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Traffic Alert and Collision Avoidance System

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Operational Simulation

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March 1985
Final Report

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16. Abstract

This report describes one of a series of studies being conducted to develop the Traffic Alert and Collision Avoidance System (TCAS). The purpose of this study was to conduct a pilot evaluation of the relationship between TCAS displays, an operational crew station, aircraft performance, TCAS logic and operational TCAS procedures. The specific objectives of the evaluation were to be:

- Develop and evaluate the operational procedures associated with TCAS alerts under both normal and abnormal flight operations
- Assess changes in flight deck operations associated with TCAS
- Assess operational procedures as related to ATC control
- Assess the impact of TCAS display requirements on flight deck systems and geometry

During the evaluation experienced transport pilots were presented TCAS alerts while flying a high fidelity B737-200 training simulator. Their response to the alerts was observed and recorded as were their opinions concerning the system. As a result of reviewing pilot responses to 552 TCAS encounters with a total of 970 intruder aircraft, it is recommended that TCAS be revised to achieve more consistantly correct pilot response.

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PREFACE

This report documents one of a series of studies being conducted to develop and implement an effective collision avoidance system. The primary purpose of the study was to implement in simulation a TCAS which would match as closely as possible the system which would be flight tested and to use that system to perform a pilot evaluation of the relationship between the TCAS displays, an operational crew station, aircraft performance and the TCAS logic. The study was also designed to evaluate the operational procedures for TCAS and the impact of the system on standard ATC and flight deck operations.

The authors wish to express appreciation to the many pilots who participated in the evaluation and to the various organizations and comapnies which permitted and encouraged participation; FAA, ATA, ALPA, and Flying Tiger, Piedmont, Republic TransWorld, United, and USAir airlines. The contract sponsor is the Federal Aviation Administration and technical guidance was provided by Mr. Richard Weiss, APM-430, the contract moniter.

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LIST OF ABBREVIATIONS

ADI	Attitude Director Indicator
AID	Airborne Intelligent Display
ALPA	Airline Pilots Association
ANOVA	Analysis of Variance
APA	Allied Pilots Association
ARP	Aerospace Recommended Practice
ASA	Aircraft Separation Assurance
ATA	Air Transport Association
ATC	Air Traffic Control
BCAS	Beacon Collision Avoidance System
BEU	BCAS Experimental Unit
CAS	Collision Avoidance System
CDTI	Cockpit Display of Traffic Information
X	Chi-squared
CPA	Closest Point of Approach
CRT	Cathode Ray Tube
dB	Decibel
df	Degrees of Freedom
DME	Distance Measuring Equipment
EADI	Electronic Attitude Director Indicator
EHSI	Electronic Horizontal Situation Indicator
FAA	Federal Aviation Administration
fpm	Feet per minute
ft-L	Footlambert
G	Gravity
HSI	Horizontal Situation Indicator
HUD	Head-up Display
Hz	Hertz
IAS	Indicated Airspeed
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
IVSI	Instantaneous Vertical Speed Indicator
KIAS	Knots Indicated Airspeed
LED	Light Emitting Diode
MCC	Master Control Console
ml	Millilambert
msec	Millisecond
MSL	Mean Sea Level
NASA	National Aeronautics and Space Administration
nmi	Nautical Miles
PA	Proximate Advisory
PROM	Programmable Read Only Memory
PWI	Proximity Warning Indicator
r	Correlation Coefficient
RA	Resolution Advisory
RAM	Random Access Memory
SAE	Society of Automotive Engineers
S.D.	Standard Deviation
sin	Sine of an angle
S/N	Signal to Noise Ratio
TA	Traffic Advisory
TAV	TCAS Audio Video
TCA	Terminal Control Area
TCAS	Traffic Alert and Collision Avoidance System
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
X	Arithmetic Mean

GLOSSARY

Abnormal Conditions	-	Conditions or situations which require other than normal procedures.
Advisory Alert	-	Operational or aircraft system conditions that require crew awareness and may require crew action.
Advisory System	-	A system which provides the crew guidance that they follow only if they have some other reason to believe they should.
Alert	-	Indicator (visual, auditory or tactile) which provides information to the crew in a timely manner about an abnormal situation.
Caution Alert	-	Abnormal operational or aircraft system conditions that require immediate crew awareness and require prompt corrective or compensatory crew action.
Corrective Alert	-	Resolution Advisory which requires a corrective action by the pilot, e.g., "Limit climb 500 feet per minute" when the present value is greater than 500 fpm.
Developmental Simulation	-	Phase I of the TCAS display program with the objective to develop minimum information requirements for the TCAS II display system and to recommend a candidate configuration.
Detection Time	-	The time from alert initiation or change of state (caution to warning) until when the pilot indicates a recognition of the condition by depressing the detection button.
Executive System	-	A system which provides the crew guidance that they are required to follow unless they have reason to believe that they shouldn't.
G	-	Acceleration equivalent to gravity or 32.2 feet per second squared.
Hertz	-	Unit of frequency equal to one cycle per second.
Intruder	-	Any aircraft tracked by TCAS

Non-mode C Aircraft	-	An aircraft that has an ATCRBS transponder but does not have altitude reporting capability.
Operational Simulation	-	Phase II of the TCAS display program with the objective of developing and evaluate operational cockpit procedures for a TCAS encounter.
Own Aircraft	-	The test subject simulation aircraft equipped with the hypothetical TCAS II system.
Preventive Alert	-	Resolution Advisory which informs the crew of an action they should not take even though they are not presently doing it, e.g., "Limit climb to 500 fpm" when the present value is less than 500 fpm.
Procedure	-	Predetermined set of actions to be taken by a crewmember in a specific operational situation. May or may not be written in a readily accessible form (e.g., checklist).
Proximate Aircraft	-	Any aircraft that are not a TCAS defined threat (TA or RA) and are within 1200 feet altitude and 4 nmi range.
Resolution Advisory	-	A warning level alert - a display indication given to the pilot recommending a vertical maneuver to increase or maintain separation relative to an intruding aircraft.
Response Time	-	The time from alert initiation (RA) until the pilot had performed the correct response.
TAU	-	A derived quantity usually expressed in seconds, which represents the estimated time to the point of closest approach between the own aircraft and an intruder. It is defined as range divided by range rate.
TCAS I	-	A less sophisticated collision avoidance system designed primarily for general aviation. This system provides proximity alerts, but does not provide resolution advisories.

TCAS II	-	A more sophisticated system providing collision avoidance capabilities in high density areas and designed for larger aircraft.
Threat Aircraft	-	Any aircraft which trigger a TCAS alert, either RA or TA.
Time Critical Warning	-	Warning condition in which time to respond is extremely limited and the response to the alert is the most important action the pilot can make at that specific time (e.g. ground proximity, takeoff abort, windshear, etc.)
Traffic Advisory	-	A caution level alert - a display indication that there is traffic in the immediate vicinity which could cause a resolution advisory. The information contains no suggested maneuver.
Traffic Information Display	-	A display used to provide the pilot with information about TCAS defined intruder aircraft. It may also be used to present information about non-tau based surrounding traffic ("proximate aircraft").
Transponder	-	Piece of equipment on an aircraft which when interrogated by a radar signal emits a coded reply containing specific information about the aircraft.
Unequipped Aircraft	-	An aircraft that has no TCAS system and may or may not have a mode C transponder.
Warning Alert	-	Emergency operational or aircraft system conditions that require immediate corrective or compensatory crew action.
Workload	-	A relative term indicating the amount of total mental and physical task loading on a crewmember.

1.0 Introduction

The Federal Aviation Administration (FAA) has been sponsoring a series of studies to develop an airborne separation assurance system called the Traffic Alert and Collision Avoidance System (TCAS). These studies include analytical and design efforts as well as flight simulations and actual flight tests. The Boeing Commercial Airplane Company has been contracted to conduct a two phase program using flight simulation to test and evaluate certain aspects of TCAS. This report will document the final phase of this effort and provide conclusions and recommendations based on the total study effort.

1.1 Background

On June 23, 1981, the Federal Aviation Administrator announced his decision to proceed with the implementation of an aircraft separation assurance concept called the Traffic Alert and Collision Avoidance System (TCAS). This system was designed to meet a set of previously defined criteria: "(a) be capable of operating without dependence on any ground equipment; (b) be inexpensive enough to meet the needs of general aviation and provide the higher order services and functions desired by the larger airplane users; (c) be fully compatible with the ATC system, and capable of performance improvement or expansion when coupled with the ATC system; (d) be such that it can be accommodated by the Department of Defense, but not compromise their specific requirements; and (e) it must be available in production in 36 to 48 months".(1) The objective of this approach was to provide a range of separation assurance equipment alternatives that can provide collision protection for the full spectrum of airspace users and operate without dependence on ground equipment.

TCAS comprises two principal levels of system sophistication. The simplest and lowest cost level, TCAS I, has an integral transponder capable of responding on Modes A, C, and S. This system, as a minimum, will alert the pilots of aircraft in close proximity by using visual and/or aural alerts. The principal users of TCAS I would primarily be general aviation. The TCAS II system, on the other hand, is a more sophisticated system (in terms of sensors, computative capability and displays) at a higher cost. It is, therefore, more

appropriate for air carrier utilization. As has been pointed out in FAA sponsored symposiums the technological risk of the program has been reduced because most of the technology associated with the TCAS II system was developed under the earlier Beacon Collision Avoidance System (BCAS) program. One of the major advancements over the earlier systems noted in the news release made available at the time of the initial presentation, is the ability to provide the pilot with traffic advisory information in all airspace independent of the ground ATC system. This release notes that TCAS "will have an integral scanning directional antenna with direction finding accuracy capable of supporting a cockpit display of traffic information".(2)

TCAS II is an onboard system composed of a computer that is equipped with collision-avoidance logic, special antennas (at least one directional antenna), a Mode-S transponder (an Air Traffic Control Radar Beacon System (ATCRBS) transponder that sends an altitude signal along with the other transponder information and can be individually queried), and displays for the traffic and resolution advisories. This system determines the bearing, range, and altitude, and various rates of nearby aircraft; it then projects the nearby aircraft's path relative to the own aircraft. Depending on the relationships of the two paths, the system will issue an appropriate alert. Of equal importance to the overall functioning of the system sensors and logic is the presentation of the TCAS information to the crew in such a way that it can be used effectively in an operational environment. Once the presentation media is identified, the way in which the information is to be used must be defined.

It is difficult to evaluate even a limited array of display devices in an operational aircraft, and it is similarly difficult to perform comprehensive workload analyses since the variety of possible flight and intrusion scenarios is necessarily limited by safety considerations. Therefore, in August, 1982, the Boeing Commercial Airplane Company, Crew Systems Technology was awarded a contract by the FAA for the purpose of assisting in the determination of flight deck display and procedural requirements and the operational impact of implementating the TCAS II system in commercial transport aircraft. The program was a two-phase effort, the Developmental Simulation and the Operational Simulation. The first phase combined a number of resolution advisories as well as traffic advisory display concepts with an integrated crew alerting system for

evaluation by government, industry, and airline pilots. The second phase had airline flight crews exercise the TCAS II system in a fully certified operational transport training simulator, in order to validate the characteristics of the selected TCAS II display configuration and to evaluate operating procedures, crew activity, ATC interaction, and system functioning in an operational environment.

These simulation studies and the experimental designs, recommendations and system concepts are based on the assumption that the TCAS II system is an "Executive" system. "Executive" herein means that the crews are required to perform the escape maneuver unless they have reason to believe that they should not do so. This assumption was consistent with the system descriptions presented in the various conferences conducted by the FAA concerning TCAS. An example of this can be seen in the documentation from the second TCAS conference where it is stated about the TCAS logic that "it must be understood that the parameter settings used [in the TCAS logic] depend upon a prompt and positive response on the part of the pilot".(3)

Since an indicator which provides information to the crew in a timely manner about an abnormal situation is the definition of an alert, the cornerstone of any display concept including TCAS should be the voluntary guidelines on alerting systems issued by the FAA in 1981.(4) These guidelines were a culmination of seven years of research sponsored by the FAA and directed toward the improvement and standardization of flight deck alerting systems. They were produced through a joint effort by the Boeing, Lockheed, and McDonnell Douglas Aircraft Companies and describe, in detail, the recommendations for presentation of alerts of any urgency (see Figure 1.1-1). From the research conducted during this program, a set of warning level alerts were identified that were defined as "time-critical". The report (4) describes the alerting methods and media for presenting the time-critical warnings. If TCAS is implemented as an executive system, the Resolution Advisory fits the definition of a time critical warning. Therefore, in selecting the display characteristics to be tested in the developmental simulation, it was necessary to review the crew

CONDITION	CRITERIA	ALERT SYSTEM CHARACTERISTICS		
		VISUAL	AURAL	TACTILE
WARNING	Emergency operational or aircraft system conditions that require *immediate* corrective or compensatory crew *action*	Master visual (red) plus centrally located alphanumeric readout (red)	Unique attention-getting warning sound plus voice*	Stick shaker (if required)
CAUTION	Abnormal operational or aircraft system conditions that require *immediate* crew *awareness* and require prompt corrective or compensatory crew action	Master visual (amber) plus centrally located alphanumeric readout (amber)	Unique attention-getting caution sound plus voice*	None
ADVISORY	Operational or aircraft system conditions that require crew *awareness* and may require crew action	Centrally located alphanumeric readout (unique color)	Unique attention-getting advisory sound	None
INFORMATION	Operational or aircraft system conditions that require cockpit indications, but not necessarily as part of the integrated warning system	Discrete indication (green and white)	None	None

*Voice is pilot selectable.

Figure 1.1-1 Guidelines for Standardizing Alerting Functions and Methods

alerting data base and select those characteristics most likely to provide the most effective information transfer. (10)

The final effort of the developmental simulation was to recommend a TA and RA display combination and the characteristics of the displays for the subsequent phases of the program and flight verification. Since the TCAS information can be classified as alerts, the displays should perform the functions attributed to the alerting system which are:

1. Attracting the attention of the crew and directing that attention to the alert condition so that corrective action can be taken.

2. Informing the flight crew of the location and nature of the alert condition. Sufficient information should be provided to enable the crew to initiate timely, corrective action.

3. Providing the crew feedback on the adequacy of their corrective action.

4. Providing the crew with a mechanism(s) to control the system.

The need for each of these functions was identified by Cooper (9), Boucek, Erickson, Berson, Hanson, Leffler, and Po-Chedley (12), and in SAE Aerospace Recommended Practice ARP-450D (14). The manner in which these basic functions are to be implemented will determine the effectiveness of the alerting system. ARP-450D states that "safety of flight is greatly enhanced by an alerting system designed to provide early crew recognition of flight crew operational error, as well as aircraft system or component status or malfunctions". For example, the system should attract the crew's attention to an alerting situation, but should not be so disruptive that it degrades peformance of other crew tasks, information processing, or the decision-making required to take corrective actions. The guidelines for designing these basic functions are described in the Aircraft Alerting Systems Standardization Study.(4)

In this framework, the goals of the display development effort were: to present information in such a way as to minimize the time for the flight crew to

detect, assess and respond to the alerts; to keep information processing and memorization requirements at a minimum; to guide all display and alert logic by the quiet, dark cockpit philosophy; and finally, to minimize distraction and startle effects so as to reduce disruption of aircraft control.

The candidate TCAS display concept developed during the Phase I study and recommended for further evaluation is presented in Figure 1.1-2. This concept was implemented in an operational training simulator and closely replicated the system that will be used in future flight tests. Twelve experienced transport pilots flew and evaluated the system in 552 encounters with 970 intruder aircraft. The following report describes this study.

1.2 Report Organization

Section 2 of this report contains an executive summary of the major activities and findings of the Operational Simulation evaluation effort. A general description of the test facility is presented in Section 3. The methodology, equipment and results of the evaluation are discussed in Section 4. Discussion of the major findings and their relationship to the overall program may be found in Section 5. Issues which remain unresolved and have an impact on the program are enumerated in Section 6. Finally, the conclusions and recommendations reached as a result of the simulation efforts are presented in Section 7. The Appendices at the end of this report describe, in detail, the test facility and the equipment that was added to implement TCAS. The complete written training package has been provided. Also included are the observational data collection form, the questionnaires that were used to obtain pilot input and a description of the mission and intruder scenarios.

- MASTER ALERTS
  - A unique warning sound and red light on the glareshield should be used for all warning level alerts
  - A unique caution sound and amber light on the glareshield should be used for all caution level alerts
- RESOLUTION ADVISORY DISPLAY
  - A visual display should be provided that will graphically present not only the recommended vertical maneuvers but also any vertical speed limitations or restrictions
  - A voice alert should continuously present the same information as the visual display until it is manually canceled or the alerting situation no longer exists
- TRAFFIC INFORMATION DISPLAY
  - Before a plan view display of traffic could be recommended as a necessary system component, further testing was required to assess its impact on the total aircraft system operations
  - For the testing effort, the TA display should provide a coded (by alert urgency) graphic presentation of the traffic information including at least bearing, altitude, horizontal separation, and vertical movement information

Figure 1.1-2 Candidate TCAS Display Concept

2.0 Executive Summary

The following section will present an overview of the Operational simulation and the conclusions reached as a result of the simulation efforts as they relate to the current Traffic Alert Collision Avoidance System (TCAS) program concept. This section is meant solely as an expanded summary, for more detailed discussion of each section, refer to the main body of the report.

2.1 Introduction

In August 1981, the Boeing Commercial Airplane Company was awarded a contract by the FAA for the purpose of assisting in the determination of flight deck display requirements and operational procedures for implementation of the TCAS II system in commercial transport aircraft. The program was a two-phased effort: the "Developmental Simulation" evaluated the display requirements of the TCAS II system and identified display configuration concept(s) to be tested further (10); and the "Operational Simulation" evaluated the operating procedures, identified problems in the interaction with air traffic control, and evaluated the display system concept.

These simulation efforts were directed toward the TCAS II system, and based on the assumption that TCAS II is an executive system; the pilots are required to follow the system guidance unless they have reason to believe they should not. (See procedures in Figure 4.2-4).

TCAS II is an onboard system composed of a computer that is equipped with collision avoidance logic, special antennas (at least one directional antenna), a Mode-S transponder (an air traffic control transponder that sends an altitude signal along with the other transponder information and can be individually queried), and displays for the traffic alerts. This system determines the bearing, range, and altitude of nearby aircraft; it then projects the nearby aircraft's path relative to the own aircraft. Depending on the relationships of the two projected paths, the system will issue an appropriate alert. Of equal importance to the overall functioning of the system sensors and logic is the presentation of the TCAS information to the crew in such a way that it can be used effectively in an operational environment. Once the presentation

media is identified, the way in which the information is to be used must be defined.

The Phase I effort (Developmental Simulation) was designed to study the information presentation to the crew. The major objectives of the developmental simulation were: to evaluate the alerting effectiveness of candidate TCAS display system concepts; to evaluate display sophistication with respect to different levels of flight deck sophistication; to determine the viability of including caution level alerts prior to the warning alerts; to identify the minimum information requirements for the caution and warning alerts; and to recommend a TCAS display concept to be used in future testing. In selecting the display characteristics to be tested for TCAS, it was necessary to review the crew alerting data base and select those characteristics most likely to ensure compliance with the guidelines.

The final effort of this phase was to recommend a candidate Traffic Advisory (TA) and Resolution Advisory (RA) display combination and the characteristics of the displays for the subsequent phases of the program including operational simulation and flight testing. The resulting functional concept recommendation is presented in Figure 1.1-2.

The Phase II effort (Operational Simulation) was directed toward using the concept derived in Phase I to investigate the way in which the information was used and the interaction between the crew and the TCAS system.

2.2 Operational Simulation Summary

The major objectives of the operational simulation were: to develop and evaluate the operational procedures for response to the different TAs and RAs; to assess changes in crew procedures associated with TCAS utilization; to explore the man-machine interface and information transfer capabilities of the TA and RA displays; to identify needs, if any, to improve format, location, and/or symbology; to assess the workload (activity) impact of TCAS in an operational environment under normal and abnormal conditions in simulated IFR flight. Although the weather represented during the test was essentially VMC 'on top", the lack of resolution in the video system to present objects with visual

angles small enough to provide a realistic representation of the intruder aircraft at the ranges required by TCAS precluded the use of any visual representation of these aircraft. While the lack of visual intruders did not permit TCAS to be evaluated with respect to visual target acquisition, the information gained from the study is relevant because the system should function in all visual conditions and a great many operational aspects of the system can be evaluated without reference to the visual environment. Furthermore, the pilots were not informed of the absence of visual targets, and they were encouraged to visually search for intruders whenever the visibility conditions permitted. They were not relieved of any of their visual responsibilities in performing the flight task. These aspects of the simulation permitted the evaluation of pilot performance in those situations when the crew does not visually acquire the intruder and will therefore have to rely on the information presented by TCAS to perform their maneuvers. The system should be able to accommodate these situations.

In order to provide an operationally realistic environment for the TCAS evaluation, a certified B737 training simulator with six degrees of motion and a full visual capability was used as the TCAS test aircraft. In an attempt to generate data which would be comparable and relevant to the planned, future flight tests, the TCAS system implementation in the simulator represented as closely as possible the system that will actually be flown in the Piedmont flight test (Figure 4.2.1-1). Master TCAS warning and caution lights were located in front of both crew members. Each crew member also had a modified IVSI to present the RA information. A CRT traffic advisory display (Figure 4.2.1-3) was located in the weather radar position (on the forward panel of the center aisle stand). A separately installed speaker presented the alerting tones and voice messages.

In order to provide realistic system responses, the FAA furnished a version of the TCAS logic that was being flown at Lincoln Laboratories and it was implemented in the TCAS simulator. This logic package (Version 9.1) was the latest one available at the time of testing; however, a new version (Version 11) is now being implemented for follow-on flight testing. The use of version 9 in simulation should have had no effect on the test because the selection of intrusion scenarios was coordinated with the FAA and MITRE to prevent testing

situations that would be presented differently by the two logic versions. One major display difference between the two versions was that the vertical direction arrow for the intruders, although implemented in the simulator, was not triggered by the version 9.1 logic. This arrow is designed to inform the crew when the intruder is climbing or descending greater than 500 fpm and is intended to aid in pilot acceptance of altitude crossing maneuvers. However, the effect of this absence on the test data was felt to be minimal based on the conclusions reached in the flight test program which state that "the condition of the vertical rate arrow to the altitude tag does not appear to resolve the problem (of altitude crossing) since the arrow commonly appears in situations where no altitude crossover is required" (15) and which seem to express some doubts as to the effectiveness of the arrow.

A software package was also developed that would simulate the transponder signals of intruder aircraft flying any specified profile. The intruder aircraft could then be launched at the TCAS test aircraft resulting in TCAS advisory situations. A data collection system was installed to permit a time-based recording of the own aircraft parameters as well as those of the intruder(s) and all events that occurred in the cab such as switch and light states or displayed messages. An audio and video recording system was also installed in the cab to keep a permanent record of the crew activity.

Six two-man flight crews from United, Republic, Flying Tiger, Trans World, Piedmont, USAir airlines, and representing both the airline management (ATA) and airline pilots (ALPA), participated in the operational simulation. A detailed description of the flight crews and their flight experience can be found in section 4.3. The crews were scheduled for two days each and flew a combined total of 70 flights. Each flight was approximately 31 minutes in length and were actual segments of operational air-routes (i.e., Seattle to Yakima, Seattle to Chicago, etc.).

The pilots were sent a training package before their scheduled session (see Appendix B). The package contained an explanation of how and why TCAS works and the handbook procedures to be used for both traffic and resolution advisories. Upon their arrival at the simulator, the test conductor answered any

procedures questions they may have had on the training material and updated the edures with the changes that had occurred between the time of printing and the test. A one hour inflight training session was then conducted to familiarize the crews with the TCAS displays and the expected procedures and maneuvers. The pilots were also informed during the test flights when it was detected that they were not following the prescribed procedures.

The procedures given to the crews were written as supplementary procedures to the Operations Manual (as are those for Ground Proximity Warning System). The TA procedure called for a visual search for traffic and permitted minor changes in the flight path based on visual acquisition. The RA procedure called for undertaking a visual search for traffic, activation of the seat-belt sign, disengaging of the autopilot, performance of the maneuver using a .25G vertical acceleration (equivalent to a "Go Around" or a start of descent), and notification of the controlling agency if a clearance were broken. The crew coordination procedures were not dictated; permitting each crew to develop a set of procedures with which they felt comfortable. The procedures adopted by the crews provide an indication of procedures that could be recommended for standardization (see section 4.6.1).

A wide range of flight situations were simulated, including: diversions, holding patterns, engine out, aborted takeoff, go around, jet routes, high altitude descents/climbs, winds/turbulence, and runway obstacles. These situations increased crew workload and gave the pilots a wide range of TCAS experience. Each of the flights had eight planned TCAS situations resulting in a total of 552 situations for the entire evaluation program. These situations resulted in 970 intruder aircraft of which 465 generated traffic advisories and 261 progressed to resolution advisory. Using flight test statistics this number of TA's would have taken 2386 flight hours to occur (a TA is expected to occur every 5.1 hours[16]) and 9696 flight hours for this number of RA's (an RA every 37.2 hours[16]). Thus each crew would have had to fly 398 hours for this number of TA's and 1616 hours to see this number of RA situations. The pilots were informed during training that this is an unnaturally high rate of alerts and that they should treat each situation as an individual rather than be influenced by the total number of alerts. Some of the TCAS situations were chosen because they were more appropriate for simulator testing than

flight testing. As an example, multiple encounters are extremely difficult to set up during flight test. All of the TCAS situations were chosen to avoid testing differences that exist between the different versions of logic. All of the test scenarios coordinated with the FAA Office of Flight Operations, Lincoln Laboratory and the MITRE Corporation to insure that they were appropriate. An ATC controller interacted with the crew throughout the flight, giving them their clearances and responding to their calls.

Even though the overall quality of the TCAS presentation was rated as good by 88 percent of the pilots, seventy-five percent of the pilots reported observing one or more inappropriate, or incorrect alerts during testing. The vast majority of situations that led to this report were altitude crossing maneuvers (e.g., when the intruder is below the own aircraft and climbing and the TCAS alert tells the pilot to "Descend") even though most pilots reported that they knew the intruder was moving vertically by the changes in the relative altitude seen on the TA display. Another cause of these questioned alerts arose from the fact that the TCAS logic does not recognize (for the purpose of issuing a RA) multiple intruders unless they are all in the RA category. This situation can lead to alerts that are perceived by the pilot to be in error (considering the total traffic situation). For example, in the test there was one scenario that had two intruder aircraft- both on collision courses. The closest threat (RA) was 100 feet above the own aircraft, and the other intruder (TA) was 700 feet below. For this situation, the RA for the closest aircraft was a "Descend" command. The crews expressed difficulty with this situation because they anticipated that the system would have had them climb above both intruders.

Even though the RA maneuver was performed in some of the presentations of this scenario, at times it was late due to the indecision of the crew. Both horizontal maneuvers and vertical climb maneuvers opposite the RA ("Descend") were also ocassionally observed as a result of this scenario. All of these responses were inappropriate, given the present TCAS operational accuracy and maneuvering time criticality. In fact, late maneuvers resulted in a separation of less than 50 feet; and should the intruders have been TCAS equipped, the climb maneuvers by the own aircraft could also have resulted in collisions, because the intruder's RA could also have been "Climb."

Most of the pilots (75 percent) had little or no problems with the written procedures. One exception was with multiple intruders, especially when one of the intruders was vertically located in the same direction as the maneuver. A second exception was the amount of time to accomplish the procedure. Seventy-five percent of the pilots reported in their post flight questionnaire that they felt time pressure especially when the normal flight deck workload was high (i.e., during approach). Fifty percent of the pilots commented that horizontal maneuvers should be included as an option. In fact, fifty percent of the crews (3 of 6) used horizontal maneuvers as a response to the TCAS situation at some time during their flights.

The operational procedures used for the test stressed that the information on the TA display was primarily intended to serve as an aid for the visual acquisition of intruder aircraft. Procedures permitted the pilots to make minor changes in flight path to avoid an RA, but only after the intruder has been visually acquired. The question arises, as to what the pilots do with the TA information if they cannot visually acquire the intruder. In the simulation, even though they were reminded of the appropriate procedures during both the training and test flight, and the reasons for these procedures, every flight crew was observed to make intentional, positive and recognizable maneuvers (in the judgment of the on-board observers) changing either altitude or heading in response to some of the TA's even though there was no visual acquisition. Any training program for flight operations should emphasize the procedures in such a way as to stress the importance of avoiding maneuvers based on TA information.

Crew coordination varied slightly among the crews. In general, the most common crew procedure adopted was that the flying pilot searched for outside traffic, recognized the RA and instituted the maneuver, and the nonflying pilot monitored the TA display, called out traffic information, cancelled master alerts, and called ATC as appropriate. This procedure was successful in allocating tasks, but it is not necessarily the only appropriate coordination procedure.

The observer pilot felt that a lot of time was spent studying the TA display even though the pilots were not relieved of their outside visual tasks. Each crew was presented the situation which had an intruder on final approach combined with a runway obstruction (aircraft moving onto runway). Most (84%) of the nonflying pilots expressed consternation that they did not see the obstruction, which they would be expected to on approach, because they were watching the TA display. All of the flying pilots did, in fact, see the obstruction and performed the appropriate go-around maneuver.

The amount of interaction with ATC also varied among the crews. The lowest level was to inform ATC when a clearance was broken. Other types of calls included requests for information on nonaltitude reporting intruders; assistance in TCAS aborts; assistance in multiple intruder situations; and block altitudes and maneuvering space prior to RA. The time that ATC calls were made also varied from the initiation of the TA to the completion of the RA maneuver. One crew, in particular, indicated an attempt to predict the RA by calling ATC and asking for specific maneuvering space prior to the RA alert. Before the system is totally operational, a standard set of crew reporting procedures should be adopted.

All of the pilots felt that both master aural and master visual alerts were needed to attract the crew's attention. The types of aurals used in the study (all of which met the recommendation of the Aircraft Alerting Systems Standardization Study [4]) were rated as good or excellent by 75 percent of the pilots. The most common pilot comments concerning the master alerts were: that they must be cancellable; that the aural alerts be distinctive especially in retrofit aircraft which have a lot of aural sounds; that transition from a high urgency alert to a lower urgency alert should not be announced with the master alerts.

The RA was usually clear and unambiguous; however, rapid changes in the alert (re: climb - limit descent 500 fpm - limit descent 1000 fpm) sometimes led to confusion. This problem has been solved with the present version (Version 11) of the logic. None of the pilots felt that the modifications to the IVSI detracted from the primary purpose of the instrument. The voice system used for simulation was judged to be inadequate by 63 percent of the pilots even though

88 percent wanted voice as part of the system. When the TCAS logic cannot resolve a conflict or it finds that an RA that had been presented was no longer correct, a "TCAS ABORT" (subsequently changed to "TCAS INVALID") alert will be issued. This condition was demonstrated to the crews during training, but did not occur during the test flight because of the inability of the logic to provide the alert. The procedure presented for this situation was to use all the information available, (i.e., the last RA, the outside visual scene, the TA display, flight situation, ATC) to determine the appropriate maneuver. Fifty percent of the pilots objected to the fact that the system even used an abort alert. They felt that developing a procedure to deal with these alerts would be very difficult. Seventy-five percent of the pilots reported that they could not use the TA display information to resolve the TCAS abort situation. The most often-expressed preferred procedure was to maneuver horizontally. If an abort alert is retained it is important that procedures acceptable to the pilot community be defined for that alert.

The TA display was rated as usually or always clear and unambiguous by all of the pilots, and the quality and usefulness of the display was rated as good to excellent by 88 percent. The CRT used for the TA display was a B757/767 technology weather radar tube which is a high resolution stroke written color CRT. The ratings may not have been as high with a tube of lesser quality. The inclusion of color on the display was rated as considerably to extremely useful by 88 percent of the pilots, and the same percentage rated the presentation of the intruder's angle of arrival as good to excellent. When the pilots were instructed not to perform horizontal maneuvers, they were again informed that at this time the TA information is accurate only to one clock position for bearing (i.e., ± 15 degrees). During the post test debriefing, fifty percent of the pilots commented that the display was misleading as to the accuracy of the bearing information and that the system should be more accurate, so that horizontal maneuvers could be given. There was a feeling expressed in the program debriefing questionnaire by a majority of the pilots (64 percent) that the use of automated threat advisories may sometimes encourage the pilot to become complacent and devote insufficient time to visual scanning for nontransponder-equipped aircraft. In fact, 50 percent of the pilots commented that this would be a major problem in TCAS use. It was also commented that any training program should address this issue.

The performance evaluation, although not one of the objectives of the study, revealed a number of interesting data concerning the system. For the data that was collected on three of the crews, twenty-six percent of the RA situations evaluated resulted in slant range separations less than 600 feet. When investigating the minimum vertical separation of these encounters, it was revealed that in 18 percent the vertical separation was less than 100 feet, in 46 percent it was less than 400 feet, and in 75 percent it was less than 500 feet.

In analyzing the data from one crew it was found that in the performance of the RA maneuver, it took more than 13.4 seconds for to achieve a 1500 feet per minute vertical rate of climbing in 16 percent of the scenarios and more than 10.8 seconds to establish the required 1500 fpm descent. The change in flight path was less than 301 feet for 16 percent of the climb maneuvers and 323 feet for descend maneuvers. When the climb/descend arrow was presented with an existing vertical speed greater than 1000 feet per minute, but less than 1500, the crew made no response. When the climb/descend arrow was presented with an existing vertical speed exceeding 1500 fpm, the crew tended to reduce the vertical rate. Preventive alerts resulted in crew actions which increased the difference between the existing vertical rate and the restricted rate. Finally, negative alerts (such as "DON'T CLIMB") generated responses that were inconsistent with the alert (e.g., a climb response to a "DON'T CLIMB" alert) in 50 percent of their test occurances.

2.3 Unresolved Issues

Since the final responsibility for the aircraft safety rests with the pilot, he must feel confident in using the TCAS system for it to be effective. Even though the TCAS system used in the simulation tests was rated as good by most of the pilots, there were a number of key issues that remain to be resolved concerning the operational use of the system. The following issues concerning system design and utilization were raised by the results of the operational simulation:

1. The TCAS system as it is presently configured may not consistantly generate response performance (either in type of response or in time to respond) commensurate with the assumptions which underlie the TCAS logic. Further evaluation is required to determine what changes can be made to either the assumption or the pilot interface to improve performance.

2. The information presented by the system may encourage the pilot to anticipate the RA maneuver or to maneuver based on the TA. A means will have to be found to eliminate or resolve conflicts that arise when the preconceived maneuver is not the maneuver selected by the system. Furthermore, some means must be developed to discourage using the TA display data as a basis for a maneuver during a TA alert. The question which arises is how to accomplish this objective; can it be done with training or will it require system modification?

3. TCAS logic presently considers only RA aircraft in establishing the escape maneuver. Situations were observed wherein this logic caused crew indecision. Further evaluation is required to determine if another approach to multi-traffic logic can produce more appropriate crew responses.

4. The pilots' reluctance to perform altitude crossing maneuvers must be resolved. Evaluations must be performed to determine if this can be accomplished with training and eventual system familiarity, or if system solutions are necessary.

5. Reliable and acceptable procedures for the "TCAS INVALID" alert are required; if none can be developed then a system modification should be investigated.

6. A means must be developed to preclude the increase in ATC verbal communication, especially with TA's and non-mode C equipped intruders, adding excessively to the existing communication load. Inability to contact ATC in high traffic areas must not affect the use of the TCAS.

7. Sixty-four percent of the pilots responded in the program debriefing questionnaire that the potential exists, as with any automated system, that

the pilots will take the system function for granted and reduce their outside visual scan. Is this phenomenon a problem with TCAS and what means can be used to prevent it from occurring?

2.4 Conclusions and Recommendations

The operational simulation revealed a number of important questions concerning operational use of the TCAS system as presently implemented which now need to be adequately answered. Key to these questions and an observed result from the simulation studies is that there are are pilot response times to the TCAS resolution advisory which are longer than expected. TCAS II, as an executive system, makes certain logic decisions based on the assumption that pilot response will be achieved in eight seconds. This time allotment based on previous research is on the low side of what should be expected. Longer response times and pilot indecision would invalidate the assumptions upon which the TCAS logic is founded. The unresolved issues and the results from the simulation studies point out areas in system functioning which can, in fact, result in pilot responses which are longer than expected. Based on these results, it is recommended that as first steps the system be modified to meet FAA recommended alerting system guidelines which were formulated to optimize pilot response performance. Additionally, examine the assumptions imbedded in the TCAS logic which are based on pilot response times to assure that the pilot system interaction relative to performance conflicts are resolved.

If TCAS is implemented as an executive system, then the FAA alert standardization guidelines for warning and caution level alerts are applicable. The guidelines would infer that after accepting the above definition proper color coding of IVSI information is needed to reduce the probability of misinterpretation and to ensure color coding consistency within the system. The information provided by the TA display should be investigated to develop a presentation which will perform the desired function of the display (aid in visual acquisition) while not encouraging the crews to maneuver on the information or anticipate the RA.

If TCAS is implemented as an advisory system (pilots do not follow the guidance unless they have reason to believe they should), then the warning

level alerts are not appropriate. The system should be based on caution and advisory alerts and informational presentations which would require a caution master visual, caution and advisory master aurals and the RA and TA displays (with no red color coding) as the primary alerting components with voice available as a pilot option for RA's. Furthermore, this fundamental change in utilization philosophy resulting in a new set of system recommendations should be further evaluated in an operational environment to determine their impact on flight operations performance.

Finally, a set of tasks is recommended which address the unresolved issues. Tasks are proposed to further evaluate the pilot-TCAS interface in the areas of training, logic development, and display design and formatting in Section 7.0 of this report.

3.0 Test Facility

The operational nature of the study objectives required the use of a facility which provided the highest fidelity in simulating an operational aircraft environment. The facility chosen was the Boeing 737-200 training simulator which has a 6 degree of freedom motion base with a 4 window computer generated color visual scene. The facility has the capability of providing in-flight faults; it has a visual airplane model which was used to generate runway obstructions, but was not used for presenting intruder aircraft, and it has an operational navigation system, all of which were utilized in generating the appropriate environment. The simulator, as it was configured for the operational study, was undergoing FAA certification as a Phase II simulator (a substitute for in-flight training). This system provided the platform from which the TCAS concept and procedures could be systematically evaluated. Figures 3.0-1 and 3.0-2 present exterior and interior views of the simulator.

In addition to the training cab, the TCAS simulation system was implemented to accurately represent TCAS under a variety of intrusion situations. The system consisted of eight basic elements: (a) the alert controller which was the controlling element for the alerting lights, tones, and voice; (b) the scenario controller which controlled all intruder flight paths and emulated the tracking position of the TCAS logic; (c) the CAS logic which was the latest available working logic at the time of the study (Version 9.1); (d) the graphic generator which drew the plan view of the intruding aircraft on the TA display (CRT); (e) the disk data storage unit which is self-contained real time data collection system for all flight parameter data; (f) the TCAS displays which duplicated the system which will be flight tested; (g) the communications network which permitted two-way communication among the crew, ATC controller and test conductor; finally, (h) the audio and video recorders which kept permanent records of each test flight.

Figure 3.0-1 Exterior–Boeing 737-200 Training Simulator

Figure 3.0-2 Interior–Boeing 737-200 Training Simulator

The underlying objective in the development of the TCAS simulation system was to provide a flexible tool which could be utilized in the TCAS program. The resulting system meets this objective. It is capable of reproducing the TCAS alerting functions in a wide variety of situations that range from work on the bench to high fidelity simulations. The modular design of the system permits the utilization of new TCAS logic versions as they become available. Because the scenario controller generates the intruder flight paths, any encounter scenario can be generated to test the system. The voice generation model can provide an accurate reproduction of any voice model whether it is commercially available or experimental in nature. The model used for the evaluation was a reproduction of the voice that will be used in flight test. The data collection module is a floppy disk based recording and playback system which is not dependent on the host computer. Using the disks that were recorded during the actual flight, the system can play back the TCAS display responses for all encounters along with the pilot responses so that they may be studied in depth. A full description of the simulation facility and the TCAS simulation system is presented in Appendix A.

4.0 Operational Simulation - Evaluation Description and Results

The primary purpose of the operational simulation phase was to implement a TCAS which would match as closely as possible the system which would be flight tested and to evaluate that system in a high fidelity simulator. The following sections will describe, in detail, the evaluation that was performed and the results obtained.

4.1 Evaluation Objectives

The TCAS operational simulation was designed to perform a pilot evaluation of the relationship between a set of TCAS displays, an operational crew station, aircraft performance, the TCAS logic, and the impact upon standard ATC as well as flight deck operational procedures. The major objectives of the simulation were: to develop and evaluate the operational procedures for the different types of TA and RA alerts; to assess changes in crew procedures associated with TCAS utilization; to explore the man-machine interface and information transfer capabilities of the TA and RA displays; to identify needs, if any, to improve format, location, and/or symbology; to assess workload (activity) impact of TCAS in an operational simulation environment under normal and abnormal conditions in simulated IFR flight.

4.2 Evaluation Design

The operational simulation was not intended to be an experiment in which variables were systematically and parametrically investigated. Therefore, the study was designed to provide the pilot experience with system utilization in a wide variety of situations so that their use and assessment of the system and its operation could be more readily applied to flight operations.

Although the weather conditions represented during the test were essentially VMC, the lack of resolution in the outside visual scene prevented the presentation of objects with visual angles small enough to provide a realistic representation of the intruder aircraft at the ranges required by TCAS. Therefore, no TCAS intruders were presented visually. The pilots were not informed of the absence of visual targets, and were encouraged to visually search for

the intruders whenever the visibility conditions permitted. These instructions were strengthened by using the visual airplane that was available in the simulator as a runway obstruction and ground traffic. The crews therefore were not relieved of any of their visual responsibilities in performing the flight task. It was felt that the restrictions did not adversely affect the study because the simulation permitted the evaluation of crew performance in those situations in which they do not visually acquire the intruder aircraft and will thus have to rely solely on the information presented by TCAS to perform their maneuver. The TCAS system should be able to accommodate this type of situation. The outside visual scene did provide the means by which the crew could clear the airspace for maneuvering.

4.2.1 TCAS Implementation

The major objective to be met when implementing TCAS in the simulator was to simulate, as closely as possible, the system which would be flight tested. The candidate display system recommended in the Developmental Simulation was used, including the CRT based graphic display of traffic advisories. Figure 4.2.1-1 illustrates the actual location of the display system elements on the 737-200 flight deck.

The master visual alerts for TCAS were provided by two split legend lighted switches, one of which was located in front of each pilot. The top half of each switch was the warning indication which was color coded red. This light was accompanied by the warning aural alert which sounded like a European siren. The bottom half of each switch was the caution alert which was color coded amber. The sound which accompanied the caution light was a C-chord which had a cycle of 2 seconds on and 8 seconds off. All master alerts could be cancelled by depressing either of the switches. The master visual alerts were located within the respective crewmember's primary field of view (both head up and head down - see reference 4).

The resolution advisories were presented to the crew member by means of modified Instantaneous Vertical Speed Indicators (IVSI) and a voice display. Figure 4.2.1-2 depicts the modifications made to the standard IVSI's to accommodate the TCAS alerts. The red arrows were used for "CLIMB" and "DESCEND"

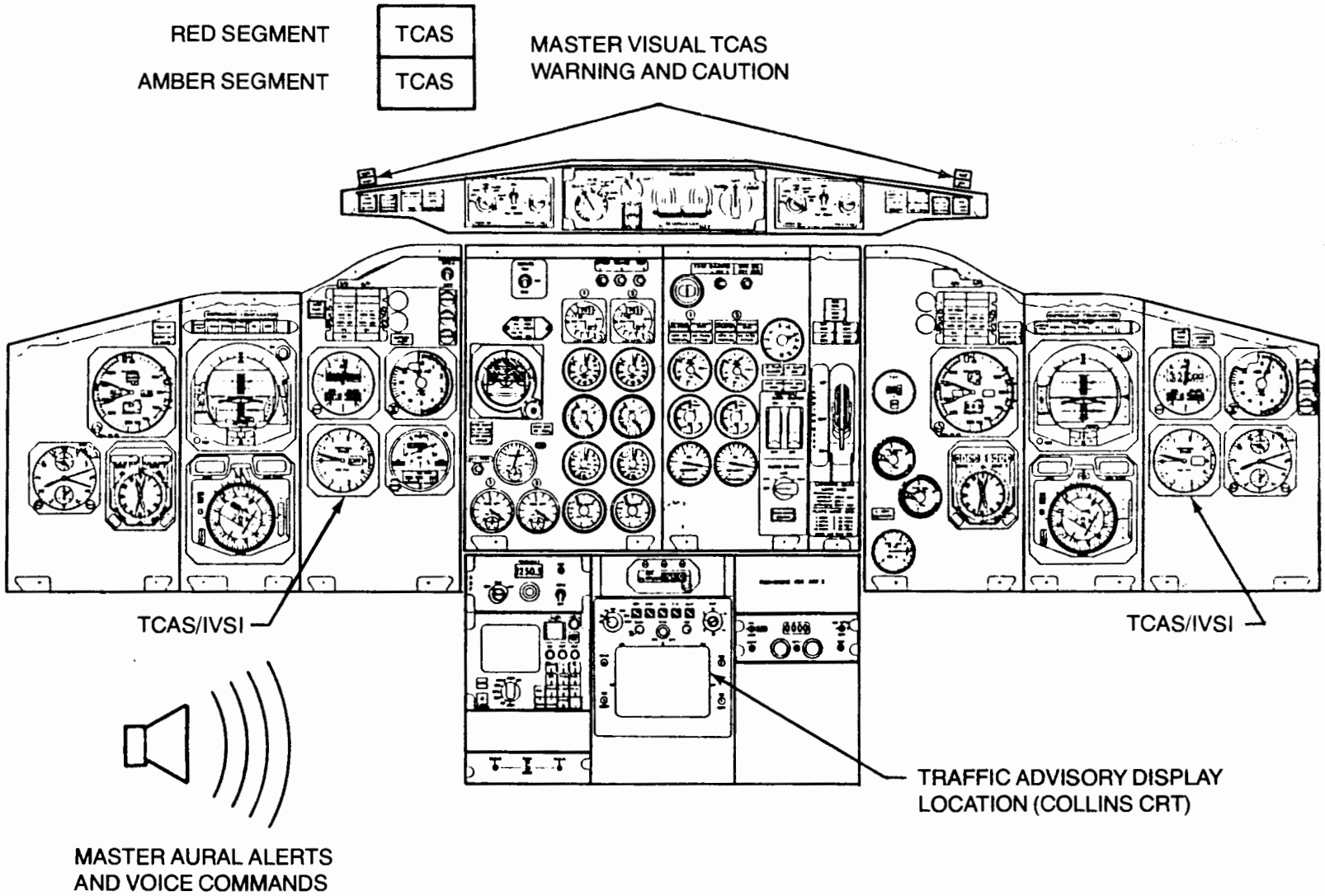

Figure 4.2.1-1 TCAS Alerting System for Operational Testing

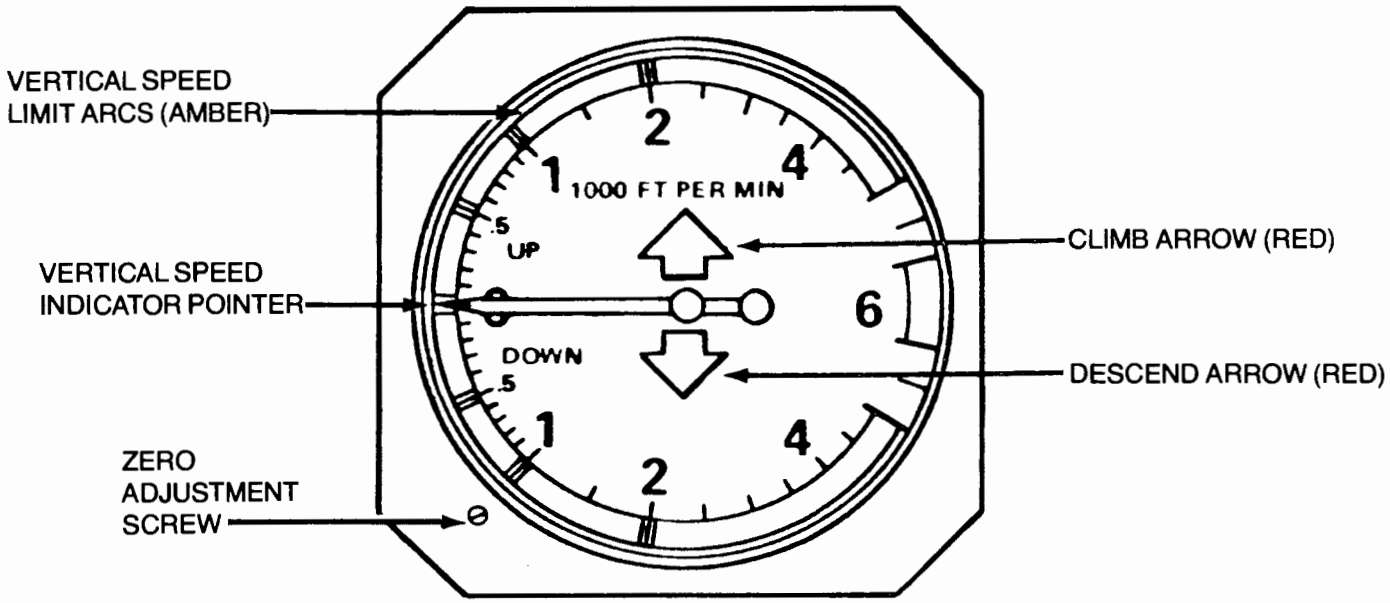

Figure 4.2.1-2 TCAS Resolution Advisory Display Used in Simulation

advisories while the amber eyebrow lights indicated vertical speed limits (VSL), negative alerts (e.g., "DON'T CLIMB") and vertical speed minimums (VSM). A set of the resolution advisories is presented in Table 4.2.1-1. A voice presentation of the RA which corresponded to the visual presentation was played and repeated until cancelled by one of the pilots pressing the master alert switch.

Even though the pilot opinion data from the developmental simulation indicated that the digitalker voice model was unacceptable, the same voice was used in the operational simulation. This model was used because the FAA had specified it as the model scheduled for use in the Piedmont flight test.

The CRT traffic advisory display was located in the weather radar position (on the forward panel of the center aisle stand; the CRT used for the TA display was a B-757/767 technology weather radar tube, which is a high resolution stroke-written Color CRT. This display provided a cleaner, sharper image than would be expected using conventional weather radar displays. It also did not have any of the jitter, false tracks, or partial tracks that could be experienced. Therefore, a "best case" display was implemented.

The format for this display was a plan view of the traffic situation (see figure 4.2.1-3). The display was activated only when an intruder was generating a TA or RA. When activated, it not only showed the threat aircraft, but also any aircraft within 4 nautical miles range and 1200 feet in altitude. The threat aircraft were colored either red or amber depending on their severity and the proximate aircraft were blue. Each intruder was depicted at a bearing, which corresponded to its actual angle-of-arrival, although the true TCAS system is accurate to one clock position (±15°) in bearing. Associated with each intruder symbol was its altitude relative to the own aircraft. As can be seen in the TCAS description (Appendix B), the display scheduled for flight testing also has a vertical rate arrow associated with the altitude tags. Although programmed in the simulation software, this arrow was not activated for the test by the version of TCAS logic being used. A circle was drawn around the own aircraft symbol (chevron) to indicate a 2 nautical mile range.

Table 4.2.1-1 Resolution Advisory Set Used in Simulation

CLIMB	DESCEND
MAINTAIN CLIMB 500 ft/min	MAINTAIN DESCENT 500 ft/min
MAINTAIN CLIMB 1000 ft/min	MAINTAIN DESCENT 1000 ft/min
MAINTAIN CLIMB 2000 ft/min	MAINTAIN DESCENT 2000 ft/min
DO NOT DESCEND	DO NOT CLIMB
LIMIT DESCENT 500 ft/min	LIMIT CLIMB 500 ft/min
LIMIT DESCENT 1000 ft/min	LIMIT CLIMB 1000 ft/min
LIMIT DESCENT 2000 ft/min	LIMIT CLIMB 2000 ft/min
TCAS ABORT	

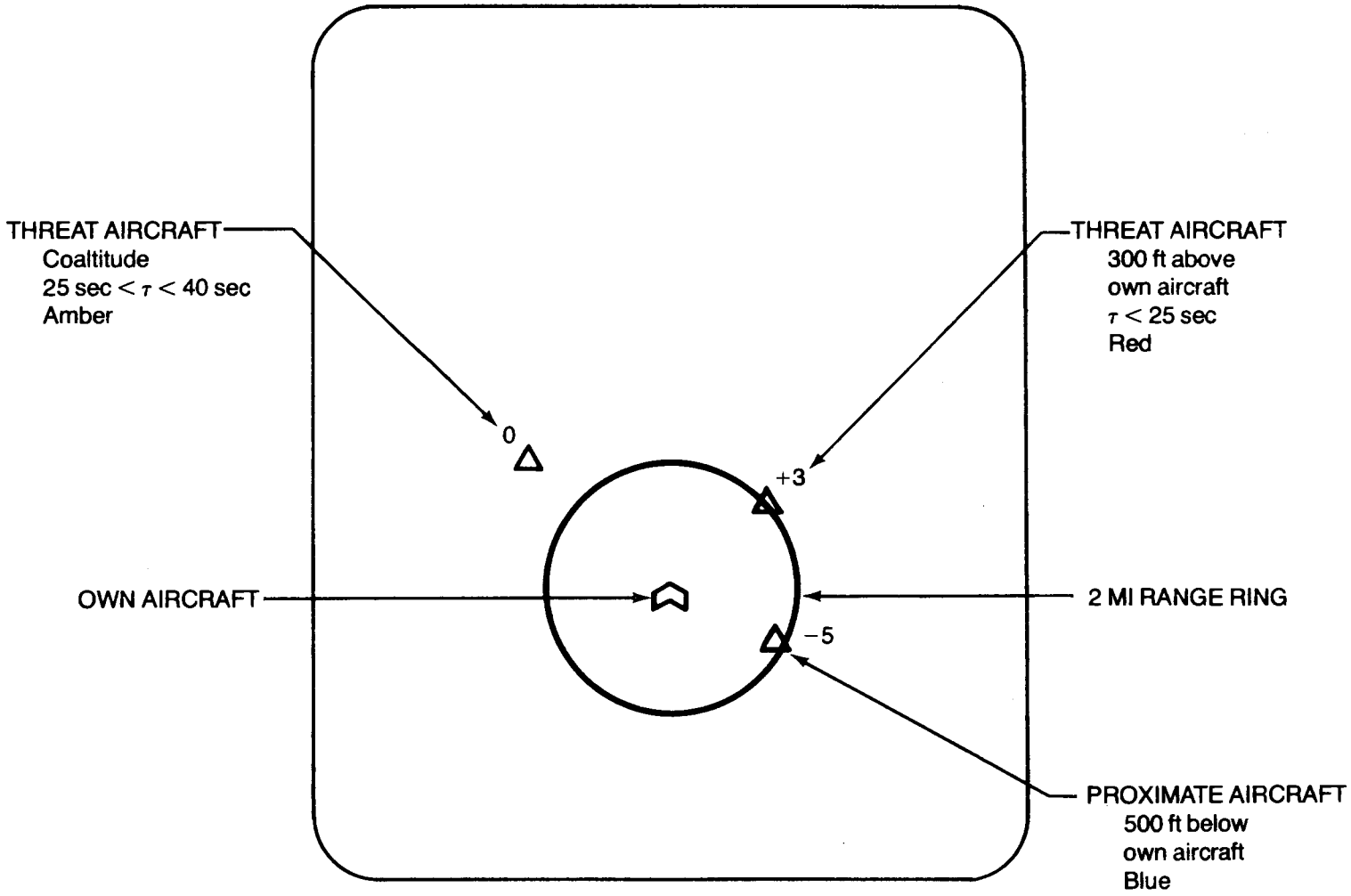

Figure 4.2.1-3 TCAS Traffic Advisory Display Used in Simulation

The TCAS logic package, implemented in the simulator was the latest working version at the time of testing, and was identical to the logic being used in the flight test program being conducted at that time. A new version of the software was being developed and implemented for the follow-on flight testing. However, the simulation effort is valid because the types of intrusion scenarios which would be handled differently by the new logic were identified and avoided in the simulation. Thus all conditions tested apply to the new logic as well as the earlier version.

4.2.2 Flight Scenarios

In order to make the simulation as realistic as possible, the crews flew actual operational flight legs. Seven different scenarios were developed so that during the test flights each crew member was the flying pilot only once for each scenario. The three airfields used for the flight plans were: Boeing Field; Yakima Airport; and Moses Lake Field. A wide range of flight situations was simulated during the test flights including: diversions, holding patterns, engine out, aborted takeoff, go-around, jet routes, high altitude descents/climbs, winds/turbulence, and runway obstacles (see Table 4.2.2-1 and Appendix F). It should be noted that on scenario number three each crew was presented a runway obstruction when they were on final approach. This obstruction consisted of an aircraft moving onto the runway for takeoff. This served two purposes: (1) it caused a go-around; and (2) it reinforced the requirement to search for outside aircraft. These situations provided a realistic range of workload (activity) for the crew thus enabling them to experience TCAS under a variety of conditions. The fidelity of the flight environment and activities also permitted the crews to mentally and physically treat the simulation in a realistic manner.

4.2.3 Intrusion Scenarios

The flight paths of the threat and proximate aircraft were chosen with two basic objectives in mind; (1) they should cause TCAS alerts which would be the same for the tested TCAS logic (Version 9.1) and that which was being developed (Version 11); and (2) they should detract little, if any, from the realism of the simulation. Several "special" encounters had been defined by

Table 4.2.2-1 Operational Simulation Flight Plans

- BOEING FIELD TO YAKIMA — divert Boeing Field — hold
- BOEING FIELD TO YAKIMA
- YAKIMA TO MOSES LAKE — runway obstruction/missed approach
- MOSES LAKE TO YAKIMA — engine out — divert Moses Lake
- MOSES LAKE TO BOEING FIELD
- BOEING FIELD TO CHICAGO — terminate en route
- CHICAGO TO BOEING FIELD — start en route

the FAA for inclusion in the study. These encounters were designed to trick TCAS into providing inappropriate or incorrect information to the crew in order to see how they would respond; however, they were not included in the test because the new logic is designed to correct for those situations. In order to meet the selection objectives, it was also necessary to eliminate the extreme encounters. These threats may have tested the system to its limits but would have made the evaluation less realistic. Table 4.2.3-1 enumerates some of the traffic encounters used during the study and Appendix F provides plans and side views for all intrusion scenarios. Even though the average of 18 intruders per encounter (970 aircraft in 552 encounters) seems extremely high in terms of actual operational environment, all of these aircraft do not represent threat aircraft. Fifty-two percent of these aircraft were proximate aircraft which were displayed along with the TA or RA intruders. In fact, there was an average of less than one TA per encounter (465 TA's in 552 encounters) and the TA's went to RA's on the average of less than one time in every two encounters. An encounter in the test was defined as the launching of intruder aircraft by the computer. Some of the launched aircraft did not generate TCAS alerts because of unforeseen pilot action which is why there were less traffic advisories than there were encounters. The multiple alert encounters were therefore, a mixture of either multiple TCAS intruders or a TCAS intruder with one or more proximate aircraft. Such encounters were included for two reasons: (1) this type of situation is much more difficult than the single intruder and both the TCAS system and the operational procedures should be able to handle it; and (2) this situation can be better evaluated in the simulator because there is more control over all the aircraft, and it is repeatable. In actual flight tests, multiple aircraft encounters are costly, difficult to set up, and there is also a much higher risk.

4.2.4 Operational Procedures for TCAS

The procedures for the use of TCAS were coordinated with the FAA and written as supplementary procedures to the Operations Manual. Because of the fluid nature of the TCAS program at the time of testing, some of the operational procedures were changed between the printing of the training material and the test. These changes were explained to the crews and the test was performed with the revised procedures. These procedures, as given to the crews, are

presented in full in Figure 4.2.4-1 and Appendix B with an indication of the revisions. The TA procedure called for a visual search for the traffic and permitted minor changes in the flight path, only after visual acquisition of the traffic. The RA procedure for a corrective alert called for continued search for traffic, activating the seat-belt sign, disengaging of the autopilot, performance of a maneuver (if required) using a .25 G-vertical acceleration (equivalent to a "Go-Around" or a "Start of Descent"), and notification of the controlling agency if a clearance were broken. The RA procedure for a preventive alert was much the same as for a TA. It called for the pilot to maintain the IVSI needle outside the lights, and undertake visual search for traffic. Minor changes in flight path were again permitted only on visual acquisition of the traffic.

The definition of procedures to be used by each crew in coordinating their activities during a TCAS alert were intentionally not provided. Crew coordination is highly dependent on individual airlines. It was felt that a more natural usage of TCAS could be obtained if each crew would allocate responsibilities in a manner which was most comfortable to them. It was further felt that by reviewing the coordination procedures which were agreed upon by the crews, that a standard set of procedures would be able to be identified. The most common procedures followed by the crews for this set of equipment are identified in section 4.6.1.

The only set procedure concerning the interaction between the crew and ATC called for a report to ATC if a clearance was violated. Other interaction with ATC, generated as a result of TCAS, was left to the discretion of the crew. From the communication records, it was possible to determine the interaction patterns.

4.3 Pilot Sample

Six two-man flight crews from United, Piedmont, Republic, Flying Tiger, Trans World, and USAir airlines, representing both the airline management (Air Transport Association) and the airline pilots (Airline Pilots Association), participated in the operational simulation. Eight of the pilots were senior captains and four were senior first officers. This pilot participation was coordinated

Table 4.2.3-1 TCAS Encounter Scenarios

- LEVEL FLIGHT
  - Altitude offset
  - Longitudinal offset
  - No offset
  - Head on
  - Angled approach
  - Tail chase
- ALTITUDE CHANGING
  - Coaltitude passage with longitudinal offset
  - Assigned altitude level-off in close proximity
  - Own ship with vertical rate
  - Intruder with vertical rate
  - Both own ship and intruder with vertical rate
- FINAL APPROACH
  - Parallel runways
  - Turn to final
- MULTIPLE TRAFFIC
  - RA 1 causes RA 2
  - Two TAs in same sector

TRAFFIC ALERT AND
COLLISION AVOIDANCE SYSTEM

THREAT ADVISORY

Upon recognition of visual or aural advisory accomplish the following immediately by recall:

Undertake a visual search for traffic. Minor changes in flight path may be accomplished based on visual acquisition.

NOTE: Information provided by proximity advisory aircraft observed on the traffic advisory display should be used as an aid in visually identifying the threat advisory aircraft.

A "minor change in flight path" as used above means maneuvering that does not violate the ATC clearance. Other than minor changes would require coordination with ATC.

RESOLUTION ADVISORY
(IVSI needle out of illuminated bands)

Upon recognition of visual or aural alert, accomplish the following immediately by recall:

Maintain flight path to keep the vertical rate needle out of the illuminated bands on the IVSI until the alert terminates.

Undertake a visual research for traffic. Changes in flight path may be accomplished based on visual acquisition.

If maneuvers result in deviation from ATC clearance, first officer will advise ATC or controlling agency.

NOTE: Information provided by proximity advisory aircraft observed on the traffic advisory display should be used as an aid in visually identifying the resolution advisory aircraft.

RESOLUTION ADVISORY
(IVSI needle within illuminated bands)

Upon recognition of visual or aural warning this procedure should be accomplished immediately by recall:

Fasten Belt Switch. . . . . .ON

Autopilot
(if applicable). . . . . .DISENGAGE

Pitch Attitude . . . . . .ADJUST

Immediately rotate nose up or nose down as required to maintain vertical rate out of illuminated bands on the IVSI. The maneuver should be deliberate and positive, accelerating at .25G.

If a climb or descend arrow is displayed, begin a corresponding vertical rate of 1500 ft/min or continue current rate if it is equal to or greater than 1500 ft/min.

Thrust Levers . . . . . .ADJUST

Advance or retard thrust levers as required to maintain the vertical rate until the warning terminates.

Controlling Agency . . . . . .NOTIFY

First officer will advise ATC or controlling agency of deviation and request new clearance.

Undertake a visual search for traffic. Changes in flight path may be accomplished based on visual acquisition.

NOTE: Information provided by proximity advisory aircraft observed on the traffic advisory display should be used as an aid in visually identifying the resolution advisory aircraft.

Figure 4.2.4-1 Operational TCAS Procedures

The TCAS resolution advisory (corrective warning) offers the pilot a course of action predicated only on mode-C equipped aircraft within a closure time of less than 25 seconds. Once the advisory is issued, it is solely the pilot's prerogative to determine what course of action, if any, he will take.

Excessive delay in responding to the resolution advisory or late maneuvering by the intruder may cause the system to abort.

ABORT

Upon recognition of visual or aural abort warning, this procedure should be accomplished immediately by recall:

Return to and/or maintain last assigned clearance.

Use all available information to determine your course of action.

Nofity ATC immediately of situation and request assistance; i.e., "SEATTLE CENTER, BOEING SEVEN THREE SEVEN TCAS ABORT, PLEASE ADVISE."

Undertake a visual search for traffic. Changes in flight path may be accomplished based on visual acquisition.

NOTE: Information provided by proximity advisory aircraft observed on the traffic advisory display should be used as an aid in visually identifying the TCAS aborted aircraft.

Deleted during training.

Changed during training.

Figure 4.2.4-1 (Concluded)

by the FAA Office of Flight Operations. Eight of the pilots were experienced in the 737, two of the remaining four were DC-9 pilots, and the other two were current line captains. All of the pilots were qualified on more than one jet transport aircraft and over half the pilots were qualified on more than two. As a group, each of the pilots averaged over 12,000 flight hours of experience. A summary of their experience is presented in Table 4.3-1. Numerical entries on the right hand side of the table indicate the specific experience by aircraft type and recency of the experience (A is most recent).

4.4 Evaluation Methodology

During the evaluation, each crew was scheduled for ten hours of evaluation which was spread over a two day period. With the training and test flights, the schedule resulted in a total of 14 flight legs per crew (2 training flights and 12 test flights).

Each flight was approximately 31 minutes in length and contained 8 potential TCAS alert situations. This number of alerts is not indicative of the number expected in actual system operation where TA alerts have been seen approximately once every 5.13 hours and RAs once every 37.15 hours. A larger than expected number of alerts were chosen for the simple reason that to give each crew a sufficient amount of TCAS experience with realistic time periods between the alerts would have required testing time far in excess of the scope for the study. It was felt that the system evaluation would not be affected by the alert rate as long as enough time was available between the alerts for the crew to return to their flight path and stabilize the aircraft. Where the higher rate will have an effect, is in the pilot performance data. The larger number of occurrences that occur in alert systems research has been shown to reduce the surprise and uncertainty factors which have resulted in shorter response times than would be expected in actual operational situations. The constant reinforcement of response also reduces the amount of forgetting and should increase the probability that the pilot will respond correctly.

In order to meet the major objectives of the study, it was necessary to develop a comprehensive training program for TCAS to ensure that the participating crews would utilize the system as intended. A week before they were scheduled to participate, each pilot received a written training package.

STATISTIC	PILOT** EXPERIENCE	SPECIFIC AIRCRAFT EXPERIENCE (NUMBER OF PILOTS)								
	FLIGHT HOURS (1,000)	RECENCY*	707	727	737	747	DC-8	DC-9	DC-10	BAC-111
MEAN	12,325	A		2	2	1	1	4	2	
STANDARD DEVIATION	7,083	B	1	6	1	1	2			1
RANGE	5,100 TO 27,500	C	2		3	1	1			
		D			2					

*A is the most recent aircraft flown

**Pilots participation coordinated by the FAA Office of Flight Operations

Table 4.3-1 Summary of Pilot Experience

It was comprised of two parts: the TCAS system information and the operational procedures. The portion of the package which contained the explanation of how and why TCAS works was a condensed version of the training materials written for the FAA by Mitre Corporation for use in the flight tests (see Appendix B).

The second section of the package contained the set of handbook procedures to be used for both Resolution Advisories (preventive and corrective) and Traffic Advisories that were approved by the FAA for use in the operational study phase. The cover letter accompanying the training package requested that the pilots be familiar with the material before arriving at the simulator.

The study participation began with an introduction to the simulation facility and a short review of the program. The pilots were free to ask any questions they had concerning the training materials. After all the questions had been answered by the instructor pilot, the crews began their in-cab training session. They were given a briefing which covered the 737 simulator, the types of flight plans that would be flown, the TCAS display system, and the revisions that had been made to the precedures and displays since their training manual was printed.

Before they flew the actual study flight plans, each crew received one hour of hands-on in flight training. During this time, 16 TCAS alerting situations were presented. The instructor pilot explained the alerts as they occurred and the subject pilots were able to maneuver the aircraft to get a feel for the TCAS responses. Therefore, the training flight served a twofold purpose - to acquaint the crews with the flight characteristics and dynamics of the simulation airplane model and the types of flight plans being used; and to become proficient at interpreting and responding to the TCAS alerts. Finally, the training continued between the test trials in that the crews were informed when it was detected that in actual operations they were not following the prescribed procedures. When they performed a maneuver different from the advised resolution maneuver, they were reminded that the intruder could be TCAS equipped and performing a coordinated maneuver. The total on-site training session took approximately 2 hours to complete.

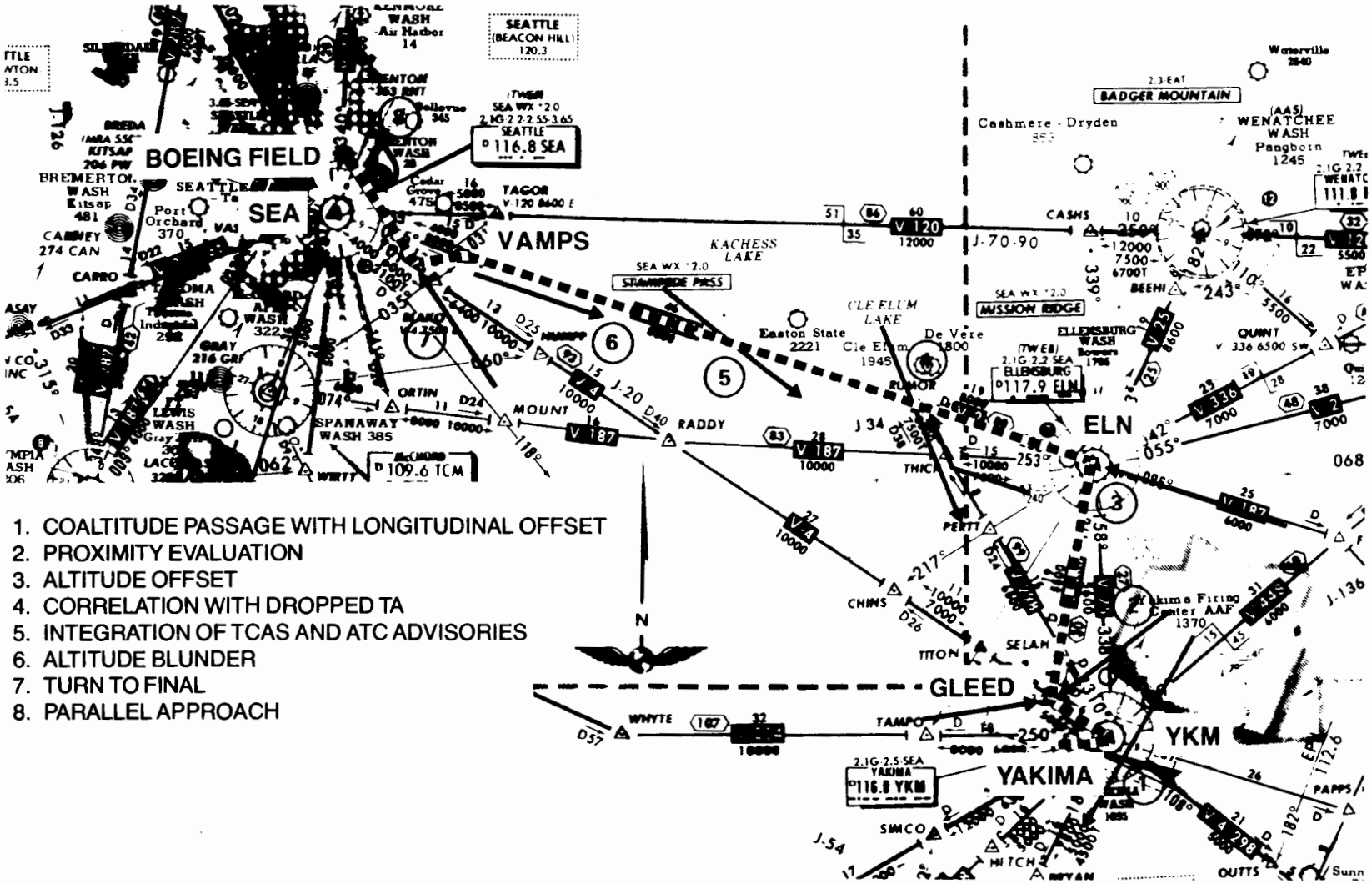

Figure 4.4-1 Typical Mission Scenario With Encounter Scenario

The data collection flights began with a preflight briefing from the on-board observer pilot. The crew received clearance from ATC and began their flight. TCAS alerts were planned to activate eight times during each flight and the crews were expected to respond. Figure 4.4-1 presents a typical flight scenario with the TCAS encounters included. Using the instructor's console in the training cab, the on-board observer also served as the ATC controller, providing enroute clearances and traffic advisories and responding to communications from the flight crew. (Appendix F presents the ATC script for each flight.)

The first test day, consisting of the training session and five data flights, lasted approximately five hours. The second day, with seven data flights and a debriefing session, was four and a half hours long. Brief rest periods were taken throughout the sessions in an effort to reduce fatigue. After each flight, the crew was asked to respond to a short questionnaire about the situations occurring during that flight (see Appendix C). At the end of the second day, the pilots participated in a debriefing session. Their impressions of the TCAS concept and the application of these concepts were solicited. Relevant pilot comments were recorded for further evaluation. The pilots were then given an extensive questionnaire which they completed at their leisure and returned at a later date (see Appendix D).

4.5 Measurement Techniques

The nature of this study was designed to be an operational evaluation rather than a parametric test; therefore, the primary measures used in this study phase, were observational data and subjective opinions. Some pilot performance data, however, was collected and is presented in descriptive form only, e.g., means and standard deviations. Results from this evaluation are discussed based on three data sources: observational data; pilot opinion data; and pilot performance data.

4.5.1 Observational Data

The purpose of the observational data was to provide a record of what happened during each flight and how the crew responded to each TCAS situation. A trained observer was present on every flight to record this data. Not only had the

observer been trained as to what data needed to be documented, but he was also an experienced jet transport pilot so that he could relate the pilots' responses to each situation. The observational data was collected for every TCAS encounter by using a recording form designed for the purpose (see Appendix E). The real time observations were augmented by audio and video recordings which were used during analysis to clarify the data.

4.5.2 Pilot Opinion Data

The evaluation pilots could express their feelings at any time during the study and they were recorded by means of a live microphone. In addition, there were three formal methods of gathering pilot opinion. After each flight, the crews were given a short (four question) questionnaire to describe that specific flight and the TCAS encounters that had occurred (Appendix C). This questionnaire permitted the crews to express an immediate opinion while the flight was still fresh in their minds. At the end of their session, both pilots, the observer, and test conductor met for a debriefing session. During this time, a set of open-ended questions were asked and the pilots' responses were recorded. The discussion was generally informal and tried to encourage each crew to express their feeling about the system they had flown. Finally, each pilot was given an extensive questionnaire (see Appendix D) to complete later, allowing time to consider the questions at length.

4.5.3 Performance Data

Performance evaluation with objective data was not a requirement of the study, however, some pilot performance data were collected. The TCAS simulation system had a sophisticated capability for recording performance data. Flight parameters were recorded for the own aircraft, the intruder aircraft, and the TCAS system (see Table 4.5.3-1). In addition to these data, the closest point of approach, pilot response time, and the accuracy of the response were also recorded. Experimental control exerted on the simulation was minimized in order to permit the designed realistic operational environment; therefore, sophisticated statistical treatment of the data was not practical.

Table 4.5.3-1 Real Time Flight Parameters Available (One Sample per Second)

ALL AIRCRAFT	TIME LATITUDE LONGITUDE	LATERAL VELOCITY VERTICAL VELOCITY ALTITUDE
INTRUDER AIRCRAFT	RANGE RANGE RATE	ALTITUDE RATE ANGLE OF ARRIVAL
TCAS DISPLAY AND SWITCH STATUS	TA INITIATION RA INITIATION ALERT CANCELLATION	VOICE ALERT RA MANEUVER

Recording the 552 TCAS encounters in 70 flights resulted in a tremendous data base of approximately 1800 data points for each of the 15 parameters for each flight. When these data were combined with the audio and video recordings, the resultant amount of analysis required to fully investigate the data was well beyond the scope of the study. A limited analysis was performed, however, on a portion of the data to indicate trends and to demonstrate how the data in this study may be used.

4.6 Evaluation Results

The results section is partitioned into three segments according to the type of data being described. The results of the observational and pilot opinion data are based on 552 planned encounters in which there were a total of 970 intruder aircraft. Of these aircraft, 465 generated traffic advisories and 261 aircraft progressed from traffic advisory to resolution advisory. The pilot performance results were based on a small portion of these encounters as described fully in that section.

4.6.1 Observational Results

The three major areas of interest for the observational data gathering were: (1) the way in which the crews followed the TCAS procedures; (2) how the crews coordinated their activities; and (3) what interaction took place between the crews and ATC during an alert.

Even though the handbook did not permit maneuvers based on the traffic advisory information unless the intruder was visually acquired (not possible in this study), and the pilots were told that the TA information was not adequate for maneuvering, all of the crews maneuvered on some of the traffic advisories. A maneuver, defined by the observer, was any change in the aircraft flight path which was initiated after the TA and before the RA and met one or more of the following criteria: (1) flying pilot verbally indicated a deviation was made based on the TA information, (2) non-flying pilot called ATC to either coordinate a maneuver or state that maneuvering was performed, but in either case the flying-pilots' maneuver was performed before ATC cleared the maneuver, (3) flying pilot maneuvered the aircraft through the autopilot by

engaging a profile inconsistent with the ATC clearance, i.e., disengaging altitude hold and establishing a vertical rate during cruise, level-off or descent during climb, or (4) flying pilot maneuvered the aircraft (disengaging the autopilot if engaged) by changing the vertical rate or horizontal path more than would be expected in normal flight operation. This maneuvering continued even after the instructor pilot reminded the crews that they were not following the procedures. When considering all of the encounters, maneuvering on the TA information was observed 10 percent of the time. Looking at the data further, it was also found that half of the crews used the traffic information to perform horizontal maneuvers. Since TCAS is presently a vertical separation system, the horizontal maneuvers were not procedurally permitted at all.

Crew coordination, although it varied slightly, was very consistent among the crews. In general, the flying pilot searched for outside traffic, recognized the RA when it came and instituted the evasive maneuver. The non-flying pilot monitored the TA display, called out the traffic information presented on the display, performed switching tasks (e.g., cancel master alerts or turn on seat belt sign) and interacted with ATC. During the encounters both pilots, though especially the non-flying pilot, devoted much attention to the TA display.

The scenario which had a runway obstruction created a situation about which 75 percent of the pilots expressed concern. They reported they did not see, as the non-flying pilot, the obstruction, because they were visually involved with the TA display. In all cases the flying pilot saw the obstruction and performed the go-around maneuver, yet the pilots still had concern about this situation.

Interaction with ATC varied widely among the crews. One crew strictly followed procedures and only called ATC when they had broken clearance. The remaining crews informed ATC of their intent to change their flight path and initiated the change often before getting a reply from ATC. Some of the crews requested horizontal maneuvers which would allow them to escape from the threat aircraft. Most of the crews requested information on TA aircraft, especially the altitude unknown intruders. Finally, one crew anticipating the RA maneuver, began requesting block altitude clearance in the anticipated direction. After failing to correctly anticipate the maneuver, they then requested block

clearance covering both climb and descend maneuvering space. Other types of calls included requests for assistance for TCAS aborts and for multiple intruder situations. The time that the ATC was first called also varied widely from the initiation of the TA to the completion of the RA maneuver. This type of ATC communication may put excessive pressure on the existing communication system and result in delayed ATC response to TCAS situations.

4.6.2 Pilot Opinion Results

The overall quality of the system presentation was rated as good by 88 percent of the pilots. In response to the question "Did you experience any of the following problems with the alerting system in the test aircraft? .... inappropriate, unnecessary or incorrect alerts?" Seventy-five percent of the pilots reported observing one or more inappropriate, or incorrect alerts during testing. The vast majority of situations that led to this report were altitude crossing maneuvers (e.g., when the intruder is below the own aircraft and climbing and the TCAS alert tells the pilot to "Descend"). Confusion existed even though most pilots reported that they knew that the intruder was moving vertically by the changes in the relative altitude seen on the TA display and called out by the non-flying pilot. Another cause of questioned alerts could have arisen from the fact that the TCAS logic does not recognize (for the purpose of issuing a RA) multiple intruders unless they are all in the RA category. This situation led to alerts that were perceived by the pilot to be in error (considering the total traffic situation). For example, in the test there was one scenario that had two intruder aircraft-both on collision courses, the closest threat, an RA, was 100 feet above the own aircraft, while the other intruder, a TA, was 700 feet below. For this situation, the RA for the closest aircraft was a "Descend" command. All of the crews had trouble with this situation because they anticipated that the system would have had them climb above both intruders. Even though the correct maneuver was performed in less than 50 percent of the presentations of this scenario, at times it was late due to the indecision of the crew. Both horizontal maneuvers and vertical climbing maneuvers opposite the RA ("Descend") were also observed as a result of this scenario. All of these responses were inappropriate, given the present TCAS operational accuracy and maneuvering time criticality. In fact, late maneuvers resulted in a separation of less than 50 feet. Had the

intruders been TCAS equipped, the climb maneuvers by the own aircraft would have been inappropriate because the intruder's RA also would have been "Climb" which would have resulted in a TCAS abort for both aircraft.

When the TCAS logic cannot resolve a conflict or it finds that an RA that had been presented was no longer correct, a "TCAS ABORT" alert will be issued. This condition was demonstrated during the training runs, but did not occur during the test flight because of the inability of the logic to provide the alert. The procedure presented for this situation was to use all the information available, (ATC callouts, flight deck information, TA display, outside visual, etc.) to determine an appropriate maneuver. Even though all of the pilots rated the quality of the RA display as good to excellent, 50 percent objected to the fact that the system even needed an abort alert. They felt that developing a procedure to deal with these alerts would be very difficult. The pilots felt that if an abort alert is required for system operation, it is important that specific procedures be defined for that alert. The most often-expressed preferred maneuver was to deviate horizontally.

There was a feeling by a majority of the pilots (64 percent) that the use of automated threat advisories may sometimes encourage the pilot to become complacent and devote insufficient time to visual scanning for nontransponder-equipped aircraft. In fact, 50 percent of the pilots commented that visual scanning complacency would be a major problem in TCAS use. It was also commented that any training program should address this problem.

All of the pilots felt that both master aural and master visual alerts were needed to attract the crew's attention. The types of aurals used in the study (as recommended by the Aircraft Alerting Systems Standardization Study (7)) were rated as good or excellent by 75 percent of the pilots. The most common comments concerning the master alerts were: that they must be cancellable; that the aural alerts be distinctive especially in retrofit where there are a lot of aural sounds; that transition from a high urgency alert to a lower urgency alert should not be announced with the master alerts.

The RA was rated as usually clear and unambiguous. Rapid changes in the alert (re: climb - limit descent 500 fpm - limit descent 1000 fpm), however, sometimes led to confusion. This problem has been solved with the present version 11 logic. Some crews also had difficulty with multiple alerts. The alert, "Don't Climb-Don't Descend", was especially confusing because all the eyebrow lights on the IVSI were illuminated with no open space to direct them to the appropriate vertical speed. None of the pilots felt that the modifications to the IVSI detracted from the primary purpose of the instrument. Eighty-eight percent of the pilots indicated that the RA usually gave them enough time to react. The voice system used for simulation was judged to be inadequate by 63 percent of the pilots even though 88 percent wanted voice as part of the system.

The TA display was rated as usually clear and unambiguous by all of the pilots, and the quality and usefulness of the display was rated as good or excellent by 88 percent. The inclusion of color on the display was rated as considerably or extremely useful by 88 percent of the pilots, and the same percentage rated the presentation of the intruders angle of arrival as good or excellent. During training the pilots were instructed not to perform horizontal maneuvers. They were informed at that time that the TA display is accurate only to one clock position for bearing. Fifty percent of the pilots commented that the format of the display was misleading as to the accuracy of the bearing information ($\pm$ 15°) and that the system should be more accurate, so that horizontal maneuvers could be used. Seventy-five percent of the pilots reported that they could not use the TA display to resolve the TCAS abort situations.

When considering systems with and without the TA display, the pilots made the following ratings for a system with a TA display: all of the pilots felt there would be an increase in workload, 67% felt that the change would be quite acceptable, 25% said that it would be marginally acceptable and 8% rated it unacceptable. Eighty-eight percent of the pilots felt that acceptance of the system and integration with ATC would be easier with the TA display.

Most of the pilots (83 percent) stated that they had little or no problems understanding and complying with the written procedures. One of the major

exceptions was with multiple intruders, especially when one of the intruders was vertically located in the same direction as the maneuver. A second exception was the amount of time to accomplish the procedure. Seventy-five percent of the pilots reported in the post flight questionnaire that they felt time pressure especially when the flight deck workload was high (i.e., during approach). Fifty percent of the pilots commented that horizontal maneuvers should be included as part of the system. In fact, 50 percent of the crews used horizontal maneuvers at some time during their flights even though they were instructed that only vertical maneuvers were permitted.

Seventy-five percent of the pilots felt that there were situations for which the prescribed procedures were not appropriate. Here again, the altitude crossing situation was most often mentioned (89% of the pilots). Fifty percent of the pilots reported a problem with the TA procedure in that they wanted to be able to maneuver on that alert.

The final question concerning the TCAS display implementation asked the pilots to enumerate the features they would most like to see incorporated into the system. The following are the results of this open response question (i.e., no features were suggested as possible answers):

1. Resolution Advisory -
   IVSI and voice with a master warning light and sound were identified by 88 percent of the pilots.

2. Traffic Display -
   Graphic display with a master caution light and sound was the display identified by all the pilots, if the display was part of the system.

3. Type of Traffic Display Information -
   Fifty percent of the pilots wanted information for threats, the other 50 percent wanted information for threats and proximate aircraft.

4. Other Features Requested -
   Horizontal maneuvers (50 percent)
   Interaction with other aircraft systems (i.e., Flight Management system, Ground Prox, etc.) to coordinate the maneuver with other avionic information (50 percent).

4.6.3 Performance Results

Even though a performance evaluation was not one of the objectives of the study, the system implemented had the capability of recording many flight parameters and data was collected on three of the flight crews. This data was used to perform the aircraft separation analysis. The six pilots, from whom the data was collected, were highly experienced, they averaged 16,000 flight hours. Five of the pilots were captains and one was a first officer. All of the pilots were rated on three or more jet transports. Three pilots were rated on the 737 and one was DC-9 rated. Five of the six held a 727 rating.

Table 4.6.3-1 presents the encounter data base for the aircraft separation analysis. It can be seen that the results are based on a total of 473 intruding aircraft which produced 152 resolution advisories. When TCAS measures the closest point of approach (CPA) for logic purposes, the result is a slant range value. The following results present not only this range, but also its vertical component.

Of the 152 resolution advisories, sixty-eight percent (104) occurred with more than one aircraft present on the TA display and thirty-two percent (48) had only the RA threat aircraft present. Table 4.6.3-2 provides a tabulation of the CPA data. Four separate miss distance categories are presented. The 240 foot category was chosen to represent those cases which, when rounded to the nearest .1 nautical mile, would be considered as zero separation. The second category remains within the critical envelope defined by TCAS. The third category is inside the high altitude envelope for TCAS and the fourth level is outside all TCAS boundaries.

Five percent of the resolution advisories (8) resulted in aircraft separation less than 240 feet. Twenty-six percent of the RA's (39) resulted in a CPA of less than 600 feet. The rest of the TCAS situations (113) had CPA's greater than 600 feet. The next step was to determine, for those aircraft that were approaching within 600 feet slant range, what portion of that distance was contained in altitude separation. Table 4.6.3-3 presents the figures for this set of resolution advisories. There are three categories associated with the altitude separation. They can each be put into perspective if one considers

Table 4.6.3-1 Database for the Aircraft Separation Analysis (3 Crews)

	MULTIPLE AIRCRAFT ENCOUNTERS	SINGLE AIRCRAFT ENCOUNTERS
TOTAL NUMBER OF AIRCRAFT	386	87
TOTAL NUMBER OF ENCOUNTERS	173	87
NUMBER OF RESOLUTION ADVISORIES	104	48

Table 4.6.3-2 Closest Point of Approach (3 Crews)

	MULTIPLE AIRCRAFT ENCOUNTERS (N = 104)	SINGLE AIRCRAFT ENCOUNTERS (N = 48)
*CPA LESS THAN 240 ft	6 (6%)	2 (4%)
FROM 240 ft TO 600 ft	21 (20%)	10 (21%)
FROM 600 ft TO 900 ft	25 (24%)	4 (8%)
FROM 900 ft TO 6100 ft	52 (50%)	32 (67%)

*CPA = Closest point of approach slant range

Table 4.6.3-3 Altitude Separation When CPA Is Less Than 600 ft (3 crews)

ALTITUDE SEPARATION	MULTIPLE AIRCRAFT ENCOUNTERS (N = 27)	SINGLE AIRCRAFT ENCOUNTERS (N = 12)
LESS THAN 100 ft	6 (22%)	1 (8%)
FROM 100 ft TO 400 ft	8 (30%)	3 (25%)
FROM 400 ft to 500 ft	7 (26%)	4 (33%)

that TCAS issues the RA when the calculated vertical separation at CPA will be less than 750, 850 or 950 feet (depending on sensitivity level) and a range test is passed. In point of fact, TCAS aborts if it determines that the two aircraft are going to have less than 100 foot vertical separation in the sense direction. Seven of the encounters which had slant range separation of less than 600 feet also had an altitude separation of less than 100 feet. In reviewing these seven encounters, it was found that 5 of those encounters also had a slant range less than 240 feet and in 2 of those cases, the slant range was less than 60 feet. All totaled, when the CPA was less than 600 feet, 46 percent of the time the altitude separation was less than 400 feet and 75 percent of the time it was less than 500 feet.

An in depth analysis was performed on a single 737 experienced crew in order to identify trends and potential problem areas. The results from this analysis include: the ability to achieve a 1500 foot per minute rate during a "Climb/Descend" maneuver; the time taken to achieve a 1500 foot per minute rate; maximum vertical speed achieved during maneuvers; extent of the flight path deviation; and response in the opposite direction from the resolution advisory maneuver.

One hundred sixty-six aircraft resulted in 50 resolution advisories. The resolution advisories consisted of: 20 climb/descend alerts; 16 vertical speed limts; 2 vertical speed minimums; and 12 negative alerts (don't climb/descend). Thirty-five of the resolution advisories were corrective alerts (IVSI needle in the lights - pilot action required) and 15 were preventive (IVSI needle not in the lights - no action required).

Table 4.6.3-4 presents a breakdown of the climb/descend advisories. When looking at the performance characteristics of responses to these alerts, it can be seen that for the climb maneuver it took more than 13.4 seconds to achieve a 1500 feet per minute rate in 16 percent of the cases (Mean + one standard deviation). A second measure used was the time it took to change from a climb alert to some lower level alert. In 16 percent of the cases it took more than 20.8 seconds for this change to occur and the deviation in flightpath, as a result of the alert, was less than 301 feet. The results from the "Descend" advisory are similar to the "Climb". It took more than 10.8 seconds to achieve

Table 4.6.3-4 Summary of Responses to the Climb and Descend Alert (1 crew)

		CLIMB RA (N = 13)	DESCEND RA (N = 7)
DID NOT ACHIEVE 1500 fpm		5	3
TIME TO ACHIEVE 1500 fpm	MEAN SD	9.6 sec 3.8 sec	6.7 sec 4.1 sec
TIME TO CHANGE RA	MEAN SD	14.6 sec 6.2 sec	13.4 sec 8.9 sec
MAXIMUM VERTICAL SPEED	MEAN SD	1946.75 fpm 457 fpm	-2781 fpm 921.0 fpm
FLIGHT PATH DEVIATION	MEAN SD	376 ft 74.4 ft	615.8 ft 292.1 ft
RESPONSE OPPOSITE RA		1	2

a 1500 feet per minute rate in 16 percent of the cases and more than 22.3 seconds for the RA to become less severe. Flight path deviation was less than 323 feet for 16 percent of the cases. In 38 percent of the climb situations and 43 percent of the descend situations, the crew failed to achieve a 1500 feet per minute rate. On three occasions, the crew made an escape maneuver opposite the resolution advisory.

In breaking down the data from this crew further, it was found that a climb/descend arrow presented when the existing vertical rate was greater than 1000 feet per minute, resulted in no crew response. If the climb/descend arrow was presented when the vertical rate was greater than 1500 feet per minute, the crew reduced their vertical rate. The preventive alert was used to tell the crew that they were not in difficulty at that point (IVSI needle was out of the lights) and they should use care to see that the needle remained out of the lights. Eighty-seven percent of the time that a preventive alert occurred, the crew maneuvered further away from the lights. Finally, the negative alerts (Don't Climb/Descend) generated responses inconsistent with the alert, e.g., "Don't Climb" resulting in a climb maneuver 50 percent of the time.

5.0 Discussion

The Phase II simulation effort was designed to assess TCAS equipment and procedures using experienced flight crews in a high fidelity simulator flying operational type flight plans under moderate workload conditions. Thus the simulation combined some of the major aspects of the operational environment to evaluate the system performance. Because the test was done in simulation, no safety pilot was required and therefore, none of the crew members had any prior knowledge of the TCAS situations. This resulted in a spontaneous response to the alerts and an indication of the types of crew coordinations that might be expected to occur in line operation.

A major difference between the simulation and the actual operational environment was the lack of visual intruders. This difference may have had an effect on the visual search aspect of using the system, but should not have affected the procedures for using TCAS since the system must be able to accommodate those situations in which the crew does not visually acquire the intruder. Aside from this difference, every effort was made to create an atmosphere which, to the pilot mentally and physically, represented the real world. Crew reaction to the simulation indicated that this effort was successful. All of the pilots rated the amount of simulation time, the variety of TCAS situations encountered and the equipment used as good or excellent. Ninety-two percent of the pilots recommended only minor changes at most to the ATC interaction and all of the pilots recommended only minor changes at most to the type of aircraft used.

Training is an important factor anytime a pilot attempts to operate a new system. Two aspects of training enter into consideration for this study, the proficiency with and understanding of the TCAS operation and the crew's ability to fly the simulator. Each crew had the training material for TCAS for a week before testing, and but also had a two hour training session which included an hour of hands-on training in the simulator. During this training they each experienced 16 TCAS encounters which progressed through TA to RA. An instructor pilot guided them through and explained each of these situations. By the end of the training period the pilots had experienced TCAS operation in a wide variety of situations and rehearsed their piloting skills in the B737.

It was felt that this amount of training would be adequate for the crews to evaluate the TCAS system and operational procedures, especially since the test flights were flown immediately after training. In the opinion of the instructor pilot, the crews were adequately trained for this purpose. Support for this opinion can be found in the study results: where it would be expected that if the crews were still learning the system during the test flights, different operational patterns would be observed throughout the test and this was not the case. Therefore, if after two hours of training and seven hours of testing the use of the system remained relatively unchanged, it is not expected that an increase in training would change the system utilization especially in the operational environment where there is a potentially large time separation between training and system use.

Eight of the twelve subject pilots had experience in the B737 aircraft and all of the pilots were rated on multiple aircraft. While it is true that an hour of training in a Class II simulator is not enough to qualify for a type certificate, the test, did not require a type rating, but rather that the crews use their basic airmanship and experience to evaluate the system. At the completion of training, the instructor pilot felt that all crews exhibited adequate performance for the purposes of the test. The majority of the pilots (83%) said that they felt comfortable with the simulation after their training session and only one pilot said he didn't get comfortable until after about the fourth test flight. In rating the overall training and briefings 83 percent of the pilots said that they would at most recommend only minor changes to the training session. Therefore, in the judgment of both the instructor pilot and the majority of subject pilots, the training provided was adequate to perform the TCAS evaluation.

Care must be used when interpreting the performance results because of the nature of the study. Even though the pilots were informed during training that they would see an unnaturally high rate of alerts and that they should treat each situation as an individual rather than be influenced by the total number of alerts, the larger number of alerts had the effect, as with most alerting studies, of causing the pilots to expect the alerts which results in responses which are faster than would be normally expected. The frequency of

alerts also has the effect of providing the crews more practice in responding to the TCAS situation. Both of these factors lead to the results of alerting system testing normally being treated as lower limit values with the expectation that in actual operation, response time will be longer, flight path deviations smaller and error rates greater. It also must be remembered that the performance data was taken from a limited number of pilots and should be used as trend indicators only.

Most pilots (88 percent) liked the system presentation rating it as good or excellent; however, the traffic display used in simulation was very high resolution with small line width, high brightness graphics, fine color control, and no displayed errors (e.g., dropped tracks, jumping symbols, jitter, etc.). This rating may change as a result of using displays with different qualities. All the pilots felt that the display was clear and most of them felt that the TA display was useful, even though it increased their workload. One problem they had with the TA information and procedures is that they wanted to use the display to maneuver the aircraft without making visual contact with the intruder. The data revealed that all the crews made distinct, deliberate, and recognizable maneuvers during some of the TA alerts, even after being reminded that such maneuvering was contrary to the established procedures and telling them why that procedure was established. In general, this was a crew-coordinated maneuver. The non-flying crew member, who was reporting information from the TA, was usually involved verbally with the decision to make the maneuver. It is expected that the flying-pilots' willingness to maneuver during the TA will be highly dependant on the situation and may be influenced by such things as: time since training; the actual situation; the presence of a check pilot on board; the phase of flight; ATC interaction; etc.. Crew interaction was also evident when the decision was made not to follow the RA maneuver. A typical example of the interaction was observed in the following transcript of a crew conversation:

-TA alert-
Flying pilot - "TCAS 200 feet above us."
Non-flying pilot - "and they're descending."
FP - "Well we might as well climb to go over them." (starts climbing)
-RA "DESCEND"-

FP - "I'm going to cheat on this one, I'm not going to do what it tells us."
NFP - "There is another one right behind him."
FP - "I'm going to go over both of them."

A second example happens in a multiple-intruder situation where one intruder is slightly above co-altitude (50-100 feet) and the second intruder is 900 feet below.

-TA alert-
NFP - "TCAS alert twelve o'clock same altitude converging. Stand-by for the red warning."
FP - "Tell them (ATC) we want a higher altitude." (Starts climbing)
NFP - "This is Boeing 737 requesting higher center"
-RA "CLIMB"
ATC - "Roger BOEING 737 I can give you 19, over"
NFP - "Say again"
ATC - "I'm sorry, I can give you 18000, over"
NFP - "Roger 18. OK he is 500 feet below you and we have another one below us at 12 o'clock."
FP - "I'll tell you what I did. We had a guy right at our altitude and another guy was below so I said 'let's go up' rather than wait for the warning."

These examples are just two of many incidents that illustrate how the crews use the available information to adjust their procedures to their perception of the situation.

Even though the information on the TA display is primarily intended to serve as an aid for the visual acquisition of intruder aircraft, the crews used it to change the flight path of their aircraft. Since pilots are trained that they should use all the data on the flight deck to safely operate their aircraft, it is a natural reaction for them to maneuver based on the information they are given by the TA display. This response may be further reinforced by the fact that they have been trained that the TA alert could be followed by an RA alert if the flight paths of the two aircraft don't change. In actual operation, it will be very difficult to counter this reaction through training

because the TCAS system itself will be working against the training. Consider, if only one TA in every eight goes to a resolution advisory (Piedmont Phase I flight test) and if the crew maneuvers on the TA: then 7 times out of 8, the crew could well believe that their maneuver prevented the RA when it actually didn't.

The crews also were observed to anticipate the resolution advisory based on information provided by the TA display. This use of the TA led directly to a large proportion of the pilots reporting that they had inappropriate or incorrect alerts. These reports were made even though (to the authors knowledge) there were no inappropriate or incorrect alerts presented as far as the TCAS logic was concerned. The vast majority of these reports occurred as a result of a TCAS escape maneuver which called for the own aircraft to cross the altitude of the threat aircraft. The reluctance of pilots to change their flight path toward another aircraft is a natural reaction which will be extremely difficult to overcome. One aspect of the simulation that must be taken into account when considering the pilots' reluctance to perform altitude crossing maneuvers is the absence of the intruder vertical rate arrow on the simulation TA display. Even though this symbol was programmed into the simulation system, the logic used for the test did not activate it. This arrow is intended to inform the crew when the intruder is climbing/descending at a rate greater than 500 fpm and to aid the crew in accepting altitude crossing maneuvers.

Results from flight tests indicate that the lack of the vertical rate arrow in the simulator had little impact on the pilots' reluctance to perform altitude crossing maneuvers. Crew procedures observed during simulation included the non-flying pilot reporting relative altitude changes between their own and intruder aircraft. This report could have been used by the flying pilot to obtain an indication of the intruders vertical rate. Furthermore, the conclusion reached in flight test stated that "the addition of the vertical arrow to the altitude tag does not appear to resolve the problem (of altitude crossing) since the arrow commonly appears in situations where no altitude crossover is required."(15) Therefore, the results which indicate that incorrect or inappropriate alerts are occurring seem to be a function, not of the system hardware/software, but rather of the situation perception that the system has given the crew.

One of the results of this type of perceptional conflict is that the pilot may decide to perform some maneuver other than that given by the RA. Such a maneuver must be done under the assumption that the threat aircraft will continue to do what it is presently doing. A danger arises if the threat aircraft is also TCAS equipped. Since the TCAS escape maneuver is a coordinated maneuver when both aircraft are equipped, performing a maneuver other than what is called for by the RA could cause the situation to deteriorate.

As the system is presently configured, the resolution advisory is always presented as a warning, i.e., red light and warning sound. There is every indication from previous work and from the present study that such a warning is not always appropriate. The underlying criteria for a warning alert is that immediate action is required and pilots have been trained to expect to make an immediate response to red alerts. Therefore, the warning alert is appropriate for corrective alerts; however, no action is required for preventive alerts. The data revealed that in 87 percent of the preventive alert situations, the pilots took action when none was required. While it is true that the resulting action was away from the danger, it was still an unnecessary action and may result in a needless increase in workload for the whole system (e.g. increased ATC interaction, increased crew work, etc.) The negative alerts suffered from a similar problem. Since these alerts are a combination of a negative "Don't" and an active word "Climb" and are presented as a warning, it would be expected that the action word would be more powerful because warnings require immediate action. The results supported this hypothesis when the negative alerts resulted in responses which were not consistent with the alert in 50 percent of the cases.

Finally, the response trends indicate that the pilots may not respond as rapidly as the TCAS logic is currently programmed to assume. The length of time to reach a 1500 feet per minute rate and to reduce the urgency of the resolution advisory were marginal with respect to the time available. Considering that these response times are expected to be underestimates of the actual time required, the time assumptions used in the TCAS logic may be too short. The amount of flight path deviation observed during the TCAS situations also did not reach the values expected to be achieved in response to the the TCAS

alerts. Some confusion was demonstrated concerning the meaning of the arrow, especially when the own aircraft had a vertical rate in the same direction as the arrow. Typically, when the rate was less than 1500 fpm, but greater than 1000 fpm, no response was made indicating that the pilot felt that the existing rate was adequate. On the other hand, when the rate was greater than 1500 fpm, the pilots tended to reduce the rate toward the 1500 fpm value. Both of these errors would be easily noticed, and therefore, probably eliminated if the vertical speed limit arcs (see figure 4.2.1-2) were used for the climb/descend alert instead of the arrows.

6.0 Unresolved Issues

The results of the operational evaluation of TCAS II in the simulator indicate a number of key issues concerning the use of the system and its interface with the crew which remain to be resolved. Since the final responsibility for the aircraft safety rests with the crew, they must feel confident in using TCAS for the system to be effective. The remainder of this section will be devoted to enumerating some of the issues concerning TCAS that were raised by the operational simulations.

- Information Presentation -

As stated earlier, the pilots have been trained to use all the information provided on the flight deck in safely operating their aircraft. When TCAS gives the pilots enough information so that they think they can anticipate the "correct" maneuver, what do they do with the information? The data indicate one procedure they adopt is to maneuver during the TA. However, if there is no premature maneuver, the question remains as to how the crew resolves the conflict if the maneuver prescribed by the RA is not what was anticipated. The decision then has to be made whether to follow their own judgement or to respond to TCAS. The results of this decision process can be seen in the data which indicate that the majority of pilots reported incorrect or inappropriate alerts even though there were no alerts of this kind included in the evaluation. Therefore, it is reasonable to suggest that if the information presented by the system creates this kind of perception and conflict for the crews, an adverse reaction to system use could be fostered. Furthermore, a set of procedures could be adopted by a crew for situations of this type which would be totally inappropriate in some cases. An example is the instance where the flying pilot decides to perform a maneuver which is in the opposite direction from the RA maneuver, without realizing that the threat aircraft may also have TCAS which has issued an RA maneuver in the exact direction he has chosen to take. Some of these problems may be alleviated as crews become more familiar with the system, however, resistance will be very high because of the natural reluctance of pilots to perform certain maneuvers such as altitude crossing and major deviations from the ATC clearance.

In addition to crossing altitude maneuvers, multiple aircraft situations also pose a difficult problem for the crew. The presence of the TA display implies that they should be able to use it and interpret the situation. However, the resolution advisory only considers those threats which are generating RA's when determining the escape maneuver. This type of encounter, many times, resulted in the RA conflicting with the crew perception of the situation. The hesitation generated by these circumstances caused the maneuver, when it was performed, to be less than the optimum system solution to the problem.

- TCAS Invalid -

The "TCAS ABORT" is a highly stressful situation. Even though the name of the alert has been changed to "TCAS INVALID" the situation creating the alert has not changed. If the crews have been trained that one meaning of this alert is that vertical separation in the direction indicated by the system is going to be less than 100 feet, the very presence of the alert will create a high level of stress, especially when the time to achieve a solution to the situation may be less than 25 seconds. Therefore, the conditions causing the "ABORT" alert need to be investigated to see if a set of procedures can be developed for use in these situations. Furthermore, it may be discovered that because the abort alert occurs with so little time remaining until the point of closest approach that no procedure is appropriate and that the system must be modified to prevent the occurrence of this alert.

- Increased Communication -

The amount of communication between TCAS equipped aircraft and ATC could add pressure to the present verbal load. The increase in communication, in turn, will make it more difficult to contact ATC. Therefore, how the crews will react to the inability to contact ATC with a TCAS message in high traffic areas is in question.

- Display Requirements -

The present TCAS system color coding and alert generation philosophy is not consistent with recognized design guidelines for either an advisory or an

executive system. The use of the colors red and amber have been reserved (*by FAR Part 25, ARP 450 and the FAA design guidelines) for warning and caution alerts. The use of the color red has been limited to warning situations when an immediate action is required of the crew and caution alerts require immediate awareness and prompt action. In the present TCAS design, the color red is used for a RA and amber for a TA. The problem arises because some RA's require immediate action (corrective alerts) and some require no action at all (preventive alerts) and the TA's also require no action. This problem is further complicated by the fact that some RA's have an action word, e.g., "Climb" preceded by a negative word, e.g., "Don't". These alerts are also red in color (immediate action), and when they are preventitive (i.e., the pilot is not climbing and no action is required) they result in an increase in the probability of performing an inappropriate response. Finally, it is inconsistent coding to announce an alert with one color (i.e., red master alert for RA's) and use another color on the primary system display (i.e., amber eyebrow light or green arrow on the IVSI). This conflicting display formatting could lead to confusion and response delays. All of the questions involving color and alert urgency could be inapplicable if TCAS is implemented as an advisory system. In that case, only immediate attention is required by the system and the RA alerts should not be coded as warnings but rather as cautions. This means that no red indicators are appropriate.

- Training -

The training requirements generated by the system also need to be evaluated. The training session for the test, although quite extensive in both time and material covered, did not result in the crews always following the operational procedures. Consideration must be given to the fact that the training will have to be effective for situations which occur infrequently and are highly variable when they do occur.

Finally, and very important, with respect to the unresolved issues is a clear determination of the system utilization philosophy. The differences between an executive and advisory system require that different design guides be used for the pilot interface.

To summarize, the issues which need to be addressed are:

1. The TCAS system as it is presently configured may not, with an acceptable consistancy, generate response performance (either in type of response or in time to respond) commensurate with the assumptions which inderlie the TCAS logic. Further evaluation is required to determine what changes can be made either to the assumptions or the pilot interface to improve performance.

2. The information presented by the system may encourage the pilot to anticipate the RA maneuver or to maneuver based on the TA. A means will have to be found to eliminate or resolve conflicts that arise when the preconceived maneuver is not the maneuver selected by the system. Furthermore, some means must be developed to discourage using the TA display data as a basis for a maneuver during a TA alert. The question which arises is how to accomplish this objective; can be done with training or will it require system modification?

3. TCAS logic presently considers only RA aircraft in establishing the escape maneuver. Situations were observed wherein this logic could contribute to crew indecision. Further evaluation is required to determine if another approach to resulting traffic logic can produce more appropriate crew responses.

4. The pilots' reluctance to perform altitude crossing maneuvers must be resolved. Evaluations must be performed to determine if this can be accomplished with training and eventual system familiarity, or if system solutions are necessary.

5. Reliable and acceptable procedures for the "TCAS INVALID" are required, if none can be developed then a system modification should be investigated.

6. A means must be developed to preclude the increase in ATC verbal communication, especially with TA's and non-mode C equipped intruders, adding excessively to the existing communication load. Inability to contact ATC in high traffic areas must not affect the use of the TCAS.

7. Sixty-four percent of the pilots responded in the program debriefing questionnaire that the potential exists, as with any automated system, that the pilots will take the system function for granted and reduce their outside visual scan. Is this phenomenon a problem with TCAS and what means can be used to prevent it from occurring?

7.0 Conclusions and Recommendations

The following section will combine the results of the two simulation studies with the existing data relevant to crew performance to generate the conclusions and recommendations.

- Response Time -

As was noted in an earlier section, the TCAS simulation studies and recommendations have been based on the assumption that TCAS was an "Executive" system. This assumption was based on the urgency of the situation and the time frame available to the crew for responding to the system information. The TCAS response logic allocates 8 seconds to the pilot for response time. Previous research (10, 11, 12) has shown that for an executive system, it takes the pilot approximately 2-3 seconds to detect the resolution advisory (these figures represent simulator data and therefore are expected to be an underestimate of operational values), 5-6 seconds to recognize the alert, evaluate the situation and decide what to do, and 1-2 seconds to perform the response. Using these data, a response time of 8-10 seconds is the quickest we can expect some significant portion of the pilot population to respond (these figures are supported by the Billman, et. al. report (13) which models the pilot response at 5.6 seconds with a standard deviation of 2.1). Analytical studies of aircraft climb capabilities of a B727 (see Figure 7.0-1) indicate a worst case 24 seconds to achieve a 500 foot altitude change (flaps 30, gear down, 140 kn) and a best case of 10 seconds (clean, 11000 ft. altitude, 320 kn delayed thrust increase with a 25 kn loss in airspeed). Therefore, the data indicate that when the pilot and the system responses are combined, the response to the RA must be immediate (the definition of a warning level alert) and the awareness of the TA must be immediate (the definition of a caution level alert) to facilitate the RA response. This time budget alone indicates that strong consideration should be given to implementation as an executive system.

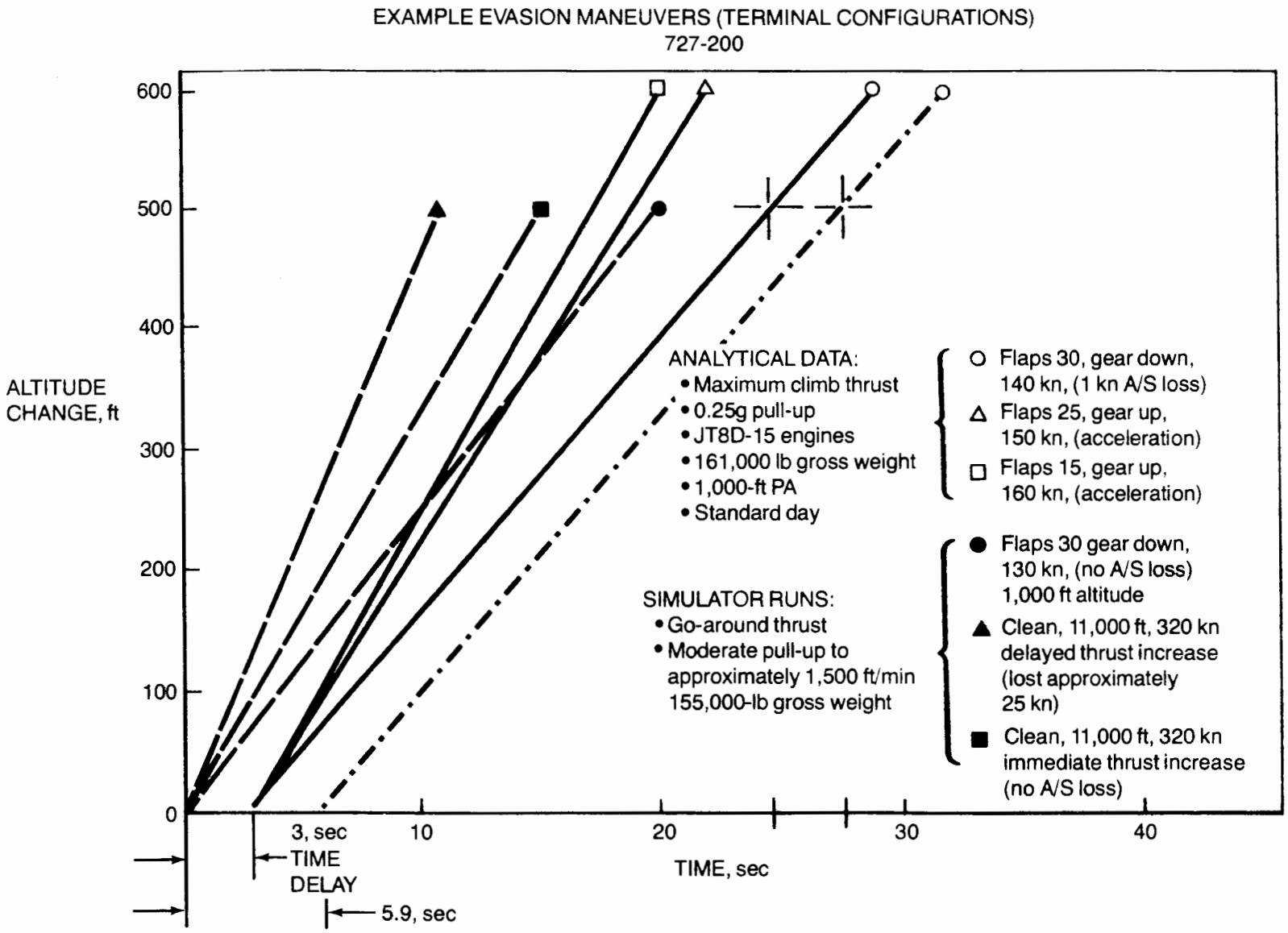

Figure 7.0-1 TCAS Performance Summary

In light of the operational study data, the system definition of optimum resolution should be re-examined. More consideration must be given to the pilot factor. If the RA calls for a maneuver which causes the pilot to hesitate (e.g., crossing altitudes), then the 8 seconds budgeted in the logic for pilot response time may not be adequate. Thus, the pilot factor, in this case pilot hesitation could change the "optimum" solution to an inferior solution or even an inadequate maneuver.

- Color Coding -

The display concept should conform to the voluntary guidelines issued by the FAA for standardizing crew alerting (4). The color of display elements is a very important aspect in the way the crew uses the information that they are given. The results from the operational simulation show that the crews are responding to the alerts based on the urgency depicted by the color. The responses to the negative and preventive RA's reveal the power of the warning alert and its meaning of immediate action. Therefore, the system design must be responsive to a consistent use of color and meaning. If TCAS is implemented as an executive system, corrective, resolution advisories are the time-critical alerts and should be color coded red and provide the crew with an indication of the action required to resolve the situation. Figure 7.0-2 provides the system components and the color coding recommendations for implementation as an executive system. Preventive alerts, however, do not require immediate action and therefore, should not be presented as warnings, but rather as cautions which require immediate attention. Negative alerts (e.g., "DON'T CLIMB") don't fit into the time-critical category because they do not describe the crew action required to resolve the alert condition even though they could require immediate action when they are corrective. If the situation necessitates an action, then the corresponding action words should be used (i.e., "LEVEL OFF", "REDUCE CLIMB RATE").

- RA Display -

Some of the confusion generated about the correctness of an RA could be a result of the display itself. The amber (caution) eyebrow lights are used for all RA situations even though they are always announced by a red (warning) master alert. This cross coding of information promotes confusion which may raise the probability of error in an inherently stressful situation. The coding on the RA display should indicate whether an immediate action is required of the crew. Even though no errors could be attributed directly to the red arrows during either of the simulation tests, they have been noted as a possible source of confusion and an unnecessary memory item for some time. The ambiguity of the arrows is unacceptable for an executive system where any time-critical warning must be easily interpreted and completely unambiguous. As the display is presently designed, the crew must remember various interpretations of the arrow depending on the vertical speed at the time of the alert. In one case it means to achieve a fixed vertical rate (1500 fpm) while in another case it means to maintain at least the existing vertical speed (when greater than 1500 fpm). A few pilots have commented that the arrow is miscolored and should be green. The difference in opinion here is a result of display interpretation. To date, there has been only one time-critical alert on the flight deck, that being ground proximity. The pilots are familiar with alerts which provide status information (green arrow showing safe area). However, the research on time- critical (4, 11) alerts indicate that the pilot needs guidance to perform the appropriate response in time (red indicating immediate action and the arrow showing direction). <u>However, the fact that the alert was misinterpreted during the test is sufficient reason that the display should be re-evaluated</u>. The recommendation is that the arrows be removed from the display in favor of using the eyebrow lights for all alerts. This implementation would be consistent with the instruction of "keeping the needle out of the lights". It is further recommended that the eyebrow lights be implemented to provide a gap (±250 fpm) around zero so that the command "FLY LEVEL" has an area on the IVSI where the pilot can keep his needle. Finally, the eyebrow lights should have a dual color code to indicate the difference between preventive (caution) alerts and corrective (warning) alerts.

- TA Display -

A portion of the difficulties exhibited during the use of TCAS seem to arise as a result of the information presented by the TA display. The data indicate that the pilots are considering the information presented as adequate to make maneuver decisions even though they were instructed to the contrary. If the primary purpose of this display is to facilitate visual acquisition of the intruder aircraft then the information being presented on the display should be re-evaluated from the perspective of altering that information to prevent premature maneuvering and anticipation of the RA, while still providing an aid to visual acquisition. A possible example of this approach could be removing the relative altitude of the intruders from the display. This may slightly increase the time to visually acquire the intruder, however, it would also remove the primary cue that the pilots are using both to maneuver and anticipate the RA.

- Voice Display -

The voice used in the simulation tests was judged to be unacceptable by a majority of the pilots. This result, in conflict with bench tests of the voice quality, illustrates the fact that system components must be evaluated in the environment in which they will ultimately be used. System decisions should be based on data which include pilot-in-the-loop performance evaluations from environments which represent that which is expected and not solely on software or hardware considerations or subjective opinion.

- Operational and Crew Procedures -

The operational procedures developed for the simulation test were acceptable to the majority of the pilots (83%). Even though 75 percent of the pilots reported situations for which the prescribed procedures were not appropriate, this was caused by the geometry of the situation (altitude crossing) rather than the procedure itself. The most often cited complaint concerning the

procedures was about the restriction placed on maneuvering on the TA information. Since the procedures themselves seemed appropriate for the system as it was used in testing, it is recommended that those procedures be used in the flight evaluation with the exception of the procedures used for the "TCAS INVALID" alert. The procedure used in testing "use all information available to resolve the problem" provides the crew no positive help in a very stressful situation. It is recommended that a more positive procedure be developed for evaluation in flight test. An example of such a procedure could be "stop present maneuver and return to and/or maintain last assigned clearance".

Crew coordination during a TCAS situation is an important aspect of system operation. As a result of observing the crew operations during the test, the following coordination procedure is recommended as one, but not the only one, that could be used for flight evaluation.

Flying Pilot
- disengage autopilot
- control aircraft
- cross check TA display
- search for threat aircraft
- respond to RA

Non-Flying Pilot
- read and verbally report on TA display
- search for threat aircraft
- turn seatbelt sign on
- turn off master alerts
- interact with ATC

- Advisory System Implementation -

It should be pointed out again that the above recommendations assume an executive system. It is possible that TCAS will be implemented as an advisory system (pilot responds to the alert only if he has reason to believe he should). This fundamental change in system utilization philosophy would generate a totally different set of system recommendations which must then be re-evaluat-

ed to assess their impact on flight deck operation. As an example, recommendations based on the FAA's standardized alerting guidelines which would be consistent with this type of utilization would no longer classify and present the RA alerts in the warning category, but rather as cautions which require immediate attention. The TA alerts would be presented as advisories requiring crew attention and all other traffic would be considered system information to the crew. Color coding would be appropriate for the TA display as long as red is not used as one of the colors and amber is used only for RA intruders. The RA display and master TCAS alert should be amber. The caution aural should be used for all RA's and a single stroke tone (e.g. "chime) for all TA's. A voice message should be available at the pilot's option for all RA alerts. Additionally, the operational procedures, pilot acceptance, pilot performance, ATC compatability, and total system impact must be assessed using the new TCAS system concept. Figure 7.0-2 presents the recommended TCAS display system characteristics for both an executive and an advisory system in an aircraft that does not have an integrated warning and caution system as described in the FAA guidelines (4). If the aircraft does have a standardized alerting system, then TCAS should be integrated into that system.

- Areas for Continued/Further Development -

In conclusion, it is evident that the importance of the unresolved issues indicates that the appropriations of the assumption embedded in the TCAS logic which are based on pilot performance must be reviewed, the pilot-system interaction relative to performance conflicts must be examined and the TCAS-pilot interface should be modified to meet the FAA recommended guidelines for crew alerting devices before the system is introduced as either an executive or an advisory system.

Other areas which should be investigated include: training, system logic, and display design and formatting. Several tasks are recommended in the area of training. Pilot performance relative to the time since training should be investigated to establish retraining requirements. unlearning and long term memory research should be used as an input to the safety study to account for

ICAS alert	Executive system alert characteristics (Crew action required)					Advisory system alert characteristics (Crew action recommended)				
	Alert level	Master alerts	RA display	Voice	TA display	Alert level	Master alerts	RA display	Voice	TA display
Corrective Resolution Advisory	Time-Critical Warning	Red — visual Warning — aural	IVSI — eyebrow Lights — red to the appropriate vertical speed	Automatic message same as RA display	RA intruder colored red	Caution	Caution aural	IVSI amber eyebrow lights (no red) to the appropriate vertical speed	Pilot option	If color coding is used, RA intruder colored amber (no red). Other types of coding optional
Preventive Resolution Advisory	Caution	Amber — visual Caution — aural	IVSI — eyebrow Lights — amber to the appropriate vertical speed	Pilot select-able — message same as RA display	RA intruder colored amber but coded differently from TA (e.g., shape, size, flashing, etc.)	Caution	Caution aural	IVSI amber eyebrow lights (no red) to the appropriate vertical speed	Pilot option	If color coding is used, RA intruder colored amber (no red). Other types of coding optional
TCAS Invalid	Time — Critical Warning	Red — visual Warning — aural	IVSI — red "TCAS INVALID" indicator, all other lights off	Automatic "TCAS INVALID"	RA intruder colored red	Caution	Caution aural	IVSI — amber "TCAS INVALID" indicator — all other lights off	Pilot option	If color coding is used, RA intruder remains amber (no red). Other types of coding optional
Traffic Advisory	Caution	Amber — visual Caution — aural	None	Pilot select-able — message same info as TA display	TA intruder colored amber	Advisory	Advisory aural	None	None	If color coding is used, TA intruder colored TA color (not red or amber). Other coding optional
Proximate aircraft	Information	None	None	None	Proximate aircraft displayed only when an RA or TA is present. Colored white	Information	None	None	None	Proximate aircraft displayed only when an RA or TA is present. Colored white

Figure 7.0-2 Recommended Display System Characteristics for Retrofit Based on System Utilization Philosophy

the time between training and system operation when estimating the pilot factor probabilities. More emphasis should be placed on response biases to identify those pilot responses which are most resistant to training. If these response biases continue to be training resistant with reasonable training programs, then the overall system design may have to be modified to accommodate them.

The system logic which is now optimized as far as the hardware is concerned should be evaluated from the user's point of view according to the following tasks: Examine the effect of considering all proximate and TA traffic when issuing an RA. Review the "TCAS INVALID" situations and determine if the system is capable of providing the pilot with alternative maneuvering advice. Review the requirements for altitude crossing maneuvers with respect to pilot reluctance to perform this type of maneuver.

Finally, the following tasks associated with the design and format of the system displays are recommended. Review display requirements with respect to the new technology flight decks. Investigate methods for reducing anticipatory confusion during an RA, including cueing, information reduction, and training approaches. Redesign the system in a manner which is consistent with recommended practices for information transfer and with the system utilization philosopy. Evaluate the potential benefits and risks of using both preventive and negative alerts. Assess the effect of presenting information concerning the intruder that is not presently being displayed, e.g., whether or not it is TCAS equipped.

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APPENDIX A

OPERATIONS SIMULATION

TEST FACILITIES

A.0 Boeing 737 Training Simulator

The Boeing Company, because of strong interest in possible implementation of TCAS in commercial aircraft, made its Customer Training Center available for the TCAS Operational Simulation Study. Boeing's training center contains four Redifusion full flight simulators: B-737, B-747, B-757 and B-767. To provide continuity with a projected follow on TCAS study with Piedmont B737 aircraft, the B-737 simulator was used for the TCAS study.

The Redifusion B-737 full flight simulator is a six degree freedom of motion system, Phase I certified by the FAA and undergoing Phase II certification during the testing time frame. The four forward windows are illuminated by high resolution (1000 line) color monitors that incorporate infinite focusing devices. A General Electric Compuscene 4000 System drives the external vision color monitors. The host computer is a Gould/SEL model 32/77 minicomputer and it controls the simulator with Redifusion developed software. Figure A.1 depicts the training center layout.

A.1 TCAS Hardware Mounted in B-737 Cab

For this study, several TCAS unique pieces of hardware were added to or substituted for the B-737 certified flight deck hardware (Figure A.2). The simulator was being used for customer training throughout this study so all of the TCAS hardware had to be installed before each session and removed afterwards. All the hardware was designed with this constraint in mind.

Master Warning/Caution Switch (Figure A.3)

A lighted Master Warning/Caution switch was located directly in front of each pilot.

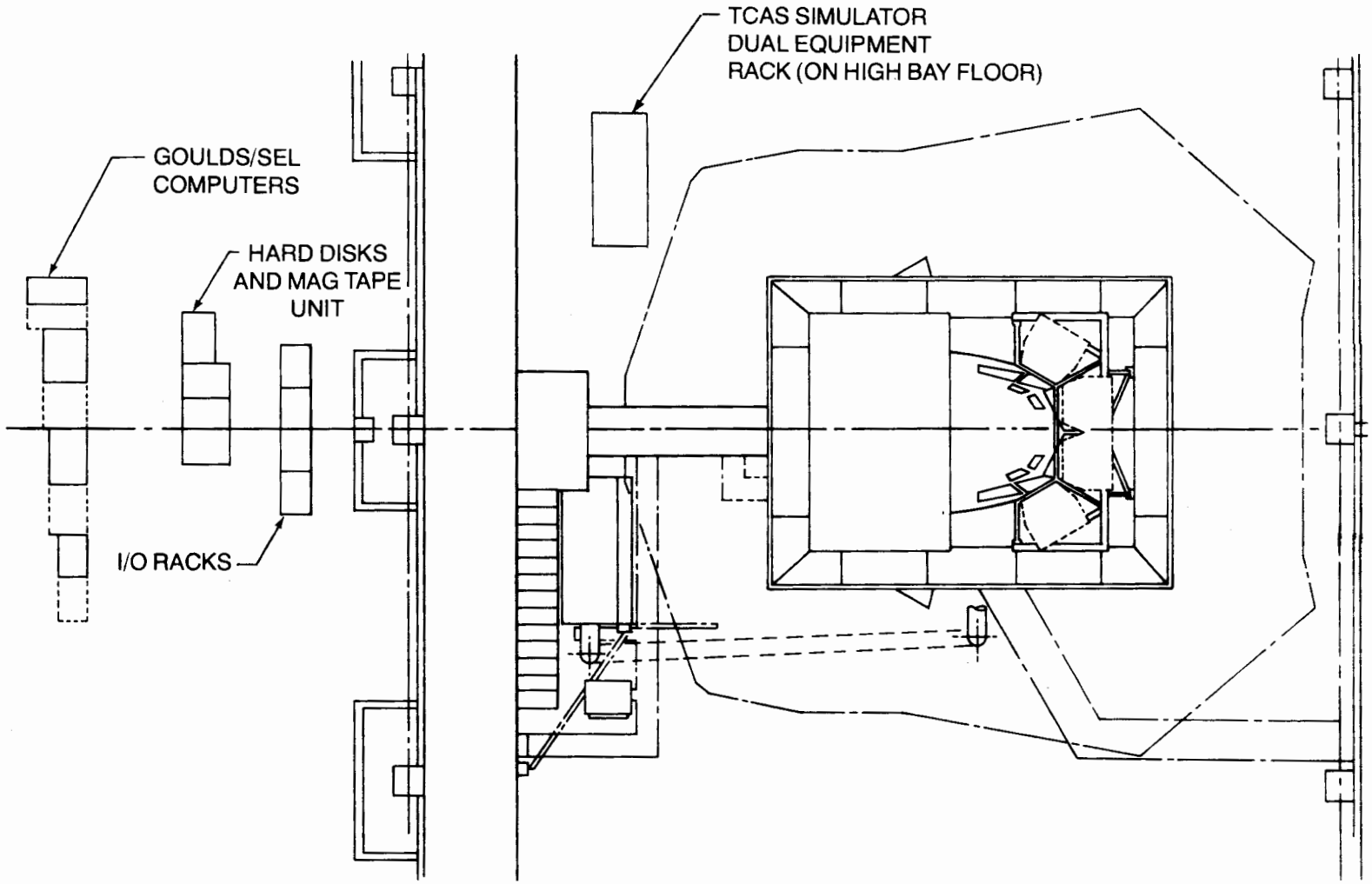


Figure A.1 Boeing Training Center – B-737 Full Flight Simulator Layout

15-20 BUILDING
SCALE 1:50

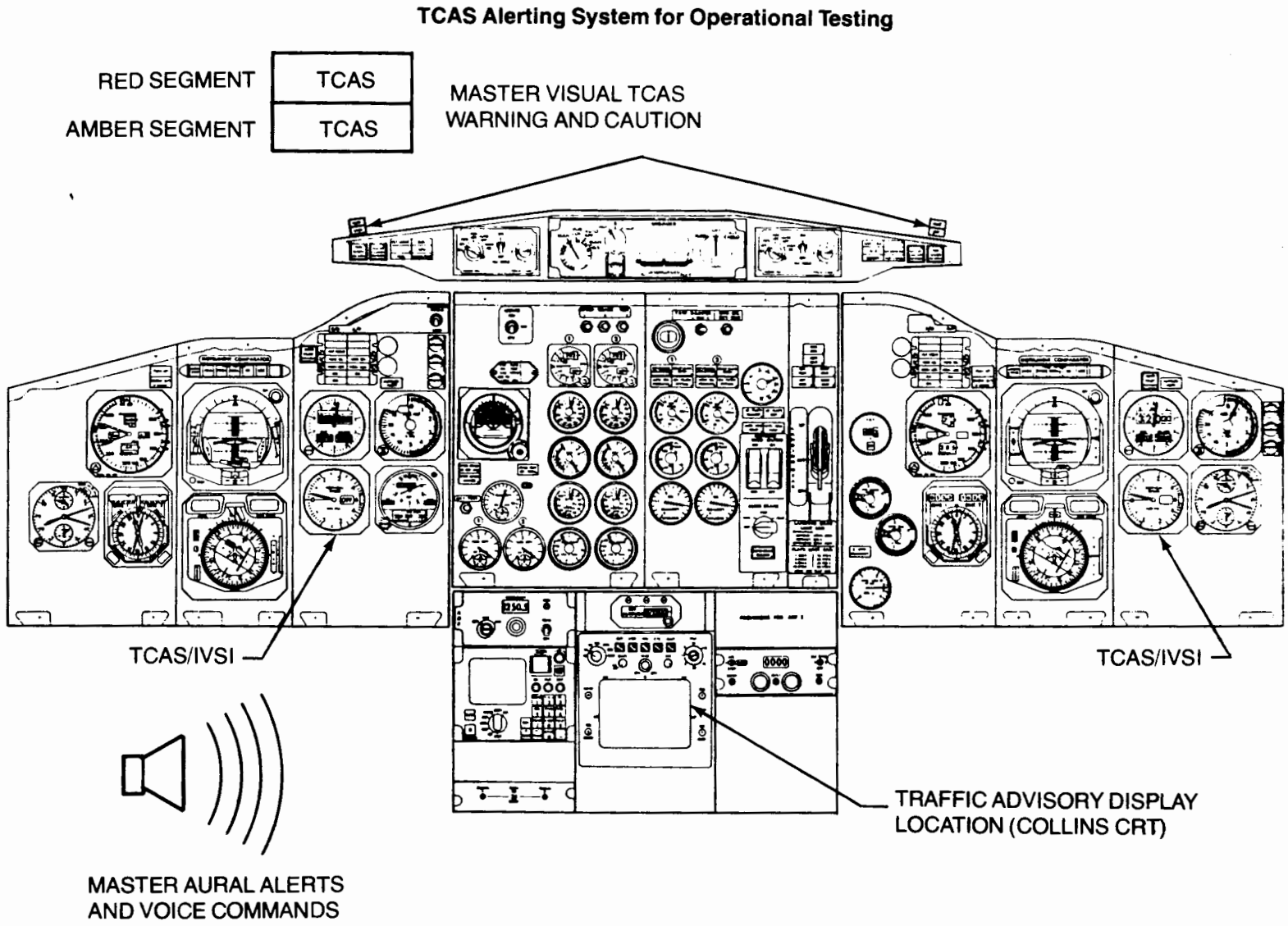


Figure A.2 B737 Front Panel Layout for TCAS Study

Collision Avoidance System IVSI (Figure A.4)

Each pilot's instantaneous vertical speed indicator (IVSI) was replaced with modified units that contained TCAS lamps. The specially modified IVSI's were provided by Teledyne Avionics. Teledyne provided both synchro and servo driven IVSI's because of a simulator change part way through the study. The B-737 that was finally used required servo driven IVSI's. Teledyne was quite helpful in supplying engineering support and fast turn-around on requested changes to the IVSI's. Teledyne's support was done at no cost to the contract or Boeing.

Traffic Advisory (TA) Display (Figure A.5)

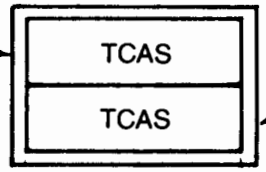
The B-737 dummy weather radar was replaced by a Collins color display (form factor B) which functioned as the TA display. A range selection switch was mounted with the TA display. It allowed the pilots to alternate between 6 or 12 mile map scales.

Event and Bailout Request Switches

Each pilot was provided an event switch which were mounted on the yoke handles. The test conductor was given a small box with event and bailout request switches. All the event switches were monitored by the Alert Controller (discussed below) and switch activations were recorded by the data recorder. The bailout request switch caused the Alert Controller to indicate a TCAS abort condition.

Speaker for Alerting Tones and Voice Messages

A speaker box was located, facing forward, about three feet behind the left hand pilot's seat. The box contained a four inch diameter speaker and a microphone for the automatic level control.



TCAS WARNING LIGHT (RED)

ILLUMINATED

- TCAS detects traffic that falls within the criteria for a resolution advisory to be presented on the IVSI

TO EXTINGUISH

- Pressing either TCAS light will extinguish both lights and silence the aural warning. Resets the system for any new TCAS alerts

TCAS CAUTION LIGHT (AMBER)

ILLUMINATED

- TCAS detects traffic that falls within the criteria for a traffic advisory to be presented on the traffic information display

TO EXTINGUISH

- Pressing either TCAS light will extinguish both lights and silence the aural caution. Resets the system for any new TCAS alerts

Captain's and first officer's glareshield

Figure A.3 Lighted Warning/Caution Switch

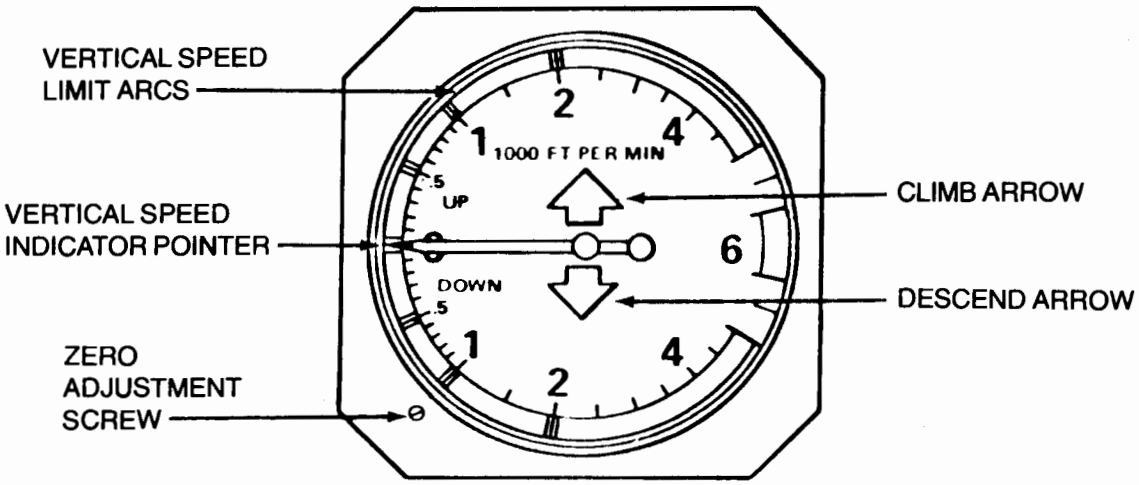


Figure A.4 TCAS Vertical Speed Indicator

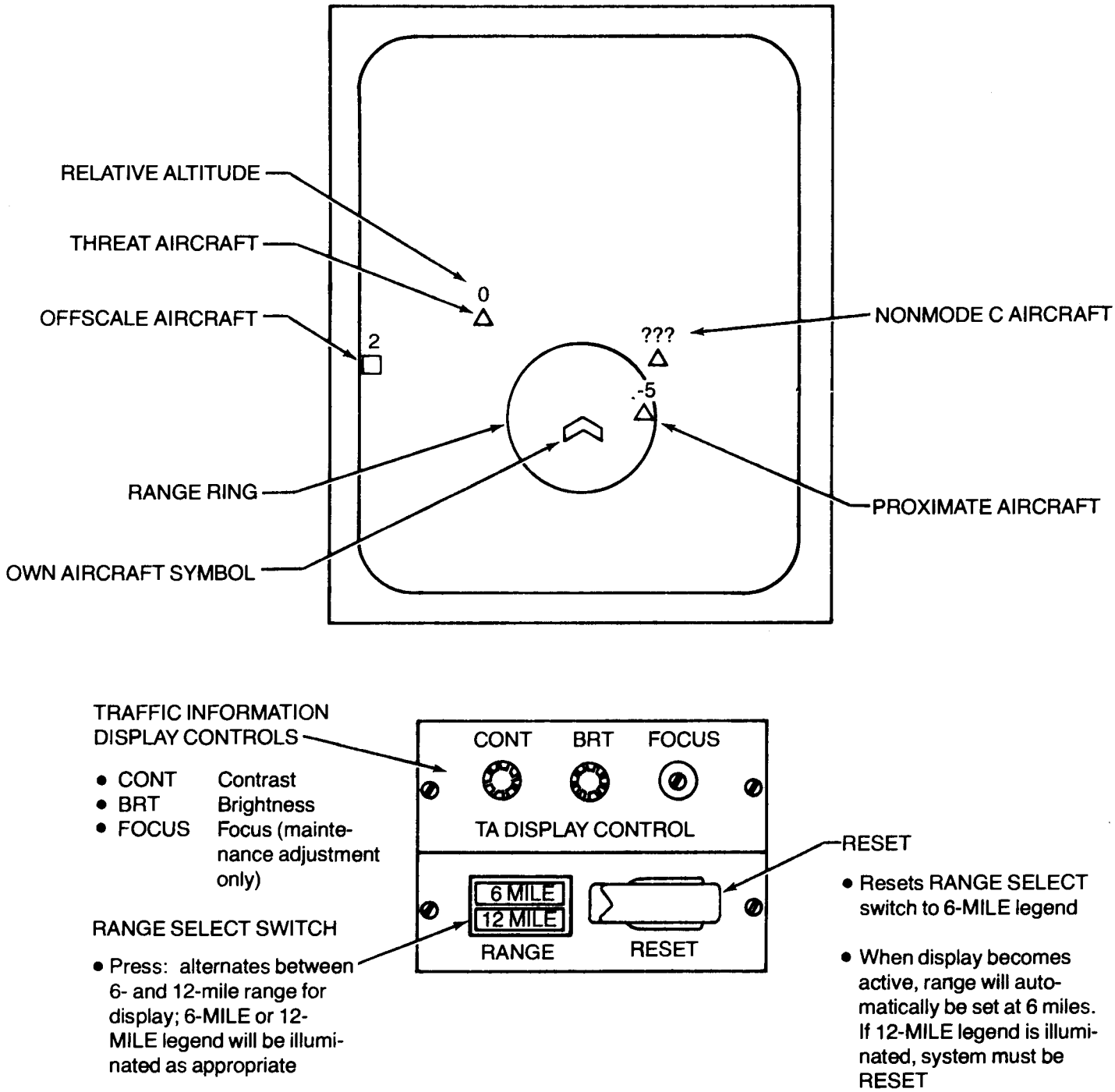


Figure A.5 Traffic Advisory Display

Control and Monitor Equipment

A low light level black and white video camera was mounted behind the pilots to allow a video record of the study. The camera was fitted with a wide angle (25 mm) lens so that much of the front panel was covered.

The test conductor was provided with a terminal that tied into the TCAS Scenario Controller. From this terminal, the test conductor was able to select and initiate the TCAS intrusion scenarios.

A.2 TCAS Support System

There were five primary subsystems that were used to control and operate the cab mounted TCAS hardware. Figure A.6 shows a layout of the TCAS support systems.

TCAS Scenario Controller

An Intel microcomputer system was used for the TCAS Scenario Controller. This system included: 5 Mhz I-8086 microcomputer, I-8087 math co-processor, 64K bytes of RAM, 96K bytes of EPROM, one RS-232 port and four 16-bit parallel input/output ports. A specialized operating system, TCAS program and static data base were all stored on EPROM.

The Scenario Controller was the heart of the TCAS Support System. As such, it directly or indirectly controlled all the other TCAS subsystems and had the sole link to the airplane simulator Gould/SEL computer system. The Scenario Controller functions were:

- o provide simulated intruder track data to TCAS Logic Unit
- o monitor B737 simulation status, position, and velocity
- o provide interface with test conductor
- o collect event switch closure and RA, TA, and PA status data from Alert Controller
- o collect test data and transmit to the data recording system

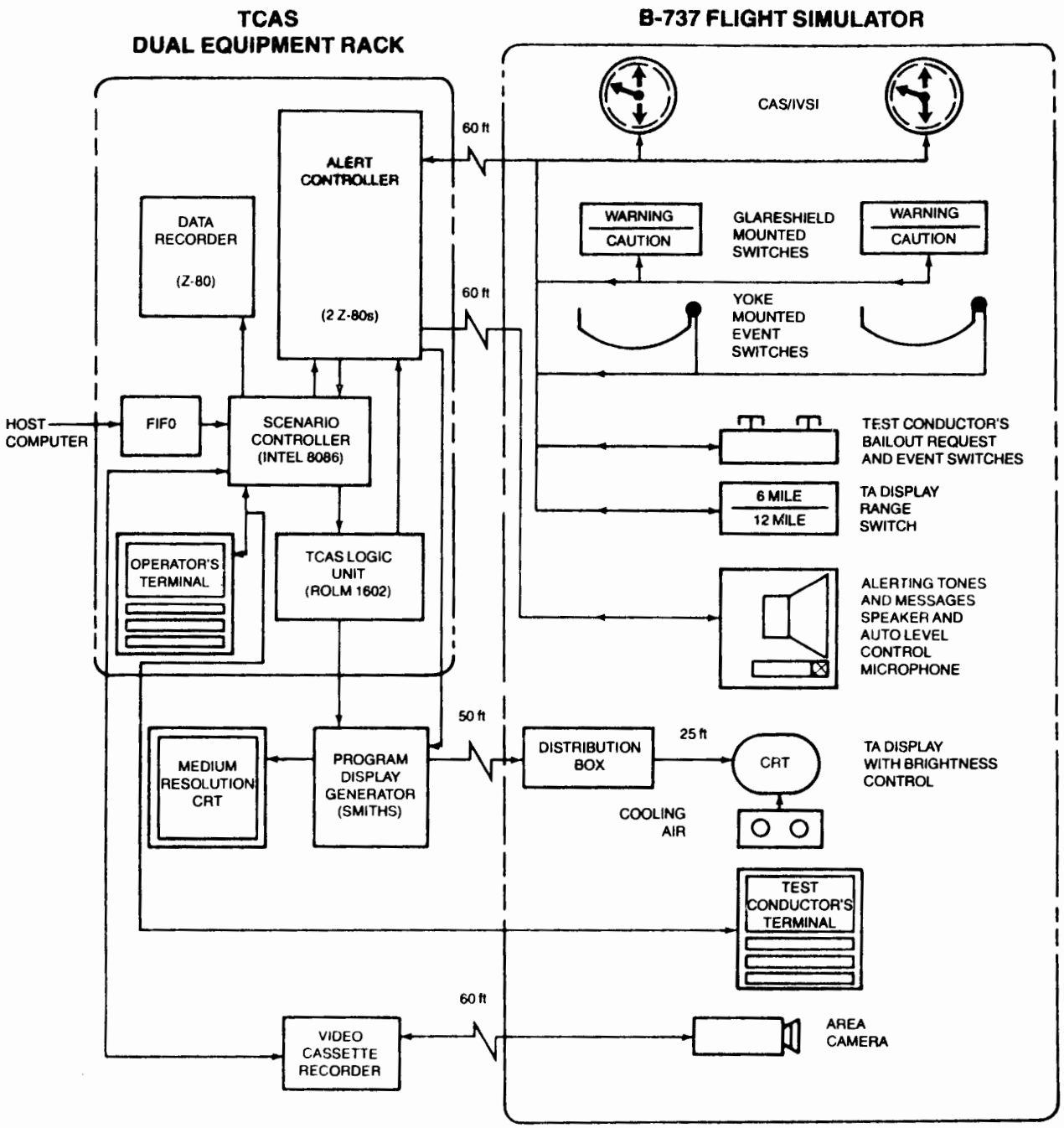


Figure A.6 Support Systems Layout

TCAS Logic Unit

The TCAS Logic Unit was a Rolm model 1602 which was compatable to that used by Lincoln Labs and FAATC in their flight test programs. Miter TCAS software (version 9: provided by Linclon Laboratories) was modified to provide the specific input/output requirements for the Scenario Controller, Alert Controller and TA Display Generator. No other portion of the Miter software logic was modified. The TCAS Logic Unit's functions were:

- to provide TCAS logic necessary to produce IVSI control and graphic specification
- input own aircraft and intruder data from Scenario Controller
- output IVSI TCAS lamp information and TA display status to Alert Controller
- output graphic specification to the display generator

Display Generator for Traffic Advisory Display

A Smiths Industries Programmable Display Generator (PDG) was used to drive the Traffic Advisory Display (a Collins color hybrid raster-stroke display unit). The Smiths' PDG was custom built for Boeing and has features which lend it to color display research work.

The PDG is controlled internally by a bit-slice microprocessor. It can generate two independent graphic displays for up to four display units. The display units can be RGB, beam penetration or composite video. The RGB displays can be hybrid raster-stroke design. For the TCAS study, only stroke mode was used to drive the Collins display unit. The PDG's functions during the TCAS study were:

- input range switch selection from Alert Controller
- input display specifications from Scenario Controller
- create display control from the display specifications and range switch action and output these controls to Collins display unit

Alert Controller

The Alert Controller was built by Boeing to act as a general purpose aircraft simulator alert controller and driver. It uses two Z80 microprocessors to control alert events, monitor switch actions, generate alert tones and voice messages and input data from other systems.

The voice alerts were generated by a Boeing refined voice encoder/decoder board. This voice system uses 2000 bytes of memory per second of speech and produces a high quality reproduction of voice patterns it records. Two voice message data bases were stored on EPROM. One voice data base was generated by Boeing. The other data base was purchased from National Semiconductor. National was quite helpful in generating and supplying, on short notice, words unique to the TCAS study.

The National voice data base was designed to be used with their voice synthesis system, Digitalker^{tm}. The Alert Controller did not have a Digitalker system in it so one was used to produce the voice messages. These voice messages were then recorded onto EPROM by the Alert Controller's voice encoding board. The Boeing voice system accurately reproduced the Digitalker's output.

The TCAS voice messages were contructed using individual words, many from National's general purpose vocabulary set. These messages, therefore, were not as intelligible as we desired. We believe (and National concurs) that carefully prepared alerting messages, i.e., messages recorded in their entirety, would be much more intelligible.

For the TCAS study, the Alert Controller's functions included:

- monitoring TCAS/IVSI lamp patterns and TA display status from TCAS Logic Unit

- provide alerting system logic necessary to control all alerting tones and voice messages and visual alerts
- drive TCAS lamps on IVSIs, master warning/caution switch lamps and TA display range switch lamps
- monitor all TCAS switches in simulator
- provide alerting tones and voice messages
- pass to Scenario Controller all switch actions, IVSI lamp status, and TA display status sent from TCAS Logic Unit
- output TA display range switch actions to TA display generator

Table A.1 lists the TCAS/IVSI lamp patterns as sent from TCAS Logic Unit and the corresponding voice messages.

Data Recorder

Data collected by the Scenario Controller was sent to a Zilog microprocessor system. The Zilog system used a Z80 microcomputer, 60K byte dynamic RAM and a single 300K byte floppy disk.

Table A.1 TCAS IVSI Lamp Patterns as Sent From TCAS Logic Unit and Voice Messages Used for TCAS Study.

RA	TCAS MESSAGE	CAS/IVSI LAMPS										
		10	9	8			5				1
1	CLIMB	1	0	0	0	0	0	0	0	0	0
2	DESCEND	0	1	0	0	0	0	0	0	0	0
3	DON'T CLIMB	0	0	1	1	1	1	0	0	0	0
4	LIMIT CLIMB 500 ft/min	0	0	1	1	1	0	0	0	0	0
5	LIMIT CLIMB 1,000 ft/min	0	0	1	1	0	0	0	0	0	0
6	LIMIT CLIMB 2,000 ft/min	0	0	1	0	0	0	0	0	0	0
7	DON'T DESCEND	0	0	0	0	0	0	1	1	1	1
8	LIMIT DESCENT 500 ft/min	0	0	0	0	0	0	0	1	1	1
9	LIMIT DESCENT 1,000 ft/min	0	0	0	0	0	0	0	0	1	1
10	LIMIT DESCENT 2,000 ft/min	0	0	0	0	0	0	0	0	0	1
11	MAINTAIN CLIMB 500 ft/min	0	0	0	0	0	1	1	1	1	1
12	MAINTAIN CLIMB 1,000 ft/min	0	0	0	0	1	1	1	1	1	1
13	MAINTAIN CLIMB 2,000 ft/min	0	0	0	1	1	1	1	1	1	1
14	MAINTAIN DESCENT 500 ft/min	0	0	1	1	1	1	1	0	0	0
15	MAINTAIN DESCENT 1,000 ft/min	0	0	1	1	1	1	1	1	0	0
16	MAINTAIN DESCENT 2,000 ft/min	0	0	1	1	1	1	1	1	1	0
17	TCAS ABORT*	1	1	1	1	1	1	1	1	1	1

*FAA-proposed voice message for advisory evaluation alarm.

APPENDIX B

TRAINING MATERIALS

The following is a copy of the TCAS training material that was sent to each of the participating pilots one week before their test date. The passages marked with a vertical line (|) did not appear in the material that was sent to the pilots, but was added during their onsite training. The passages that are shaded ( ) did appear in the material that was sent to the pilots, but was deleted during their onsite training session.

TRAFFIC ALERT AND COLLISION AVOIDANCE SYSTEM - SYSTEM DESCRIPTION

The Federal Aviation Administration has sponsored development of the Traffic Alert and Collision Avoidance System (TCAS II) to reduce the risk of midair and near midair collisions. TCAS II warns pilots about potential collision threats and actively attempts resolution of developing near misses and collisions with advisories indicating evasive vertical maneuvers.

This guide is to be used as part of the training program for pilots participating in the Phase II operational TCAS simulation. It provides the crew and observers background information necessary to understand and use TCAS II properly. Pilot procedures for this Operational Simulation are described in the second part of the document.

TCAS II is an onboard system composed of a computer equipped with collision avoidance logic, a Traffic Advisory display unit (CRT or LED), a Resolution Advisory display (a modified IVSI), special antennas and a Mode-S transponder (a new ATC transponder with significant new capabilities). TCAS measures the bearing, range, and altitude of aircraft in the vicinity of own aircraft and projects the paths of nearby aircraft. Depending upon the projected path of each aircraft as well as own projected path, TCAS may display an advisory. The decision to issue or to not issue an advisory is principally determined by range and altitude tests applied to nearby aircraft. The TCAS logic within the equipped aircraft implements an alarm volume about that aircraft. Figures 1A and 1B give examples of the range and altitude alarm volumes. Figure 1C shows how the range and altitude alarm volumes are combined to form a joint alarm volume. Aircraft, which are currently close or projected to soon be close, pass the range and altitude tests and cause advisories to be generated.

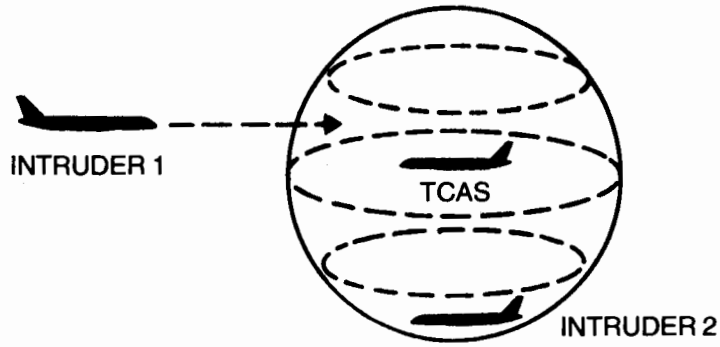
Advisories Issued

Advisories issued to aid visual acquisition are Traffic Advisories. Advisories issued to correct a flight path or to prevent a maneuver which could cause insufficient separation are Resolution Advisories.

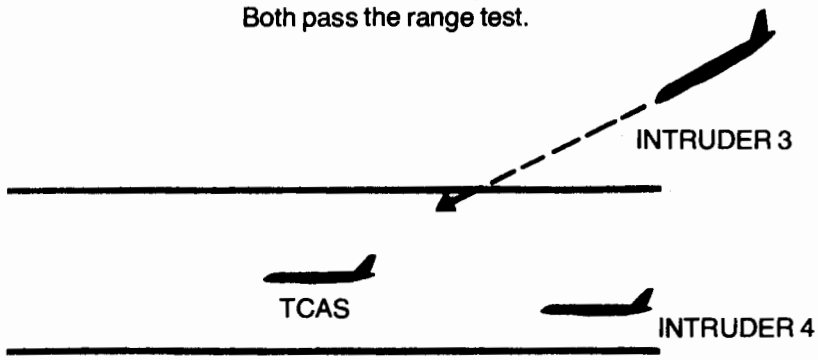
Traffic Advisories

There are two kinds of Traffic Advisories: Threat Advisories and Proximity Advisories. Neither requires the pilot to alter present course.

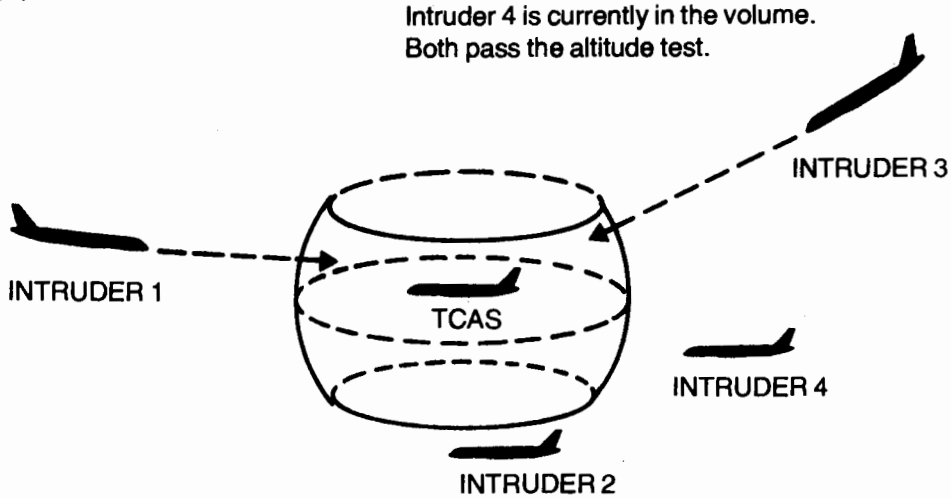
Threat Advisories (TA's) identify traffic of interest and help prepare the pilot for a subsequent Resolution Advisory. They can confirm traffic called by ATC and support the conventional means of resolution ("see and avoid"). The tracked flight path of a nearby aircraft is projected and the time to closest point of approach (CPA) is computed. If time to CPA is below a given threshold, a Threat Advisory is issued. The thresholds for time to CPA vary according to the occupied airspace. Threats are declared later at lower altitudes to minimize excessive alerts in denser traffic (e.g. airport terminal areas). See Figure 2 for an example of an encounter which causes an advisory based upon time to closest point of approach.



(A) RANGE ALARM VOLUME: Intruder 1 is projected to be in the volume.
Intruder 2 is currently in the volume.
Both pass the range test.



(B) ALTITUDE ALARM VOLUME: Intruder 3 is projected to be in the volume soon.
Intruder 4 is currently in the volume.
Both pass the altitude test.



(C) ALARM VOLUME: Intruder 1 and Intruder 3 pass both the range and altitude tests.
Intruder 2 passes only the range test.
Intruder 4 passes only the altitude test.
Intruder 1 and Intruder 3 will cause advisories.

Figure 1 Alarm Volumes

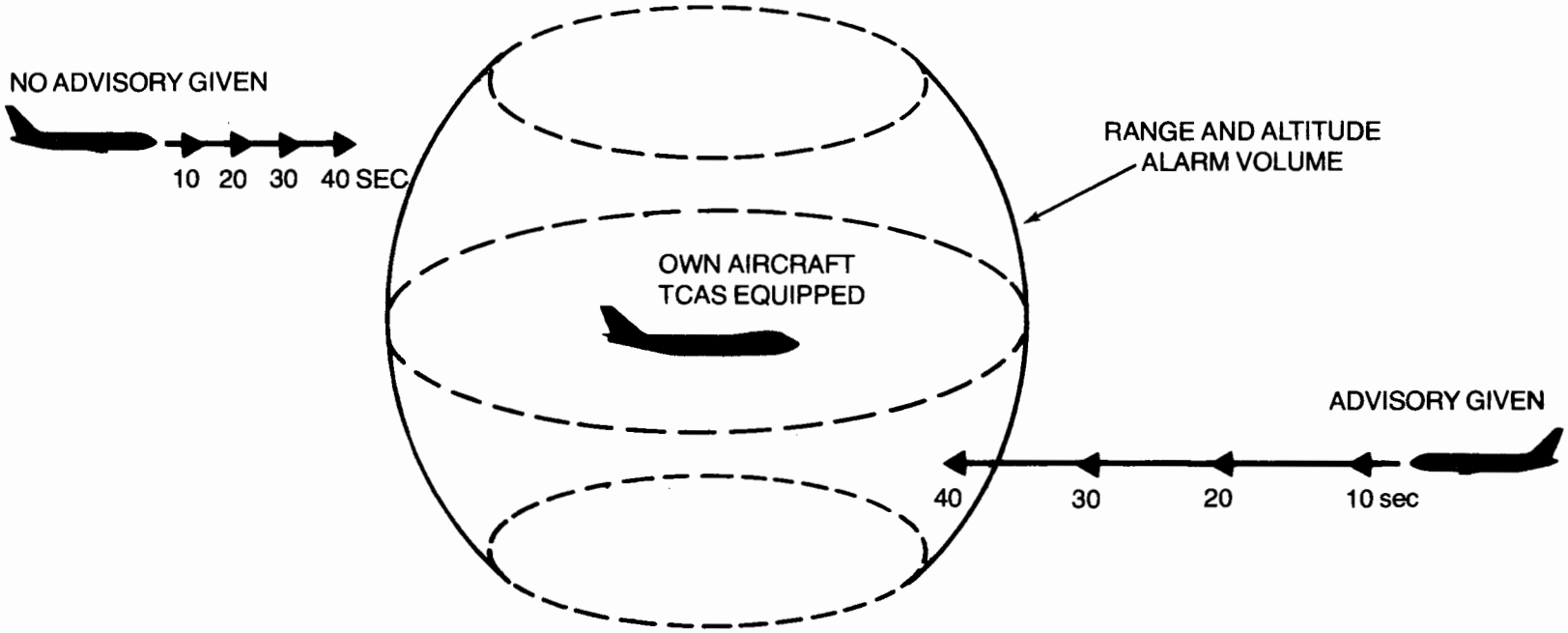


Figure 2 Threat Advisories Based on Time to Closest Point of Approach

Proximity Advisories are only given when a Threat or Resolution Advisory is already present. These inform the pilot of other close traffic to aid identification of the true threat. They are based solely upon the current range and altitude of the traffic instead of projected paths and time to closest point of approach. If an aircraft has crossed established range and altitude thresholds a Proximity Advisory is given. The bearing, altitude, and range information given in the Proximity Advisory are useful when conducting visual searches for traffic.

Resolution Advisories

Resolution Advisories (RA's) advise the pilots how to increase separation using vertical maneuvers. Like Threat Advisories, Resolution Advisories are based upon time to CPA but the thresholds used are 15 seconds lower than those used for Threat Advisories. Figure 3 shows two secnarios which are identical except for the closing rates of the aircraft. The closing rate in Figure 3A is substantially greater than that in figure 3B; therefore, the RA in Figure 3A appears when the aircraft are 10 nmi apart, whereas the RA in Figure 3B appears when the aircraft are 2.5 nmi apart. In both cases, the RA appears approximately 30 seconds prior to CPA.

The specific RA's are:

1.	CLIMB -	Begin a climb at 1500 fpm or continue climb at current rate if current rate is greater than 1500 fpm.
2.	DESCEND -	Begin a descent at 1500 fpm or continue descent at current rate if current rate is greater than 1500 fpm.
3.	DON'T CLIMB -	Do not climb. Remain level or descend.
4.	DON'T DESCEND -	Do not descend. Remain level or climb.
5.	Vertical Speed Limits -	(VSL's) - Do not exceed the posted limit in the indicated direction. Limit Climb/Descent to 500 fpm Limit Climb/Descent to 1000 fpm Limit Climb/Descent to 2000 fpm
6.	Vertical Speed Maintains -	Do not reduce vertical rate below posted level in the indicated direction. Maintain Climb/Descent at 500 fpm Limit Climb/Descent to 1000 fpm Limit Climb/Descent to 2000 fpm

These advisories are displayed until safe separation is assured. The indicated action should be continued until the RA is no longer displayed.

Resolution Advisories - TCAS Features Affecting Choice of Advisory

The following sections describe major portions of the TCAS logic involved in the choice of Resolution Advisory.

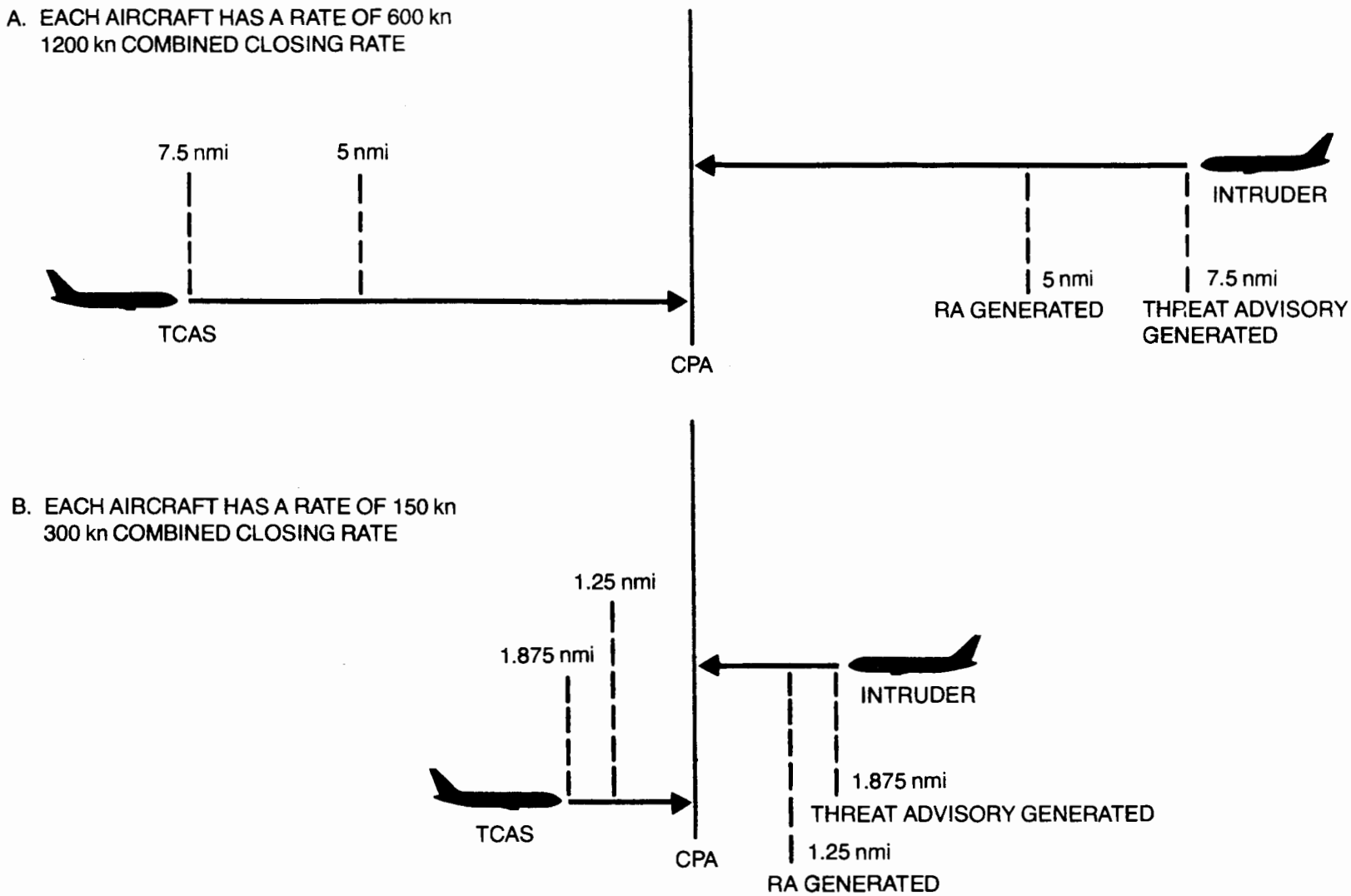


Figure 3 Generation of Resolution Advisories Based Upon Time to Closest Point of Approach

Choosing Directional Sense and the Appropriate Advisory

When an RA is warranted, TCAS chooses a directional sense (upward or downward) for the advisory (Figure 4). Table 1 lists each RA (from strongest to weakest) and its sense. After the sense of the RA is selected, TCAS considers each advisory with that sense to determine the vertical separation at CPA provided by each RA. The weakest advisory providing adequate separation is chosen for display in order to minimize the disruption of the flight path.

TABLE 1
DIRECTIONAL SENSE OF RESOLUTION ADVISORIES

UPWARD SENSE ADVISORIES	DOWNWARD SENSE ADVISORIES
Climb	Descend
Don't Descend	Don't Climb
Limit Descent to 500 fpm	Limit Climb to 500 fpm
Limit Descent to 1000 fpm	Limit Climb to 1000 fpm
Limit Descent to 2000 fpm	Limit Climb to 2000 fpm
Maintain Climb at 500 fpm	Maintain Descent at 500 fpm
Maintain Climb at 1000 fpm	Maintain Descent at 1000 fpm
Maintain Climb at 2000 fpm	Maintain Descent at 2000 fpm

Changing Advisories

Advisories can be changed to strengthen or weaken an advisory as the threat gets closer to own aircraft. The sense of the advisory, however, will not change. You will not receive an upward sense advisory, (e.g. CLIMB) followed by a downward sense advisory (e.g. limit climb to 500 fpm), but a weak upward sense advisory (e.g. limit descent to 500 fpm) may be changed to a stronger upward sense command (e.g. DON'T DESCEND).

Extreme Altitudes

TCAS inhibits the strongest advisories (i.e., CLIMB and DESCEND) when current altitude is too near the ground to permit a safe descent or too near the ceiling of own aircraft's flight envelope to permit a climb or when landing configuration prevents a rapid climb. The DESCEND command is converted to a DON'T CLIMB and the CLIMB command is converted to DON'T DESCEND. These conversions prevent descents into the terrain and attempts to exceed climb capabilities, but since both limitations are anticipated when the directional sense is selected, the chosen RA will generate adequate separation.

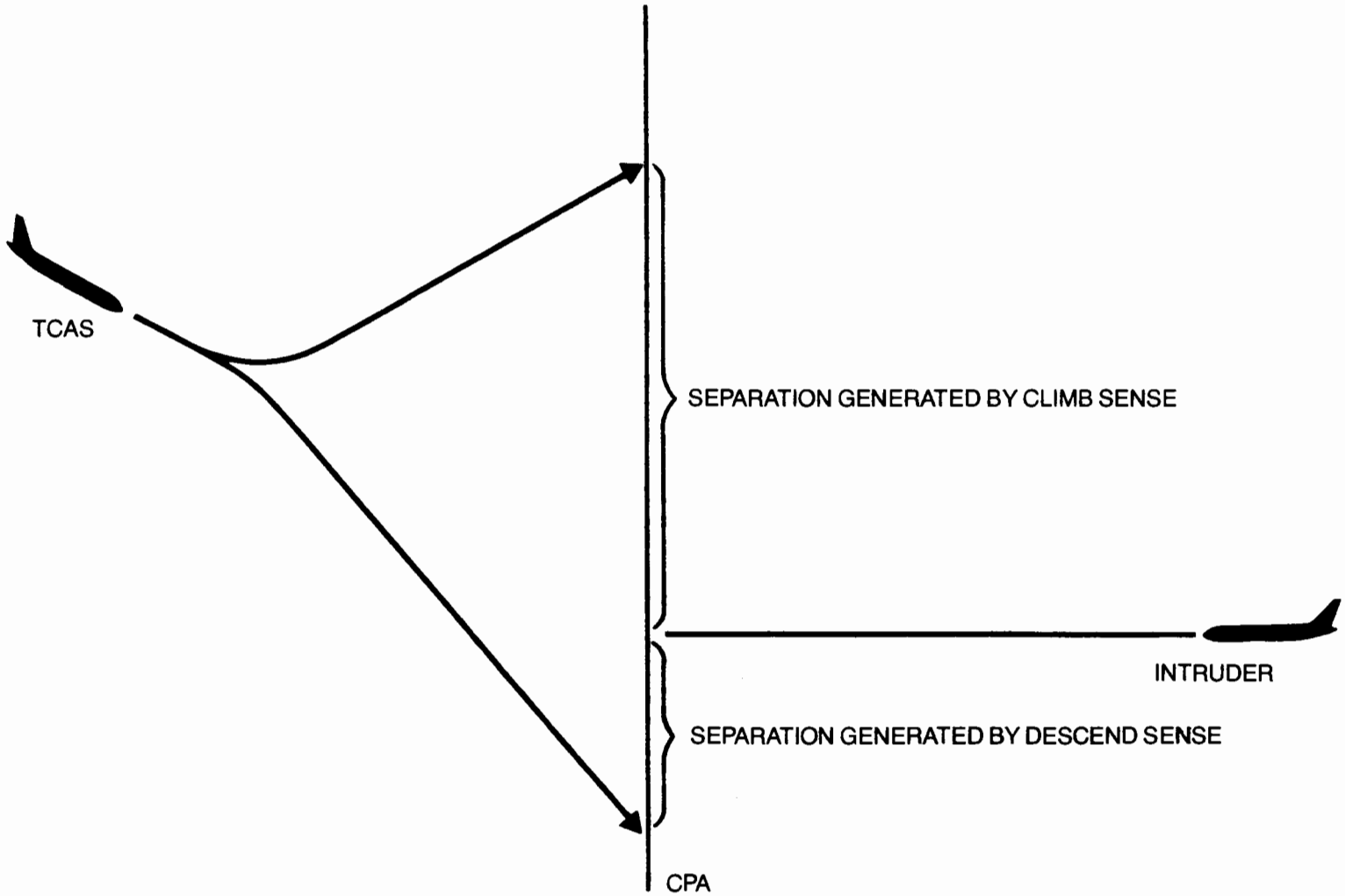


Figure 4 Choosing Directional Sense – Upward Sense Chosen

Coordination

Resolution Advisories between two TCAS equipped aircraft are coordinated. The first TCAS to identify the other as a threat chooses an RA. This choice is communicated to the second aircraft and the second aircraft's TCAS chooses a compatible maneuver. Although the pilot of either aircraft may decide not to follow the displayed RA, it must be emphasized that because of this coordination neither pilot should maneuver in a direction opposite to that displayed by TCAS.

Crossing Altitudes

TCAS will select an altitude crossing maneuver when advising a TCAS aircraft to cross another altitude provides the safest separation. Figure 5 is an example of a geometry where crossing altitudes is clearly the best maneuver. At point A the aircraft are coaltitude, but the range is great enough to provide safe separation. In this example, a maneuver in the upward sense will reduce separation between the aircraft.

Late Advisories

An aircraft whose track is picked up late may cause an RA without the usual 15-second TA preceding it. This may occur because sensitivity level just changed, because TCAS had difficulty receiving the threat's signals, because threat's or own transponder was just turned on, or because of late maneuvering which changes the projected path.

Maneuvering Intruders

Resolution Advisories are based on projected paths. TCAS has no knowledge of pilot or ATC intentions, so even though TCAS updates its surveillance information once each second, any maneuver the intruder makes after the advisory is given can cause the displayed Resolution Advisory to be incorrect. TCAS does not switch sense during a conflict (e.g. from upward to downward). When a late maneuver causes a condition in which an advisory may be incorrect, TCAS can no longer resolve this conflict and gives a TCAS ABORT advisory. Figure 6 gives an example of an intruder which suddenly levels off invalidating the previously given TCAS advisory.

TCAS Displays

Traffic Advisories are displayed on a color CRT. The symbol 2/3 down the screen represents own aircraft heading up. The circle around own aircraft represents an area with a two nautical mile radius. Nearby aircraft are displayed as triangles. The color represents the type of advisory. A signed number next to the triangle represents altitude relative to own in hundreds of feet. Three question marks in lieu of the number means the altitude of the traffic is unknown. An up or down arrow following the number indicates the vertical direction of traffic climbing or descending with a rate of at least 500 fpm. Range and relative bearing can be determined from the position of the traffic's symbol. Offscreen targets, traffic with range too large to be shown on the screen, are shown at the edge of the field as squares instead of triangles.

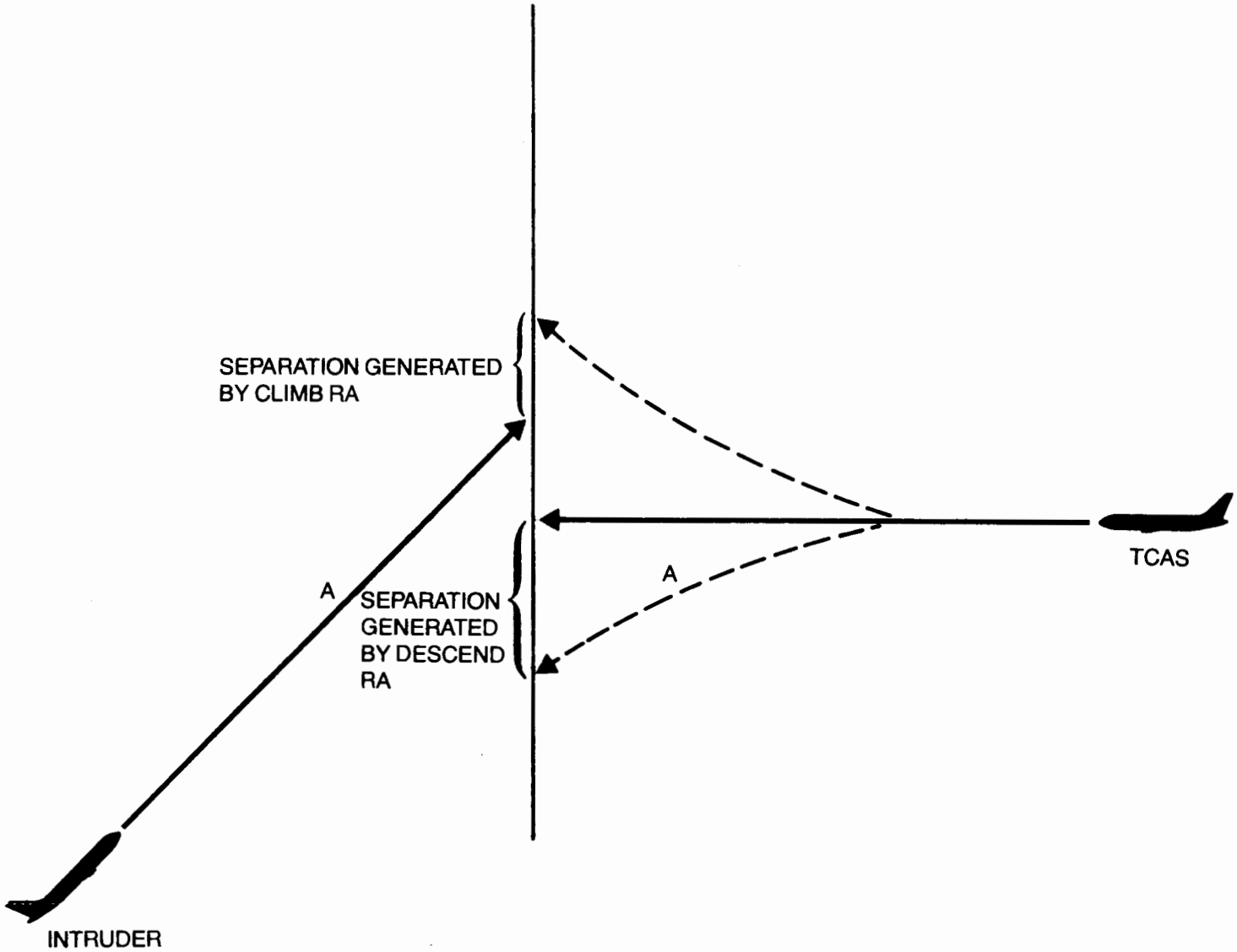


Figure 5 Choosing the Altitude Crossing Maneuver

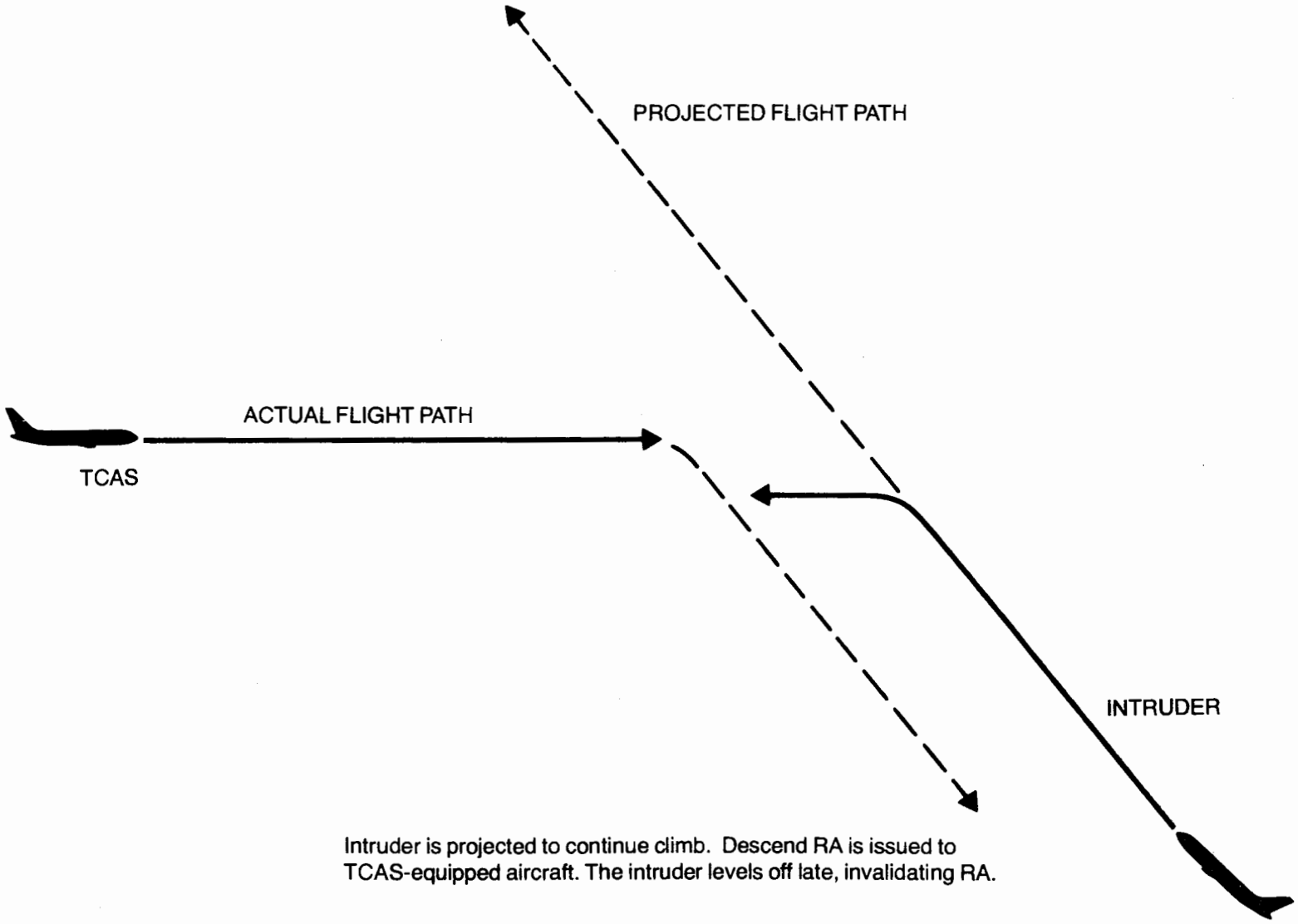


Figure 6 Maneuvering Intruder

Proximity Advisories

Proximity Advisories are displayed in white. Range, altitude, bearing, and vertical direction are given as shown in Figure 7. For non-altitude reporting aircraft, three question marks are given instead of the altitude. Proximity Advisories are shown only for aircraft within 2 nmi range and 1200 feet vertical separation (if known).

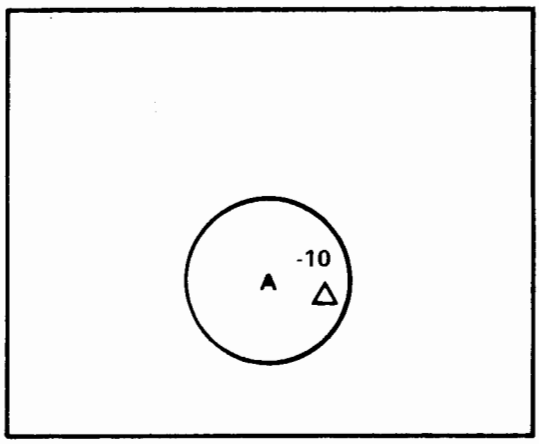
Threat Advisories

The display of Threat Advisories is identical to the Proximity Advisory except the threat symbol and data block are amber. The Threat Advisory display is accompanied by a unique aural alarm (a C-Chord) and the lighting of a TCAS warning/caution light in amber. The C-Chord will repeat every 2 seconds until the amber light/button is pressed.

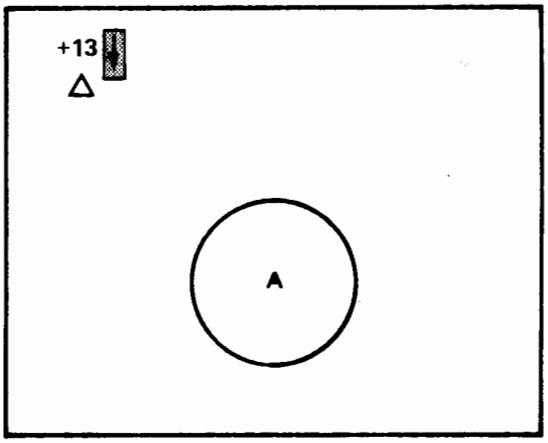
Resolution Advisories

Vertical maneuvers are displayed on the modified IVSI. See Figure 8 for an example of each RA. An alarm sounds when the RA is introduced and again upon any change, so long as corrective action is still required. The CRT is used in conjunction with the modified IVSI to give position information for intruders causing Resolution Advisories. The range, altitude, bearing and vertical direction are given on the CRT as usual. The format is the same as that used for Traffic Advisories, but the information is shown in red (There is one exception to the format. The display for intruders causing RA's will never show ??? as the altitude. Altitude must be known in order to receive an RA). The alarm consists of a repetitive European siren for two seconds followed by a spoken version of the RA displayed on the IVSI. The TCAS caution/warning indicator lights red. The alarm can be deactivated by pushing the red lit indicator. The pilot should use the CRT to identify the threatening aircraft causing the RA and follow the IVSI instructions to increase separation. Figure 9 shows the progress of an encounter along with the displays on the CRT.

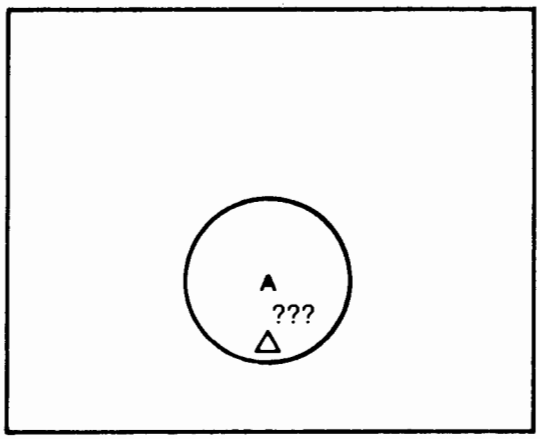
When a maneuvering intruder has caused the effectiveness of a displayed RA to become suspect TCAS signals that the RA may not be appropriate. All of the lights on the IVSI flash, the European alarm sounds, and a voice announcement ("TCAS ABORT") is given.



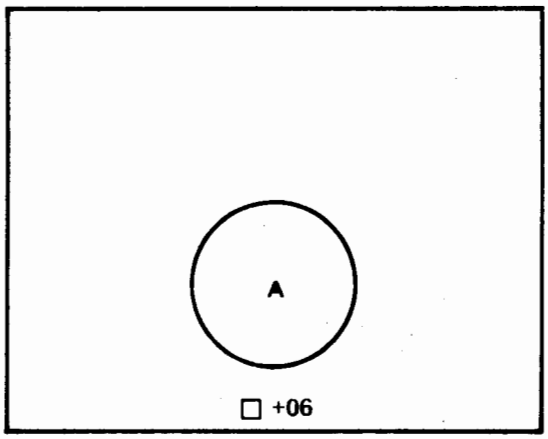
(A) A target 1000 ft below and level at 3 o'clock.



(B) A target 1300 ft above and descending at 11 o'clock.

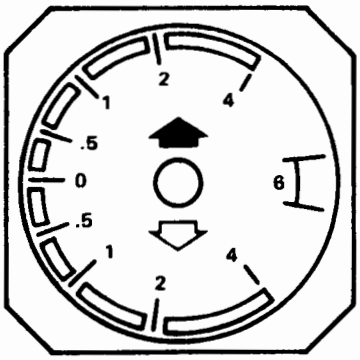


(C) A target with altitude unknown at 6 o'clock.

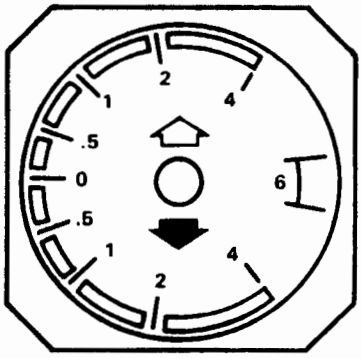


(D) An offscreen target 600 ft above and level at 6 o'clock.

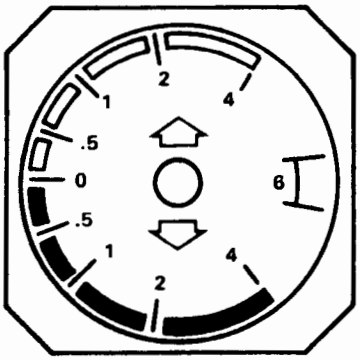
Figure 7 Traffic Advisories



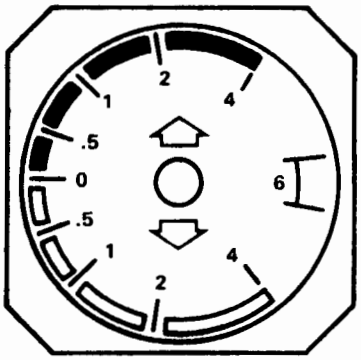
CLIMB



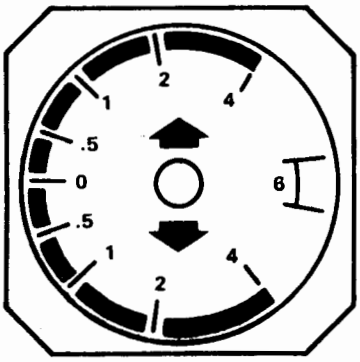
DESCEND



DO NOT DESCEND



DO NOT CLIMB



TCAS ABORT

Figure 8 IVSI Displays

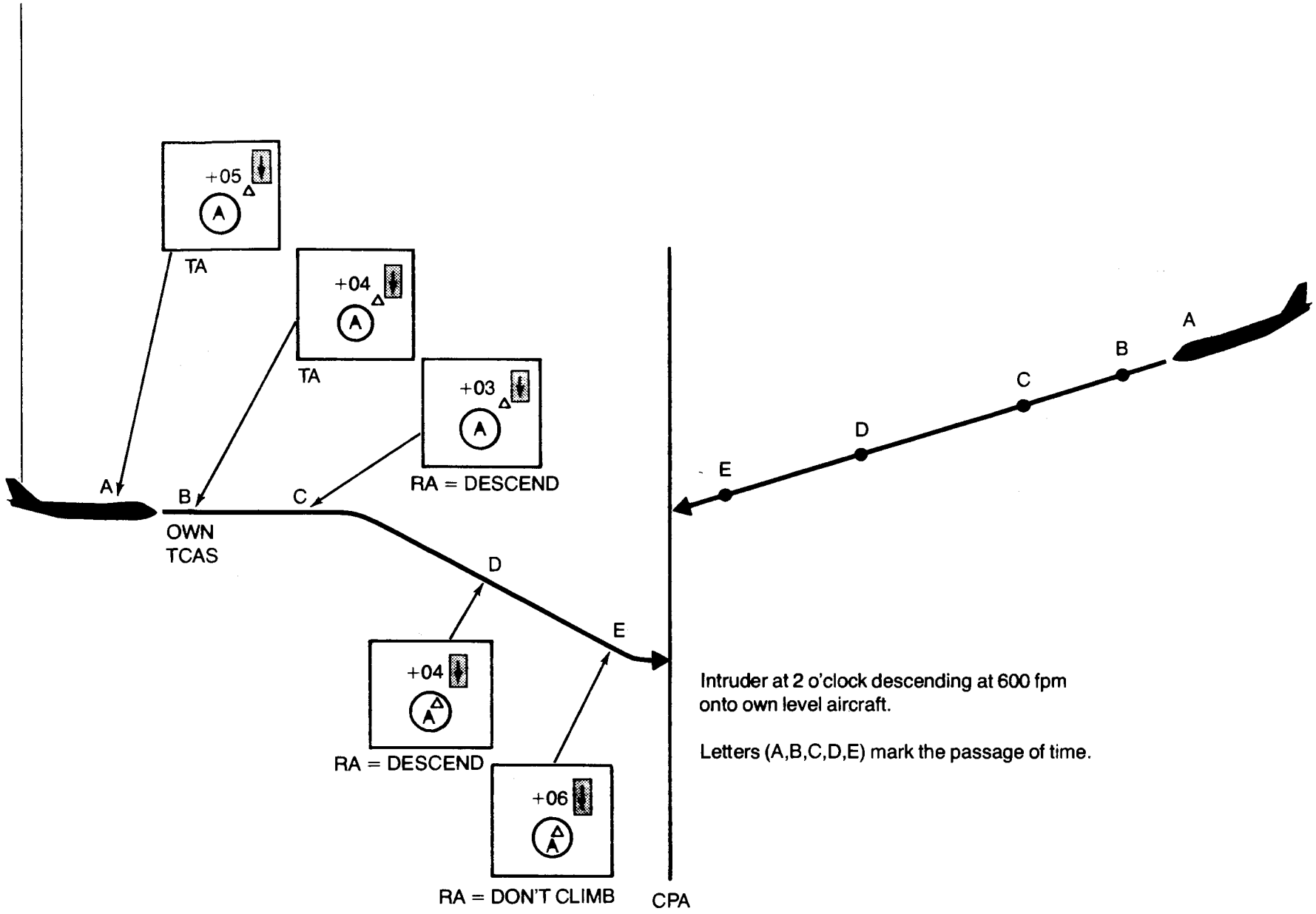
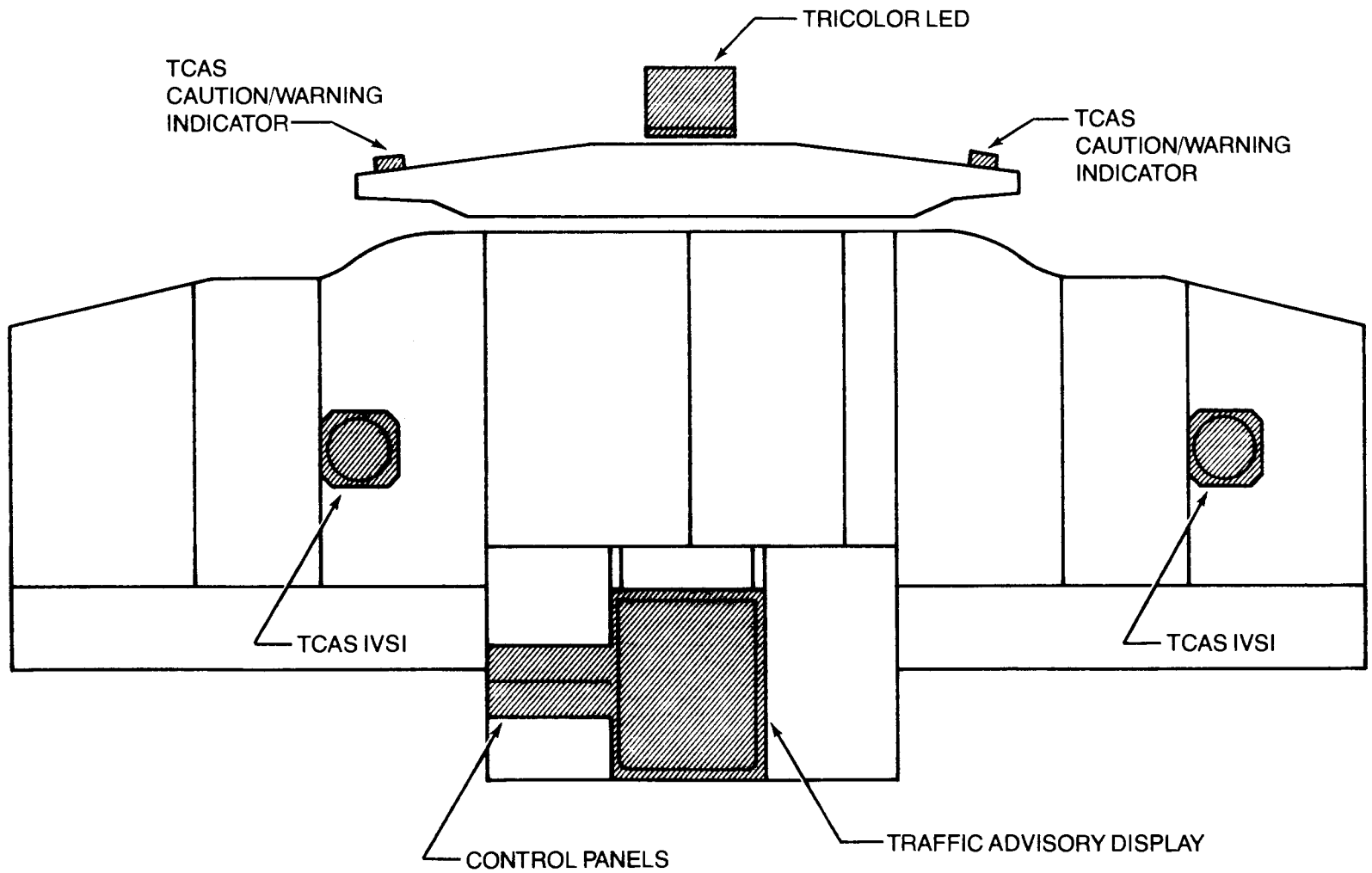
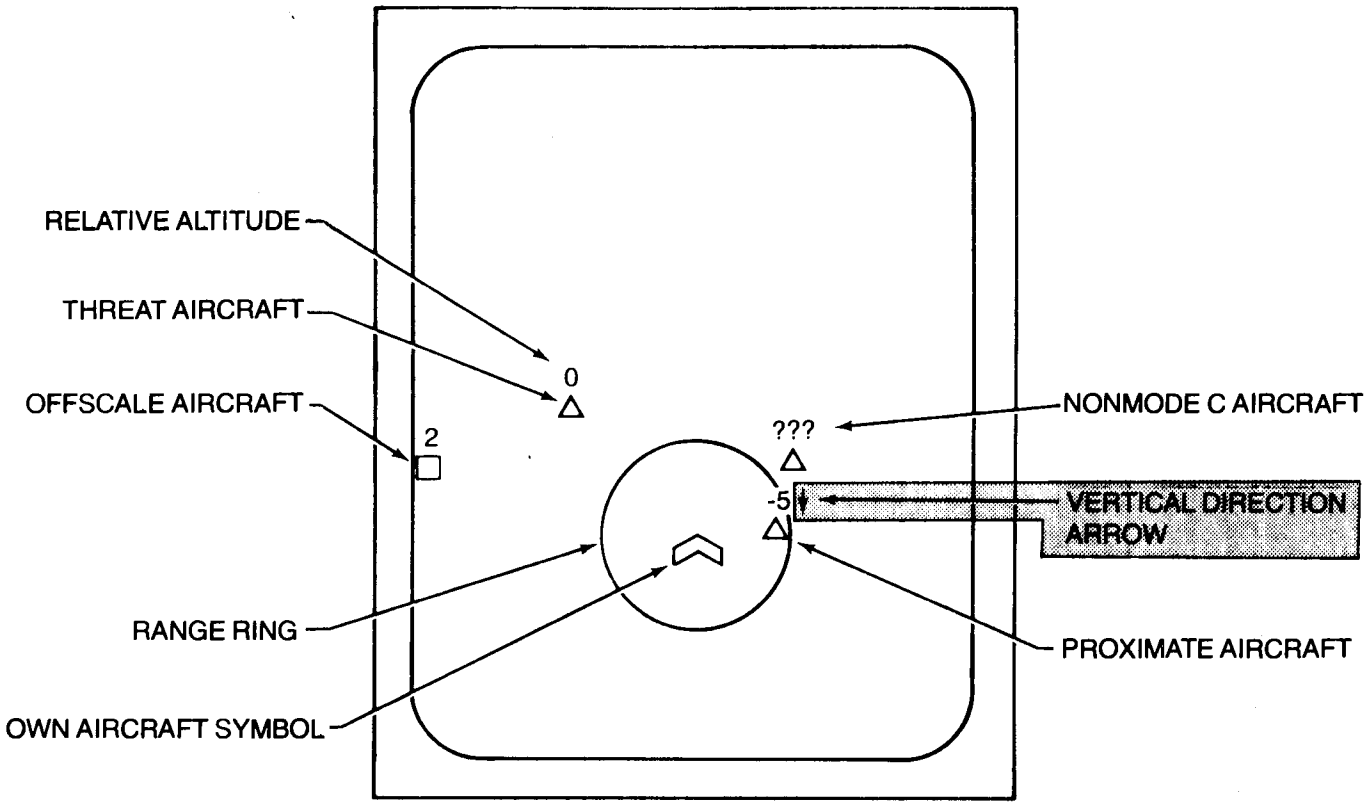


Figure 9 An Observer's View and the Pilot's View Via the CRT Display of an Encounter



TCAS Equipment-Installation B-737 Simulator



TRAFFIC ADVISORY DISPLAY

This display is active only when a threat or resolution advisory is present. The display initializes on a 6-mile radius range scale, which can be pilot selected to a 12-mile radius range. In either scale, the displayed range ring represents a 2-mile radius range about the own aircraft symbol displayed in a fixed position. These symbols are color coded white.

Nearby aircraft are displayed as triangles. The color represents the type of advisory. A signed (±) number next to the triangle represents altitude relative to own aircraft in hundreds of feet. Three question marks in lieu of the number means the altitude of the traffic is unknown. An up or down arrow following the number indicates the vertical direction of traffic climbing or descending with a rate of at least 500 fpm. Range and relative bearing can be determined from the position of the traffic symbol. Offscreen targets, traffic with range too large to be shown on the screen, are shown at the edge of the screen as squares.

COLOR CODE

Proximity Advisories	— Blue
Threat Advisories	— Amber
Resolution Advisories	— Red

Pilot's Forward Radio and Radar – Traffic Advisory Display

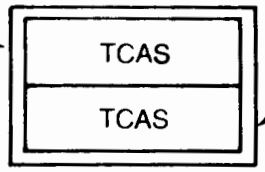
TCAS WARNING LIGHT (RED)

ILLUMINATED

- TCAS detects traffic that falls within the criteria for a resolution advisory to be presented on the IVSI

TO EXTINGUISH

- Pressing either TCAS light will extinguish both lights and silence the aural warning. Resets the system for any new TCAS alerts



TCAS CAUTION LIGHT (AMBER)

ILLUMINATED

- TCAS detects traffic that falls within the criteria for a traffic advisory to be presented on the traffic information display

TO EXTINGUISH

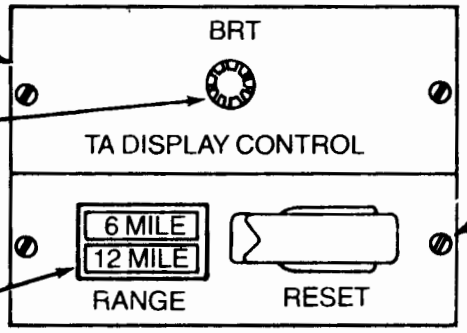
- Pressing either TCAS light will extinguish both lights and silence the aural caution. Resets the system for any new TCAS alerts

Captain's and first officer's glareshield

TRAFFIC INFORMATION DISPLAY CONTROLS

BRT

- BRIGHTNESS



RANGE SELECT SWITCH

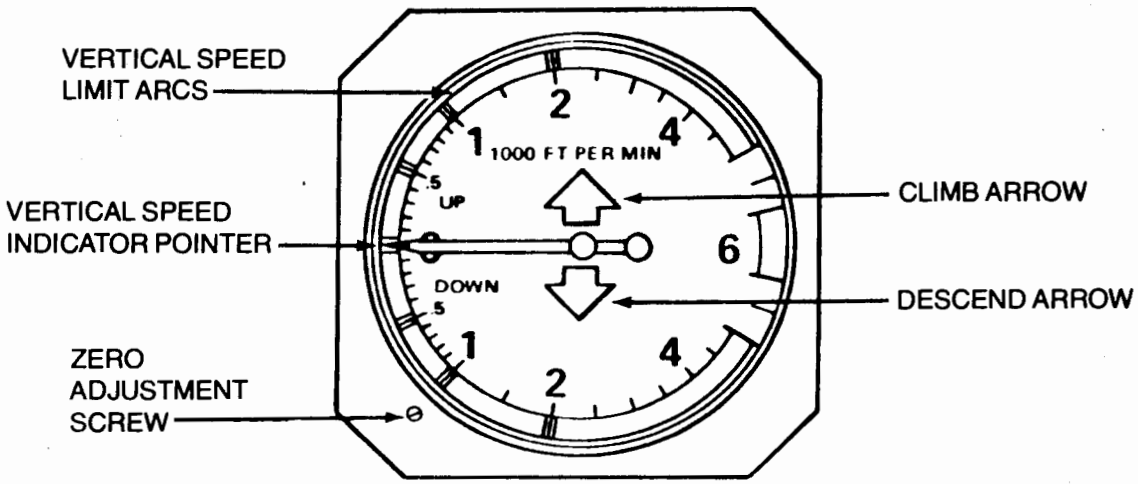
- Press: alternates between 6- and 12-mile range for display; 6-MILE or 12-MILE legend will be illuminated as appropriate

RESET

- Resets RANGE SELECT switch to 6-MILE legend
- When display becomes active, range will automatically be set at 6 miles. If 12-MILE legend is illuminated, system must be RESET

Pilot's forward radio and radar

Traffic Alert and Collision Avoidance System



TCAS VERTICAL SPEED INDICATOR

VERTICAL SPEED INDICATOR

Zero adjustment screw is used to set vertical speed indicator pointer to zero when airplane is on the ground or to reset pointer in the air when airplane is stabilized in its longitudinal axis at zero rate of climb.

NOTE: The vertical speed indicators utilize their respective static ports; or, the alternate static ports may be selected with the static source selector in the ALTERNATE position.

The vertical speed indicator pointer depicts rate of climb or descent from 0 to 6,000 ft/min. The instruments are marked in 100-ft increments from 0 to 1,000 ft/min and in 500-ft increments from 1,000 to 6,000 ft/min. The indication is instantaneous because two accelerometers are used to generate pressure difference whenever there is a change in normal acceleration.

TCAS ADVISORY DISPLAY

Resolution advisories from TCAS are displayed by means of the climb and descend arrows and vertical speed limit arcs.

Climb and descend advisories are displayed by illuminating climb and descend arrows respectively. Vertical speed limits are displayed by illuminating one or more vertical speed limit arcs. When a limit is displayed the aircraft should be controlled so that the IVSI needle does not enter the lighted arc.

NOTE: If the TCAS logic is unable to derive a satisfactory solution, the alert is displayed by lighting of all lights on the display.

Captain's and First Officer's Panels – TCAS Vertical Speed Indicator

TRAFFIC ALERT AND COLLISION AVOIDANCE SYSTEM

THREAT ADVISORY

Upon recognition of visual or aural advisory accomplish the following immediately by recall:

Undertake a visual search for traffic. Minor changes in flight path may be accomplished based on visual acquisition.

NOTE: Information provided by proximity advisory aircraft observed on the traffic advisory display should be used as an aid in visually identifying the threat advisory aircraft.

A "minor change in flight path" as used above means maneuvering that does not violate the ATC clearance. Other than minor changes would require coordination with ATC.

RESOLUTION ADVISORY
(IVSI needle out of illuminated bands)

Upon recognition of visual or aural alert, accomplish the following immediately by recall:

Maintain flight path to keep the vertical rate needle out of the illuminated bands on the IVSI until the alert terminates.

Undertake a visual research for traffic. Changes in flight path may be accomplished based on visual acquisition.

If maneuvers result in deviation from ATC clearance, first officer will advise ATC or controlling agency.

NOTE: Information provided by proximity advisory aircraft observed on the traffic advisory display should be used as an aid in visually identifying the resolution advisory aircraft.

RESOLUTION ADVISORY
(IVSI needle within illuminated bands)

Upon recognition of visual or aural warning this procedure should be accomplished immediately by recall:

Fasten Belt Switch. . . . . .ON

Autopilot
(if applicable). . . . . .DISENGAGE

Pitch Attitude . . . . . .ADJUST

Immediately rotate nose up or nose down as required to maintain vertical rate out of illuminated bands on the IVSI. The maneuver should be deliberate and positive, accelerating at .25G.

If a climb or descend arrow is displayed, begin a corresponding vertical rate of 1500 ft/min or continue current rate if it is equal to or greater than 1500 ft/min.

Thrust Levers . . . . . .ADJUST

Advance or retard thrust levers as required to maintain the vertical rate until the warning terminates.

Controlling Agency . . . . . .NOTIFY

First officer will advise ATC or controlling agency of deviation and request new clearance.

Undertake a visual search for traffic. Changes in flight path may be accomplished based on visual acquisition.

NOTE: Information provided by proximity advisory aircraft observed on the traffic advisory display should be used as an aid in visually identifying the resolution advisory aircraft.

Operational TCAS Procedures

The TCAS resolution advisory (corrective warning) offers the pilot a course of action predicated only on mode-C equipped aircraft within a closure time of less than 25 seconds. Once the advisory is issued, it is solely the pilot's prerogative to determine what course of action, if any, he will take.

Excessive delay in responding to the resolution advisory or late maneuvering by the intruder may cause the system to abort.

ABORT

Upon recognition of visual or aural abort warning, this procedure should be accomplished immediately by recall:

Return to and/or maintain last assigned clearance.

Use all available information to determine your course of action.

Nofity ATC immediately of situation and request assistance; i.e., "SEATTLE CENTER, BOEING SEVEN THREE SEVEN TCAS ABORT, PLEASE ADVISE."

Undertake a visual search for traffic. Changes in flight path may be accomplished based on visual acquisition.

NOTE: Information provided by proximity advisory aircraft observed on the traffic advisory display should be used as an aid in visually identifying the TCAS aborted aircraft.

Deleted during training.

Changed during training.

Operational TCAS Procedures (Concluded)

APPENDIX C

POST FLIGHT QUESTIONNAIRE

The following questionnaire was completed by each crew at the completion of every test gflight. Response to the questionnaire was a cooperative effort by the crew and they therefore discussed each question before answering.

TCAS

OPERATIONAL SIMULATION

POST-FLIGHT QUESTIONNAIRE

Pilot: _____

Date: _____ Flight: _____

Departure Time: _____

Arrival ____ Time: _____

City Pair _____

Please complete the following questions with respect to the TCAS alerts which occurred during your last flight. Use the "comments" space freely since your input is important to develop meaningful procedures. Also use the "comments" space to enumerate any operational difficulties encountered during the flight.

1. Were all the TCAS alerts appropriate for the situations involved?

YES _____ NO _____

If not describe the situation(s) which were not alerted properly.

_____

_____

_____

2. Did the prescribed procedures fit all the TCAS situations?

YES _____ NO _____

If not describe the situation and the action you took.

_____

_____

_____

3. Did the traffic display aid you in preparing for or performing the Resolution Advisory maneuver?

YES _____ NO _____

If it did please describe how you used it and if it did not describe why it didn't.

_____

_____

_____

_____

_____

4. Describe any problems you had during the flight.

_____

_____

_____

_____

APPENDIX D

PROGRAM DEBRIEFING QUESTIONNAIRE

The following questionnaire is the program debriefing for each pilot. Because of the extensive nature of the questionnaire, the pilots were permitted to take it from the test site and return it upon completion. All forms were returned. The numbers that appear in the questions are the summary of the answers given by the pilot group. The "Comments" lines contain a record of the comments that were supplied by one or more of the pilots.

SUMMARY

Observer No._____

TRAFFIC ALERT AND COLLISION AVOIDANCE SYSTEM (TCAS)
OPERATIONAL SIMULATION
FLIGHT CREW QUESTIONNAIRE

Name:_____

Company: _____

Present Position:_____

Pilot Certificate(s) Held:_____

Total Hours:_____Past Year:_____

In the space below, identify the types of aircraft you have flown. Put a 1 above the aircraft type you have flown most recently, a 2 above the next, and so on.

3	8	8	3	4	4	2	0	1
(B-707)	B-727)	B-737)	(B-747)	(DC-8)	(DC-9)	(DC-10)	(L-1011)	(Other)

Do you regularly fly into TCA's?

YES 100% NO_____
(Approximately)_____ times a year)
(which airports?

Were you familiar with the TCAS program prior to your solicitation or selection to participate in this experiment?

YES 50% NO 17% VAGUELY 33%

COMMENTS CONCERNING TCAS: All aircraft should have altitude encoding transponders, system must be reliable, no degredation of existing safety

INSTRUCTIONS

This questionnaire will provide you with a means of evaluating the Traffic Alert and Collision Avoidance System (TCAS). In filling out the form, give each item careful consideration before answering.

Almost every question has space for you to comment on or explain your answer. Although the comments are optional, they can provide a valuabel contribution to the test program. Comments may be used to expand upon or qualify your initial answer, or to note that the question is not framed in a manner which allows your true opinion to be expressed. Therefore, please use the Comments sections liberally to ensure proper interpretation of your answers. If you are not familiar with certain aspects of the TCAS, please answer the question and indicate in the Comments section your reservations. If your comment exceeds the space provided, please continue it on the back of the page or on a separate piece of paper (be sure to number the continuation with the question number.

A. General

1. In general, do you feel that a collision avoidance system should be

___ a. Required on all aircraft immediately.

42% b. Required on all aircraft as soon as it can be implemented and demonstrated to perform reliably.

17% c. Required only on aircraft operating in terminal control areas.

___ d. Required only on aiircraft operating above certain altitude (indicate altitude _____).

33% e. Required on air carrier aircraft only.

8% f. Implemented as soon as it can be tied to the ATC system to provide total traffic control.

___ g. Not required.

Comments: Should be installed only when operable in both IMC and VMC and is reliable

2. Did you experience any of the following problems with the alerting system in the test aircraft? If so, please explain.

a. Missed the alert? Yes 17% No 83%

b. Alert too loud or obtrusive? Yes 58% No 42%

c. Couldn't distinguish between different TCAS alerts? Yes 17% No 83%

d. TCAS alerts confused with other cockpit sounds: Yes 75% No 25%

e. Inappropriate, unnecessary, or incorrect alerts? Ues 75% No 25%

f. Other problems: Yes_____ No_____ If yes, please specify:

Comments: Caution sound to similar to altitude alert. Voice was not clear. Multi-target RA's were incorrect. RA went toward intruding A/C

3. How would you rate the overall quality of the alerting system?

EXCELLENT	GOOD	FAIR	POOR	UNACCEPTABLE
No Changes Needed	Minor Changes Beneficial	Minor Changes Recommended	Major Changes Recommended	Major Changes Required
____	67%	25%	____	8%

Comments: CDTI to distracting. Use a female voice. Eyebrow lights should be red

---

B. Master Alerts

1. How well do you feel the master aircraft aural alert drew your attention to the TCAS alerts?

EXCELLENT	GOOD	FAIR	POOR	UNACCEPTABLE
No Changes Needed	Minor Changes Beneficial	Minor Changes Recommended	Major Changes Recommended	Major Changes Required
17%	58%	25%	____	____

Comments: TA sounded too much like altitude alert

2. Are both a master aural and master visual needed to ensure TCAS alert detection under all environmental conditions (noise, light, decompression, etc.) on the flight deck?

Yes 92% No 8%

Comments: Cancellation of aural is a must

3. Do you feel that the master caution alert was necessary to draw your attention to the traffic advisories?

ALWAYS	USUALLY	SOMETIMES	SELDOM	NEVER
8%	83%	8%		

Comments: Depends on workload

C. Resolution Advisory (RA)

1. In general, were the actions required by the Resolution Advisory clear and unambiguous?

ALWAYS	USUALLY	SOMETIMES	SELDOM	NEVER
17%	83%			

Comments: There was a time lag with the voice

2. Does the modification of the IVSI by addition of the TCAS lights detract from the primary purpose of the instrument?

YES	NO
___	100%

Comments: _____

3. Does the use of color on the resolution advisory display help in interpreting the information presented?

VERY MUCH	SOME	VERY LITTLE	NONE
67%	33%	___	___

COMMENTS: Colors are not correct

4. In general, were the actions indicated by the resolution advisory display during the test flights clear and unambiguous?

ALWAYS	USUALLY	SOMETIMES	SELDOM	NEVER
42%	58%	___	___	___

Comments: TCAS abort is terrible

5. Do you feel that the alerts used in the test gave you sufficient time to react?

ALWAYS	USUALLY	SOMETIMES	SELDOM	NEVER
25%	67%	8%		

6. If a ppilot visually acquires the aircraft which he believes is causing an RA can you think of any situations which would result in the pilot concluding that the RA is unnecessary? If so, what are they?

No. RA too late will cause most pilots to turn in IMC

7. Would the pilot be justified in not following the RA in these situations? Why or why not? Pilot should follow RA. When A/C performance will permit

8. Did you observe any instances in which the resolution advisory appeared to be inappropriate or incorrect? If so, please describe.

Altitude crossing. Crew anticipated one direction and got another
Multi-intruder cases

9. In the mission tests, the threat traffic advisory appeared approximately 15 seconds prior to the RA. Would you recommend any changes in this lead time? If so, what changes would you suggest? No. Don't use the TA at all. In high density airports 15 seconds would be enough time to communicate with ATC

10. How would you rate the overall quality of the IVSI display used to display resolution advisories?

EXCELLENT	GOOD	FAIR	POOR	UNACCEPTABLE
No Changes Needed	Minor Changes Beneficial	Minor Changes Recommended	Major Changes Recommended	Major Changes Required
58%	33%	8%	____	____

Comments: _____

_____

_____

_____

D. Resolution Procedures

1a. When using the full TCAS system what do you feel should be the difference between flying pilot and non-flying pilot responsibility during an RA on a two crew flight deck?

Flying Pilot - Recognize threat, perform maneuver, visually "search" for intruder

Non-flying Pilot - Monitor and cancel alerts, call out intruder information, communicate with ATC

1b. How well did the test procedures address these differences?

EXCELLENT	GOOD	FAIR	POOR	UNACCEPTABLE
No Changes Needed	Minor Changes Beneficial	Minor Changes Recommended	Major Changes Recommended	Major Changes Required
17%	17%	67%	____	____

Comments: ATC coordination procedures required

2. In following the RA, how often did you feel constrained due to prior instructions from ATC? Please comment.

ALWAYS	USUALLY	SOMETIMES	SELDOM	NEVER
____	33%	25%	25%	17%

COMMENTS: Concern for other traffic. If RA is to be followed there should be no false alarms. In holding patterns

3. Did you have problems executing the procedure prescribed by the RA?

YES	NO
17%	83%

Comments: Sandwiched between intruder and ground or 2 intruders, with engine out

4. Can you think of any situation for which the procedures used in the test would not be appropriate?

YES	NO
75%	25%

If yes please describe them Anytime RA goes toward another A/C More horizontal maneuver

5. Is there any significant difference in the use of TCAS under IFR and its use under VFR?

YES	NO
75%	25%

If yes explain VFR would require more visual scan. There is a lack of evasive options in IFR. More horizontal maneuvers. IFR would require clearance before complying with RA

E. Traffic Information Display

1. Was the information presented on the traffic display unambiguous and easy to read?

ALWAYS	USUALLY	SOMETIMES	SELDOM	NEVER
42%	50%	8%		

Comments:

2. How often did the TA display come on when it would have been better for it to have remained off?

ALWAYS	USUALLY	SOMETIMES	SELDOM	NEVER
17%		8%	50%	25%

Comments: Non-threat traffic should not be included. display was a high distraction. Problem in holding pattern.

3. How often was the TA display off when it would have been better if it had been on?

ALWAYS	USUALLY	SOMETIMES	SELDOM	NEVER
____	____	____	25%	75%

Comments: _____

_____

_____

4. How useful were colors on the traffic display for interpreting the threat information? Red for resolution alerts (warnings), Amber for traffic advisories (caution) and Blue for proximate aircraft (advisory).

EXTREMELY USEFUL	CONSIDERABLY USEFUL	USEFUL	NOT VERY USEFUL	NO USE
42%	33%	8%	17%	____

COMMENTS _____

_____

_____

_____

5. How helpful was the intruder's angle of arrival (aoa) or bearing in using the traffic display?

EXCELLENT	GOOD	FAIR	POOR	UNACCEPTABLE	NOT NEEDED
No Changes	Minor Changes Beneficial	Minor Changes Recommended	Major Changes Recommended	Major Changes Required	
50%	25%	8%		17%	

Explain: Need accurate bearing not clock position. Shape of intruder should show direction of flight

6. In what situations, if any, were the TCAS TA's an unwelcome distraction?

Comments: None. almost always. final Approach. Holding patterns. During emergency procedures.

7. In the flight test the proximity advisories were generated only for aircraft that were within 2.0 nautical miles horizontally and ± 1200 feet vertically. Would you recommend any changes in these threshold values? If so, what values would you suggest?

No change. Don't display them at all. 3 mi

8. Did you observe any instances in which the traffic advisory information appeared to be incorrect?

YES	NO
25%	75%

If yes, please describe. If AOA is accurate to only a clock position they are all correct

9. Would you suggest any changes in the symbology for displaying altitude unknown traffic?

No. Use some other symbol for altitude unknown. Use three places for altitude. Use both + and - for relative altitude

10. In what situation, if any, did the TA display help resolve the TCAS abort

Comments: None. TCAS abort is terrible. Multiple traffic

11. How much time do you anticipate taking to use the traffice display when evaluating an intrusion situation with multiple traffic (2 or 3) present on the display?

0-5 SEC	5-10 SEC	10-15 SEC	15-20 SEC	GREATER THAN 20 SEC
8%	67%	17%		8%

12. Do you feel that pilots with automated threat advisories will become complacent and devote insufficient time to visual scanning for non-transponder equipped aircraft?

ALWAYS	USUALLY	SOMETIMES	SELDOM	NEVER
8%	25%	42%	25%	____

Comments: Biggest danger of TCAS. Training must overcome this.

13. How would you rate the overall quality of usefulness of the traffic display?

EXCELLENT	GOOD	FAIR	POOR	UNACCEPTABLE
No Changes Needed	Minor Changes Beneficial	Minor Changes Recommended	Major Changes Recommended	Major Changes Required
17%	50%	17%	8%	8%

Comments: Need horizontal maneuvers. Don't need it or want it. Need history on display

Select one term for each question to describe the performance of a TCAS installation with a traffic display compared to a TCAS installation without a traffic display.

14. With the display cockpit workload is:

8%	Greatly increased.	COMMENTS: Increased crew
58%	Somewhat increased.	Communication
	About the same.	
	Greatly decreased	

15. With the display workload impact is:

67%	Quite acceptable.	COMMENT: Display can be ignored
25%	Marginally acceptable.	
8%	Unacceptable	

16. With the display protection against collision is:

50%	Greatly increased.	COMMENTS:
33%	Somewhat increased.	
8%	About the same.	
8%	Somewhat decreased.	
	Greatly decreased.	

17. With the display pilot acceptance of RA' is:

50%	Greatly increased.	COMMENTS:
33%	Somewhat increased.	
17%	About the same.	
8%	Somewhat decreased.	
	Greatly decreased.	

18. With the display integration of TCAS with ATC is:

42%	Much easier.	COMMENTS:
25%	Somewhat easier.	
17%	About the same.	
	Somewhat more difficult.	
17%	Much more difficult.	

F. Traffic Advisory Procedures

1a. When a Traffic Advisory (caution alert) occurs what do you feel should be the difference between the flying pilot's and non-flying responsibilities on a two crew flight deck?

None. NFP should watch the TA display.

1b. How well did the test procedures handle these differences?

EXCELLENT	GOOD	FAIR	POOR	UNACCEPTABLE
No Changes Needed	Minor Changes Beneficial	Minor Changes Recommended	Major Changes Recommended	Major Changes Required
17%	50%	33%		

Comments:

2. Do you have any problems with the traffic advisory procedures?

YES	NO
50%	50%

If yes, what were they? Want to change flight path

3. Can you think of any situation for which the TA procedure used in the test would not be appropriate?

YES	NO
17%	83%

If yes, what are they? Head-on with no turn allowed. Holding pattern

4. With altitude unknown intruder, what procedure would you suggest for using TCAS? None (see and be seen). Use bearing and range to scan Executive horizontal maneuver. Contact ATC. Immediately request block altitude from ATC, if ATC can't held request a vector

G. ATC Interaction

1. When compared to ATC, how did the TCAS advisories rate with respect to:

		TCAS Much Better	TCAS Somewhat Better	TCAS About the Same	TCAS Somewhat Worse	TCAS Much Worse
A.	Accuracy of positional information?	58%	17%		25%	
B.	Ability to point out only traffic of true interest.	50%	25%	8%	17%	
C.	Reliability (with respect to timely issuance of advisory)	33%	33%	33%		
D.	Amount of workload caused by receipt of traffic advisory	25%	8%	8%	58%	
E.	Your ability to understand and properly respond to the traffic situation	42%	50%	8%		

	TCAS Much Better	TCAS Somewhat Better	TCAS About the Same	TCAS Somewhat Worse	TCAS Much Worse
F. Likelihood that traffic advisory will cause distraction which is detrimental to flight safety	42%	25%	17%		17%

2. Are there any problems in using both ATC and TCAS advisories?

YES	POSSIBLY	NO
___	50%	50%

Comment: Conflicting information. Depends on procedure ATC knows intruder's intent - TCAS doesn't

3. Do you feel that the TCAS will result in more or less communication with ATC?

MUCH LESS	SOMEWHAT LESS	NO CHANGE	SOMEWHAT MORE	MUCH MORE
8%	8%	17%	42%	25%

Comments: _____

4. Under what conditions should a pilot contact ATC as a result of a TCAS advisory?

Altitude unknown intruder. If vertical maneuver more than 500'. On all alerts

5. When the pilot is in VMC, within radar coverage, and is receiving verbal advisories from ATC, how useful is the addition of TCAS adviisories?

Good back-up to ATC. Slight. None.

6. Did the presence of TCAS in the aircraft change in any way the relationship between you and the ATC controller? If so, describe.

No. ATC may become more complacent. Pilots can now make judgments based on the traffic display

7. What changes do you feel should be required in aircraft and ATC operating procedures if TCAS were implemented?

Comments: None. Address the question of responsibility and liability. Ability to check alerts.

H. Design Options

Each of the following questions deals with the options available for the design of a particular TCAS feature. Assume that the TCAS installation under consideration will be installed in a jet transport aircraft. For each feature, rate the desirability of the listed options using the following scale:

1 = Completely Acceptable	(Highly desirable)
2 = Acceptable	(Minor reservations)
3 = Neutral	(Marginal)
4 = Unacceptable	(Major reservations)
5 = Completely unacceptable	(TCAS not acceptable with this option)

At the end of these questions, you will be asked to review your answers and pick the "ideal" TCAS design.

1. Feature: Presentation of Traffic Information

		RATING				
		17%			25%	58%
A.	No traffic information provided	1	2	3	4	5
b.	Traffic information for RA's only		17%	33%	17%	33%
c.	Traffic information for all threats defined by the TCAS Algorithms	1	2	3	4	5
		42%	8%	33%		17%
d.	Traffic information for all threats plus present aircraft	1	2	3	4	5
			25%	33%	8%	33%
e.	Traffic information for all aircraft that TCAS "sees" out to maximum surveillance range	1	2	3	4	5

2. Feature: Mode Control of the Traffic Information Display

		RATING				
		25%	33%	33%		8%
a.	No traffic information present until triggered by a threat	1	2	3	4	5
		17%	25%	25%	8%	25%
b.	Continuous display of all qualified information	1	2	3	4	5
		25%	25%	25%	17%	8%
c.	Both continuous and triggered mode, pilot selectable	1	2	3	4	5
		42%	33%	25%		
d.	Changing scale	1	2	3	4	5

3. Feature: Method of Displaying Traffic

		RATING				
a.	No traffic display	1 17%	2	3 8%	4 25%	5 50%
b.	Alert light and sound	1 8%	2 42%	3 25%	4 25%	5
c.	Graphic display	1 58%	2 17%	3	4 25%	5
d.	Alert light/sound and graphic display	1 58%	2 33%	3	4 8%	5

4. Feature: Method of Displaying RA's

		RATING				
a.	Digital voice only	1	2	3 8%	4 25%	5 67%
b.	Modified IVSI only	1 17%	2 25%	3 25%	4 17%	5 17%
c.	Both voice and IVSI	1 42%	2 17%	3 8%	4 25%	5 8%

5. Review your answers to questions 1 through 4 and select the combination of design features that you feel would constitute the best TCAS design.

Type of traffic information: Not desired. As tested. Just threats

Display mode control: Controlable. Automatic

Method of displaying traffic: Not desired. As tested.

Method of displaying RA's: As tested. IVSI and tone.

Any other important feature (specify): Horizontal resolutions

6. Please mention aany aspect of the TCAS installation that you feel is inadequate - even if you know that we are already aware of the deficiency or if you know that the defect is part of the experimental nature of the system and will be changed before actual operational use begins.

Display of traffic is hazardous. Voice is not clear. Horizontal maneuvers. Need accurate bearing information

G. Test Environment Evaluation

Please rate the adequacy of the simulation test you have experienced in terms of its ability to allow you to properly evaluate TCAS. If any aspect needs improvement, please indicate how it can be improved.

RATING SCALE:

1 = Excellent	-	no changes needed
2 = Good	-	minor changes beneficial
3 = Fair	-	minor changes recommended
4 = Poor	-	minor changes recommended
5 = Unacceptable	-	major changes required

	1	2	3	4	5
1. Amount of simulation time experienced by each subject pilot	42%	50%	8%		

		42%	58%			
2.	Variety of encounter situations experienced.	1	2	3	4	5
		25%	25%	33%	16%	
3.	Briefing and training prior to flight	1	2	3	4	5
		50%	33%	17%		
4.	Type of aircraft utilized	1	2	3	4	5
		50%	50%			
5.	Avionics employed (including TCAS displays)	1	2	3	4	5
		33%	25%	33%	8%	
6.	Value of simulated ATC interaction	1	2	3	4	5
		17%	50%	33%		
7.	Cockpit workload	1	2	3	4	5
		17%	25%	42%	8%	8%
8.	Crew procedures	1	2	3	4	5
		17%	67%	8%	8%	
9.	Post-flight questionnaires and debriefing	1	2	3	4	5
		17%	25%	33%	25%	
10.	Traffic environment in which tests were conducted.	1	2	3	4	5

Comments: Need more communication on ATC frequency

APPENDIX E

OBSERVATIONAL DATA

COLLECTION FORM

This form was used by the observer pilot for every test flight. It enabled him to describe each flight and encounter in a standard format.

TRAFFIC ALERT AND COLLISION AVOIDANCE OPERATIONAL SIMULATION COCKPIT OBSERVATION FORM	Date	Time
	Mission	Flying Pilot
		Copilot

Encounter 1 TA ☐ RA ☐ NO. OF A/C

	Flying Pilot	Nonflying Pilot
Cancel Caution	☐	☐
Check TA Display	☐	☐
Change Scale	☐	☐
Search Outside	☐	☐
Cancel RA	☐	☐
Call ATC	☐	☐
Number of Comm	____	____

	Yes	No
Change Altitude During TA	☐	☐
Change Heading During TA	☐	☐
Followed TA Procedure	☐	☐

	High	Med	Low
Workload at TA	☐	☐	☐
Workload at RA	☐	☐	☐

ATC Clearance: Vector ☐ Airway ☐ Direct ☐
Published Procedure ☐

Aircraft Control: Manual ☐ Auto ☐ Alt Hold ☐
Configuration: Flaps ☐ Gear ☐ Speed Brake ☐ Power ☐

Comments: _____

Encounter 2 TA ☐ RA ☐ NO. OF A/C

	Flying Pilot	Nonflying Pilot
Cancel Caution	☐	☐
Check TA Display	☐	☐
Change Scale	☐	☐
Search Outside	☐	☐
Cancel RA	☐	☐
Call ATC	☐	☐
Number of Comm	____	____

	Yes	No
Change Altitude During TA	☐	☐
Change Heading During TA	☐	☐
Followed TA Procedure	☐	☐

	High	Med	Low
Workload at TA	☐	☐	☐
Workload at RA	☐	☐	☐

ATC Clearance: Vector ☐ Airway ☐ Direct ☐
Published Procedure ☐

Aircraft Control: Manual ☐ Auto ☐ Alt Hold ☐
Configuration: Flaps ☐ Gear ☐ Speed Brake ☐ Power ☐

Comments: _____

Encounter 3 TA ☐ RA ☐ NO. OF A/C

	Flying Pilot	Nonflying Pilot
Cancel Caution	☐	☐
Check TA Display	☐	☐
Change Scale	☐	☐
Search Outside	☐	☐
Cancel RA	☐	☐
Call ATC	☐	☐
Number of Comm	____	____

	Yes	No
Change Altitude During TA	☐	☐
Change Heading During TA	☐	☐
Followed TA Procedure	☐	☐

	High	Med	Low
Workload at TA	☐	☐	☐
Workload at RA	☐	☐	☐

ATC Clearance: Vector ☐ Airway ☐ Direct ☐
Published Procedure ☐

Aircraft Control: Manual ☐ Auto ☐ Alt Hold ☐
Configuration: Flaps ☐ Gear ☐ Speed Brake ☐ Power ☐

Comments: _____

Encounter 4 TA ☐ RA ☐ NO. OF A/C

	Flying Pilot	Nonflying Pilot
Cancel Caution	☐	☐
Check TA Display	☐	☐
Change Scale	☐	☐
Search Outside	☐	☐
Cancel RA	☐	☐
Call ATC	☐	☐
Number of Comm	____	____

	Yes	No
Change Altitude During TA	☐	☐
Change Heading During TA	☐	☐
Followed TA Procedure	☐	☐

	High	Med	Low
Workload at TA	☐	☐	☐
Workload at RA	☐	☐	☐

ATC Clearance: Vector ☐ Airway ☐ Direct ☐
Published Procedure ☐

Aircraft Control: Manual ☐ Auto ☐ Alt Hold ☐
Configuration: Flaps ☐ Gear ☐ Speed Brake ☐ Power ☐

Comments: _____

Encounter 5 TA ☐ RA ☐ NO. OF A/C

	Flying Pilot	Nonflying Pilot
Cancel Caution	☐	☐
Check TA Display	☐	☐
Change Scale	☐	☐
Search Outside	☐	☐
Cancel RA	☐	☐
Call ATC	☐	☐
Number of Comm	____	____

	Yes	No
Change Altitude During TA	☐	☐
Change Heading During TA	☐	☐
Followed TA Procedure	☐	☐

	High	Med	Low
Workload at TA	☐	☐	☐
Workload at RA	☐	☐	☐

ATC Clearance: Vector ☐ Airway ☐ Direct ☐
Published Procedure ☐

Aircraft Control: Manual ☐ Auto ☐ Alt Hold ☐
Configuration: Flaps ☐ Gear ☐ Speed Brake ☐ Power ☐

Comments: _____

Encounter 6 TA ☐ RA ☐ NO. OF A/C

	Flying Pilot	Nonflying Pilot
Cancel Caution	☐	☐
Check TA Display	☐	☐
Change Scale	☐	☐
Search Outside	☐	☐
Cancel RA	☐	☐
Call ATC	☐	☐
Number of Comm	____	____

	Yes	No
Change Altitude During TA	☐	☐
Change Heading During TA	☐	☐
Followed TA Procedure	☐	☐

	High	Med	Low
Workload at TA	☐	☐	☐
Workload at RA	☐	☐	☐

ATC Clearance: Vector ☐ Airway ☐ Direct ☐
Published Procedure ☐

Aircraft Control: Manual ☐ Auto ☐ Alt Hold ☐
Configuration: Flaps ☐ Gear ☐ Speed Brake ☐ Power ☐

Comments: _____

Encounter 7 TA ☐ RA ☐ NO. OF A/C

	Flying Pilot	Nonflying Pilot
Cancel Caution	☐	☐
Check TA Display	☐	☐
Change Scale	☐	☐
Search Outside	☐	☐
Cancel RA	☐	☐
Call ATC	☐	☐
Number of Comm	____	____

	Yes	No
Change Altitude During TA	☐	☐
Change Heading During TA	☐	☐
Followed TA Procedure	☐	☐

	High	Med	Low
Workload at TA	☐	☐	☐
Workload at RA	☐	☐	☐

ATC Clearance: Vector ☐ Airway ☐ Direct ☐
Published Procedure ☐

Aircraft Control: Manual ☐ Auto ☐ Alt Hold ☐
Configuration: Flaps ☐ Gear ☐ Speed Brake ☐ Power ☐

Comments: _____

Encounter 8 TA ☐ RA ☐ NO. OF A/C

	Flying Pilot	Nonflying Pilot
Cancel Caution	☐	☐
Check TA Display	☐	☐
Change Scale	☐	☐
Search Outside	☐	☐
Cancel RA	☐	☐
Call ATC	☐	☐
Number of Comm	____	____

	Yes	No
Change Altitude During TA	☐	☐
Change Heading During TA	☐	☐
Followed TA Procedure	☐	☐

	High	Med	Low
Workload at TA	☐	☐	☐
Workload at RA	☐	☐	☐

ATC Clearance: Vector ☐ Airway ☐ Direct ☐
Published Procedure ☐

Aircraft Control: Manual ☐ Auto ☐ Alt Hold ☐
Configuration: Flaps ☐ Gear ☐ Speed Brake ☐ Power ☐

Comments: _____

APPENDIX F

TEST FLIGHT SCENARIOS

In the following appendix, the description of each of the test flights has three components. First is the ATC script used for the flight. The live ATC controller used this script to standardize the flights across crews. This was not all that he said, however, since he also responded to crew calls. The script also indicates when each of the eight intruder scenarios was triggered.

The second piece of data for each test flight is the flight plan or mission scenario. This plan gives the route of the flight at a scale of .5 cm to the nautical mile. It also shows where in the flight each of the encounters occurred.

Finally the threat encounters or intrusioon scenarios are presented (eight for each flight). A plan and vertical view is provided for each encounter. Both views are to scale (1 inch = 1000 feet) and coordinated so that the reader can obtain an idea of spatial relationships at any time during the encounter. Direction of flight is indicated by the arrow head on the aircraft path. Marks along the flight paths of each aircraft indicate 20 second time periods so that relative position along the path can be obtained. In the vertical profile a "+" associated with a threat aircraft indicates a flight path 90° to the own aircraft and no altitude changge.

SCENARIO 1

- Boeing 737, Cleared to Yakima Airport via Kent Two Departure - Victor 4 - Yakima, climb and maintain 8000 feet, expect 17,000 feet 10 nautical miles southeast of Seattle, departure control on 119.2, squawk mode C code 2230

  o Readback correct, contact tower for takeoff

  o Boeing 737, winds calm, cleared for takeoff

- Boeing 737, turn right heading 170 direct Seattle, flight plan route

- Trigger #1

- Boeing 737, contact Seattle departure on 119.2

- Trigger #2

  o Boeing 737, Say altitude (if applicable)

  o Roger, maintain 8,000 feet

- Boeing 737, please be advised Yakima Airport closed due to volcanic dust and ash. Expect clearance for return to Boeing Field. Enter holding East of Blako on the 101 degree radial of Seattle VOR. Expect further clearance at -- (8 minutes from current time). Maintain 8,000 feet

- Trigger #3

- Trigger #4

- Boeing 737 cleared to Boeing Field via Seattle VOR, direct Nolla, expect procedure turn to Runway 13R, climb and maintain 10,000 feet

- Trigger #5

- Boeing 737, contact Seattle Approach on 123.9

  o Roger, Boeing 737, squawk code 2200....

  .... Seattle weather is 800 foot broken, 3 miles visibility, temperature 59°, winds 140 at 5 knots, altimeter 29.92 over

- Boeing 737, descend to cross Nolla at 4,000 feet, cleared procedure turn for ILS to runway 13R. Call outbound on procedure turn.

- Trigger #6

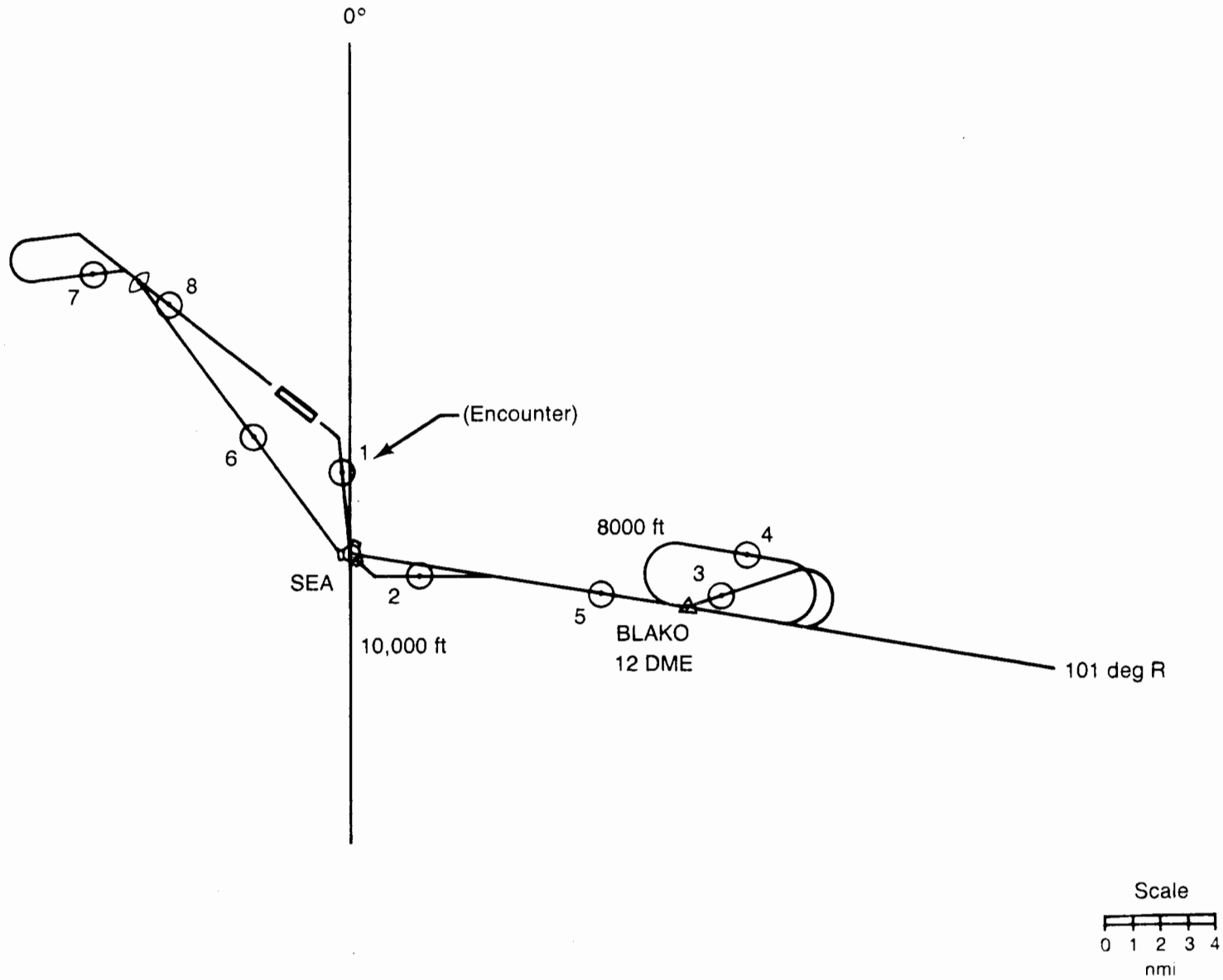
- Boeing 737, traffic 10 o'clock, 5 miles, altitude unknown

  o Roger, Boeing 737, Contact Seattle Tower on 120.6

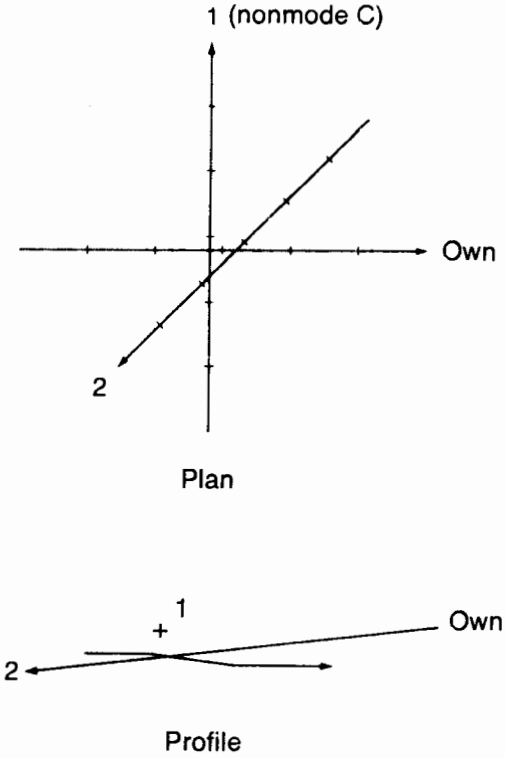
- Trigger #7

  o Roger, Boeing 737, winds variable at 5 knots, cleared to land runway one three right

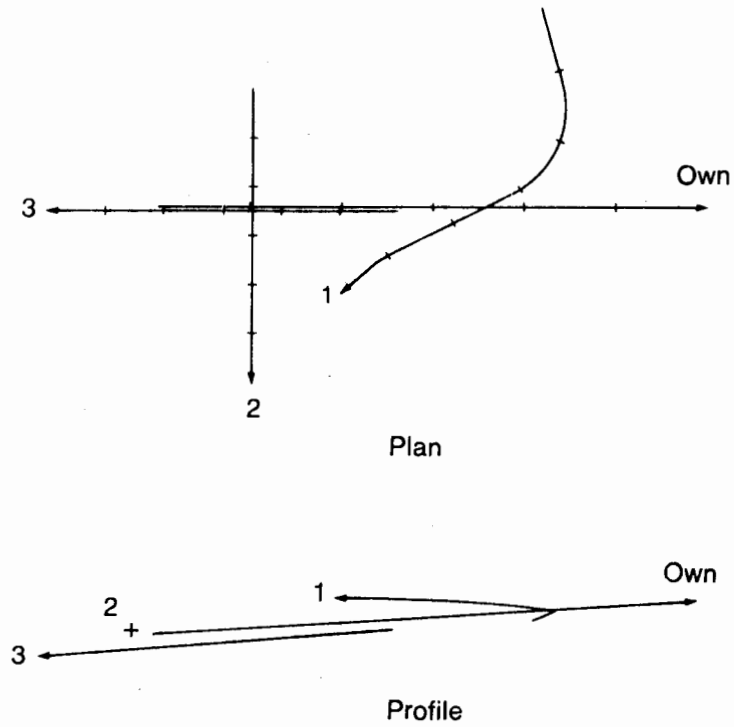
- Trigger #8



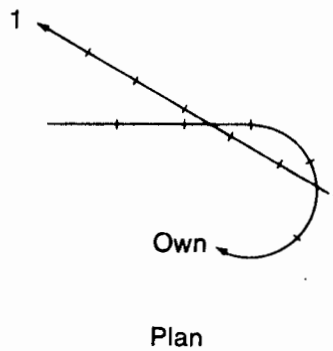
Mission Scenario 1



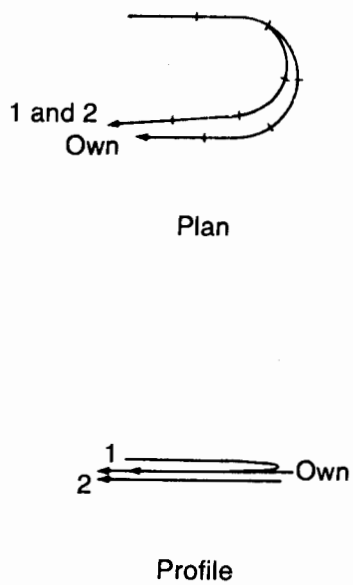
Intrusion Scenario 1A 1



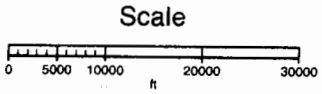
Intrusion Scenario 1A 2

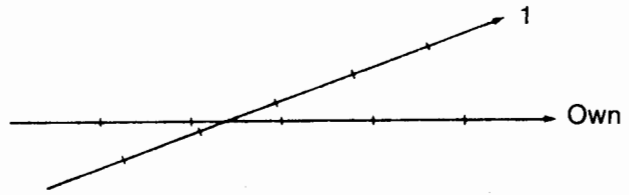


Intrusion Scenario 1A 3

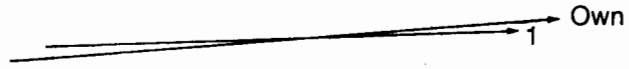


Intrusion Scenario 1A 4



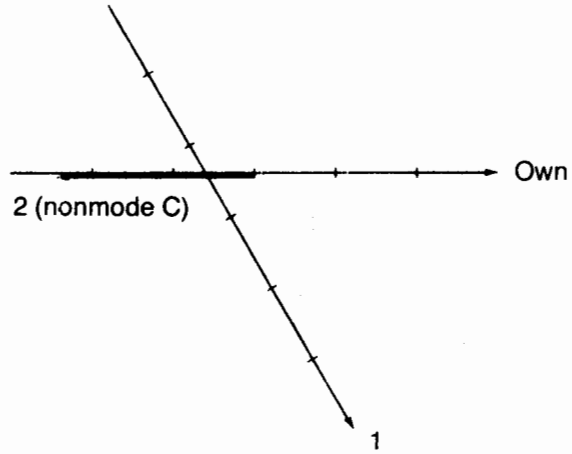


Plan

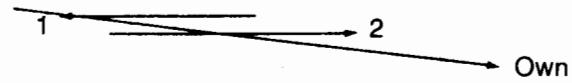


Profile

Intrusion Scenario 1A 5

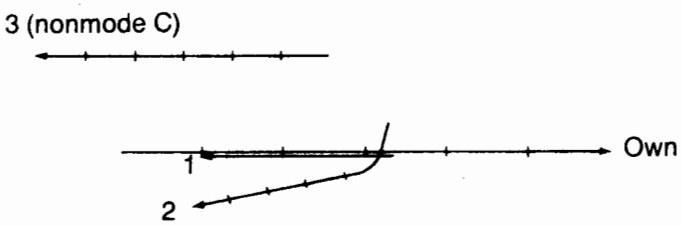


Plan

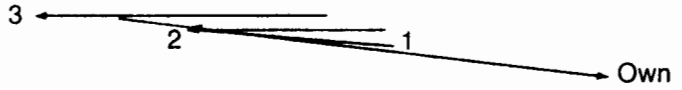


Profile

Intrusion Scenario 1A 6

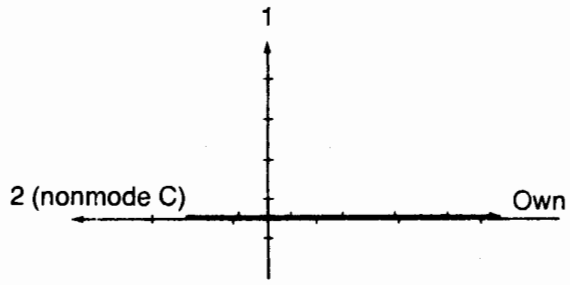


Plan

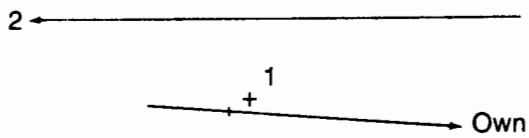


Profile

Intrusion Scenario 1A 7



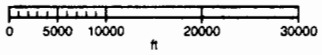
Plan



Profile

Intrusion Scenario 1A 8

Scale



SCENARIO 2

- Boeing 737, Cleared to Yakima Airport via Kent Two Departure - Victor 4 - Yakima, climb and maintain 6000 feet, expect 17,000 feet 10 nautical miles southeast of Seattle, departure control on 119.2, squawk mode C code 2230

    - o Readback correct, contact tower when ready for takeoff

    - o Boeing 737, winds 130 at 5 knots, cleared for takeoff

- Boeing 737, Contact Seattle departure on 119.2

    - o Boeing 737, Radar contact, climb to 6000 feet, maintain present heading to intercept Victor 4

- Trigger #1

- Boeing 737, traffic, 1 o'clock, 4 miles, over

- Trigger #2

- Boeing 737, Cleared to 17,000 feet, contact Seattle Center 132.6

    - o Boeing 737, ident

- Boeing 737, radar contact, call level at one seven thousand

- Trigger #3

- Trigger #4

- Trigger #5

- Boeing 737, descend to 6,000 feet so as to be at 6,000 feet prior to 6 DME from Yakima, altimeter setting 29.93

- Trigger #6

- Boeing 737, contact Yakima Approach 123.8

    - o Boeing 737, ident

- Boeing 737, radar contact, turn left heading zero eight zero for vector to runway 27 ILS approach, descend to 4,000 over

- Trigger #7

- Boeing 737, Yakima weather is currently 2000 feet overcast with 5 miles visibility, temperature is 65°, winds calm, landing runway 27, over

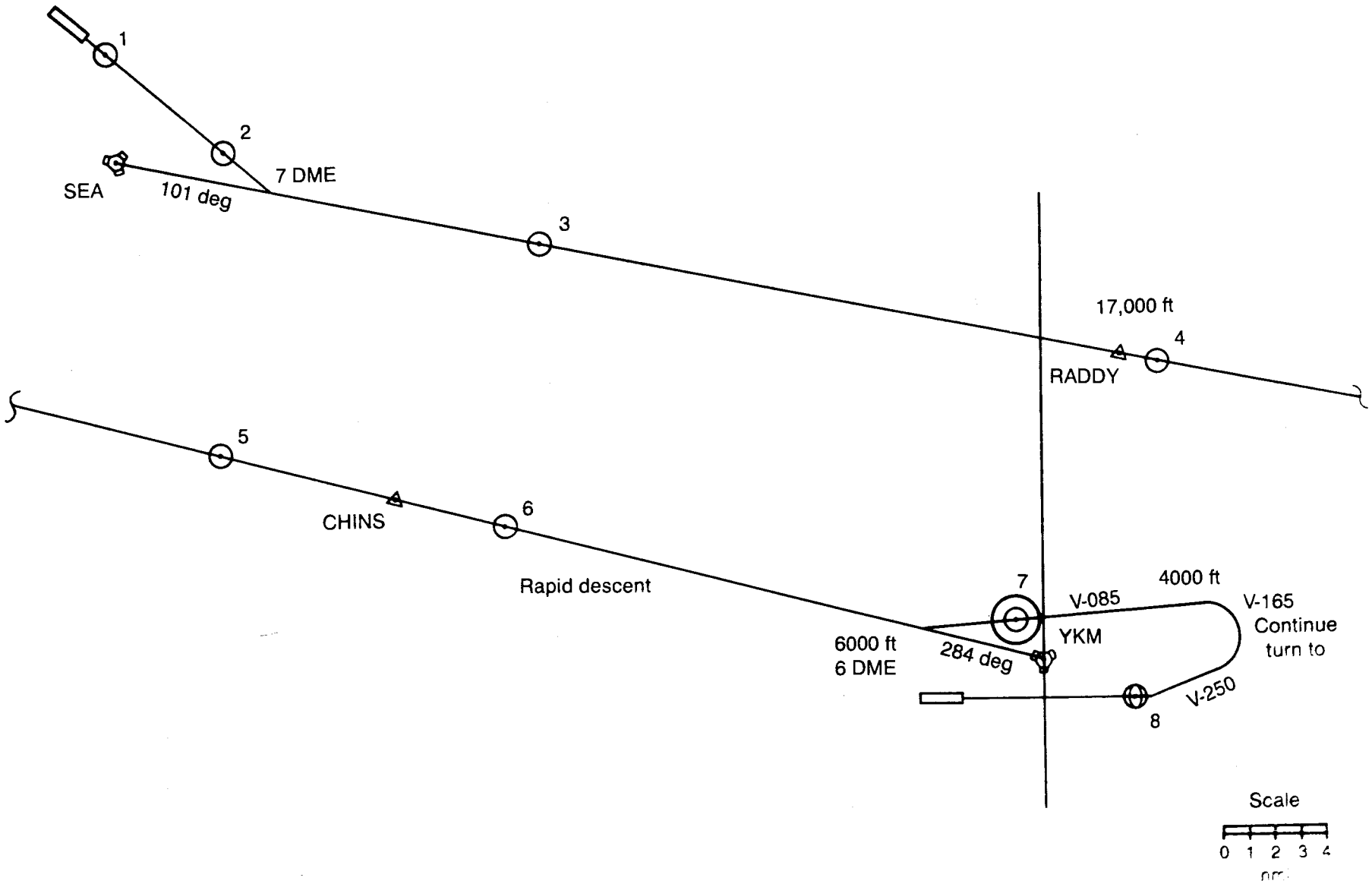
- Boeing 737, turn right heading one six five, descend to 3,500 feet

- Boeing 737, continue right turn to two five zero, cleared ILS approach to runway 27, call outermarker, over

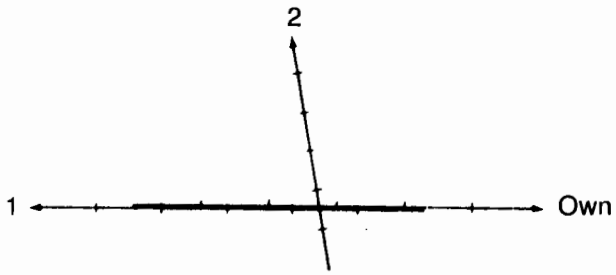
- Trigger #8

    - Boeing 737, contact tower on 118.4, good day

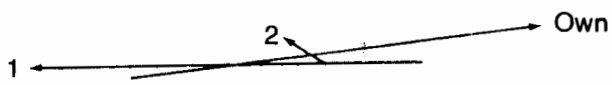
    - Boeing 737, winds calm cleared to land



Mission Scenario 2

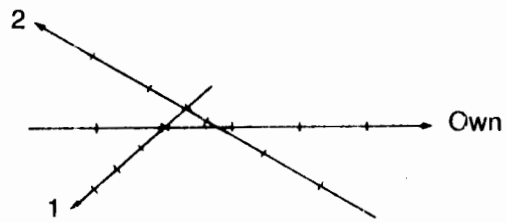


Plan



Profile

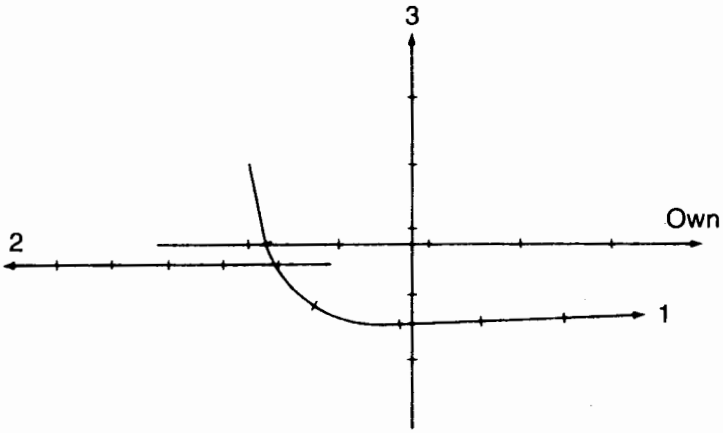
Intrusion Scenario 2A 1



Plan

Profile

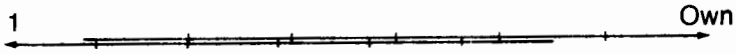
Intrusion Scenario 2A 2



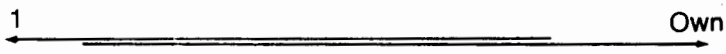
Plan

Profile

Intrusion Scenario 2A 3



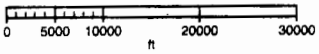
Plan

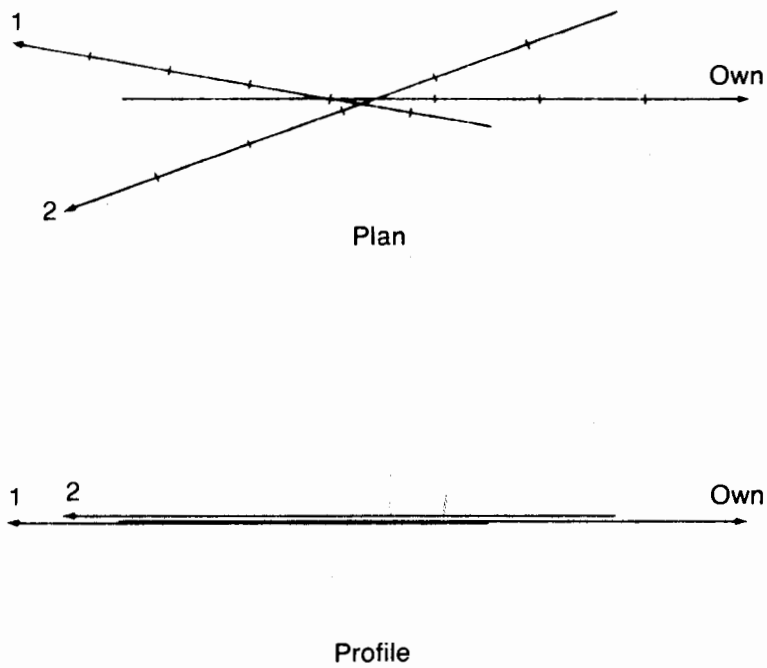


Profile

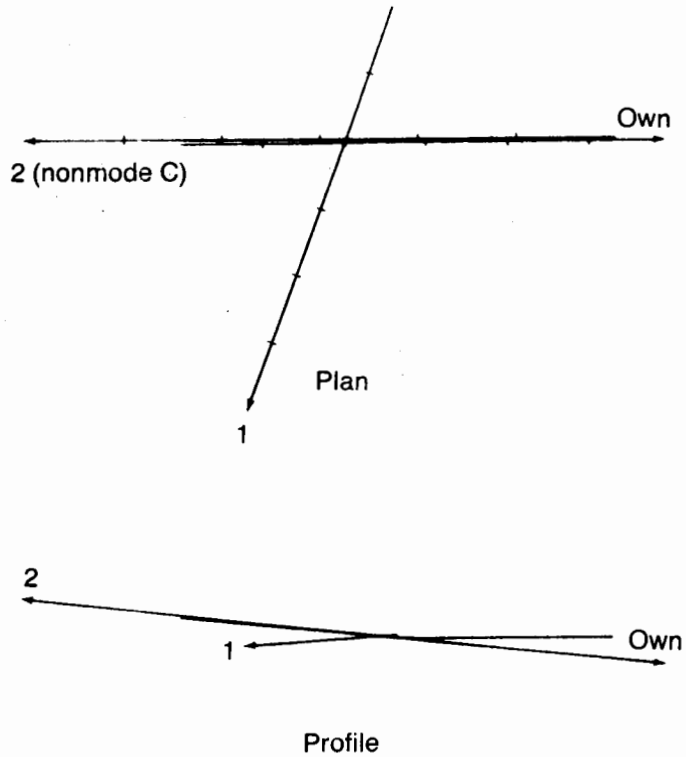
Intrusion Scenario 2A 4

Scale

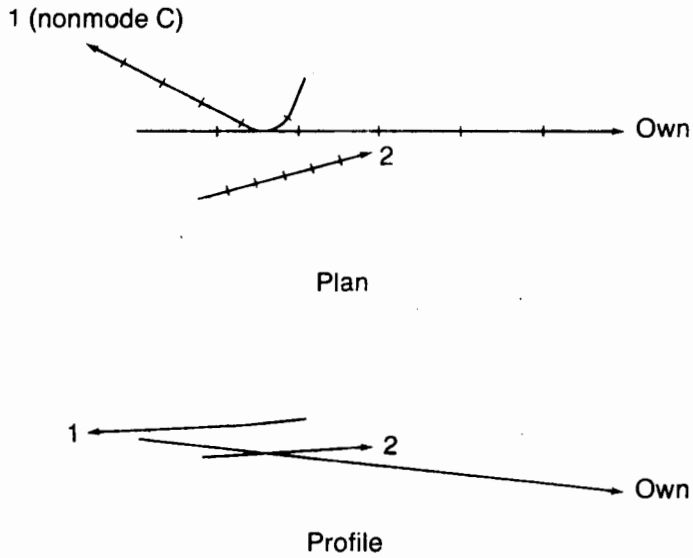




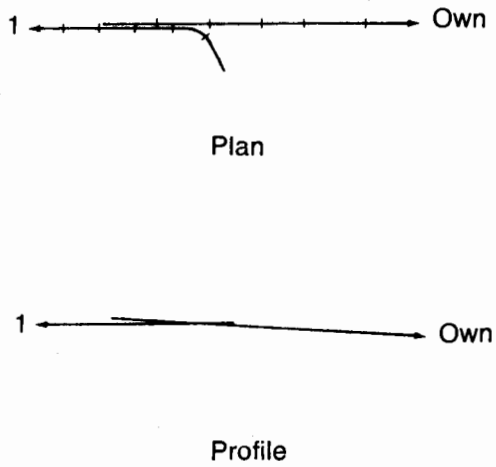
Intrusion Scenario 2A 5



Intrusion Scenario 2A 6

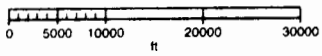


Intrusion Scenario 2A 7



Intrusion Scenario 2A 8

Scale



SCENARIO 3

- Boeing 737, Cleared to Grant county Airport via Yakima, Victor 448, Moses Lake, departure via Yakima Four Departure. Climb and maintain 3,500 feet, expect 13,000 ft crossing Yakima, squawk Mode C Code 2230. Contact tower when ready for takeoff, over

- Boeing 737, initiate turn direct Yakima passing 1000 ft AGL cleared for takeoff

- Trigger #1

  Boeing 737, cleared to 13,000 feet, contact Seattle Center on 132.6. Over

  o Boeing 737, squawk ident

  Boeing 737, radar contact, call level at 13,000 ft. Over

- Trigger #2

- Trigger #3 — Moses Lake weather presently 2000 feet scattered with 5 miles visibility, winds 250 at 10, ILS runway 32R in use

- Trigger #4

- Boeing 737, descend to 5,000 ft

- Boeing 737, contact Grant County Approach on 126.4, over

- Boeing 737, continue descent to 2,800 ft turn right to 080 degrees vectors to ILS Rwy 32 right

- Trigger #5

- Boeing 737, turn left heading 050, cleared ILS approach, contact tower 118.1 prior to outer marker

  o Boeing 737, numerous light aircraft operating in area, altimeter 29.93, winds 250 at 10, cleared to land

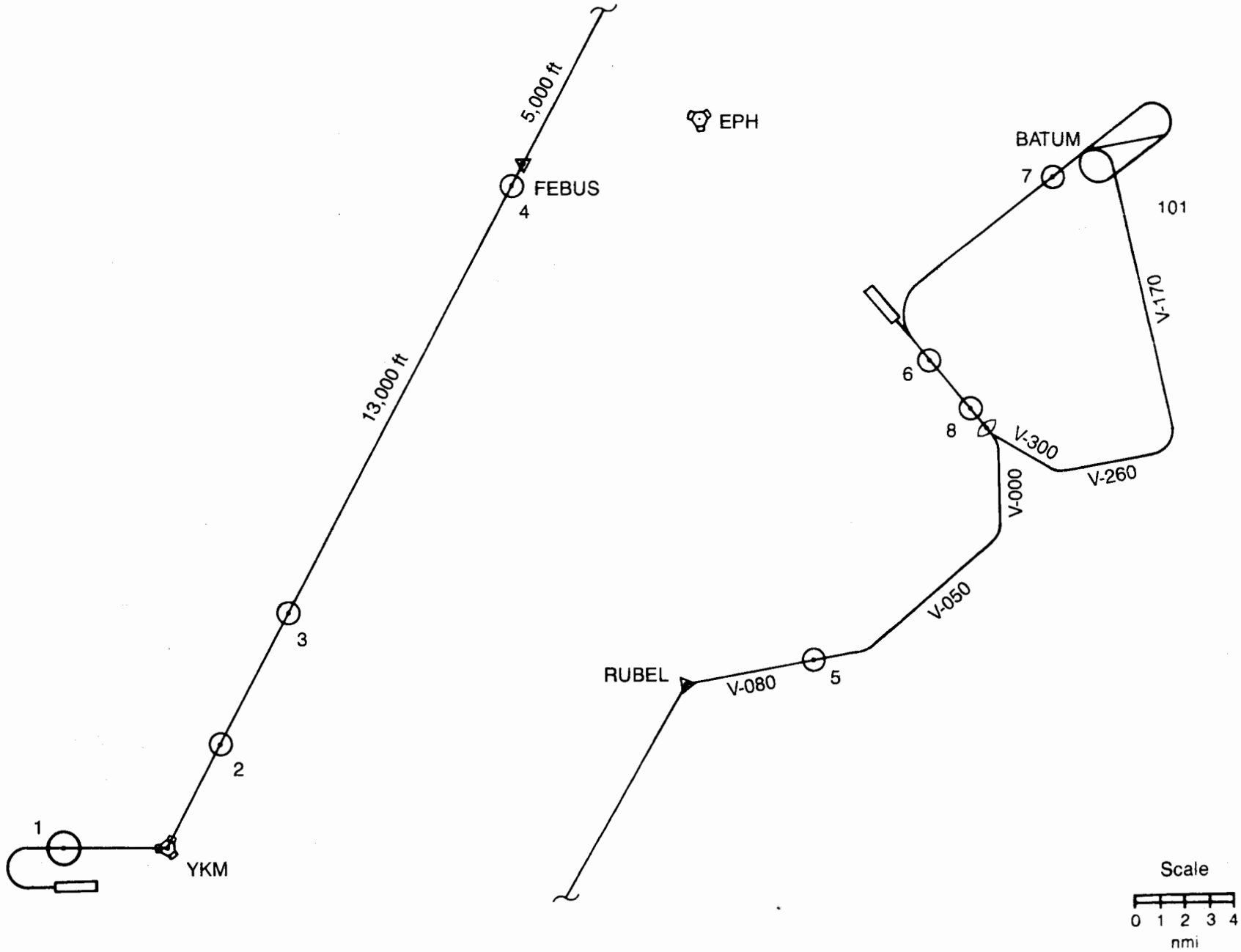
- Trigger #6

- Boeing 737, follow published missed approach procedures expect to hold at Batum 3000 feet. Over

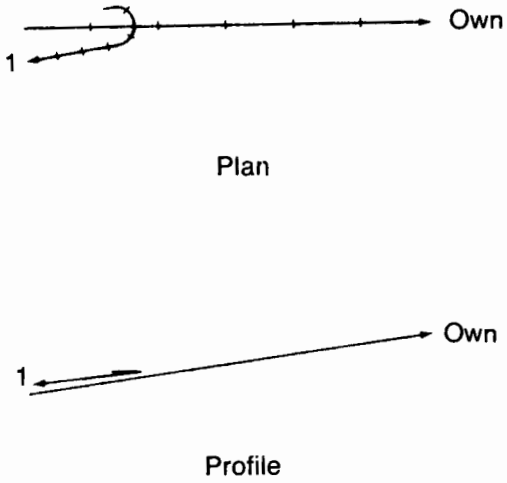
- Trigger #7

- Boeing 737, turn right heading 170 vector to ILS approach runway 32 R, descend to 2800, Over

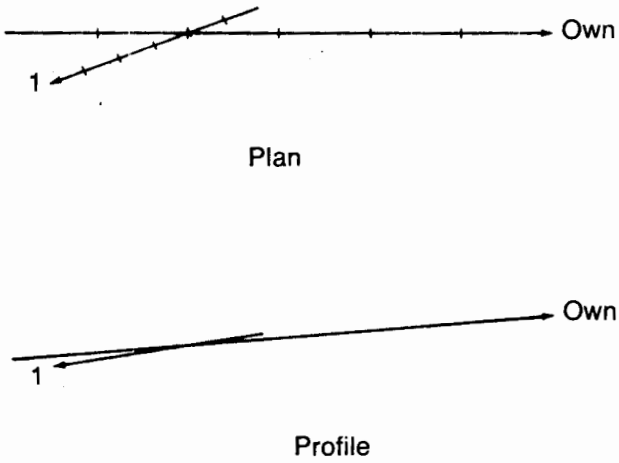
- Boeing 737, turn right heading 260



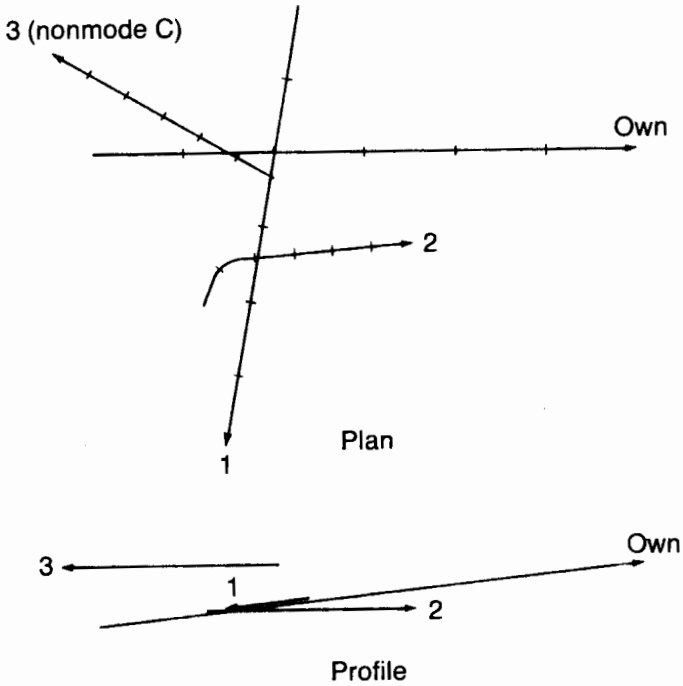
Mission Scenario 3



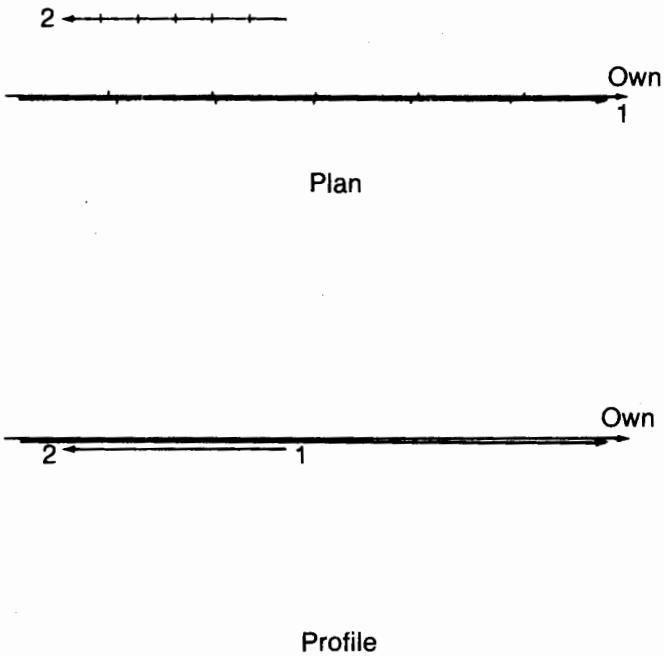
Intrusion Scenario 3A 1



Intrusion Scenario 3A 2

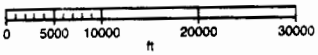


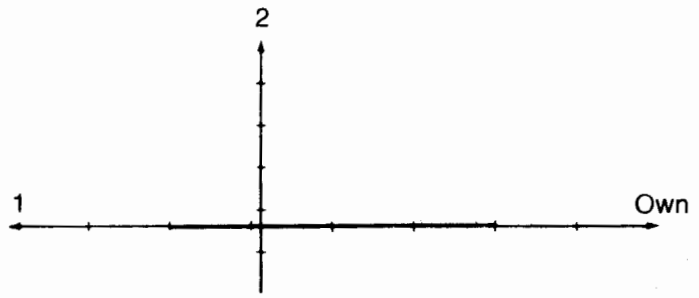
Intrusion Scenario 3A 3



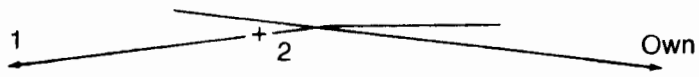
Intrusion Scenario 3A 4

Scale



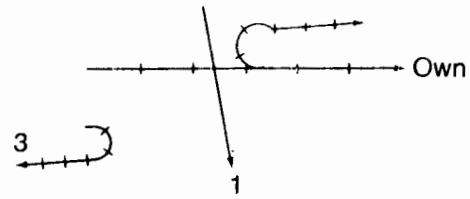


Plan

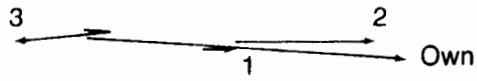


Profile

Intrusion Scenario 3A 5

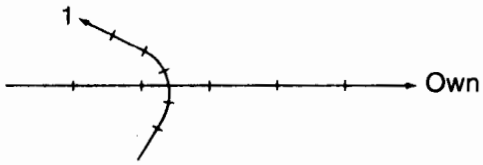


Plan



Profile

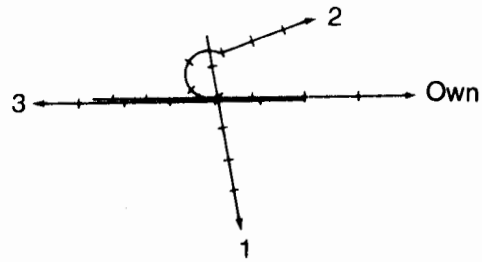
Intrusion Scenario 3A 6



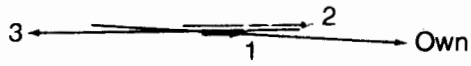
Plan

Profile

Intrusion Scenario 3A 7



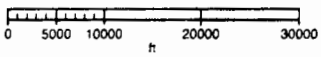
Plan



Profile

Intrusion Scenario 3A 8

Scale



SCENARIO 4

- Boeing 737, cleared to King County International, via Ephrata, V-120, Seattle, climb to maintain 16,000 feet, Grant County Departure on 126.4, squawk Mode C code 2230, readback

  o Boeing 737, readback correct altimeter 29.92, 250 at 10 knots, maintain runway heading to 3000 then direct Ephrata, cleared for takeoff

- Trigger #1

- Boeing 737, turn left direct Ephrata, flight plan route

- Trigger #2

ENGINE FAILURE

  o Roger Boeing 737 standby for amended clearance for return to Grant County Airport

- Trigger #3

- Boeing 737, turn left heading a80° for return to Moses Lake or cleared direct Pelly, descend and maintain 15,000

- Trigger #4

- Boeing 737, turn left heading 125, descend to 10,000

- Trigger #5

- Boeing 737, continue descent to 2800 radar vectors to ILS Runway 32R, Altimeter 29.91, over

- Trigger #6

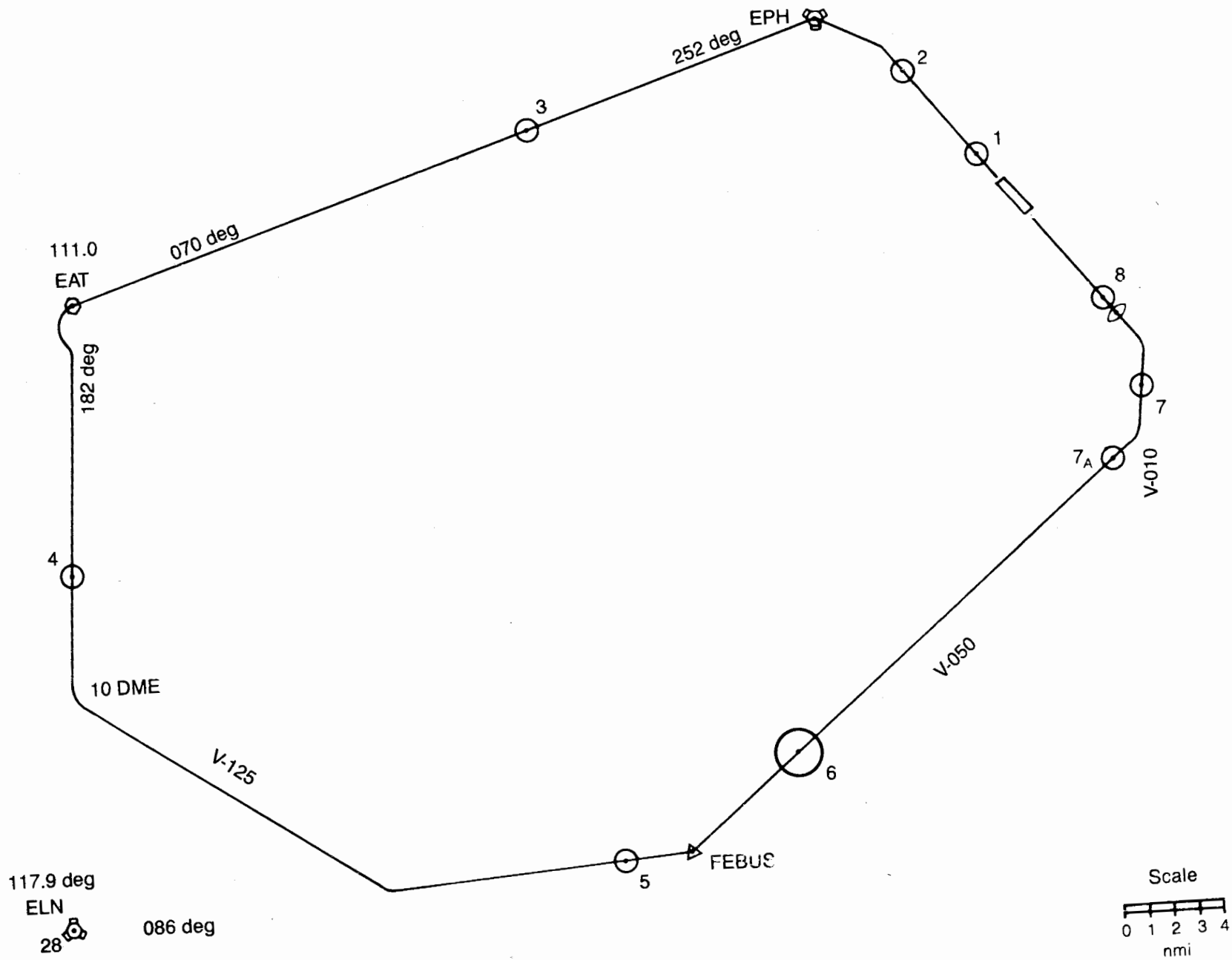
- Boeing 737, turn left heading 050, call level at 2800 feet

- Trigger #7

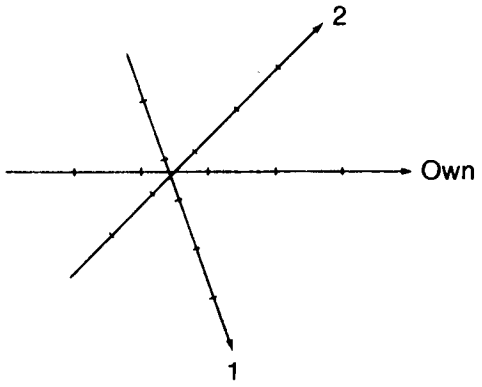
- Boeing 737, turn left heading 010, cleared ILS, contact tower 118.1

- Boeing 737, emergency vehicles both sides of runway, winds 310 at 10 knots, cleared to land

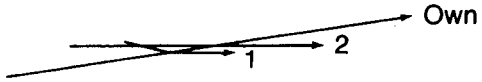
- Trigger #8



Mission Scenario 4

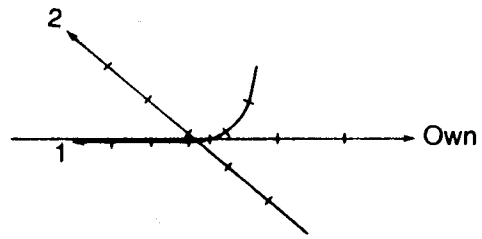


Plan



Profile

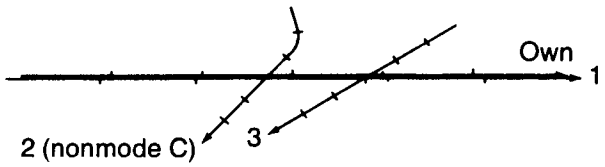
Intrusion Scenario 4A 1



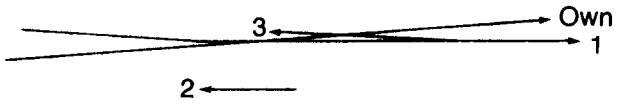
Plan

Profile

Intrusion Scenario 4A 2

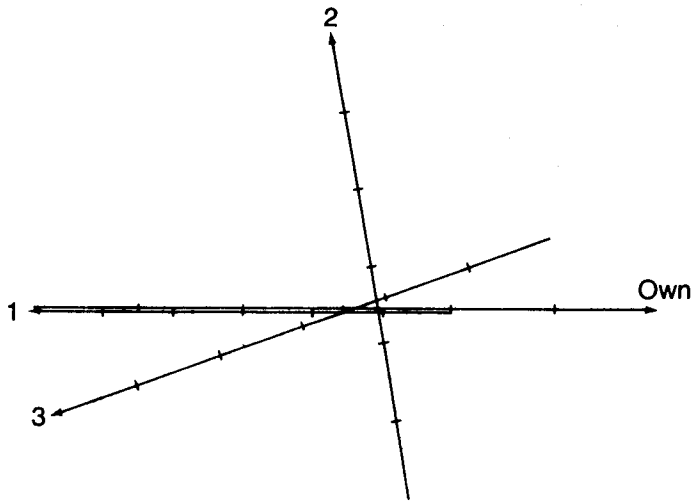


Plan

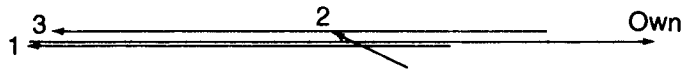


Profile

Intrusion Scenario 4A 3



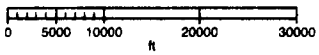
Plan

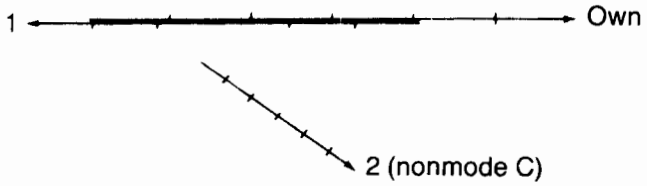


Profile

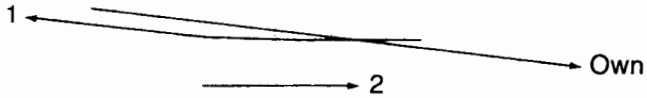
Intrusion Scenario 4A 4

Scale



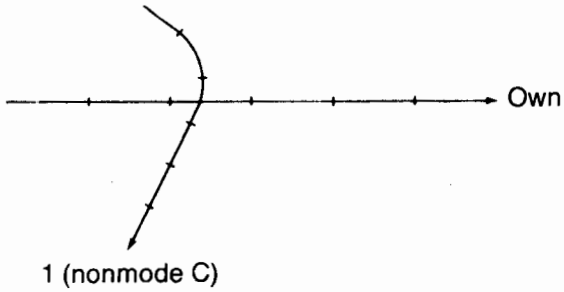


Plan

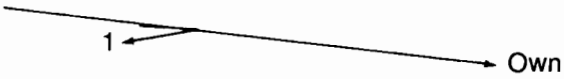


Profile

Intrusion Scenario 4A 5

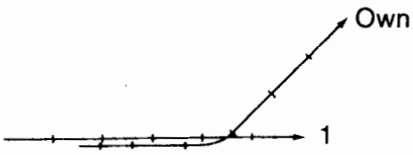


Plan

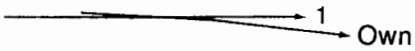


Profile

Intrusion Scenario 4A 6

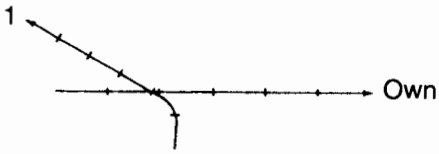


Plan

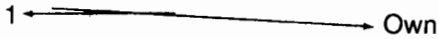


Profile

Intrusion Scenario 4A 7



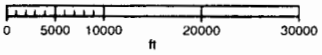
Plan



Profile

Intrusion Scenario 4A 8

Scale



SCENARIO 5

- Boeing 737, cleared to King County International via Ephrata, V-120, Seattle, climb to and maintain 16,000 feet. Departure on 126.4 squawk Mode C Code 2230, read back

- Boeing 737, winds 310 at 10, contact departure when airborne, cleared for takeoff

- Trigger #1

- Boeing 737, contact Seattle Center 132.6

  o Boeing 737, ident

- Trigger #2

- Trigger #3 (TCAS abort)

- Trigger #4

- Boeing 737, descend to 10,000 feet, contact Seattle approach on 123.9

  Seattle presently has 6.0 miles visibility, 2000 broken, winds 310 at 15

- Trigger #5

- Boeing 737, traffic 1 o'clock, 6 miles 500 feet above

- Trigger #6

- Boeing 737, continue descent to 3,300 feet, turn left heading 210 to intercept the 090 radial inbound to Seattle VOR. Expect back course to runway 31 left. Altimeter setting 29.92. Over

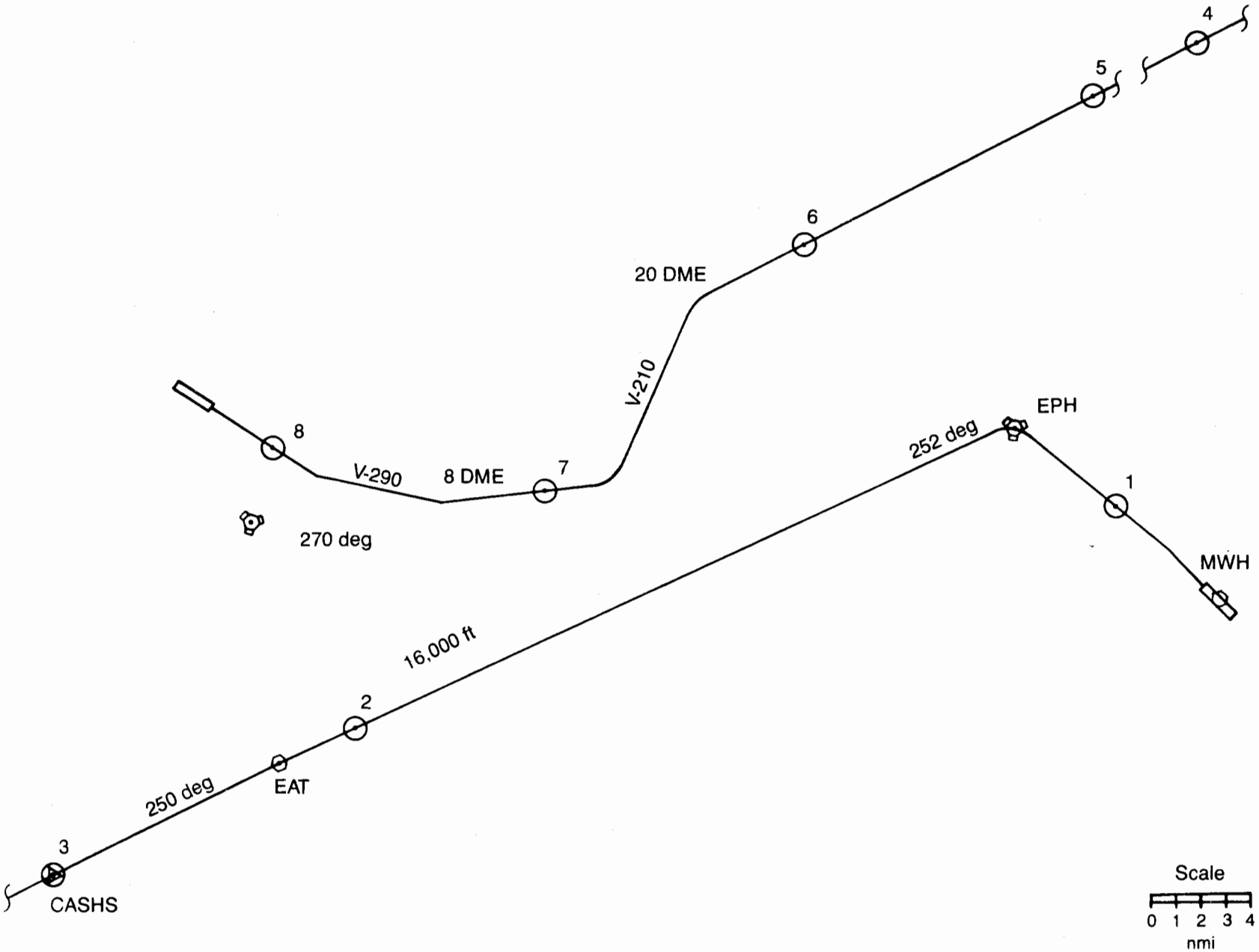
- Trigger #7

- Boeing 737, turn right heading 290 cleared localizer back course. Contact Boeing Tower 120.6. Over

  o Boeing 737, continue approach, altimeter setting 29.93, winds 310 degrees at 15 knots

- Trigger #8

- Boeing 737, cleared to land

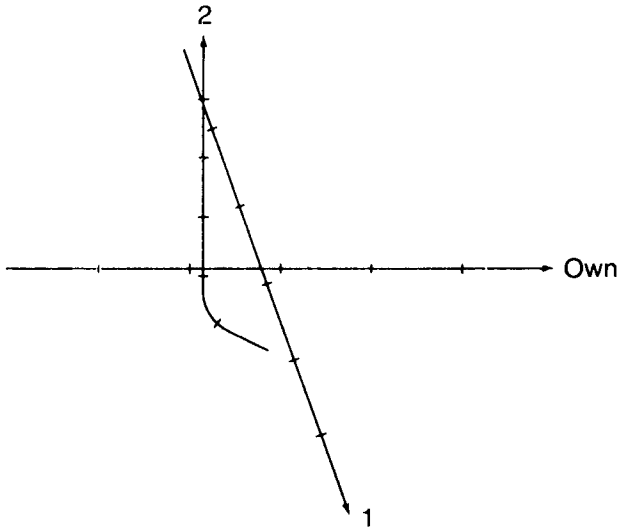


Mission Scenario 5

Plan

Profile

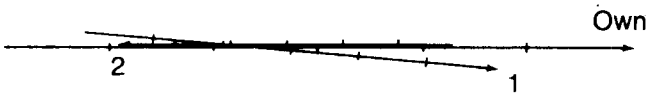
Intrusion Scenario 5A 1



Plan

Profile

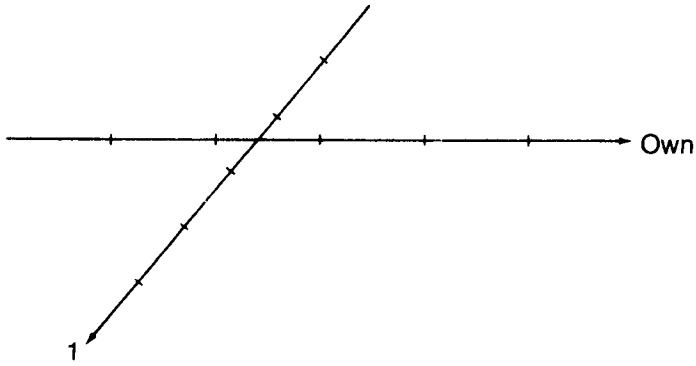
Intrusion Scenario 5A 2



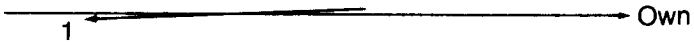
Plan

Profile

Intrusion Scenario 5A 3



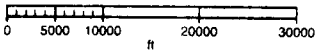
Plan

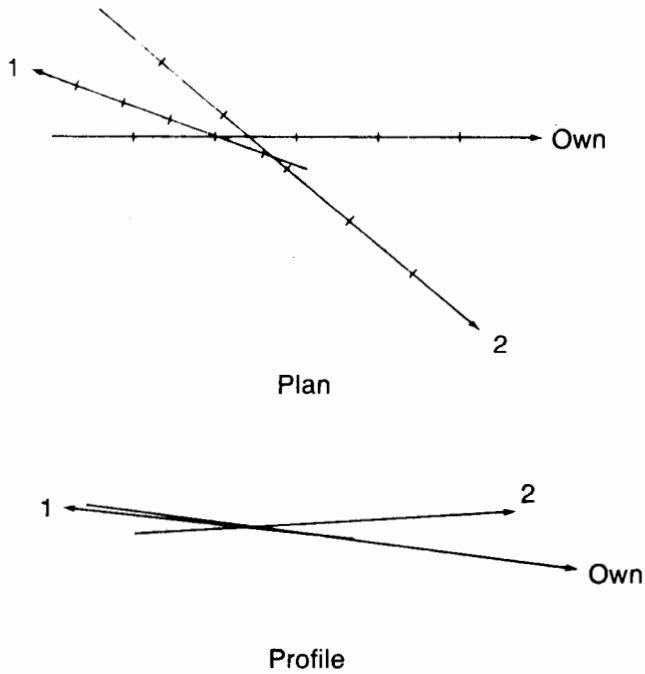


Profile

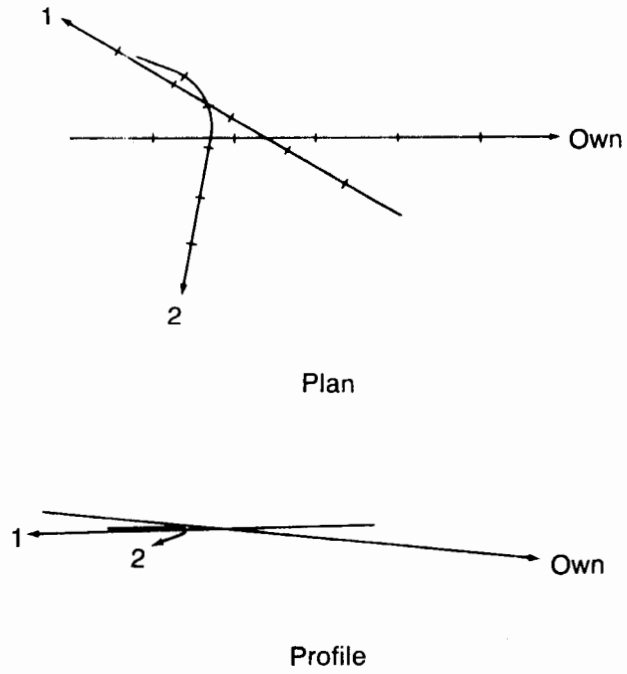
Intrusion Scenario 5A 4

Scale

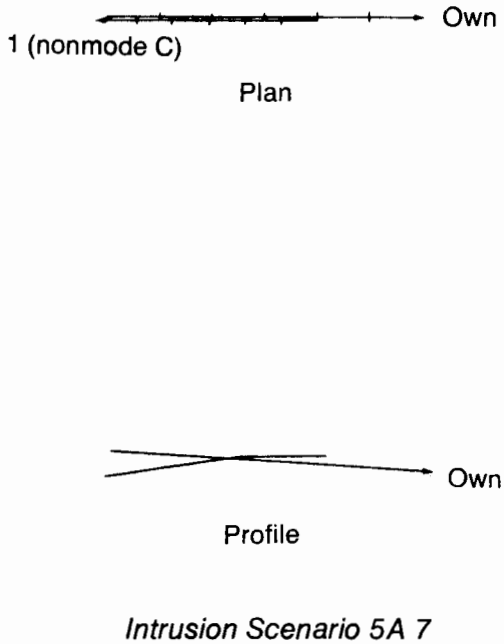




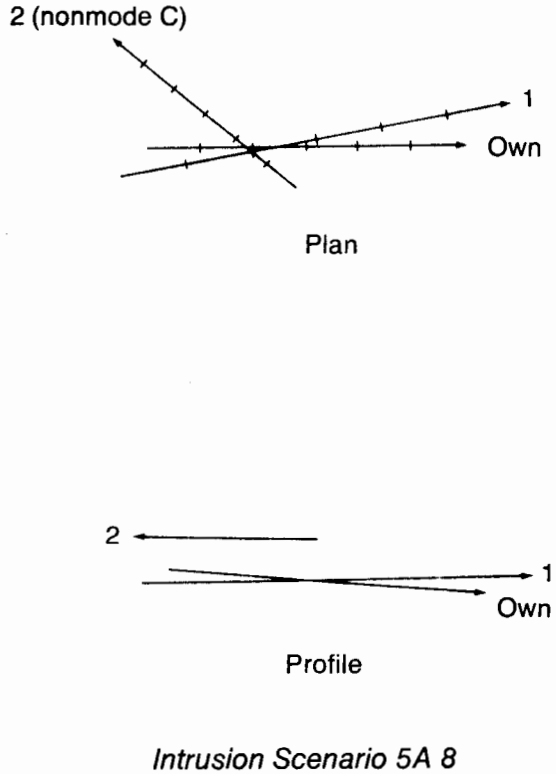
Intrusion Scenario 5A 5



Intrusion Scenario 5A 6

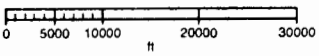


Intrusion Scenario 5A 7



Intrusion Scenario 5A 8

Scale



SCENARIO 6

- Boeing 737, cleared to Chicago O'Hare International via Kent Two Departure, flight plan route, maintain 2000 feet, expect flight level 330 15 miles east of Seattle, departure control on 123.9, squawk Mode C Code 2230, please readback

  - o Boeing 737, readback correct, winds 310 at 8 knots, contact departure when airborne, cleared for takeoff

- Trigger #1

  - o Boeing 737, continue climb to 6000 feet, maintain runway heading until intercepting Jet Route 90

- Trigger #2

- Boeing 737, contact Seattle Center on 120.3

  - o Roger Boeing 737, squawk ident .... 737 radar contact continue climb to flight level 330, Over

- Trigger #3

- Trigger #4

- Trigger #5

- Trigger #6

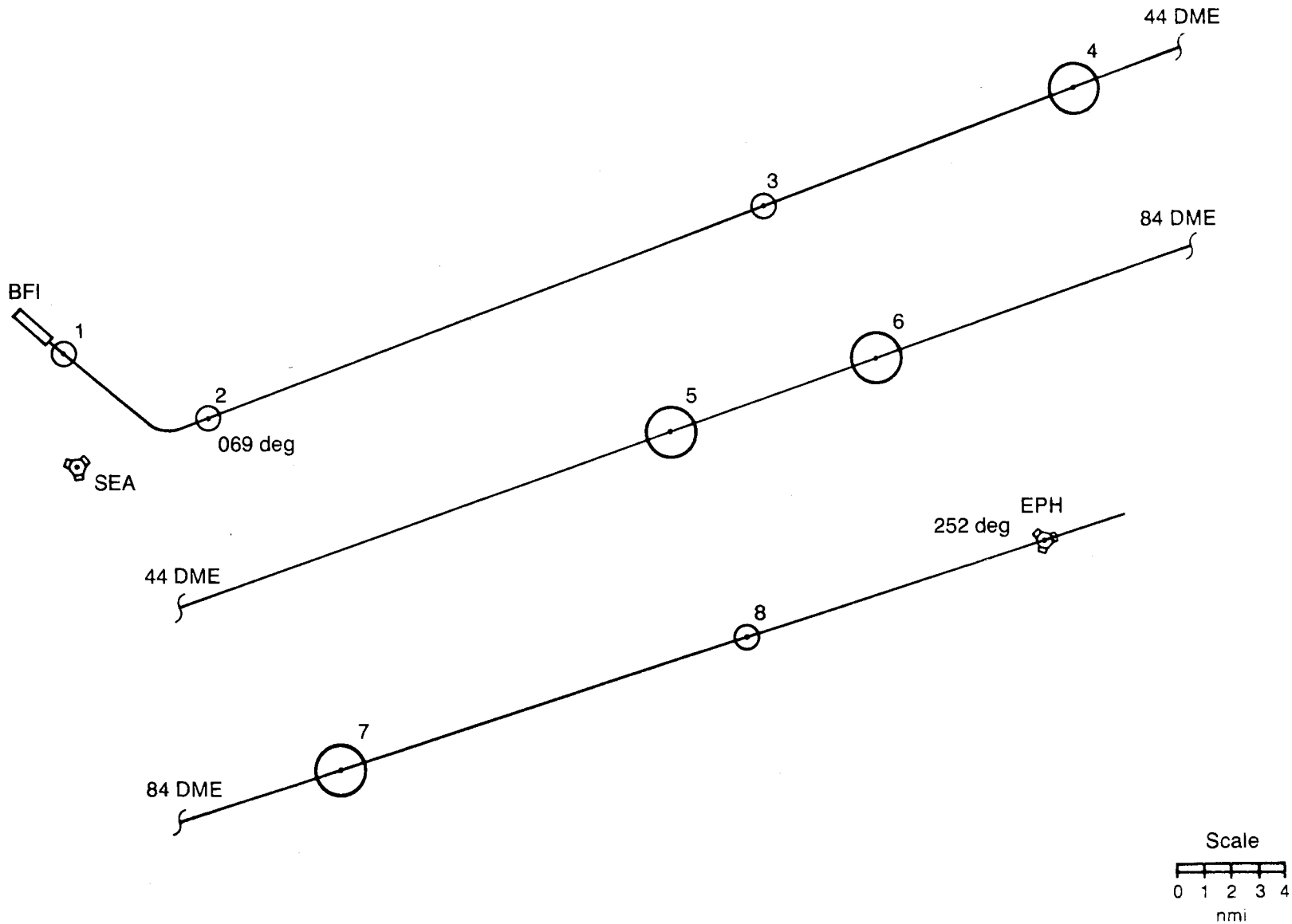
- Boeing 737, contact center on 132.6 good day

  - o Boeing 737 ident .....

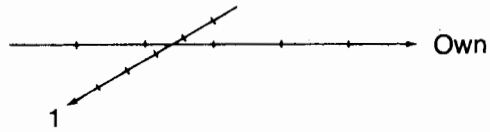
- Boeing 737, radar contact

- Trigger #7

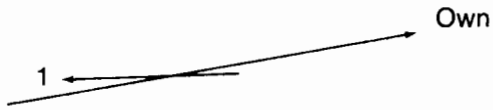
- Trigger #8



Mission Scenario 6



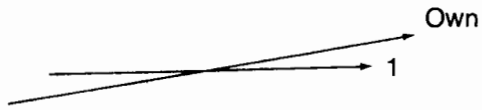
Plan



Profile

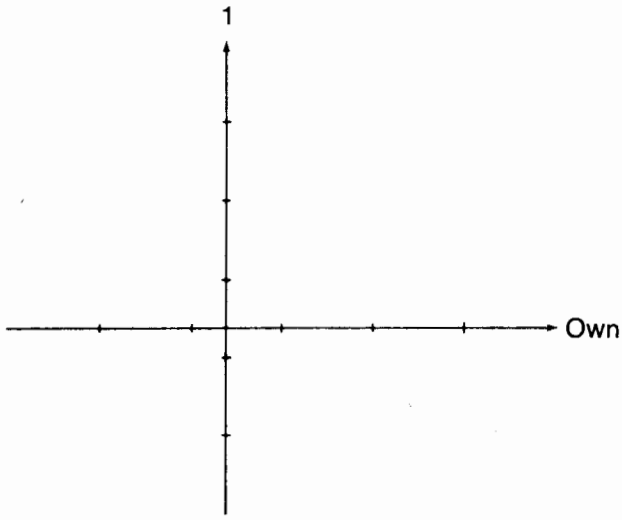
Intrusion Scenario 6A 1

Plan



Profile

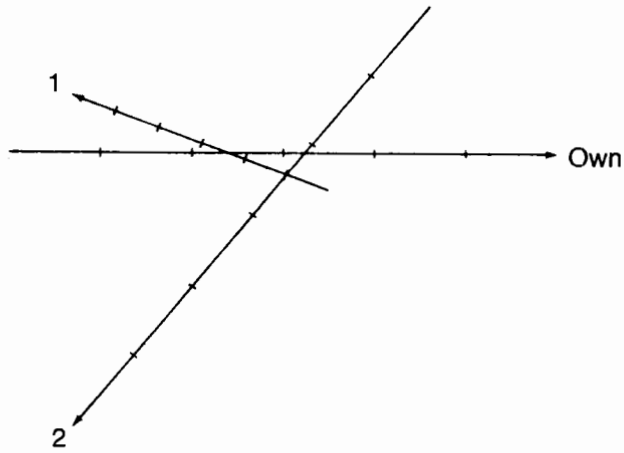
Intrusion Scenario 6A 2



Plan

Profile

Intrusion Scenario 6A 3

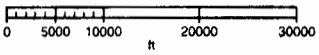


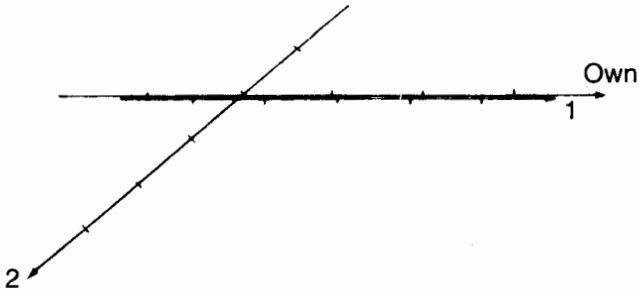
Plan

Profile

Intrusion Scenario 6A 4

Scale

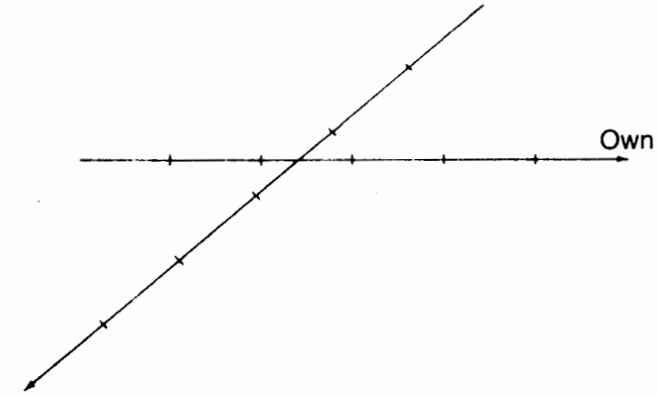




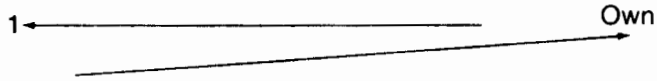
Plan

Profile

Intrusion Scenario 6A 5

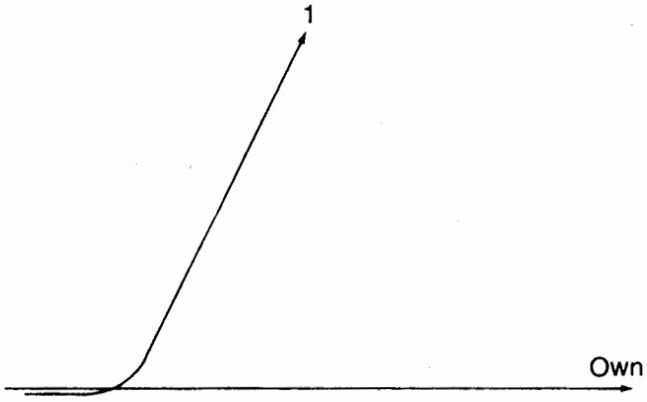


Plan

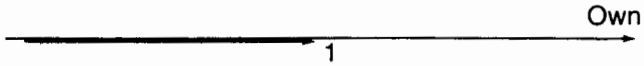


Profile

Intrusion Scenario 6A 6

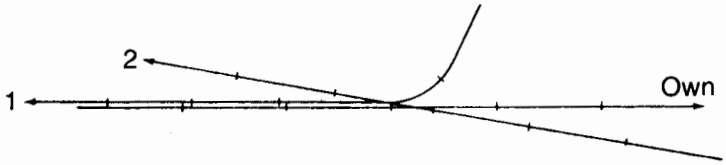


Plan



Profile

Intrusion Scenario 6A 7

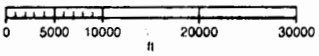


Plan

Profile

Intrusion Scenario 6A 8

Scale



SCENARIO 7

- Boeing 737, aircraft landing at King County International are experiencing delays of about 15 minutes, expect to hold at Flaak, cleared to descend to flight level 240 by 50 DME from Seattle, Over

- Trigger #1

- Boeing 737, traffic 12 o'clock 6 miles 500 feet above, Over

- Trigger #2

- Boeing 737, hold Northeast of Flaak as published on the 039 radial, expected approach clearance time is -- (+13 minutes from current time), maintain FL 240, call entering holding, Over

- Trigger #3

  o Roger Boeing 737 descend in holding to flight level 180, Over

- Trigger #4

- Trigger #5

- Boeing 737 cleared inbound to Seattle descend and maintain 6000, altimeter 29.92, Over

- Trigger #6 — Seattle weather is 800 overcast, 3.0 miles visibility with rain, temperature 56 degrees, winds 110 at 10 knots gusting to 20

- Boeing 737 contact Seattle approach control o 123.9, Over

  o Boeing 737 ident ..... turn right heading 270 radar vectors for ILS approach to runway 13R descend to 3000 feet, Over

- Trigger #7

- Boeing 737 turn left heading 180 descend to 2200 feet, cleared ILS approach runway 13R, Over

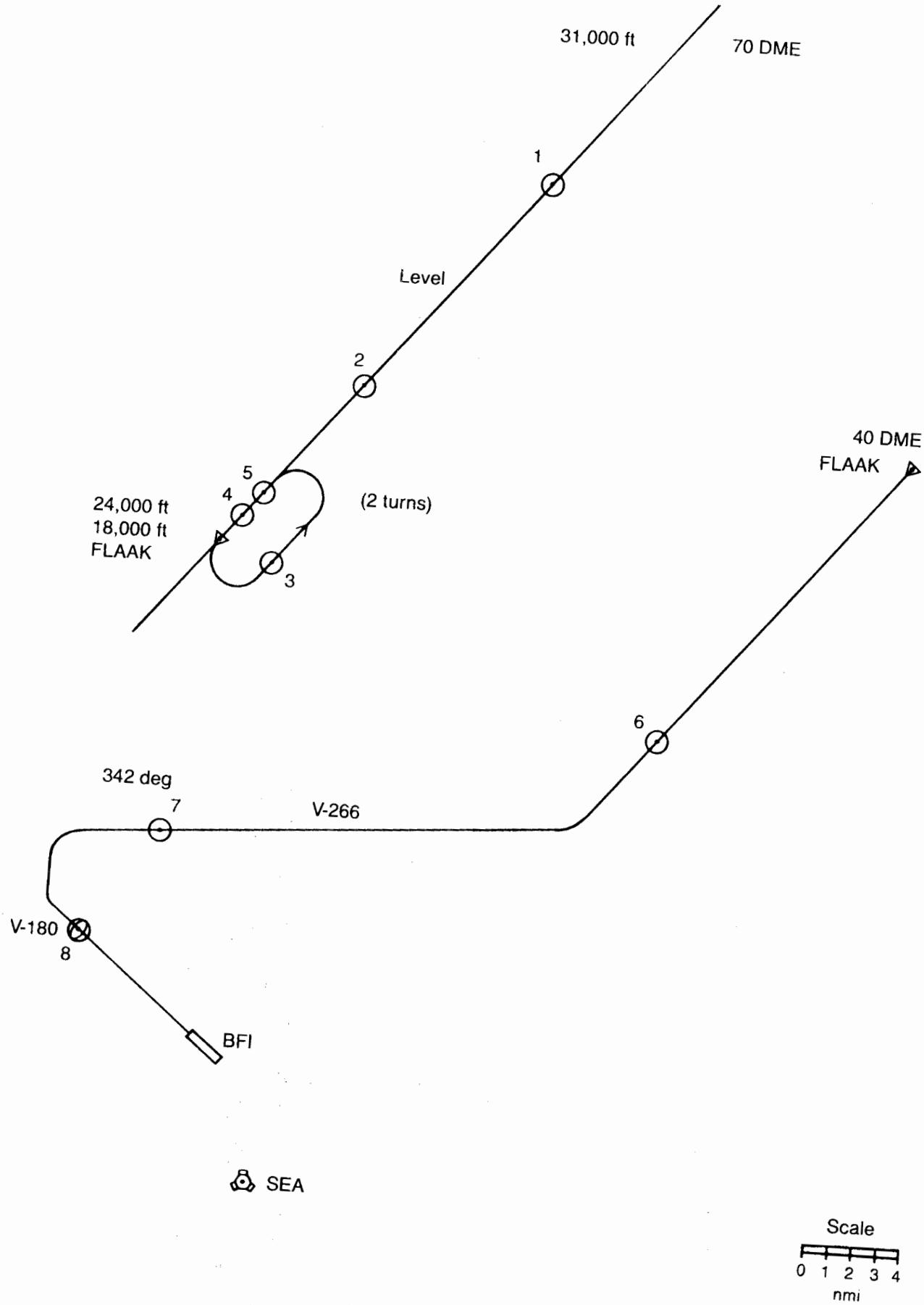
- Boeing 737, contact Boeing Tower 120.6

  o Boeing 737 call outermarker

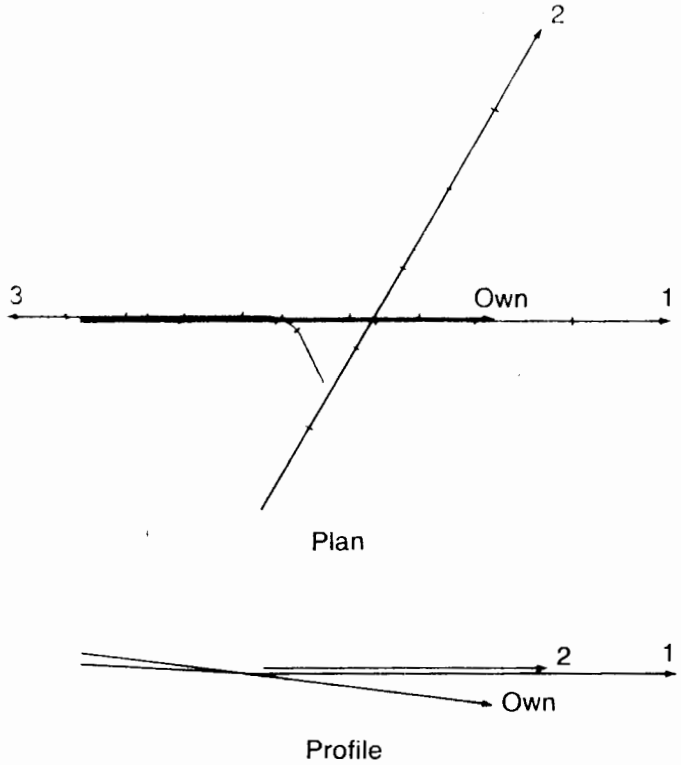
- Trigger #8

  o Boeing 737, winds are from 120 at 10 knots, cleared to land

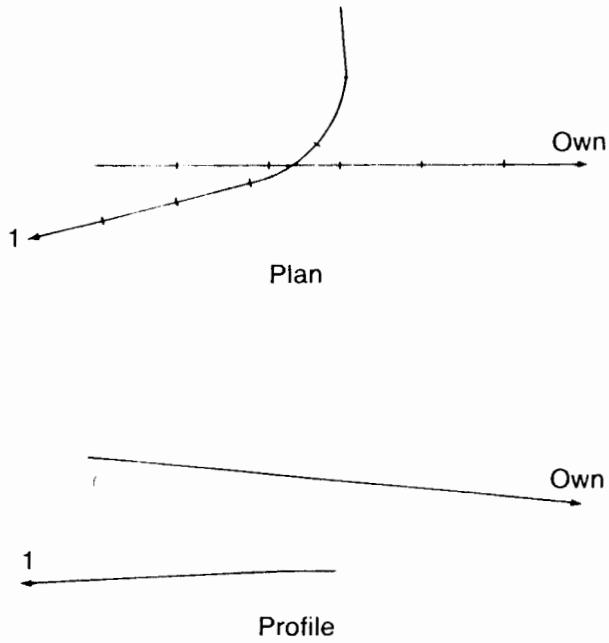
- Boeing 737, turn right heading 300 cleared ILS approach
    - o Boeing 737 winds 250 at 10 cleared to land
    - Trigger #8



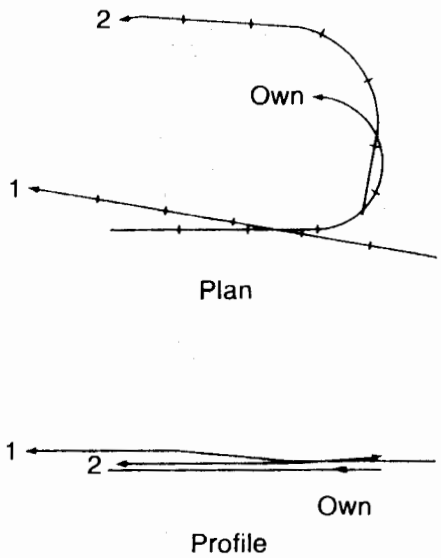
Mission Scenario 7



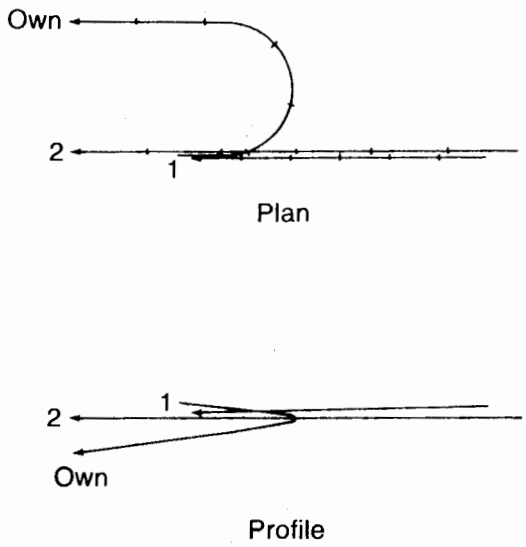
Intrusion Scenario 7A 1



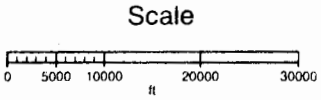
Intrusion Scenario 7A 2

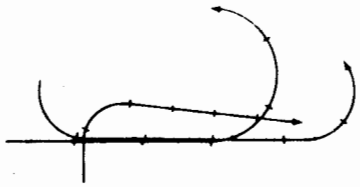


Intrusion Scenario 7A 3

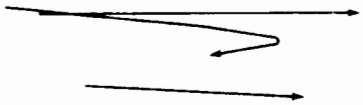


Intrusion Scenario 7A 4



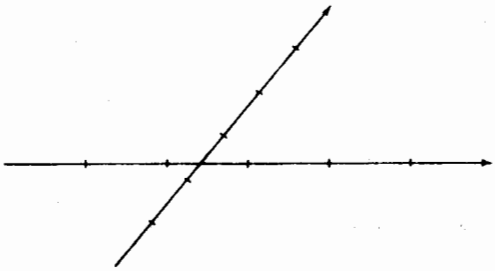


Plan

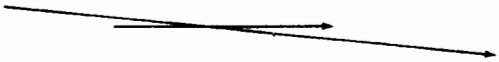


Profile

Intrusion Scenario 7A 5

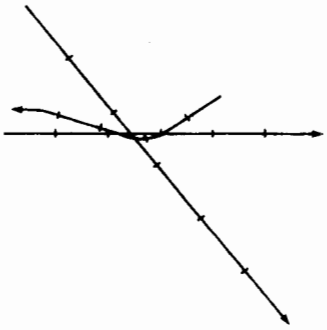


Plan

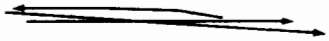


Profile

Intrusion Scenario 7A 6



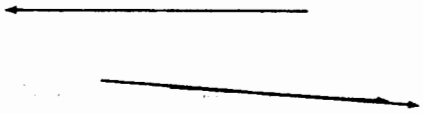
Plan



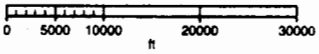
Profile

Intrusion Scenario 7A 7

Plan



Profile

Intrusion Scenario 7A 8

Scale