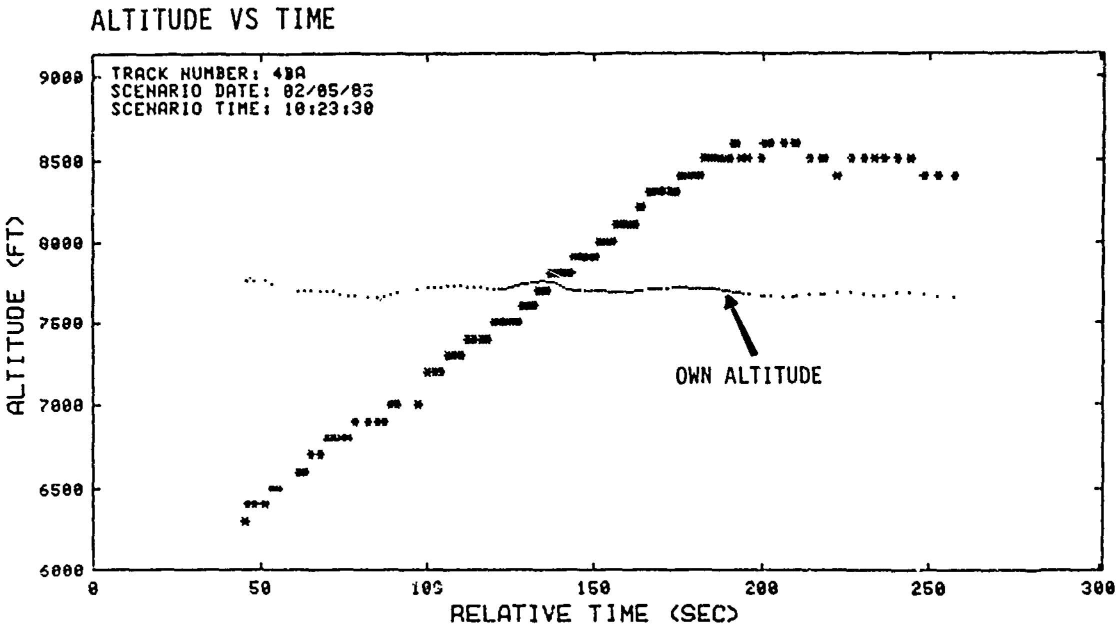
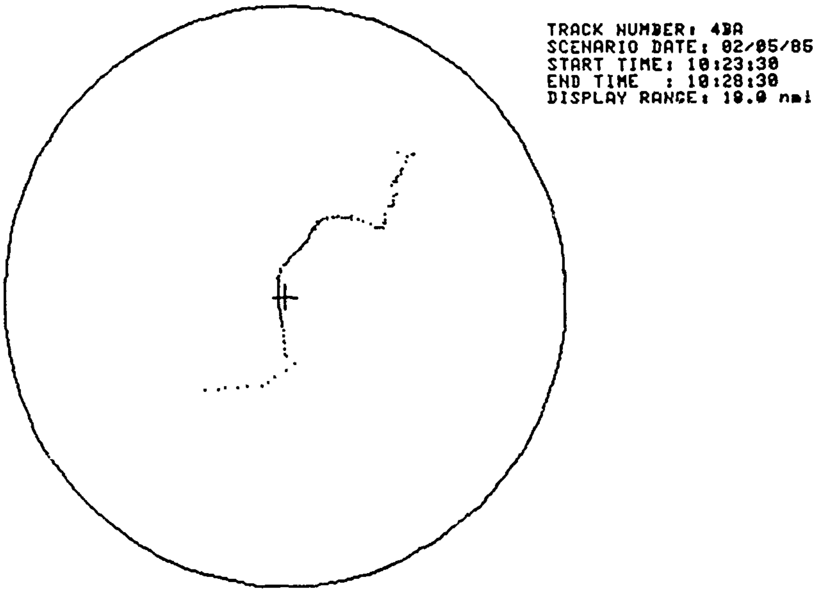


FIGURE 4.3.3-2. TARGET OF OPPORTUNITY, #2
(SHEET 1 OF 2)





TCAS-033.2A

FIGURE 4.3.3-2. TARGET OF OPPORTUNITY, #2
(SHEET 2 OF 2)

FAA TECHNICAL CENTER

	NUMBER	SUCCESSFUL TRACKS (%)	TRACK CONTINUITY (%)	BLIP/SCAN RATIO (%)
OCTOBER 25, 1984				
ENCOUNTERS ONLY	13	100	98.0	96.1
TARGETS OF OPPORTUNITY	6	100	100	92.3
NOVEMBER 13, 1984				
ENCOUNTERS ONLY	4	100	100	92.0
TARGETS OF OPPORTUNITY	2	100	100	90.0
NOVEMBER 28, 1984				
ENCOUNTERS ONLY	6	100	100	89.3
DECEMBER 20, 1984				
TARGETS OF OPPORTUNITY	7	100	100	93.1
TOTAL	38	100	99.2	93.1

LOS ANGELES BASIN

	NUMBER	SUCCESSFUL TRACKS (%)	TRACK CONTINUITY (%)	BLIP/SCAN RATIO (%)
FEBRUARY 3, 1985 AM				
ENCOUNTERS ONLY	12	100	100	94.2
TARGETS OF OPPORTUNITY	5	100	100	89.2
FEBRUARY 3, 1985 PM				
ENCOUNTERS ONLY	15	100	100	92.6
TARGETS OF OPPORTUNITY	6	100	97.3	90.0
FEBRUARY 5, 1985				
ENCOUNTERS ONLY	24	100	100	94.9
TARGET OF OPPORTUNITY	5	100	100	93.6
TOTAL	67	100	99.7	93.3

SUCCESSFUL TRACKS = PERCENTAGE FOR WHICH A TRACK EXISTED 25 SECONDS PRIOR TO CPA

TRACK CONTINUITY = FOR THE 50- SECOND PERIOD PRIOR TO CPA, PERCENTAGE OF TIME DURING WHICH A TRACK EXISTED (INCLUDING COASTS)

BLIP/SCAN RATIO = LIMITED TO THE 50- SECOND PERIOD PRIOR TO CPA AND LIMITED TO THE TIME IN TRACK, THIS IS PERCENTAGE OF THE INTERROGATIONS FOR WHICH TARGET REPORTS WERE GENERATED

FB-VG-1757

FIGURE 4.4-1. TCAS III PERFORMANCE STATISTICS were the pre-defined trajectories flown between the ETEU and an FAA target aircraft. Targets which came within 2 nautical miles and ±2500 feet in relative altitude of the ETEU at closest point of approach (CPA) were determined to be targets of opportunity. The computed statistics: successful tracks, track continuity, and blip/scan ratio are as defined in "Active BCAS: Design and Validation of the Surveillance Subsystem," Project Report ATC-103, W. H. Harman, R. R. LaFrey, J. D. Welch, M. L. Wood, Lincoln Laboratory, MIT, Lexington, MA, 17 December 1980. Successful tracks indicates the percentage of tracks that existed 25 seconds before CPA. Track continuity is the percentage of time during which a track existed (including coasts) for the 50-second period before CPA. The blip/scan ratio shows the percentage of interrogations for which target reports were generated, limited to the 50-second period before CPA and further limited to the time under track.

The upper portion of Figure 4.4-1 shows the performance statistics for 38 ATCRBS tracks, 23 encounters and 15 targets of opportunity at the FAA Technical Center in New Jersey. The number of successful tracks is 100%, the track continuity is 99.2% and the blip/scan ratio is 93.1%. The performance of the ETEU in Los Angeles in a much higher density environment is shown in the lower portion of the figure. Here, the number of successful tracks is 100%, the track continuity is 99.7% and the blip/scan ratio is 93.3% for 67 ATCRBS tracks. These statistics are slightly better than those compiled at the FAA Technical Center. There was no degradation in performance due to aircraft density.

5.0 CONCLUSION

The major goal of proving the feasibility of horizontal maneuvers for collision avoidance has been accomplished. A highly directional antenna that gives one to two degrees bearing accuracy is the major reason this is possible. The use of accurate bearing measurements adds the extra dimension needed for horizontal maneuver capability for collision avoidance. In addition, bearing is also used to filter target data and allow successful operation in high density environments.

The concept and design of TCAS III has been validated during this contract through the development and test of the two Engineering models. The extensive flight testing proved to be invaluable in the analysis and evaluation of processing algorithms. In addition, many operational features of the TCAS III equipment have been refined due to observations by the test pilots and FAA Technical Center personnel. It has been proven that the TCAS III's accurate bearing measurement capability permits the issuance of horizontal in addition to vertical resolution advisories and reduces the system's susceptibility to interference, allowing full operation in high traffic density environments.

APPENDIX A

MANUALS

BCD-TR-076	TCAS III Instruction Manual	Jul 1986
BCD-TR-099	TCAS III Computer Program Documentation, Volumes 1-3	Jun 1986
BCD-TR-143	TCAS III Operator's Manual	Jul 1986
BCD-TR-144	TCAS III Cockpit Display Manual	Jul 1986

REPORTS

BCD-TR-053	Task-I Factory Performance Test Plan for Scalar Mode Computer Program	Jan 1982
BCD-TR-058	Task-I Factory Performance Test Report, Volumes I-II	Apr 1982
BCD-TR-063	TCAS II Engineering Model Design Specification (Model A and Model B)	Apr 1982
BCD-TR-069	TCAS II Model A TEU Installation Plan	Nov 1982
BCD-TR-070	Addendum to Task-I Factory Performance Test Report	Sep 1982
BCD-TR-071	TCAS II Model A TEU Factory Acceptance Test Plan	Nov 1982
BCD-TR-073	TCAS II Model A TEU Factory Accept-Test Results Functional Tests	Nov 1982
BCD-TR-073	Addendum to TCAS II Model A TEU Factory Acceptance Test Results Functional Tests	Feb 1983
BCD-TR-074	TCAS II Model A and Model B Field Acceptance Test Plan	May 1983
BCD-TR-084	TCAS II Model B TEU Factory Acceptance Test Plan	Jun 1983
BCD-TR-090	Enhanced TCAS II Antenna Characteristics Report	Oct 1983

REPORTS (Continued)

BCD-TR-092	Simulation of Enhanced TCAS II Signal Processor Hardware Design, Volumes 1-2	Feb 1984
BCD-TR-098	TCAS III System Summary	Apr 1985

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BCD-TN-81-013 FB-467-001	Systems Considerations P. Kernan	Mar 1981
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BCD-TN-81-014 FB-467-003	Mode Selection M. B. Covington	Mar 1981
BCD-TN-81-015 FB-467-004	Full BCAS Antenna Transfer Function Algorithms A. I. Sinsky, M. V. Wilhelm	Mar 1981
BCD-TN-81-016 FB-467-005	Miss Distance Estimation from Two Range, Bearing Measurements T. L. Gabriele	Mar 1981
BCD-TN-81-023A FB-467-006A	Target Motion Model A. I. Sinsky	Jun 1981
BCD-TN-81-024 FB-467-007	Minimum Variance Estimation A. I. Sinsky, E. A. Lew	May 1981
BCD-TN-81-025 FB-467-008	Parallel Path Turn-in Escape Time T. L. Gabriele	May 1981
BCD-TN-81-026 FB-467-009	Notes from FAA-ER-250-1 J. W. Martin	May 1981
BCD-TN-81-028 FB-467-010	Self Reply Blockage Effects on Passive BCAS in an ATCRBS Environment A. D. McComas	May 1981
BCD-TN-81-032 FB-467-011	Garble Analysis M. A. Martin	Jun 1981
BCD-TN-81-033 FB-467-012	Alpha-Beta Tracking Errors for Orbiting Targets A. I. Sinsky	Jun 1981

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BCD-TN-81-036 FB-467-013	Effects of Unequal Update Intervals on Alpha-Beta Tracker Performance D. Silber, A. J. Spuria	Jul 1981
BCD-TN-81-042 FB-467-015	Full BCAS Covariance Analysis E. A. Lew, C. J. Smearman	Aug 1981
BCD-TN-81-044 FB-467-016	Interference to DABS Squitter Detection in L.A. Basin P. Kernan, A. I. Sinsky	Sep 1981
BCD-TN-81-054 FB-467-017	TCAS Monopulse Equivalent Beamwidths C. J. Smearman	Oct 1981
BCD-TN-81-055 FB-467-018	Analysis of the Effects of Angle Errors on Miss Distance Estimate D. Silber	Nov 1981
BCD-TN-81-056 FB-467-019	Detection of DABS Squitters D. C. Hecht	Nov 1981
BCD-TN-81-057 FB-467-020	Filter Requirements for TCAS Interrogator Transmitter A. I. Sinsky	Nov 1981
BCD-TN-81-058 FB-467-021	Monopulse Processor Analysis A. I. Sinsky, E. A. Lew	Nov 1981
BCD-TN-81-061A FB-467-022A	Preliminary Evaluation of MITRE Hit or Miss Algorithms S. J. Guarino	Feb 1982
BCD-TN-82-011 FB-467-023	Interference Analysis for Collision Avoidance Systems in the Los Angeles Basin from 1985 to 1995 P. Kernan	Feb 1982
BCD-TN-82-017 FB-467-024	Squinted Beam Monopulse Processor A. I. Sinsky	Apr 1982
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BCD-TN-82-035 FB-467-027	System Angle Accuracy Prediction A. I. Sinsky, R. J. Tier	Jul 1982
BCD-TN-83-004 FB-467-028	TCAS Electronic Beam Steering Unit Troubleshooting Procedure A. I. Sinsky, R. J. Tier	Apr 1983

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BCD-TN-83-008 FB-467-029	TCAS Antenna Patterns A. I. Sinsky, R. J. Tier, K. Sirageldin	Jul 1983
BCD-TN-84-004 FB-467-030	Miss Distance Prediction Algorithm A. I. Sinsky	Feb 1984
BCD-TN-84-011 FB-489-031	Logic Error Detection in PL/M Source Code J. C. Sipos	Jul 1984
BCD-TN-85-005 FB-489-032	CRC Generation for EPROM Based Computer Systems J. C. Sipos	Jun 1985

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Full BCAS Preliminary Design Review, Volume 1-2	Apr 1981
Full BCAS Design Review	May 1981
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Full BCAS Critical Design Review for the Engineering Model Task I	Sep 1981
TCAS II Bimonthly Review	Dec 1981
TCAS II Bimonthly Review	Mar 1982
TCAS II Bimonthly Review	Jul 1982
TCAS II Bimonthly Review	Oct 1982
TCAS II Bimonthly Review	Dec 1982
Enhanced TCAS II Critical Design Review for Model B TEU	Apr 1983
Enhanced TCAS II Bimonthly Review	Sep 1983
Enhanced TCAS II Bimonthly Review	Dec 1983
Enhanced TCAS II Bimonthly Review Revised Mar 1984	Feb 1984
Enhanced TCAS II Bimonthly Review System Review / Computer Programming	Jun 1984

DESIGN REVIEWS (Continued)

	Enhanced TCAS II Bimonthly Review	Nov 1984

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	Monthly Management Report	Jan 1981
	Monthly Management Report	Feb 1981
	Monthly Management Report	Mar 1981
	Monthly Management Report	Apr 1981
	Monthly Management Report	May 1981
BCD-TR-039	Full BCAS Monthly Management Report	Jun 1981
BCD-TR-042	Full BCAS Monthly Management Report	Jul 1981
BCD-TR-045	Full BCAS Monthly Management Report	Aug 1981
BCD-TR-048	TCAS II Monthly Management Report	Sep 1981
BCD-TR-049	TCAS II Monthly Management Report	Oct 1981
BCD-TR-050	TCAS II Monthly Management Report	Nov 1981
BCD-TR-051	TCAS II Task I Monthly Management Report	Dec 1981
BCD-TR-052	TCAS II Task II Design Management Report and Monthly Management Report	Dec 1981
BCD-TR-054	TCAS II Task I Monthly Management Report	Jan 1982
BCD-TR-055	TCAS II Task II Monthly Management Report	Jan 1982
BCD-TR-056	TCAS II Task I Monthly Management Report	Feb 1982
BCD-TR-057	TCAS II Task II Monthly Management Report	Feb 1982
BCD-TR-059	TCAS II Task I Monthly Management Report	Mar 1982
BCD-TR-061	TCAS II Task I Monthly Management Report	Apr 1982

MONTHLY MANAGEMENT REPORTS (Continued)

BCD-TR-062	TCAS II Task II Monthly Management Report	Apr 1982
BCD-TR-064	TCAS II Task II Monthly Management Report	May 1982
BCD-TR-065	TCAS II Task II Monthly Management Report	Jun 1982
BCD-TR-066	TCAS II Task II Monthly Management Report	Jul 1982
BCD-TR-067	TCAS II Task II Monthly Management Report	Aug 1982
BCD-TR-068	TCAS II Task II Monthly Management Report	Sep 1982
BCD-TR-072	TCAS II Task II Monthly Management Report	Oct 1982
BCD-TR-075	TCAS II Task II Monthly Management Report	Nov 1982
BCD-TR-077	TCAS II Task II Monthly Management Report	Dec 1982
BCD-TR-078	TCAS II Task II Monthly Management Report	Jan 1983
BCD-TR-079	TCAS II Task II Monthly Management Report	Feb 1983
BCD-TR-080	TCAS II Task II Monthly Management Report	Mar 1983
BCD-TR-082	TCAS II Task II Monthly Management Report	Apr 1983
BCD-TR-083	TCAS II Task II Monthly Management Report	May 1983
BCD-TR-085	TCAS II Task II Monthly Management Report	Jun 1983
BCD-TR-086	TCAS II Task II Monthly Management Report	Jul 1983
BCD-TR-087	TCAS II Task II Monthly Management Report	Aug 1983

MONTHLY MANAGEMENT REPORTS (Continued)

BCD-TR-088	TCAS II Task II Monthly Management Report	Sep 1983
BCD-TR-089	TCAS II Task II Monthly Management Report	Oct 1983
BCD-TR-091	TCAS II Task II Monthly Management Report	Nov/Dec 1983
BCD-TR-094	TCAS II Task II Monthly Management Report	Jan 1984
BCD-TR-095	TCAS II Task II Monthly Management Report	Feb 1984
BCD-TR-097	TCAS II Task II Monthly Management Report	Mar/Apr 1984
BCD-TR-100	TCAS II Task II Monthly Management Report	May/Jun 1984
BCD-TR-115	TCAS II Task II Monthly Management Report	Jul 1984
BCD-TR-117	TCAS II Task II Monthly Management	Aug/Sep 1984
BCD-TR-123	TCAS II Task II Monthly Management Report	Oct 1984/ Jan 1985
BCD-TR-123	TCAS II Task II Monthly Management Report	Feb/Apr 1985
BCD-TR-135	TCAS II Task II Monthly Management	May/Jul 1985

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