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HUMAN FACTORS ASPECTS OF THE TRAFFIC ALERT AND COLLISION AVOIDANCE SYSTEM (TCAS II)

by

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The objective of this study was to investigate three areas of interaction between pilots and the TCAS II Collision Avoidance System in order to examine the following areas of concern: (1) Did pilots maneuver on traffic advisory (TA) information? (2) Did the pilots' use of the system increase the miss distance between conflicting aircraft? (3) Would an alternate design for the resolution advisory (RA) display be more effective than the current display? The first two questions were answered with data obtained from a NASA-Ames simulation using airline crews and a Boeing 727 flight simulator. Evaluation of these data reveal 14 incidents where pilots successfully maneuvered their aircraft using TA information. Forty scenarios where the TCAS II system directed evasive maneuvers were examined. These results show that the recommended avoidance maneuvers increased aircraft miss distance in 37 cases. Alternate designs for the resolution advisory display were evaluated using

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military and civilian pilots reacting to a computer display simulation. These results demonstrate that a "red and green" RA display is more effective than the current "red only" RA display.

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Human Factors Aspects of the Traffic Alert and Collision Avoidance System (TCAS II)

by

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Submitted in partial fulfillment of the requirements for the degree of

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ABSTRACT

The objective of this study was to investigate three areas of interaction between pilots and the TCAS II Collision Avoidance System in order to examine the following areas of concern: (1) Did pilots maneuver on traffic advisory (TA) information? (2) Did the pilots' use of the system increase the miss distance between conflicting aircraft? (3) Would an alternate design for the resolution advisory (RA) display be more effective than the current display? The first two questions were answered with data obtained from a NASA-Ames simulation using airline crews and a Boeing 727 flight simulator. Evaluation of these data reveal 14 incidents where pilots successfully maneuvered their aircraft using TA information. Forty scenarios where the TCAS II system directed evasive maneuvers were examined. These results show that the recommended avoidance maneuvers increased aircraft miss distance in 37 cases. Alternate designs for the resolution advisory display were evaluated using military and civilian pilots reacting to a computer display simulation. These results demonstrate that a "red and green" RA display is more effective than the current "red only" RA display.

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TABLE OF ABBREVIATIONS

ADI: Altitude Direction Indicator

ALT: Altitude

ATC: Air Traffic Control

CPA: Closest Point of Approach

DF: Degress of Freedom

F: Variance ratio

FPM: Feet per Minute

FPS: Feet per Second

FT: Feet

IMC: Instrument Meteorological Conditions

IVSI: Instantaneous Vertical Speed Indicator

NM: Nautical Miles

p: Probability due to Chance

RA: Resolution Advisory

SECS: Seconds

SEP: Separation

SD: Sample Standard Deviation

TA: Traffic Advisory

TCAS: Traffic Alert and Collision Avoidance System

VMC: Visual Meteorological Conditions

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My sincerest thanks to my wife Geri and our children Christopher and Jennifer whose ever-present support helped me keep everything in perspective during the thesis process. Special thanks to Sherry Chappell and Chet Heard who gave me the freedom to pursue my areas of interest and gave me valuable guidance each step along the way. Thanks to Professor Satyanarayana Bodapati who introduced me to the opportunities available at the NASA-Ames Research Center. I also appreciate the expert computer assistance I received from Lyman Taylor and Tom Kozon, and the support of all the NASA-Ames personnel I worked with. Finally, I would like to thank LT John Blaha and the 36 pilots from both Patrol Squadron Thirty-One (VP-31) and NASA-Ames for volunteering their valuable time to participate in my TCAS human factors experiment.

I. INTRODUCTION

The overburdened United States air traffic control system has failed to prevent a significant number of near mid-air collisions during the last few years. The increase in air traffic due to airline deregulation has saturated the current air traffic control system and has spurred the development of practical airborne collision avoidance systems. Reference 1 contains a description of the TCAS I, TCAS II, and TCAS III systems. "TCAS" is an abbreviation for "Traffic Alert and Collision Avoidance System" (Table of Abbreviations). The major difference between the three systems, other than cost, is the amount and type of collision avoidance maneuver information that is provided to the pilot. The TCAS I system provides no avoidance maneuver commands, while the TCAS II system directs evasive maneuvers in the vertical plane only (climbs and descents). The TCAS III system provides turns in addition to climbs and descents. The major disadvantage of all three systems is that the intruder aircraft must be transponder equipped in order to be tracked by the TCAS system. Additionally, for a TCAS II or TCAS III equipped aircraft to receive collision avoidance commands, the intruder aircraft must have a mode-C (altitude reporting) transponder.

This report will deal with the TCAS II system and some of the human factors aspects of its operation. Three questions dealing with the use of the system by pilots will be examined.

(1) Did pilots maneuver on traffic advisory (TA) information?

(2) Did the use of the system increase the miss distance between conflicting aircraft?

(3) Would an alternate design for the resolution advisory (RA) display be more effective than the current display?

To answer the first two questions, information obtained from a NASA-Ames simulation using airline flight crews and a Boeing 727 flight simulator was examined and analyzed. A detailed description of this simulation is contained in Reference 2. (Note: The author of this report is a co-author of Reference 2.) The creation of an additional computer simulation at the NASA-Ames Research Center was necessary to examine alternate designs for the RA display. Results from this study are described in Chapter 5 of this report.

The research in this paper was conducted under the Navy-NASA Joint Institute of Aeronautics Program. Analysis of the data was completed using the facilities of the NASA-Ames Research Center and the Naval Postgraduate School.

II. TCAS II SYSTEM DESCRIPTION

TCAS II is a self-contained system designed to preserve ATC vertical separation by tracking aircraft, evaluating collision potential, and displaying advisories and warnings. [Ref. 3] The warnings include recommended evasive maneuvers in the vertical plane. The system computes the range, relative altitude, and bearing of nearby aircraft by interrogating their transponders and evaluating the replies. The traffic's relative altitude and position information is displayed by color coded symbols on a traffic advisory, (TA) display (Figure 1). Display characteristics differ among the airlines. The traffic advisory display covers an area at least six NM ahead of the aircraft to three NM behind the aircraft. Intruder aircraft are colored amber unless they pose a collision threat within 20 to 30 seconds. If the intruder aircraft is determined to be a threat, the TCAS computer changes the color of the symbol to red, and activates warning tones, a warning voice, and red lights on the glareshield. These warnings direct the pilot's attention to the resolution advisory (RA) display which displays recommended evasive action (Figure 1). The RA display is an IVSI (Instantaneous Vertical Speed Indicator) which has been modified with red "eyebrow" lights around the circumference to indicate whether a climb or descent is required to

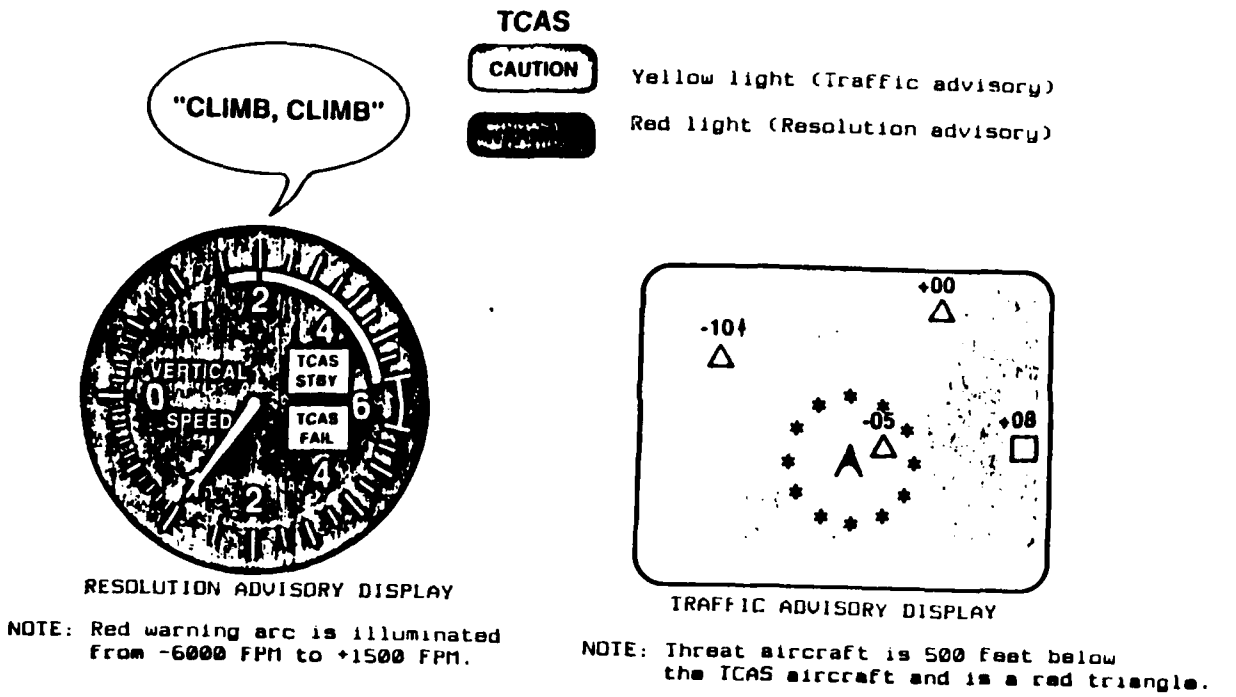


Figure 1. TCAS Components

increase separation distance. The warning lights will extinguish, and a voice will state "clear of conflict" when the collision threat no longer exists. Installation of the system requires the addition of an antenna on top of the fuselage, a computer unit (black box) and a mode-S transponder [Ref. 3]. If two conflicting aircraft are equipped with the TCAS II system, collision avoidance maneuvers will be coordinated automatically by their respective TCAS computer units through the mode-S transponder data link.

III. MANEUVERS BASED ON THE TRAFFIC ADVISORY DISPLAY

A. INTRODUCTION

The TCAS II traffic advisory (TA) display is designed to aid pilots in establishing visual contact with conflicting traffic. It may also be used to observe the flight paths of nearby traffic and monitor the relative altitude differences between the TCAS aircraft and other aircraft in the vicinity. This information allows the pilots to see dangerous situations developing and prepare for possible evasive maneuvers. Eight airline flight crews participated in the NASA-Ames study of TCAS II systems using this display as well as the resolution advisory (RA) display. [Ref. 2] They were thoroughly briefed that the traffic advisory display provided traffic information only and should not be used for evasive maneuvering. Additionally, the RA display was to be used only for evasive maneuvers in the vertical plane following a resolution advisory. In general, the pilots adhered to these guidelines. There were 14 incidents where the pilots used their own experience and judgment to maneuver the aircraft based on the traffic advisory information. Each of these incidents is examined in this report.

B. PROCEDURES

The use of the information obtained from the traffic advisory display for maneuvering was investigated using

information from three different sources.

(1) Computer printouts of the TCAS equipped aircraft's data for all occurrences of a turn or bank angle greater than ten degrees were examined for the time period from two minutes before a traffic alert through the end of the alert. Similar printouts for the resolution alerts were investigated using the same parameters. All incidents of altitude deviations of 100 feet or greater, or vertical velocity changes of greater than 500 feet per minute, were also examined for the TCAS aircraft before and during the traffic alert time periods.

(2) Two observers monitored the flight crew's actions during the simulator testing. Both individuals completed forms which contained the conditions for each alert as well as comments on their personal observations. The corrective RA analysis forms completed by the researchers during post-flight data reduction provided additional information.

(3) Cockpit video tapes were used to observe the flight crew's responses to the traffic advisory information and to confirm the incidents of maneuvering based entirely upon this information.

All maneuvers which were based on visual sightings were not considered a misuse of the system, unless the pilots made evasive maneuvers using traffic advisory information after visual contact was subsequently lost. Maneuvers based on ATC clearances or navigation maneuvers also were not considered.

C. RESULTS

The 14 incidents of maneuvering based on information obtained from the traffic advisory display are described below for all eight airline flight crews. Each crew's incidents will be grouped together to show trends.

CREW #3111: No incidents

CREW #3221: 2 altitude adjustments and 2 turns.

(1) CONDITIONS: time = 07:51:00; visual contact initially gained then lost during maneuvering; twilight; visual meteorological conditions; descending.

NARRATIVE: The crew adjusted their descent rate during the approach in response to a traffic advisory showing traffic beneath them. After clearing the traffic, they continued their approach.

(2) CONDITIONS: time = 09:06:49; no visual contact; twilight; visual meteorological conditions; climbing.

NARRATIVE: The crew turned to avoid a mode A aircraft during the initial climb after takeoff. Aircraft that are mode A transponder equipped do not have altitude reporting capability, and thus appear on the traffic advisory display without relative altitude information. Additionally, no resolution alerts or recommended evasive maneuvers can be issued for these types of aircraft. The crew discussed the incident and decided that the turn was necessary to ensure separation since the altitude of the other aircraft was unknown.

(3) CONDITIONS: time = 09:53:48; no visual contact; twilight; visual meteorological conditions; descending.

NARRATIVE: The crew was descending to an assigned altitude of 5000 feet. After evaluating the information on the traffic advisory display, they leveled off slightly above their assigned altitude and began a slow climb. A resolution advisory calling for a climb was issued a few seconds after the climb was initiated by the flight crew. After clearing the traffic, the crew descended to their assigned altitude.

(4) CONDITIONS: time = 09:58:35; no visual contact; twilight; visual meteorological conditions; descending.

NARRATIVE: The crew turned to clear mode A traffic on a localizer approach using information obtained from the traffic advisory display. After clearing the traffic, they completed the approach.

CREW #3312: 1 altitude adjustment.

(1) CONDITIONS: time = 07:47:33; no visual contact; night; visual meteorological conditions; descending.

NARRATIVE: During a descent, the crew responded to the information on the traffic advisory display which showed an aircraft 1000 feet below them. The crew decided to level the aircraft above their assigned altitude. This resulted in the crew having to notify ATC that they would not be able to meet a crossing altitude clearance. After clearing the traffic, they continued their descent.

CREW #3422: 1 turn and 1 altitude adjustment.

(1) CONDITIONS: time = 03:53:52; visual contact initially gained then lost; night; visual meteorological conditions; level flight.

NARRATIVE: The crew gained visual contact on a conflicting aircraft, but subsequently lost sight of the traffic. The traffic advisory display showed the traffic slightly to the right of the nose of their aircraft and climbing below them. A resolution alert advised the crew to "descend to cross" in order to pass under the conflicting aircraft. The pilot in command decided to descend as instructed and turn left slightly to increase the separation distance. Visual contact was regained after the evasive maneuver.

(2) CONDITIONS: time = 09:17:15; no visual contact; night; visual meteorological conditions; descending.

NARRATIVE: The crew was descending for an approach with multiple aircraft in the area when they received a traffic advisory on an aircraft climbing below their aircraft. The pilot in command anticipated the possibility of a collision and advanced the power on the engines to level off. When the pilot maneuvered, the TCAS system issued a resolution alert and gave the crew a "climb" command. The pilot followed the instructions, remained clear of the other aircraft, and finally resumed his approach.

CREW #4111: 1 altitude adjustment.

(1) CONDITIONS: time = 02:27:24; visual contact after the maneuver; twilight; visual meteorological conditions; descending.

NARRATIVE: The crew was descending for an approach when they received a traffic advisory indicating that they were descending toward another aircraft at a lower altitude. Using this information, they arrested their descent rate and attempted to notify ATC of the situation. Visual contact was finally established with the conflicting aircraft, and the crew maintained their altitude until the other aircraft passed beneath them.

CREW #4221: 3 altitude adjustments.

(1) CONDITIONS: time = 04:35:50; no visual contact; twilight; visual meteorological conditions; descending.

NARRATIVE: The crew was descending for an approach when the traffic advisory display indicated a conflicting aircraft directly ahead. The crew evaluated the range and altitude several times before deciding to level off while the aircraft was still four miles away. They continued to examine the traffic advisory information and decided that the conflicting aircraft was flying in the same direction. A decision was then made to "sneak under" the other aircraft. They continued their descent behind the conflicting traffic and completed the approach. It should be noted that this crew never received a resolution alert due to their maneuvering on the traffic advisory display information.

(2) CONDITIONS: time - 06:30:00; no visual contact; twilight; visual meteorological conditions; level flight.

NARRATIVE: ATC cleared the crew to descend. The crew hesitated due to traffic on the traffic advisory display and asked ATC for clearance to remain level. ATC reiterated that they were cleared to descend. The crew complied by "descending quickly" to stay clear of traffic. During the descent, a resolution alert calling for a descent was received by the crew. This crew monitored the traffic advisory display during maneuvering and wanted to continue the descent after the resolution alert in order to increase the altitude separation between the two aircraft. They decided against this alternative after a short discussion of their ATC clearance and terrain clearance considerations. The crew maintained their assigned level off altitude until clear of the traffic.

(3) CONDITIONS: time = 06:33:40; visual contact then lost visual contact; twilight; visual meteorological conditions; descending.

NARRATIVE: On a localizer approach, the crew initially established visual contact on the conflicting traffic. After subsequently losing sight of the traffic, the crew became concerned with the other aircraft's position and used the traffic advisory display information to stay "a little higher" than the other aircraft until they were clear. They adjusted their descent rate to maintain vertical separation. One pilot from this crew stated "We are really trusting an instrument alot".

CREW #4312: 1 turn.

(1) CONDITIONS: time = 01:25:24; no visual contact; night; visual meteorological conditions; climbing.

NARRATIVE: The crew was climbing after takeoff. They responded to a traffic advisory on the display by delaying a required turn until clear of the traffic. The pilot did not begin the turn until the other pilot informed him that the traffic on the display was no longer a threat.

CREW #4422: 1 turn and 1 altitude adjustment.

(1) CONDITIONS: time = 03:20:05; no visual contact; night; instrument meteorological conditions; descending.

NARRATIVE: While descending in IMC conditions, the crew responded to a traffic advisory by turning "hard left" to avoid a mode A aircraft. The pilot in command justified the turn by concluding that since TCAS resolution alerts and evasive maneuvers are not available for mode A traffic, he had to maneuver to ensure safe separation. The other pilot responded that the aircraft was probably in VMC conditions below the clouds. After clearing the traffic, the crew returned to course.

(2) CONDITIONS: time = 10:26:30; visual contact after the maneuver; night; visual meteorological conditions; descending.

NARRATIVE: The crew was cleared to descend by ATC. Approaching the assigned altitude, the crew received a traffic alert showing an aircraft 200 feet below them. They decided to level off and advanced power on the engines. During the level off maneuver, a resolution alert occurred calling for a descent. The crew complied with the command and descended. During the descent, they obtained visual contact while passing under the other aircraft.

D. CONCLUSIONS

Several patterns emerged from an analysis of these 14 incidents. Altitude adjustments accounted for 64% of the maneuvers (9 out of 14). The majority of the maneuvers occurred during descents (10 out of 14). Three of the turns involved maneuvers to avoid a mode A transponder equipped

aircraft. The most common scenario involved the TCAS aircraft descending toward another aircraft at a lower altitude. In each situation, the TCAS system provided the pilots ample warning for the crew to observe the dangerous situation developing on the traffic advisory display and take corrective action. The response maneuver usually resulted in a decrease in the rate of descent or a level off above the assigned altitude for a short period of time. All 14 of the maneuvers based on TA information caused small deviations from ATC clearances for short time periods. Each crew attempted to notify ATC of the deviations that were required as soon as workload permitted.

Pilot training programs will need to be implemented to standardize the use of the TCAS II system. The responsibility for safety of flight rests with the pilot in command. Aircrew training must emphasize this responsibility and allow the pilot to use all the information available to maintain a safe distance from other aircraft. However, abrupt turns away from mode A transponder equipped aircraft should be discouraged. The inaccuracy of the bearing and altitude information provided by the current traffic advisory display must be emphasized. The possibility of degrading the performance of the TCAS computer's evasive maneuver commands by maneuvering on the traffic display should also be discussed. The first altitude adjustment by Crew 4221 demonstrates how unauthorized maneuvers can degrade TCAS

system performance. Although pilots should be trained to use the system the way the designers intended, they also must remember to exercise their training, judgment, and experience to evaluate situations and take appropriate action to ensure safety of flight.

IV. MANEUVERS BASED ON RESOLUTION ALERTS

A. INTRODUCTION

The TCAS II resolution advisory (RA) display is a modified instantaneous vertical speed indicator (IVSI). The display consists of a pointer showing the aircraft's vertical speed and an arc of red "eyebrow" lights around the scale. This display is the primary instrument used in performing TCAS collision avoidance maneuvers. The pilot is warned of a potential mid-air collision 20 to 30 seconds prior to the closest point of approach (CPA) of a conflicting aircraft. [Ref. 3] The warning consists of an aural tone and a red warning light on the glareshield. These warnings direct the pilot's attention to the resolution advisory display (modified IVSI). The red "eyebrow" lights on the instrument will illuminate directing the pilot to modify the aircraft's vertical speed to "keep the IVSI needle out of the red". Simultaneously, a computer generated voice will suggest a course of action to the flight crew. The voice commands currently available are: "climb"; "climb to cross"; "adjust vertical speed"; "descend"; "descend to cross"; "clear of conflict"; and "unable to command". These commands are given assuming the pilot does not have visual contact with the conflicting aircraft. If visual contact with the other aircraft is gained, the crew may elect to maneuver using

their own judgment to avoid the conflicting traffic. Flight crew response depends on the prior training they have received. There are two types of resolution advisories issued. A preventive resolution advisory requires no immediate action but warns the crew not to climb, descend, or adjust vertical speed due to nearby traffic. A corrective resolution advisory directs the pilot to alter the vertical speed of the aircraft to ensure safe separation from nearby traffic in the vertical plane. The goal of the TCAS II system is to produce a safe vertical separation between aircraft by signaling for a smooth, controlled adjustment of the TCAS aircraft's vertical speed until clear of the conflicting traffic.

This report examines the effectiveness of the TCAS II resolution advisory display for 40 scenarios. The scenarios consist of crews using various versions of the TCAS II system while flying a Boeing 727 simulator in a simulated air traffic environment at the NASA-Ames Research Center. Only corrective resolution advisories are examined in this report.

B. PROCEDURES

An airborne collision avoidance system is only effective if the flight crews using the system are adequately trained to use the system to increase the vertical separation between aircraft. An increase in vertical separation also results in an increase in slant range (i.e. miss distance) at the

closest point of approach (CPA) between the TCAS equipped aircraft and the conflicting traffic. In order to determine the effectiveness of pilot responses to resolution alerts, 12 airline crews flew short routes in a simulated air traffic environment with numerous traffic conflicts. Forty scenarios were examined where the crews were required to perform evasive maneuvers based on TCAS warnings on the resolution advisory display. For each scenario, the following parameters were computed and examined:

(1) The amount of time between the traffic advisory (TA) and the closest point of approach (CPA) between the TCAS equipped aircraft and the conflicting aircraft.

(2) The amount of time between the resolution alert (RA) and the CPA for the two aircraft.

(3) The amount of time between the TA and RA. This is the amount of time the crew had to examine the potential conflict and prepare for the evasive maneuver.

(4) The vertical separation between the two aircraft at CPA after performing the collision avoidance maneuver.

(5) The slant range (miss distance) between the two aircraft at CPA after performing the recommended evasive maneuver.

These results were obtained using computer records which contained raw data on the following parameters: RA and TA on and off times; latitude and longitude readouts for both the TCAS aircraft and the conflicting aircraft; and altitude readouts for both aircraft. A computer program named "LLTCAS" was written to evaluate these raw data and is listed in Appendix A. Additional records detailing the scenarios included observer records and resolution advisory analysis

forms. Video tapes of the flight station of the Boeing 727 simulator were viewed to determine Air Traffic Control (ATC) clearance requirements, required level off altitudes, and flight crew responses.

In addition to the five results listed above, additional computations were made to determine the flight path the aircraft would have flown if it were not TCAS equipped. This flight path was based on the assumption that the crew did not obtain a visual sighting of the conflicting aircraft and subsequently maneuver to avoid it. Additional assumptions included the following: the crew would fly the same track over the ground; the crew would comply with all required ATC turns and navigation turns; and the crew would comply with all level off restrictions required by ATC. These assumptions are considered reasonable since the TCAS II system directs evasive maneuvers in the vertical plane only, and the altitude of the TCAS aircraft during each scenario is of primary concern. For each scenario, the altitude of the TCAS aircraft was modified in the LLTCAS program to account for the descent or climb rate in progress before the evasive maneuver occurred. The TCAS aircraft's vertical rate was calculated beginning five seconds prior to the resolution alert. The program accounted for level off clearances and maneuvers that occurred on the traffic advisory display information. The TCAS aircraft altitudes were incrementally calculated, beginning one second after the RA occurred,

until CPA or a level off altitude was reached. The same five results that were listed previously for the TCAS maneuver were then determined for the case where no TCAS maneuver was performed. The differences between the vertical separation and slant range at CPA were compared for the TCAS maneuver case and the no maneuver case.

Several corrective resolution alerts in the NASA-Ames study could not be examined due to a problem with the data files containing the conflicting aircraft's position and altitude information. The system could only record data on two aircraft at one time.

C. RESULTS

The computer output from the LLTCAS program is contained in Appendix B. It shows the results of 40 scenarios where evasive maneuvers were performed by flight crews in response to TCAS corrective resolution alerts. For each scenario, two lists of CPA times, ranges, slant ranges, and altitude separations between the TCAS equipped aircraft and conflicting aircraft are presented. The first section of data for each scenario shows the results that would have occurred if the TCAS system had not warned the pilot to maneuver, and the crew had continued to comply with their ATC clearance. The second section of data for each scenario presents the actual results obtained by performing the collision avoidance maneuvers in the vertical plane.

A summary of the data for the 40 scenarios is contained in Appendix C. It lists the following information for each scenario: the time interval between the traffic alert (TA) and CPA; the time interval between the resolution alert (RA) and CPA; the time interval between the TA and RA; the altitude difference between the TCAS aircraft and the conflicting aircraft at CPA; the altitude difference at CPA between the two aircraft that would have occurred assuming the TCAS collision avoidance maneuver had not been performed (no TCAS maneuver case); the altitude separation difference between the TCAS maneuver and no TCAS maneuver scenarios; and the slant range difference between the TCAS maneuver and no TCAS maneuver scenarios. The data from the summary are plotted in Figures 2 through 13.

Figures 2 and 3 show the time interval between the issuance of a traffic advisory (TA) to the crew and time of CPA of the two aircraft. This interval represents the amount of time available for the crew to evaluate the situation and react appropriately if a RA display had not been installed. Several crews in the study were able to predict the occurrence of some of the resolution alerts by observing potential collision situations developing on the traffic advisory display. The average time interval between the TA and CPA was 39.25 seconds with a sample standard deviation of 12.03.

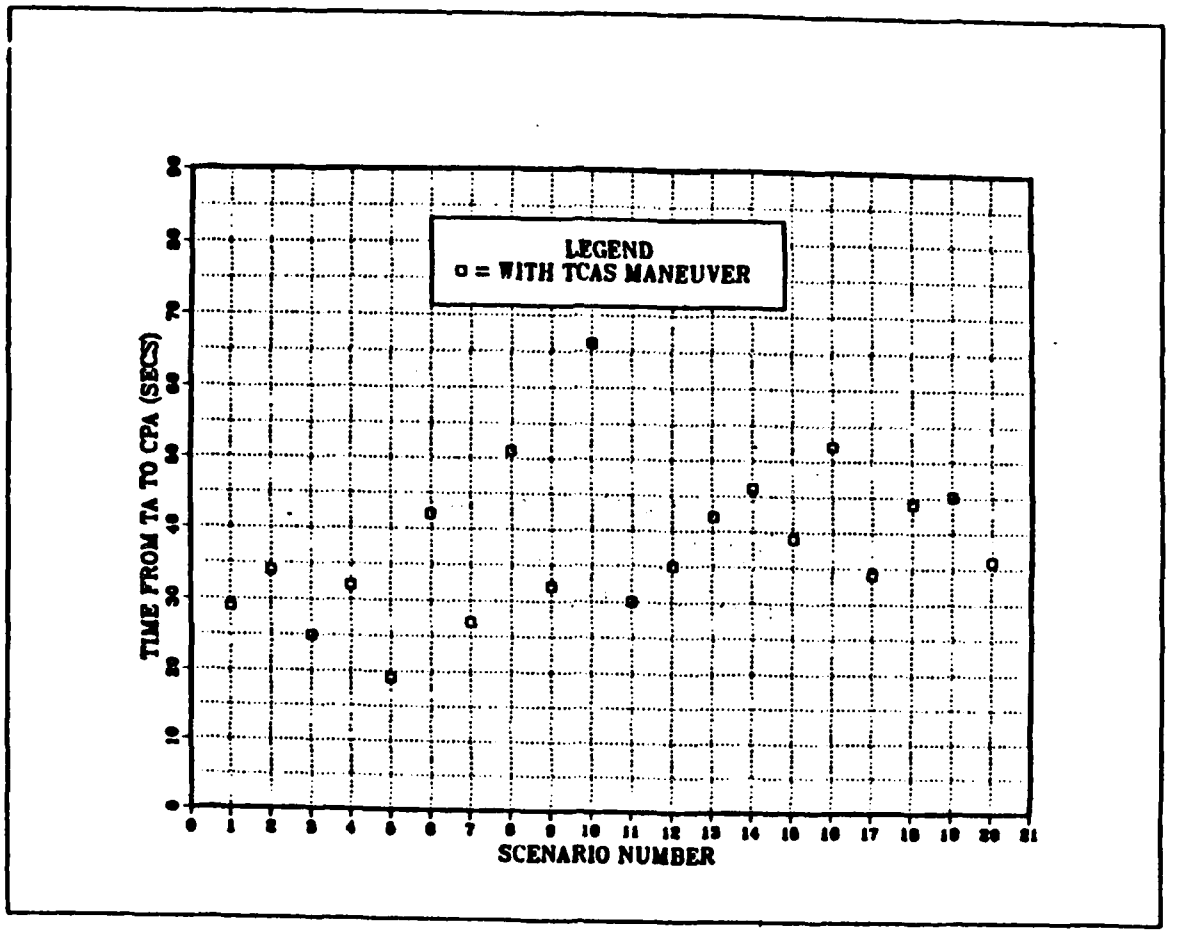


Figure 2. TA to CPA Time Interval (Scenarios 1-20)

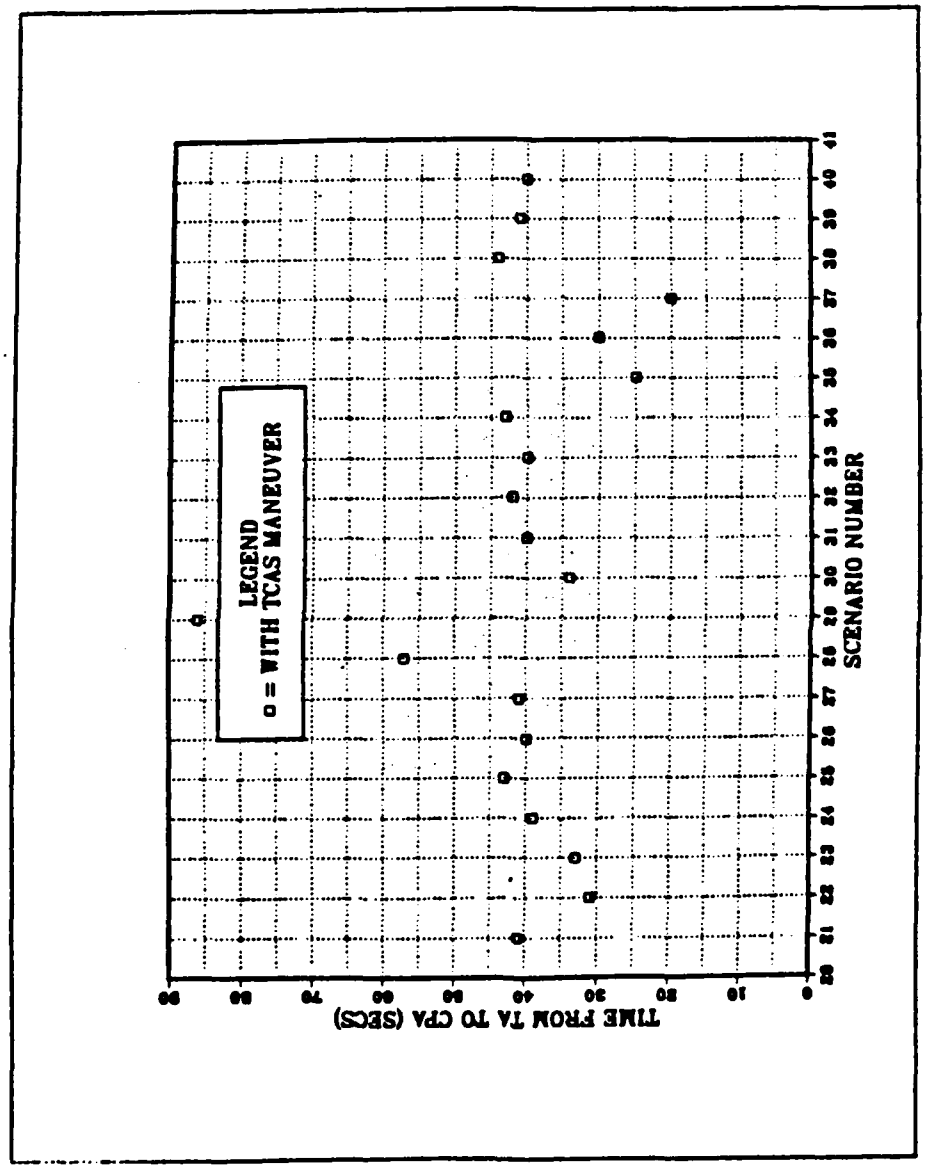


Figure 3. TA to CPA Time Interval (Scenarios 21-40)

Figures 4 and 5 show the time interval between the issuance of a resolution alert (RA) to the crew and the time of CPA of the two aircraft. This interval represents the amount of time available for the crew to interpret the information on the RA display and react by maneuvering the aircraft prior to CPA. The average time interval was 23.03 seconds with a sample standard deviation of 10.96.

Figures 6 and 7 depict the time interval between the issuance of the TA and the RA. This is the amount of time the crew had to evaluate the situation developing on the traffic advisory display (if installed) and prepare to execute the evasive maneuver. The average time interval was 16.23 seconds with a sample standard deviation of 6.24.

Figures 8 and 9 show the altitude separation between the two aircraft at CPA for the cases where a TCAS maneuver was performed and for the cases where it was assumed that no TCAS maneuver was performed. Of the 40 scenarios examined, 37 showed an increase in altitude separation at CPA as a result of the TCAS maneuver. The three scenarios that showed less altitude separation due to the TCAS maneuvers are scenarios 3, 11 and 23. All three of these cases are similar and will be analyzed thoroughly in the "CONCLUSIONS" section of this chapter.

Figures 10 and 11 show the altitude separation change resulting from the TCAS maneuver. The differences were computed by subtracting the no TCAS maneuver altitude

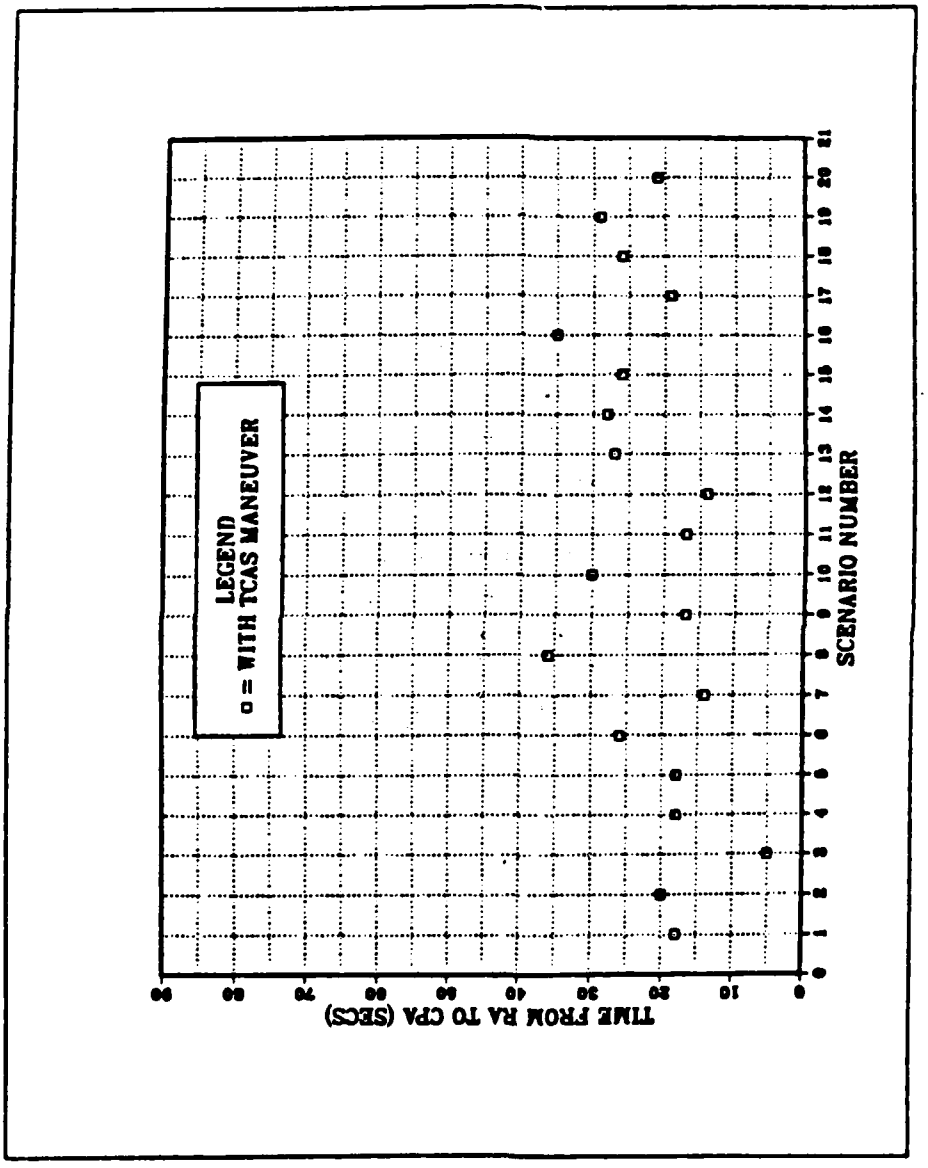


Figure 4. RA to CPA Time Interval (Scenarios 1-20)

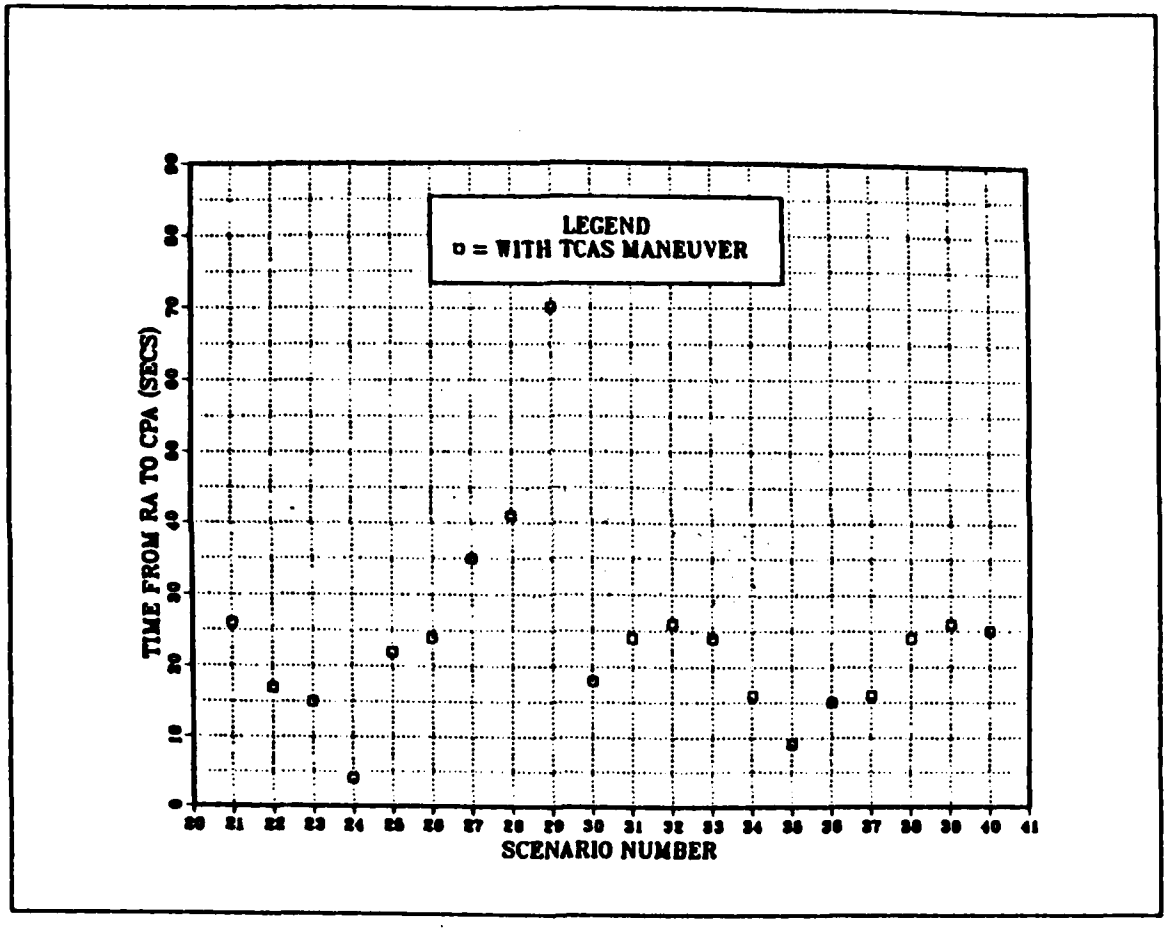


Figure 5. RA to CPA Time Interval (Scenarios 21-40)

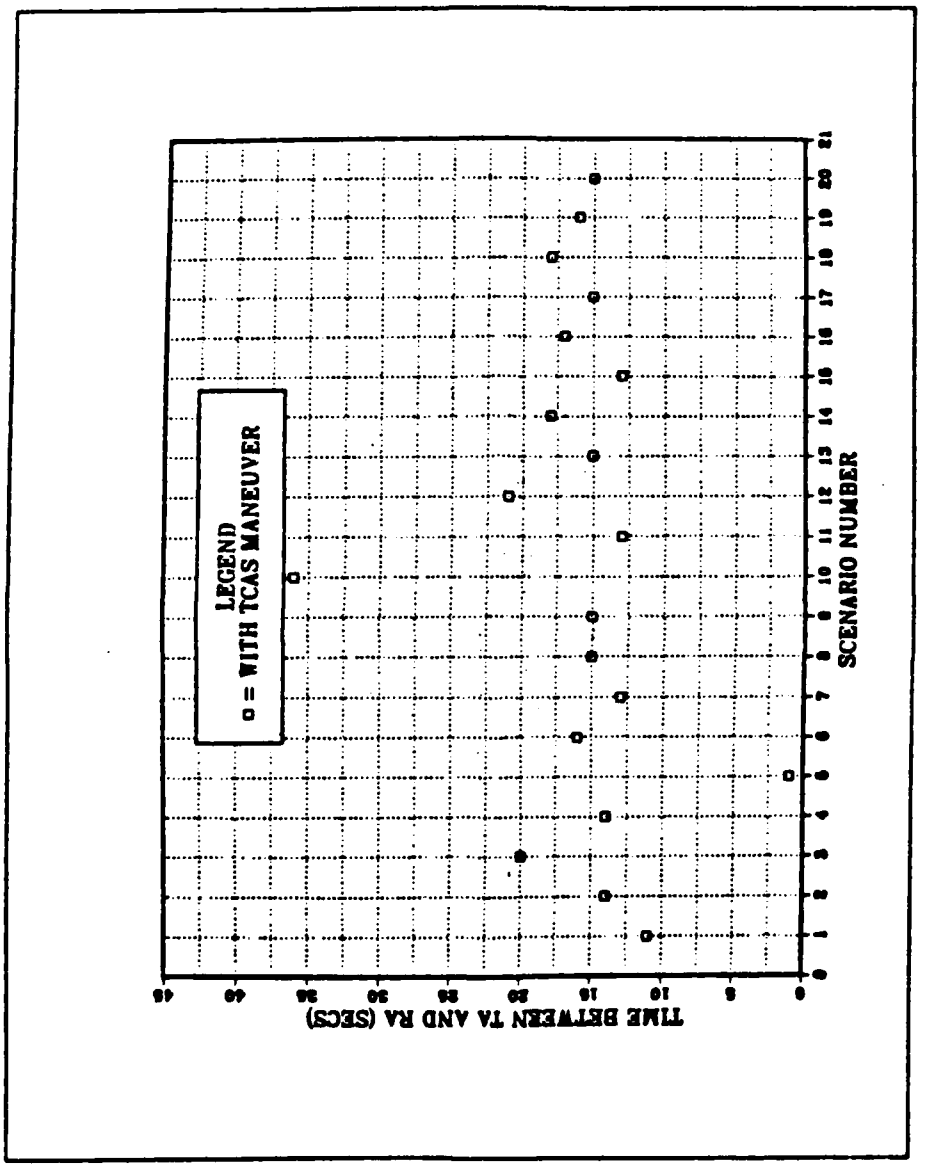


Figure 6. TA to RA Time Interval (Scenarios 1-20)

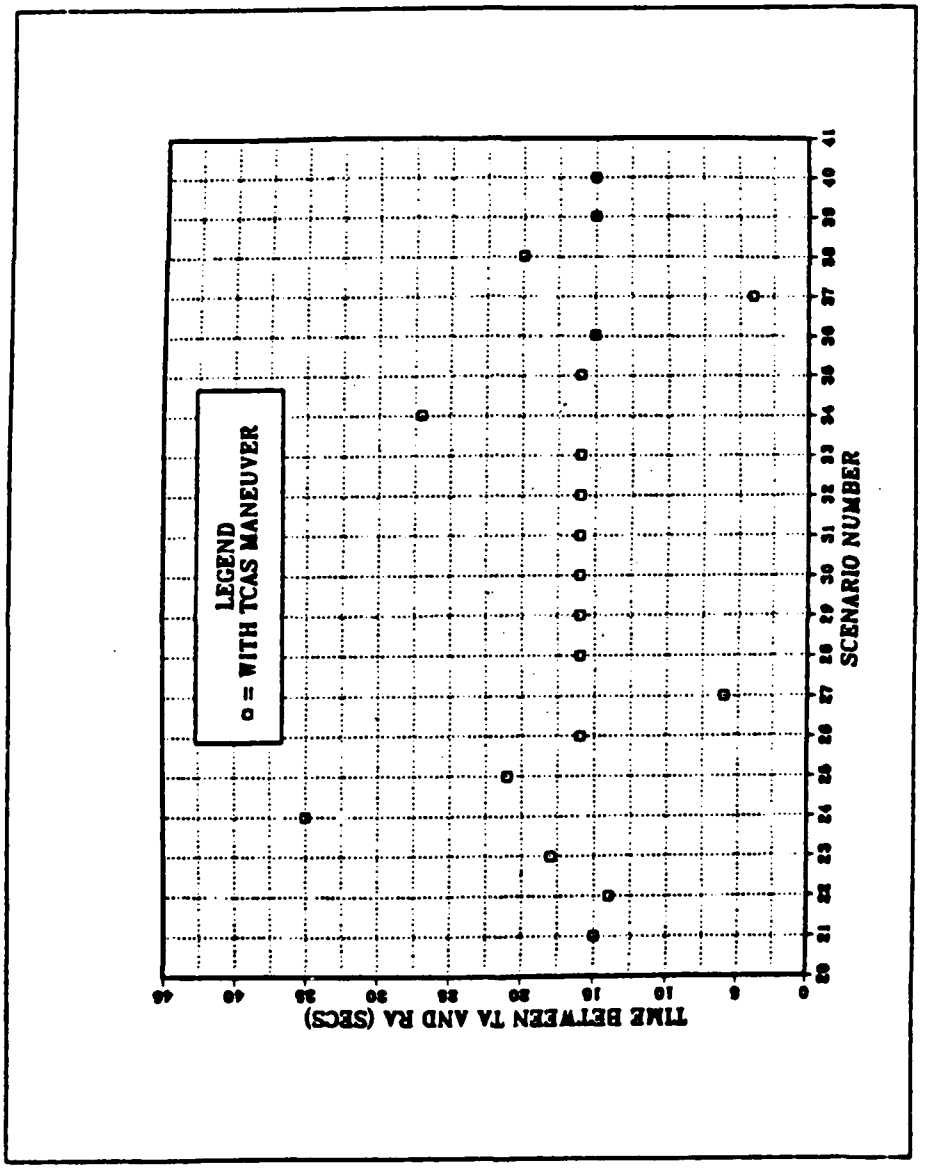


Figure 7. TA to RA Time Interval (Scenarios 21-40)

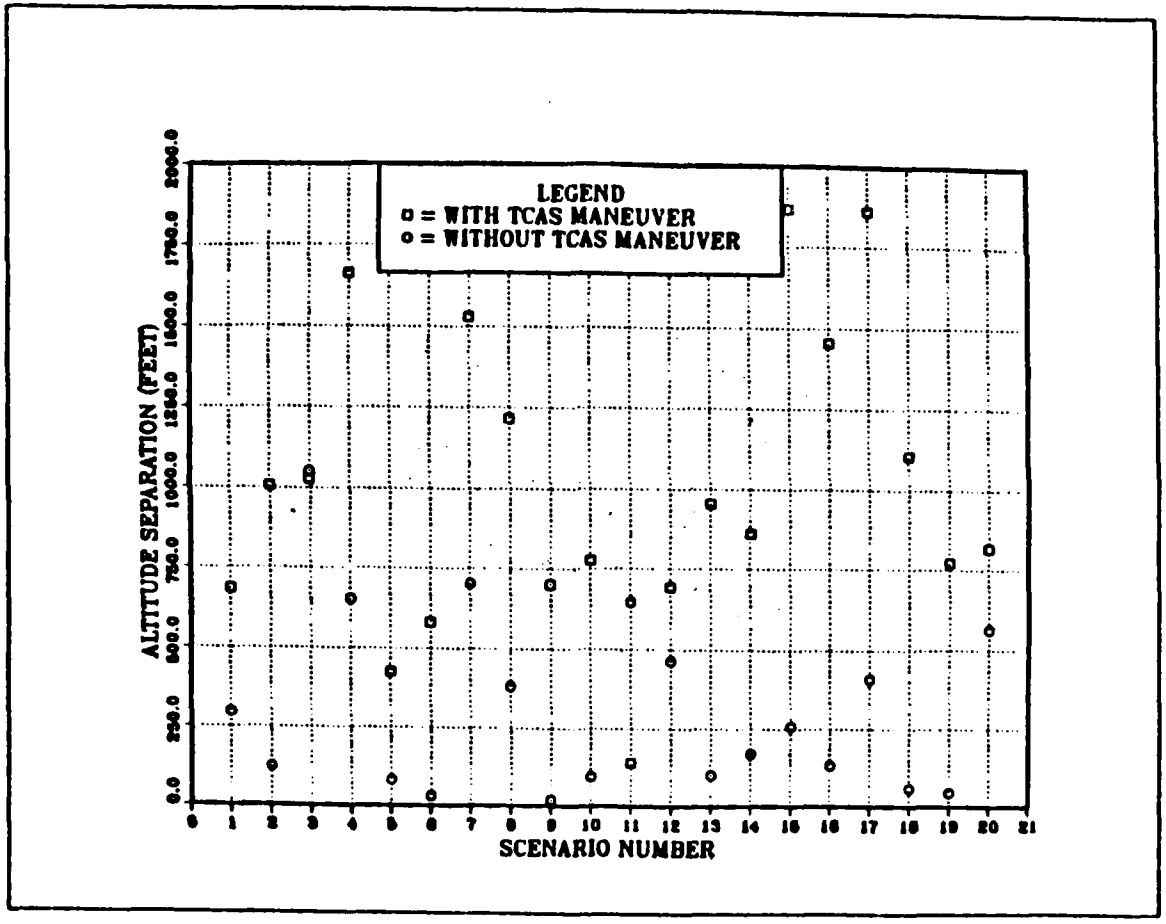


Figure 8. Altitude Separation at CPA (Scenarios 1-20)

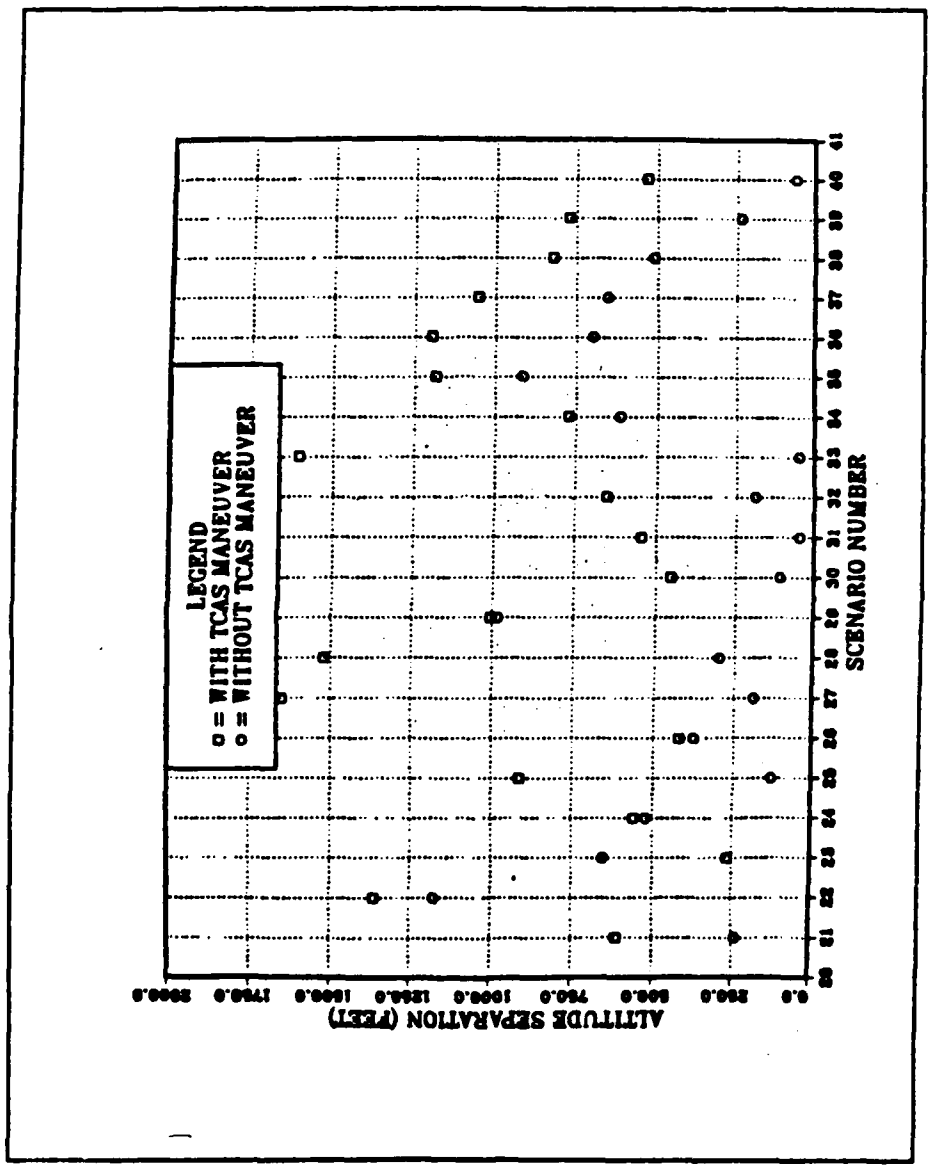


Figure 9. Altitude Separation at CPA (Scenarios 21-40)

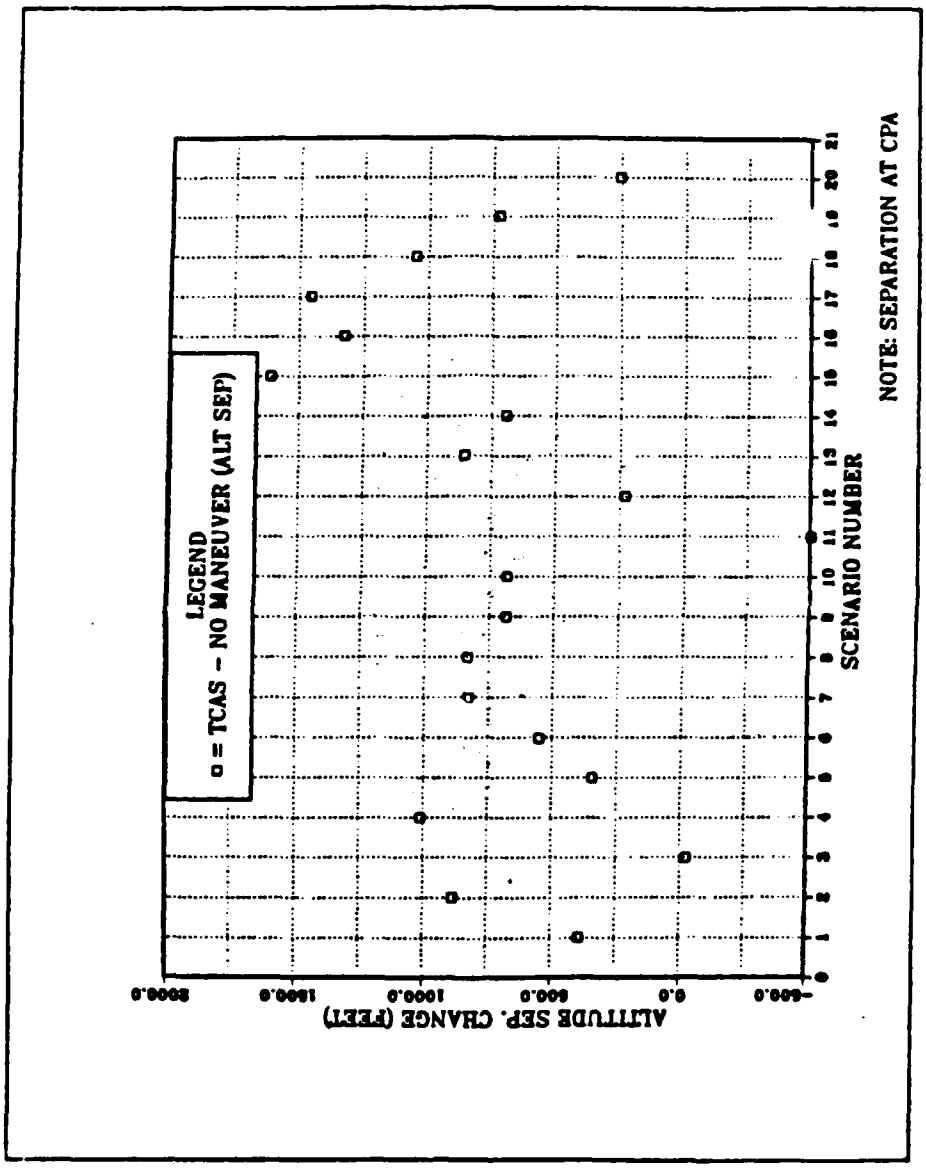


Figure 10. Altitude Separation Change (Scenarios 1-20)

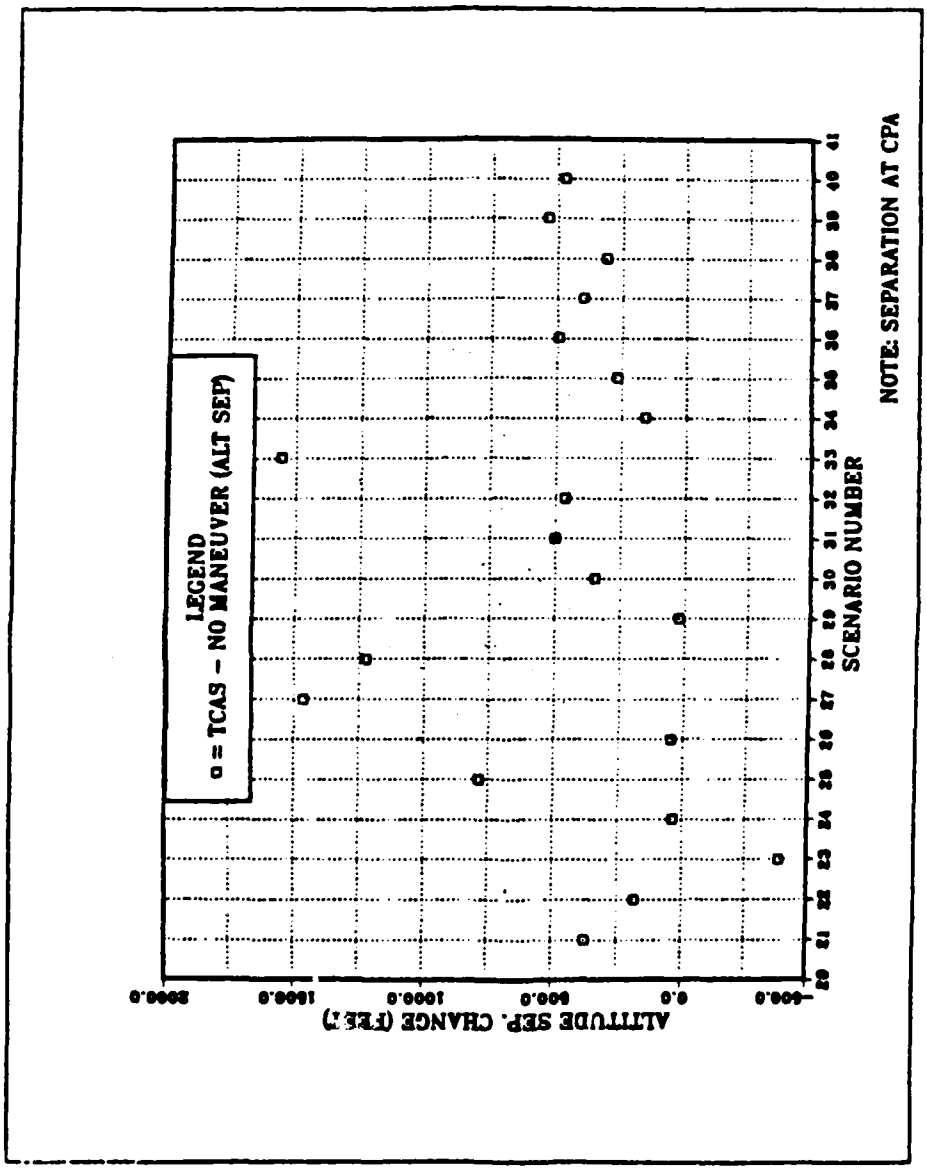


Figure 11. Altitude Separation Change (Scenarios 21-40)

separation at CPA from the results obtained by performing the evasive maneuver. Of the 40 scenarios examined, 37 showed a positive change in the altitude separation at CPA as a result of the TCAS maneuver. The three scenarios that showed negative values due to the TCAS maneuvers are the same three scenarios mentioned above. The TCAS maneuver resulted in an average increase in altitude separation of 577.9 feet.

Figures 12 and 13 show the slant range change caused by performing the TCAS maneuver. The differences were computed by subtracting the value of the no TCAS maneuver slant range at CPA from the value obtained for the evasive maneuver. As in the other figures, 37 scenarios demonstrated a positive change in the slant range at CPA as a result of the TCAS maneuver. The same three scenarios (3, 11, 23) showed negative values. The average increase in the slant range resulting from a TCAS maneuver was 187.50 feet.

The 40 scenarios used in this study will be described briefly below. The 12 airline crews who participated in the study flew similar routes and encountered similar air traffic conditions. Eight of the 12 crews flew with fully operational TCAS II systems which had both a traffic advisory display and a resolution advisory display. The other four crews (2111, 2221, 2312, and 2412) used a degraded system without a traffic advisory display.

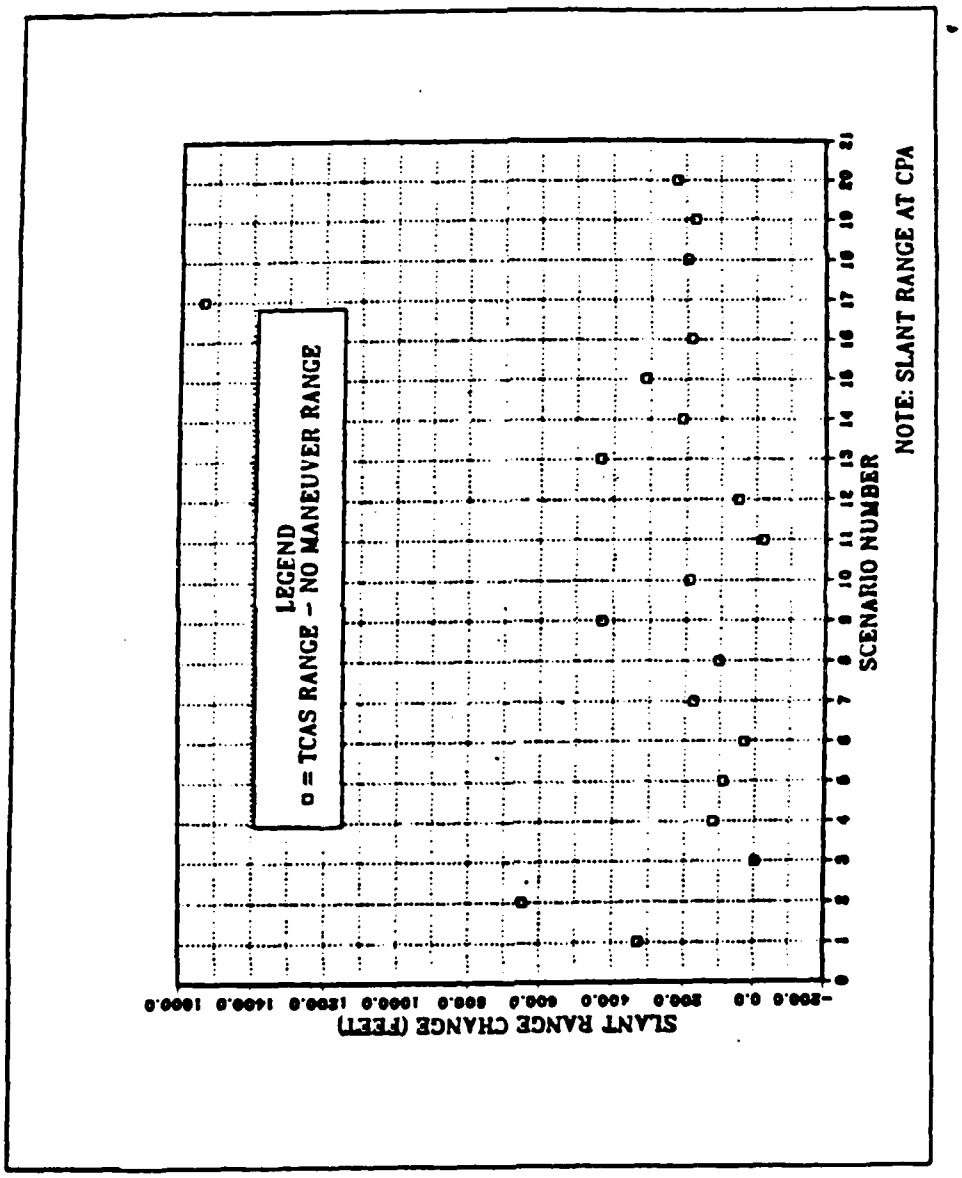


Figure 12. Slant Range Change (Scenarios 1-20)

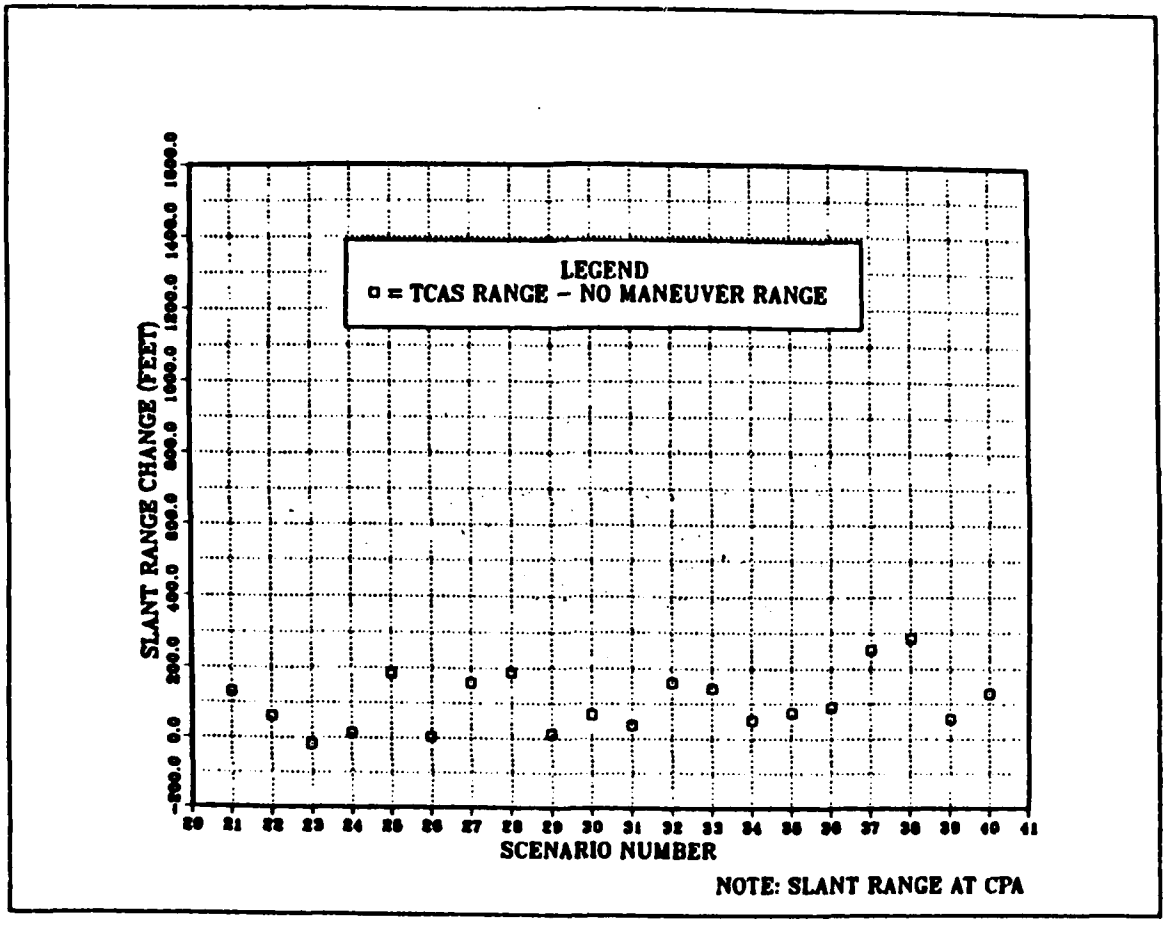


Figure 13. Slant Range Change (Scenarios 21-40)

SCENARIO #1 - CREW #2111:

CONDITIONS: time = 00:40:12; altitude = 1996 feet (FT); descending; descent rate = -4.33 feet per second (FPS) or -259 feet per minute (FPM).

NARRATIVE: The crew received a "descend" command requiring an increase in descent rate. The maneuver resulted in an increase in altitude separation and slant range (389 FT, 327 FT) at CPA compared to continuing the descent at -259 FPM.

SCENARIO #2 - CREW #2111:

CONDITIONS: time = 10:20:43; altitude = 10145 FT; level flight.

NARRATIVE: The crew received a "descend" command. The maneuver resulted in an increase in altitude separation and slant range (883 FT, 648 FT) at CPA compared to maintaining level flight at the assigned altitude.

SCENARIO #3 - CREW #2221:

CONDITIONS: time = 03:52:13; altitude = 33075 FT; level flight.

NARRATIVE: The crew received a "descend to cross" command to avoid an intruder aircraft (call sign "FOG 26") which was climbing underneath the TCAS aircraft. The CPA occurred five seconds after the command was given. The maneuver resulted in a decrease in altitude separation and slant range (-24.5 FT, -2.2 FT) at CPA compared to continuing level at the assigned altitude. This is the first of three similar incidents involving FOG 26 that is being studied to determine the cause of these undesirable results. The slant range at CPA in this case was 11458 FT (1.9 NM).

SCENARIO #4 - CREW #2221:

CONDITIONS: time = 04:14;12; altitude = 12093 FT; descending; descent rate = -32.53 FPS or -1951.8 FPM.

NARRATIVE: The crew received an "adjust vertical speed" command which required a level off. The maneuver resulted in an increase in altitude separation and slant range (1009 FT, 118 FT) at CPA compared to continuing the descent at -1951 FPM.

SCENARIO #5 - CREW #2221:

CONDITIONS: time = 07:19:46; altitude = 11070 FT; leveling at 11000 FT.

NARRATIVE: The crew received a "descend" command. The maneuver resulted in an increase in altitude separation and slant range (344 FT, 89 FT) at CPA compared to maintaining level flight at the assigned altitude.

SCENARIO #6 - CREW #2221:

CONDITIONS: time = 09:51:35; altitude = 5228 FT; descending; descent rate = -10.15 FPS or -609 FPM; clearance = "descend and maintain 5000 FT".

NARRATIVE: The crew received a "climb" command. The maneuver resulted in an increase in altitude separation and slant range (550 FT, 31 FT) at CPA compared to continuing the descent at -609 FPM to a level off altitude of 5000 FT.

SCENARIO #7 - CREW #2312:

CONDITIONS: time = 08:02:14; altitude = 32990 FT; level flight.

NARRATIVE: The crew received a "climb" command to avoid a conflicting aircraft (FOG 26) which was climbing underneath the TCAS aircraft. Unlike scenario 3, the climb maneuver resulted in an increase in altitude separation and slant range (824 FT, 176 FT) at CPA compared to continuing level flight at the assigned altitude. This scenario is similar to scenario 3 but had a 14 second time interval between RA and CPA and a slant range of 5309 FT (.87 NM) at CPA. In this case, the TCAS maneuver improved the separation between the TCAS aircraft and FOG 26.

SCENARIO #8 - CREW #2312:

CONDITIONS: time = 08:22:27; altitude = 12058 FT; descending; descent rate = -48.86 FPS or -2931 FPM.

NARRATIVE: The crew received an "adjust vertical speed" command followed by a "climb" command. The maneuver resulted in an increase in altitude separation and slant range (832 FT, 104 FT) at CPA compared to continuing to descend at -2931 FPM.

SCENARIO #9 - CREW #2312:

CONDITIONS: time = 10:02:09; altitude = 10095 FT; level flight.

NARRATIVE: The crew received a "climb to cross" command followed by a "climb" command. The maneuver resulted in an increase in altitude separation and slant range (683 FT, 432 FT) at CPA compared to maintaining level flight at the assigned altitude.

SCENARIO #10 - CREW #2312:

CONDITIONS: time = 10:06:52; altitude = 7639 FT; descending; descent rate = -28.8 FPS or -1728 FPM.

NARRATIVE: The crew received an "adjust vertical speed" command calling for no descent greater than 500 FPM. The maneuver resulted in an increase in altitude separation and slant range (683 FT, 188 FT) at CPA compared to continuing the descent at -1728 FPM.

SCENARIO #11 - CREW #2422:

CONDITIONS: time = 04:28:33; altitude = 33004 FT; level flight.

NARRATIVE: The crew received a "descend to cross" command to avoid an intruder aircraft (FOG 26) which was climbing below the TCAS aircraft. CPA occurred 17 seconds after the command was given. The maneuver resulted in a decrease in altitude separation and slant range (-505 FT, -22 FT) at CPA compared to continuing level at the assigned altitude. This is the second of three similar incidents involving FOG 26 that is under investigation. The slant range at CPA in this case was 9009 FT (1.5 NM).

SCENARIO #12 - CREW #2422:

CONDITIONS: time = 07:28:20; altitude = 2260 FT; descending; descent rate = -19.53 FPS or -1171 FPM.

NARRATIVE: The crew received an "adjust vertical speed" command calling for no descent greater than 500 FPM. The maneuver resulted in an increase in altitude separation and slant range (229 FT, 51 FT) at CPA compared to continuing the descent at -1171 FPM.

SCENARIO #13 - CREW #2422:

CONDITIONS: time = 10:28:03; altitude = 5059 FT; descending; descent rate = -3.02 FPS or -990 FPM; clearance = "descend and maintain 5000 FT".

NARRATIVE: The crew received a "climb" command. The maneuver resulted in an increase in altitude separation and slant range (855 FT, 435 FT) at CPA compared to continuing the descent to 5000 FT.

SCENARIO #14 - CREW #3111:

CONDITIONS: time = 03:36:15; altitude = 3760 FT; descending; descent rate = -32.62 FPS or -1957 FPM.

NARRATIVE: The crew received a "climb" command. The maneuver resulted in an increase in altitude separation and slant range (692 FT, 210 FT) at CPA compared to continuing the descent at -1957 FPM.

SCENARIO #15 - CREW #3111:

CONDITIONS: time = 07:14:48; altitude = 32991 FT; level flight.

NARRATIVE: The crew received a "descend to cross" command to avoid an intruder aircraft (FOG 26) which was climbing underneath the TCAS aircraft. CPA occurred 26 seconds after the command was given. Unlike scenarios 3 and 11, this maneuver resulted in an increase in altitude separation and slant range (1608 FT, 316 FT) at CPA compared to maintaining level flight at the assigned altitude. The slant range at CPA in this case was 5559 FT (0.9 NM) which is much smaller than the slant ranges in the two scenarios mentioned above. In this case, a "descend to cross" command improved the situation.

SCENARIO #16 - CREW #3111:

CONDITIONS: time = 07:37:15; altitude = 11647 FT; descending; descent rate = -26.54 FPS or -1592 FPM.

NARRATIVE: The crew received a "climb" command. The maneuver resulted in an increase in altitude separation and slant range (1323 FT, 185 FT) at CPA compared to continuing the descent at -1592 FPM.

SCENARIO #17 - CREW #3111:

CONDITIONS: time = 09:28:25; altitude = 10016 FT; level flight.

NARRATIVE: The crew received a "climb to cross" command. The maneuver resulted in an increase in altitude separation and slant range (1451 FT, 1536 FT) at CPA compared to maintaining level flight at the assigned altitude.

SCENARIO #18 - CREW #3221:

CONDITIONS: time = 06:53:04; altitude = 3937 FT; descending; descent rate = -28.49 FPS or -1709 FPM.

NARRATIVE: The crew received an "adjust vertical speed" command followed by a "climb" command. The maneuver resulted in an increase in altitude separation and slant range (1048 FT, 197 FT) at CPA compared to continuing the descent at -1709 FPM.

SCENARIO #19 - CREW #3221:

CONDITIONS: time = 09:54:04; altitude = 5175 FT; climbing; climb rate = +4.15 FPS or +249 FPM; clearance = "descend and maintain 5000 FT".

NARRATIVE: The crew used the information from the traffic advisory display to anticipate the collision situation developing and started to climb shortly before they received a "climb" command from the resolution advisory display. The maneuver resulted in an increase in altitude separation and slant range (725 FT, 172 FT) at CPA compared to continuing the descent to their assigned level off altitude of 5000 FT.

SCENARIO #20 - CREW #3312:

CONDITIONS: time = 01:21:09; altitude = 1903 FT; descending; descent rate = -13.82 FPS or -829 FPM.

NARRATIVE: The crew received a "descend" command. The maneuver resulted in an increase in altitude separation and slant range (254 FT, 224 FT) at CPA compared to continuing the descent at -829 FPM.

SCENARIO #21 - CREW #3312:

CONDITIONS: time = 02:33:07; altitude = 5189 FT; descending; descent rate = -19.59 FPS or -1175 FPM.

NARRATIVE: The crew received a "climb" command. The maneuver resulted in an increase in altitude separation and slant range (372 FT, 130 FT) at CPA compared to continuing the descent at -1175 FPM.

SCENARIO #22 - CREW #3312:

CONDITIONS: time = 07:43:86; altitude = 12156 FT; descending; descent rate = -26.06 FPS or -1563 FPM.

NARRATIVE: This is another case where the crew used the information from the traffic advisory display to anticipate the collision situation developing and started to level off before an "adjust vertical speed" command was received from the resolution advisory display. The maneuver resulted in an increase in altitude separation and slant range (184 FT, 61 FT) at CPA compared to continuing to descend at their original descent rate, which was greater than 2000 FPM prior to the crew-initiated level off.

SCENARIO #23 - CREW #3422:

CONDITIONS: time - 03:54:10; altitude = 32982 FT; level flight.

NARRATIVE: The crew received a "descend to cross" command to avoid an intruder aircraft (FOG 26) which was climbing underneath the TCAS aircraft. CPA occurred 15 seconds after the command was given. The maneuver resulted in a decrease in altitude separation and slant range (-389 FT, -19 FT) at CPA compared to continuing level at the assigned altitude. This is the third of three similar incidents involving FOG 26 that is being studied. The slant range at CPA in this case was 9075 FT (1.5 NM).

SCENARIO #24 - CREW #3422:

CONDITIONS: time = 04:20:34; altitude = 6983 FT; level flight.

NARRATIVE: The crew was leveling at 7000 FT when they received a "descend" command to avoid conflicting traffic at 7500 FT. CPA occurred four seconds after the resolution alert was issued. The maneuver resulted in a small increase in altitude separation and slant range (37 FT, 13 FT) at CPA compared to remaining level. It appears that the system did not consider the conflicting aircraft a threat until the TCAS crew arrested their descent and leveled off. The actual altitude separation between aircraft at CPA was 560 FT with a slant range of 1496 FT.

SCENARIO #25 - CREW #3422:

CONDITIONS: time = 09:17:36; altitude = 5370 FT; climbing; climb rate = +12.78 FPS or +766 FPM; clearance = "descend and maintain 5000 FT".

NARRATIVE: This case is similar to scenario 19. The crew used the information from the traffic advisory display to anticipate the collision situation developing and started to climb shortly before a "climb" command from the resolution advisory display was received. The maneuver resulted in an increase in altitude separation and slant range (784 FT, 184 FT) at CPA compared to continuing the descent to their assigned level off altitude of 5000 FT.

SCENARIO #26 - CREW #4111:

CONDITIONS: time = 07:13:19; altitude = 32994 FT; level flight.

NARRATIVE: This case is similar to scenario 15. The crew received a "descend to cross" command to avoid an intruder aircraft (FOG 26) which was climbing below the TCAS aircraft. CPA occurred 24 seconds after the command was given. Unlike scenarios 3, 11, and 23, the maneuver resulted in a small increase in altitude separation and slant range (47 FT, 2.8 FT) at CPA compared to maintaining level flight at the assigned altitude. The slant range at CPA in this case was 6629 FT (1.1 NM) which is smaller than the slant ranges in the three scenarios mentioned above.

SCENARIO #27 - CREW #4111:

CONDITIONS: time = 07:34:16; altitude = 12324 FT; descending; descent rate = -55.72 FPS or -3343 FPM.

NARRATIVE: The crew received an "adjust vertical speed" command which required no descent greater than 1000 FPM. The maneuver resulted in an increase in altitude separation and slant range (1463 FT, 158 FT) at CPA compared to continuing the descent at -3343 FPM.

SCENARIO #28 - CREW #4221:

CONDITIONS: time = 04:10:59; altitude = 32995 FT; level flight.

NARRATIVE: This case is similar to scenarios 15 and 26. The crew received a "descend to cross" command to avoid an intruder aircraft (FOG 26) which was climbing underneath the

TCAS aircraft. CPA occurred 41 seconds after the command was given. The maneuver resulted in an increase in altitude separation and slant range (1221 FT, 188 FT) at CPA compared to maintaining level flight at the assigned altitude. The slant range at CPA in this case was 5998 FT (.99 NM).

SCENARIO #29 - CREW #4221:

CONDITIONS: time - 06:31:28; altitude = 3018 FT; descending; descent rate = -13.89 FPS or -833 FPM.

NARRATIVE: The crew received a "descend" command. The maneuver resulted in an increase in altitude separation and slant range (21 FT, 13 FT) at CPA compared to continuing the descent at -833 FPM.

SCENARIO #30 - CREW #4221:

CONDITIONS: time = 01:35:13; altitude = 2064 FT; leveling at 2000 FT.

NARRATIVE: The crew received a "descend" command. The maneuver resulted in an increase in altitude separation and slant range (348 FT, 68 FT) at CPA compared to maintaining level flight at the assigned altitude of 2000 FT.

SCENARIO #31 - CREW #4221:

CONDITIONS: time = 02:46:49; altitude = 5127 FT; descending; descent rate = -12.88 FPS or -772 FPM; clearance = "descend and maintain 5000 FT".

NARRATIVE: The crew received a "descend to cross" command, the maneuver resulted in an increase in altitude separation and slant range (501 FT, 38 FT) at CPA compared to continuing the descent at -772 FPM until level at 5000 FT.

SCENARIO #32 - CREW #4312

CONDITIONS: time = 02:12:24; altitude = 5080 FT; level flight.

NARRATIVE: The crew received a "climb" command. The maneuver resulted in an increase in altitude separation and slant range (464 FT, 159 FT) at CPA compared to maintaining level flight at the assigned altitude.

SCENARIO #33 - CREW #4312:

CONDITIONS: time = 03:47:28; altitude = 3954 FT; descending; descent rate = -21.25 FPS or -1275 FPM.

NARRATIVE: The crew received an "adjust vertical speed" command followed by a "climb" command. The maneuver resulted in an increase in altitude separation and slant range (1555 FT, 143 FT) at CPA compared to continuing the descent at -1245 FPM.

SCENARIO #34 - CREW #4312:

CONDITIONS: time = 03:49:39; altitude = 2163 FT; descending; descent rate = -12.67 FPS or -760 FPM; clearance = "descend and maintain 2000 FT".

NARRATIVE: The crew received an "adjust vertical speed" requiring no descent greater than 0 FPM. The maneuver resulted in an increase in altitude separation and slant range (158 FT, 51 FT) at CPA compared to continuing the descent at -760 FPM until level at 2000 FT.

SCENARIO #35 - CREW #4312:

CONDITIONS: time = 07:07:53; altitude = 33008 FT; level flight.

NARRATIVE: The crew received a "climb" command to avoid an intruder aircraft (FOG 26) which was climbing below the TCAS aircraft. CPA occurred nine seconds after the command was given. The maneuver resulted in an increase in altitude separation and slant range (267 FT, 73 FT) at CPA compared to maintaining level flight at the assigned altitude. The slant range at CPA in this case was 3858 FT (.60 NM).

SCENARIO #36 - CREW #4422:

CONDITIONS: time = 04:23:00; altitude = 33086 FT; level flight.

NARRATIVE: This scenario is similar to scenario 35. The crew received a "climb" command to avoid an intruder aircraft (FOG 26) which was climbing below the TCAS aircraft. CPA occurred 15 seconds after the command was given. The maneuver resulted in an increase in altitude separation and slant range (495 FT, 88 FT) at CPA compared to maintaining level flight at the assigned altitude. The slant range at CPA was 5266 FT (.86 NM).

SCENARIO #37 - CREW #4422:

CONDITIONS: time = 04:43:56; altitude = 12035 FT; descending; descent rate = -37.95 FPS or -2277 FPM.

NARRATIVE: The crew received an "adjust vertical speed" command requiring no descent greater than 2000 FPM. The crew reacted by significantly reducing their descent rate. The maneuver resulted in an increase in altitude separation and slant range (400 FT, 253 FT) at CPA compared to continuing the descent at -2277 FPM.

SCENARIO #38 - CREW #4422:

CONDITIONS: time = 04:49:10; altitude = 6998 FT; level flight.

NARRATIVE: The crew received a "descend" command. The maneuver resulted in an increase in altitude separation and slant range (311 FT, 284 FT) at CPA compared to maintaining level flight at the assigned altitude.

SCENARIO #39 - CREW #4422:

CONDITIONS: time = 07:10:44; altitude = 3905 FT; descending; descent rate = -18.21 FPS or -1092 FPM.

NARRATIVE: The crew received an "adjust vertical speed" command which required no descent greater than 500 FPM. The crew significantly reduced their descent rate and even climbed slightly. The maneuver resulted in an increase in altitude separation and slant range (536 FT, 55 FT) at CPA compared to continuing the descent at -1092 FPM.

SCENARIO #40 - CREW #4422:

CONDITIONS: time = 10:26:45; altitude = 4947 FT; level flight.

NARRATIVE: The crew received a "descend" command. The maneuver resulted in an increase in altitude separation and slant range (471 FT, 129 FT) at CPA compared to maintaining level flight at the assigned altitude.

D. CONCLUSIONS

The TCAS II system maneuver commands resulted in increased vertical separations and slant range distances between TCAS equipped aircraft and conflicting aircraft for 37 of the 40 scenarios studied. The three scenarios (3, 11, 23) which showed a decrease in vertical separation and

slant range (miss distance) at the closest point of approach (CPA) are unexpected results and will be examined in depth. All three had the following common characteristics: the conflicting aircraft's call sign was "FOG 26"; the conflicting aircraft was climbing rapidly underneath the TCAS aircraft when the resolution alert (RA) was issued; the TCAS aircraft was straight and level at approximately 33000 feet; and the resolution alert called for a "descend to cross" maneuver. The time interval between the RA and CPA on all three scenarios (5 secs, 17 secs, 15 secs) was shorter than the average time for the 40 cases (23 secs). The slant ranges at CPA for these three cases were in excess of 9000 feet or 1.48 nautical miles (11458 FT, 9009 FT, 9075 FT). There were six other FOG 26 scenarios in this study (7, 15, 26, 28, 35, 36) which all showed increases in vertical separation and slant range at CPA as a result of performing the recommended evasive maneuver. Three of these six scenarios (7, 35, 36) received "climb" commands from the TCAS system. The other three scenarios (15, 26, 28) received "descend to cross" commands (similar to scenarios 3, 11, and 23); but, in these cases, the times from RA to CPA (26 secs, 24 secs, 41 secs) were longer than the average. Also, these three scenarios (15, 26, 28) showed much shorter slant ranges at CPA (5559 FT, 6629 FT, 5998 FT) than the three scenarios with decreased separation (3, 11, 23). After comparing the results of all the FOG 26 scenarios, it

appears that there may be a problem with the collision avoidance logic when the TCAS aircraft is at a high altitude and must maneuver to avoid a rapidly climbing aircraft with a slant range that is over 9000 feet. The TCAS logic may be predicting a time for CPA that is longer than the time which actually occurred for these incidents. The short times between RA and CPA may also be responsible for the incorrect responses by the TCAS system. In the three cases where the separation between aircraft decreased, it appears that a "climb" command (or no command at all) would have been better than a "descend to cross" command. Fortunately, the situations where the TCAS logic provided erroneous commands occur at long ranges and do not appear to pose a potential collision threat. An investigation of these three incidents is currently underway.

The results (Appendix B) of this study also demonstrate that three scenarios (1, 2, 9) would have resulted in dangerous situations if the recommended TCAS maneuver had not been performed. Without a TCAS maneuver, these three scenarios would have resulted in slant ranges (miss distances) of less than 500 feet with altitude separations between the two aircraft of less than 300 feet. It should be noted that no dangerous situations developed when the crews used the TCAS system.

An analysis of the flight station video recordings indicates that the "adjust vertical speed" voice command was

confusing for some of the pilots. The terminology of this command is ambiguous in that it does not specify an increase or a decrease in climb or descent rate. Several of the Captains told the pilot at the controls to "level off" when the resolution advisory display required only a decrease in descent rate. An improvement in the wording of this command or a better presentation on the RA display may help to reduce the confusion that was noted in this study.

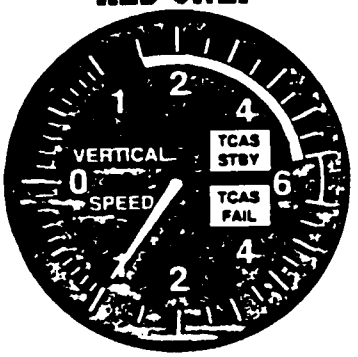
Overall, the TCAS II system should result in a significant enhancement to the "see and avoid" procedures in the cockpit and dramatically improve the safety of airline travel.

V. RESOLUTION ADVISORY DISPLAY EXPERIMENT

A. INTRODUCTION

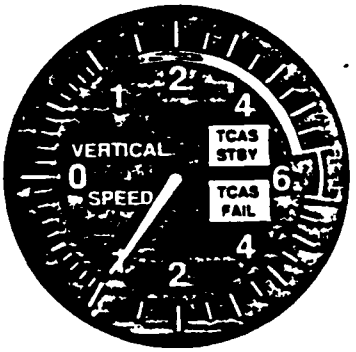
An experiment was conducted in the laboratories of the Aeronautical Human Factors Branch of NASA-Ames to evaluate pilot responses to collision avoidance maneuver commands using computer simulations of three versions of the TCAS II resolution advisory (RA) display (Figure 14). The type of RA display currently in use consists of a modified instantaneous vertical speed indicator (IVSI) which has an arc of red "eyebrow" lights to notify pilots of impending danger. The lights illuminate when the TCAS II system detects a potential collision threat and signals the pilots to evaluate their vertical velocity to increase the safety margin between the TCAS aircraft and a conflicting aircraft. Pilots are trained to respond to a resolution alert by "keeping the IVSI needle out of the red lights" by climbing, descending, or by avoiding a climb or descent rate that would put the aircraft in danger. Two modifications to the current system were designed to test the hypothesis that a different lighting pattern might be more effective than the "red only" version. In order to provide the pilots a target to aim for, instead of an area to avoid, "red and green" and "green only" lighting arrangements were developed for the IVSI. For both of the new arrangements, the green lights only illuminated

RED ONLY



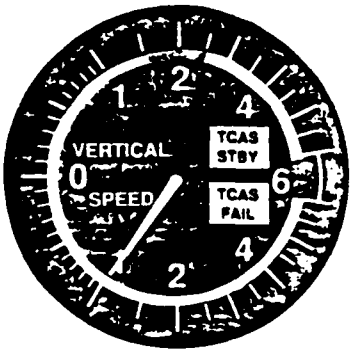
NOTE: Warning arc is red from -6000 FPM to +1500 FPM.

RED AND GREEN



NOTE: Warning arc is red from -6000 FPM to +1500 FPM and green from +1500 FPM to +2500 FPM.

GREEN ONLY



NOTE: Warning arc is green from +1500 FPM to +2500 FPM.

Figure 14. Three Versions of the RA Display

when evasive maneuvers were required (corrective RA) and not when an RA was issued to warn against an unsafe vertical speed requiring no pilot action (preventative RA). Pilots were trained to use the two alternate versions of the RA displays by applying the following rules: (1) "Get the needle out of the red and into the green" for the "red and green" version; (2) "Get the needle into the green" for the "green only" version. This report describes the experiment and the findings.

B. PROCEDURES

A graphics program was developed to present six groups of 14 RA displays to 36 volunteer pilots. The subjects had both military (75%) and civilian (25%) backgrounds, and various levels of flight experience ranging from 150 to 11000 hours of flight time (mean = 1913 hours, median = 650 hours).

For this experiment, each pilot received individual training which included a detailed briefing on each of the three versions of the RA display ("red only", "red and green", "green only") and a practice session using a demonstration program consisting of six example presentations (two of each type). The procedure used by each subject was as follows:

(1) Press two buttons on a computer mouse to allow the the computer terminal to exhibit the RA display. The IVSI depicting the current vertical speed appeared one second before the warning arc of colored lights illuminated. (Figure 14)

(2) Evaluate the position of the needle on the IVSI to determine if the aircraft is climbing or descending.

(3) Interpret the warning lights to determine whether a climb, descent or no action is required by using the general rules explained above.

(4) Respond to the warning by moving the mouse aft to climb, or forward to descend. The mouse was used to simulate a control stick (or yoke) in an aircraft and the IVSI needle was assumed to respond to a climb or descent in the normal manner.

(5) A dialog box appeared below the RA display after each response notifying the pilot that the direction of motion and reaction time had been measured.

The training emphasized that accuracy of the response direction (climb or descent) was much more important than short reaction times, since an incorrect climb or descent could significantly degrade the aircraft's safety margin.

After completion of the training session, each participant responded to 42 RA displays grouped into three sets of 14 of the same color pattern (red, red and green, green). The pilots knew in advance which version of the display would be presented because an example RA display was the first display in each set of 14. Each set also contained one preventative RA display which required no movement of the mouse (control stick). A second run of 42 displays was presented after the first run was completed. The order of presentation for the three versions of the RA display (red, red and green, green) was counterbalanced across subjects. The 14 display presentations were sequenced in one of nine random orders.

Recorded data included the direction of the response and the time period between the illumination of the colored warning arc and the movement of the mouse (reaction time). All subjects completed a subjective questionnaire at the completion of the experiment and rated the effectiveness of the three versions of the display. A statistical analysis was performed using the acquired data.

C. RESULTS

To compare the effectiveness of the three versions of the RA display, an analysis of pilot performance was conducted with reaction time and response accuracy (number of errors) as the dependent variables.

From an evaluation of the reaction time data, the following results were obtained:

(1) A significant difference in reaction time due to display color was found ($F = 19.21$, degrees of freedom (df) = 2,34, $p<.001$). A post-hoc paired comparison showed a significant difference between the "red only" and "green only" displays ($F = 32.46$, df = 1,35, $p<.001$), and also between the "red only" and "red and green" displays ($F = 26.07$, df = 1,35 $p<.001$). The "red only" showed longer reaction times (mean = 1.1856 seconds (sec), standard deviation (sd) = .5857) than the "red and green" (mean = .9998 sec, sd = .5909) and the "green only" (mean = .9524 sec, sd = .4453).

(2) Learning effects were noted in pilot reaction times for the first set of 42 displays (run1) and the second set (run2) ($F = 45.31$, df = 1,35, $p<.001$). Run2 times (mean = .9347 sec, sd = .5029) were shorter than run1 times (mean = 1.1571, sd = .5693).

(3) Figure 15 shows a significant interaction that was observed when evaluating the effects of run number and display color on reaction time ($F = 5.55$, $df = 1,35$, $p<.05$). Learning effects are more pronounced for the "red only" version of the display.

(4) Figure 16 shows the significant interaction that occurred when a comparison of the display colors and the scenario numbers (listed in Appendix D) was evaluated with respect to reaction time ($F = 5.24$, $df = 11,21$, $p<.001$). "Red only" reaction times were longer than the "green only" times for every scenario and were also longer than the "red and green" times with one exception (scenario 11). Scenario 7 produced the longest reaction times for all three display colors.

(5) No significant differences in reaction time were noted among the three versions of the display for the different commands (climbs or descents).

Evaluating the accuracy of the pilot's responses by tabulating the number of incorrect climbs and descents (errors) produced the following results:

(1) The overall error rate for the experiment was 2% with no significant learning effects noted between run1 and run2, although fewer errors occurred on the second run.

(2) A post-hoc paired comparison of the number of errors using the "red only" and "red and green" displays showed a significant difference ($F = 8.03$, $df = 1,35$, $p<.01$). The "red only" display produced the most errors (27) while the least occurred using the "red and green" display (10). The use of the "green only" display resulted in 18 errors.

(3) Figure 17 shows a significant interaction between the command called for by the display and the color of the display with respect to the frequency of errors. The "red and green" display appears to be the most effective for descent scenarios.

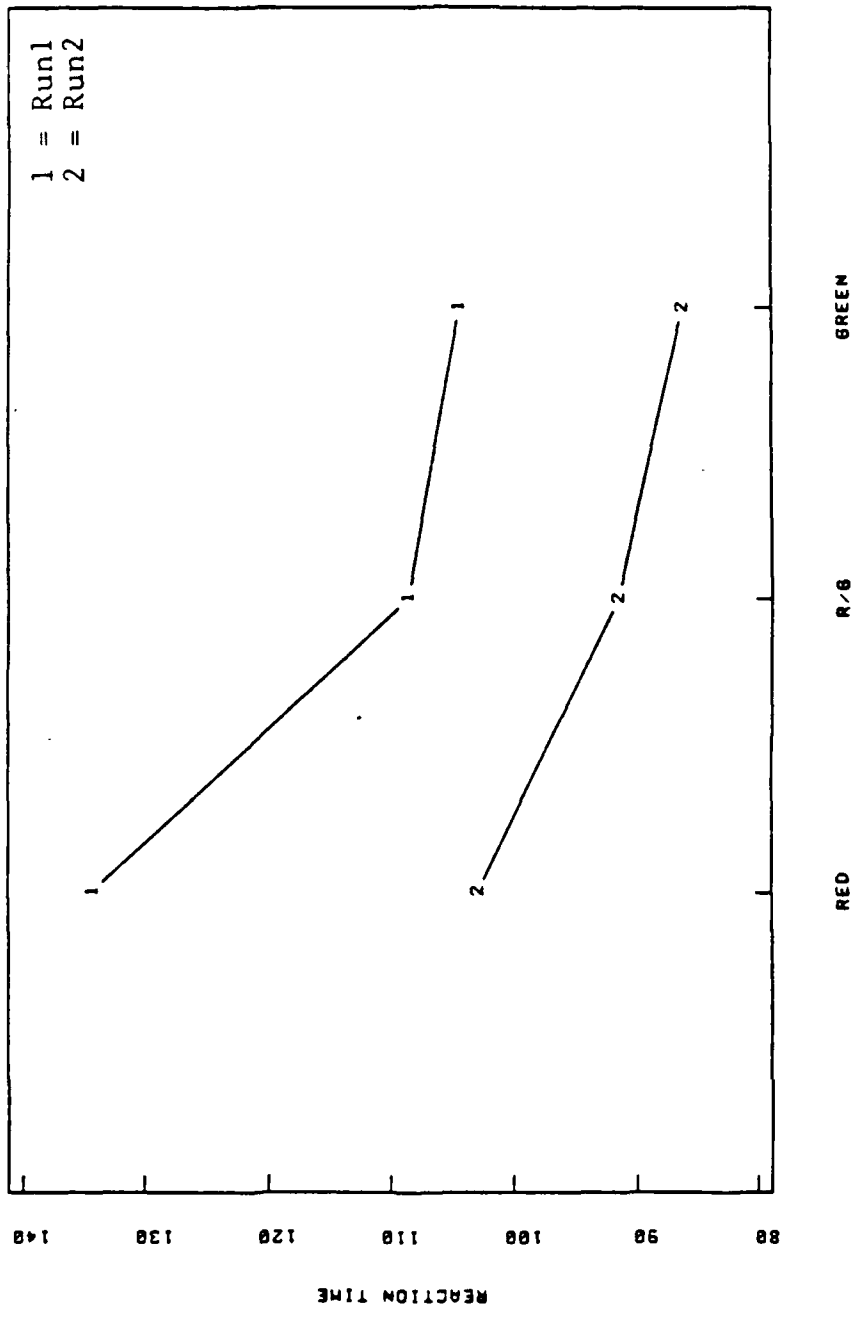


Figure 15. Reaction Time Learning Effects

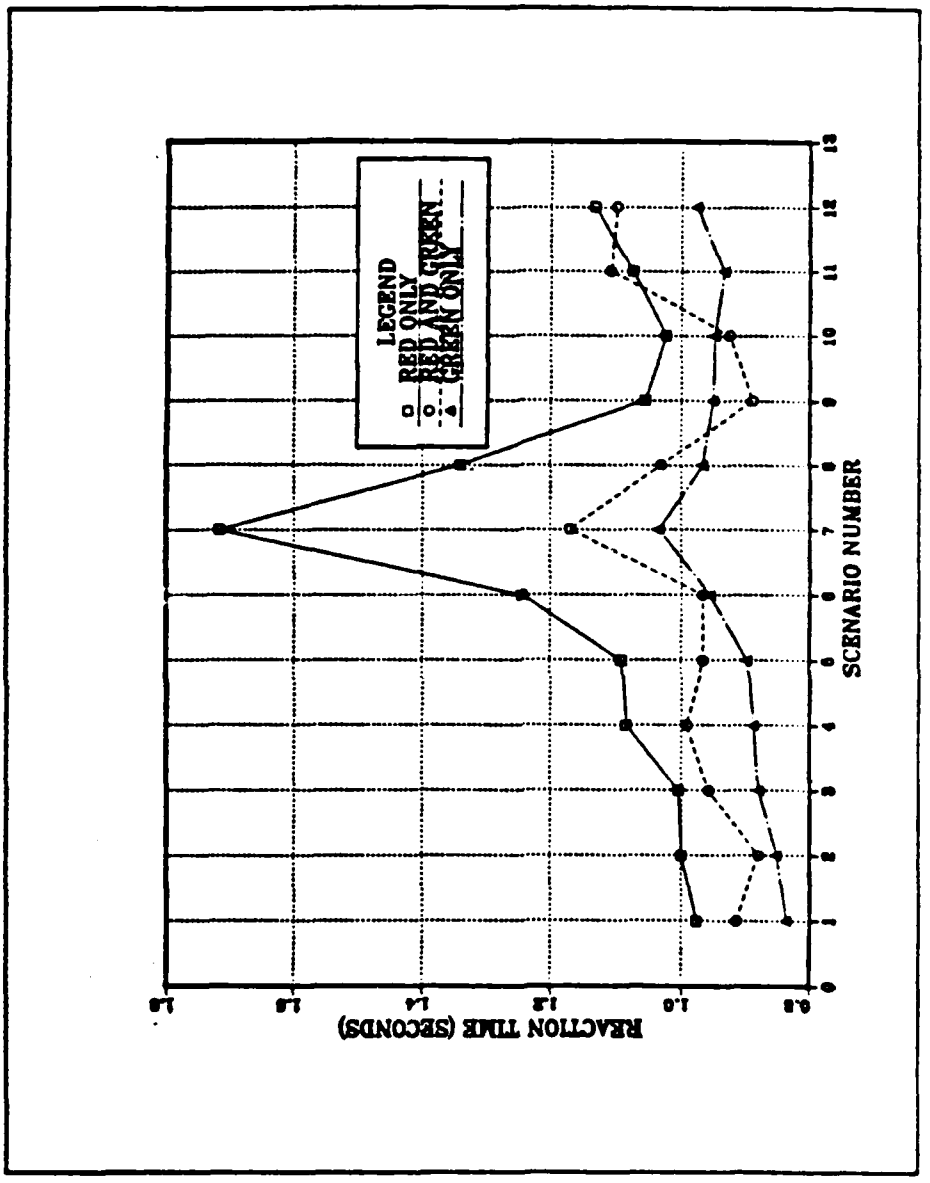


Figure 16. Scenario Reaction Times

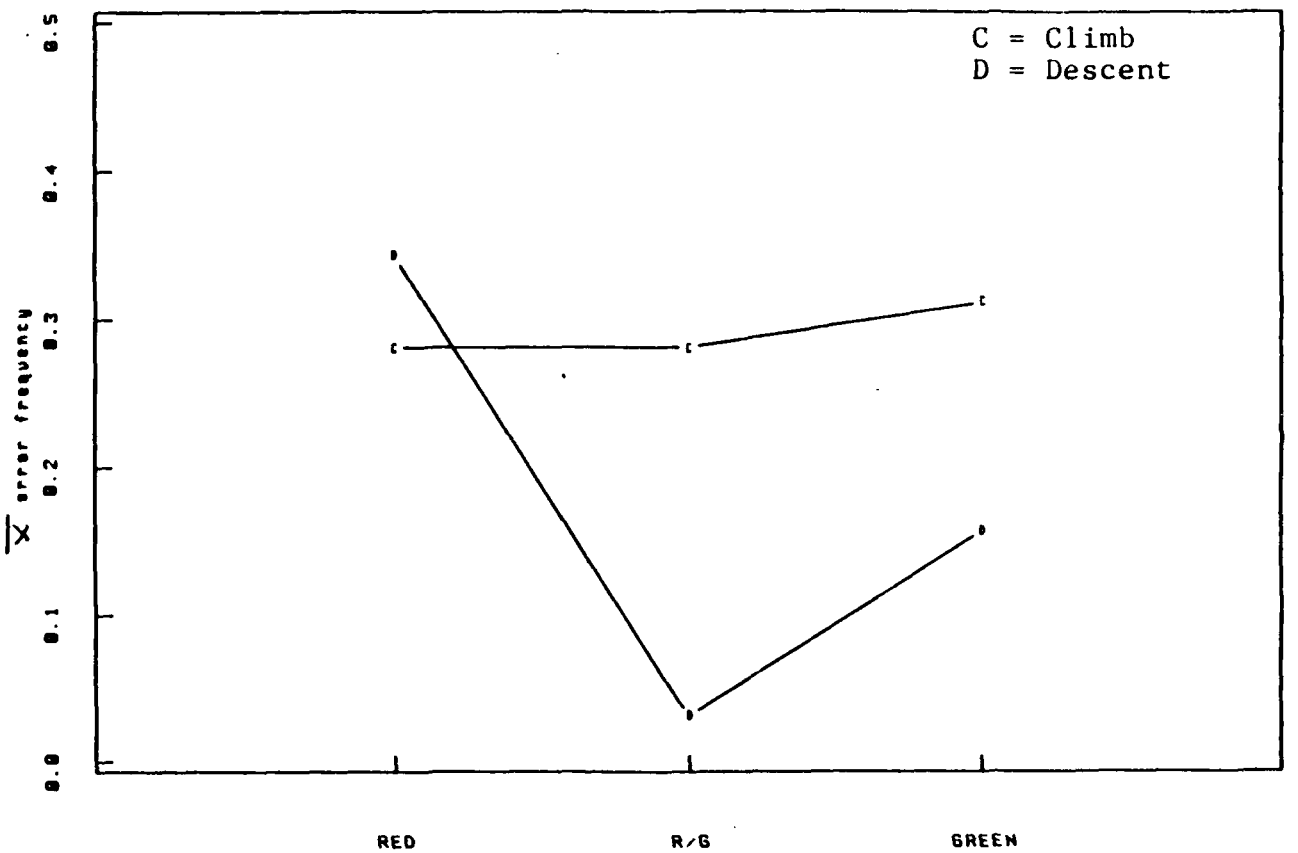


Figure 17. Climb/Descent Errors

(4) Significant effects on the number of errors were also noted for each of the display colors as a result of the scenario number. Figure 18 shows the total number of errors for each scenario. The greatest number of errors (7) occurred using the scenario 13 "red only" display. Scenario 13 was a preventative RA presentation which required no climb or descent from the pilot.

Pilot experience levels produced no significant effects on reaction time or response accuracy. Pilot preferences also showed no apparent effects on the results.

An analysis of the pilot questionnaires showed that 92% (33 out of 36) of the pilots rated the "red and green" (19) or the "green only" RA display (14) as the most effective for signaling an evasive maneuver. The current RA display in the TCAS II system ("red only") was rated the least effective of the three versions by 24 pilots (67%). Several pilots commented that they preferred the "red and green" lighting configuration because it gave them both an area to avoid and an area to aim for. Three of the more experienced pilots stated that they would prefer to receive collision avoidance commands from an altitude direction indicator (ADI) rather than an instantaneous vertical speed indicator (IVSI). They stated that maneuvers are routinely performed using the ADI vice the IVSI.

Possible sources of error in the results may have been induced by individual pilots having difficulty adjusting to the partial system simulation. Some subjects had problems using the computer mouse as a control stick and responding as they would in an aircraft. Performing this experiment in a

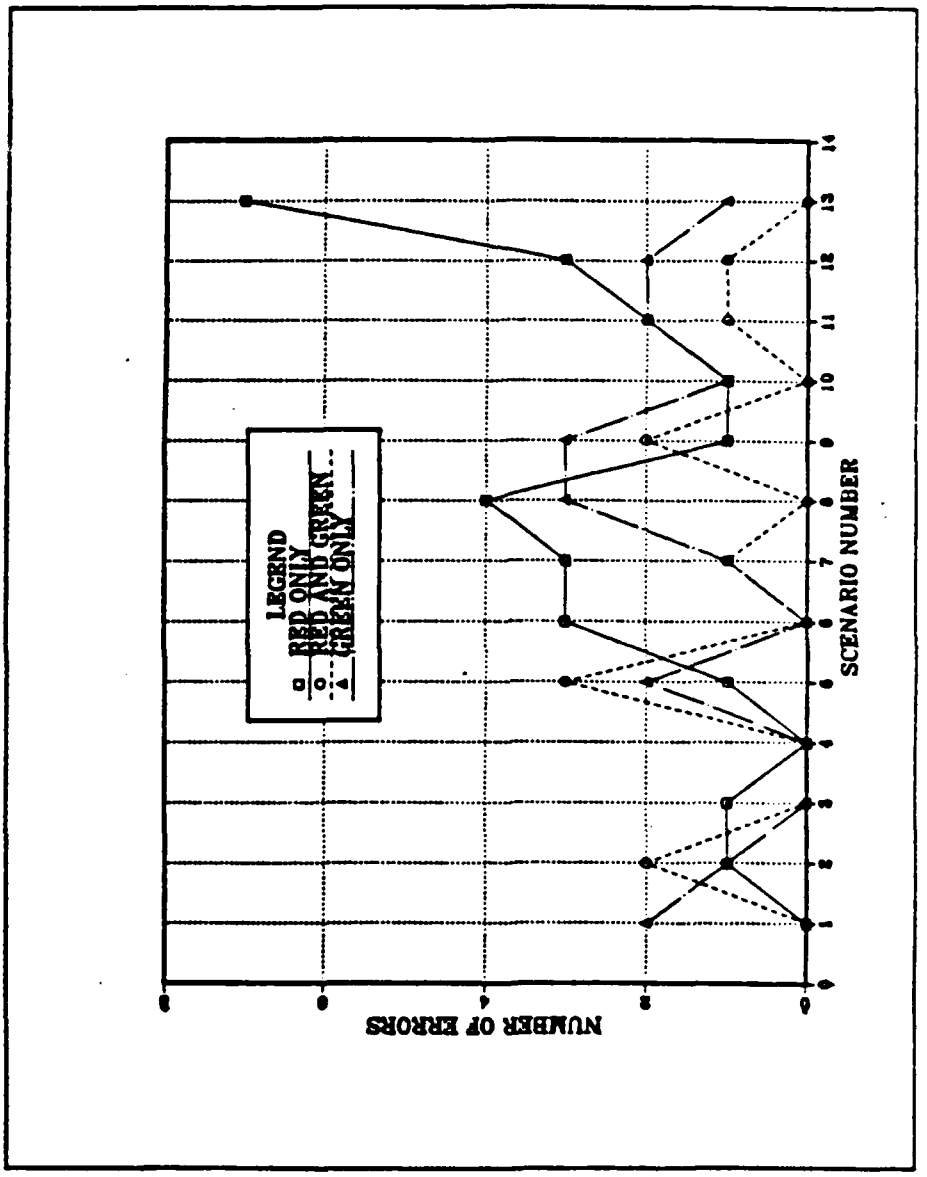


Figure 18. Scenario Errors

flight simulator with a complete TCAS II system would have enhanced the simulation. Upgrades to this experiment could include animation of the IVSI needle and the use of a "joystick" to replace the computer mouse. Animation of the IVSI needle would have allowed the measurement of the amount of overshoot of the recommended vertical speeds and a measure of the time required for each subject to reach the commanded vertical speed.

D. CONCLUSIONS

The results of this experiment demonstrate that the two alternate designs of the TCAS II resolution advisory display ("red and green", "green only") are more effective than the current display ("red only"). The alternate designs produced faster reaction times, fewer errors, and were judged to be more effective by 92% of the pilots who participated in this study. The "red and green" version of the display was more effective at preventing errors and was chosen as most effective by 53% of the pilots. The "green only" lighting pattern produced the shortest reaction times and was rated as most effective by 39% of the pilots.

Both alternate versions of the display ("red and green", "green only") were effective at eliminating unnecessary responses to preventative warnings, while the current TCAS II RA display version ("red only") produced seven errors of this type.

The information generated by this experiment may be useful for future versions of collision avoidance displays. In order to determine whether it would be feasible to change the current display, a cost-benefit analysis would have to be conducted.

VI. SUMMARY OF CONCLUSIONS

As a result of the three studies completed in this report, answers are now available for the three questions posed at the beginning of this paper.

The first study examined aircraft maneuvers based solely on traffic advisory information. There were 14 cases during the NASA-Ames simulation where the pilots successfully maneuvered the aircraft to avoid a potential collision by utilizing TA information. These maneuvers were conducted despite training which emphasized that maneuvers should be performed only on the basis of warnings displayed on the resolution advisory (RA) display. Pilot training procedures should be developed to optimize the use of the TCAS II traffic advisory display, while allowing pilots to use their experience and judgment to ensure aircraft safety of flight. The pilots appeared to gain confidence in the system as the simulation progressed and were eager to use all the available information. Standardized TCAS procedures should be developed and adopted. Additionally, frequent practice in flight simulators should provide valuable reinforcement to this training. As the pilots become more familiar with the TCAS II system and gain confidence in the collision avoidance maneuvers presented on the RA display, this tendency to maneuver on the TA information should be reduced.

The second study was concerned with the results of the TCAS-directed collision avoidance maneuvers. Computer-aided analysis of data determined that, in 37 of 40 scenarios investigated, the avoidance maneuvers directed by the TCAS II system increased altitude separations and miss distances at CPA. Three similar cases where the miss distances decreased were examined and appear not to be a threat to safety of flight. These three maneuvers were long range encounters at high altitudes and appear to result from the system logic calculating an erroneous time to CPA in excess of that actually observed. In general, the pilots responded accurately to the commands from the system and successfully avoided many potential mid-air collisions. From an examination of flight station video tapes, the presentation on the RA display occasionally caused minor confusion for the pilots. These observations resulted in the motivation to proceed with a study of alternate lighting configurations for the RA display.

The final phase of this study considered alternate designs for the RA display in an effort to determine the most effective means to direct collision avoidance maneuvers. Volunteer pilots reacted to collision avoidance maneuver commands from three different versions of the RA display ("red only", "red and green", and "green only"). The "red and green" version of the display proved to be more effective than the current "red only" version by producing

significantly faster reaction times, fewer errors, and a much higher effectiveness rating from the pilots. In general, the participants stated that they preferred an area to aim for (green warning arc) and an area to avoid (red warning arc). The "red and green" display gave both cues. This information may be useful in future upgrades of the current system or in the design of collision avoidance systems of the future.

The information contained in this report is based on simulations rather than operational testing of the system in actual aircraft. However, the results of this study should provide information useful in the development of pilot training procedures and system upgrades to maximize the operational effectiveness of the TCAS II system. With proper use, this system has the potential to dramatically enhance flight safety on the conjested airways and in the busy terminal areas of the United States.

APPENDIX A

"LLTCAS" COMPUTER PROGRAM

```
FILE: LLTCAS   FORTRAN  A1

      PROGRAM LLTCAS
*     THIS PROGRAM COMPUTES THE MISS DISTANCE (SLANT RANGE) BETWEEN
*     TWO AIRCRAFT ON A NEAR COLLISION COURSE ASSUMING NEITHER AIRCRAFT
*     TAKES EVASIVE ACTION. THE TCAS (TRAFFIC ALERT AND COLLISION
*     AVOIDANCE SYSTEM) AIRCRAFT'S LATITUDE, LONGITUDE AND ALTITUDE
*     ARE READ IN FROM RECORDS OF THE NASA-AMES 727 SIMULATOR STUDY OF
*     PILOTS USING THE TCAS SYSTEM.  THIS DATA IS COMPARED TO THE
*     LATITUDE, LONGITUDE AND ALTITUDE DATA FROM THE CONFLICTING
*     AIRCRAFT'S RECORDS.  RANGE, SLANT RANGE, AND ALTITUDE SEPERATION
*     DISTANCES ARE COMPUTED.  THE PROGRAM IS THEN MODIFIED TO PREDICT
*     THE DISTANCES THAT WOULD HAVE RESULTED IF NO AVOIDANCE MANEUVER
*     WAS PERFORMED.  THIS IS DONE BY EVALUATING THE VIDEO TAPES OF
*     THE ENCOUNTER, THE SIMULATOR DATA, AND THE FLIGHT CLEARANCES
*     ISSUED TO THE AIRCRAFT.  THE TCAS ALTITUDE IS THEN MODIFIED TO
*     EVALUATE THE MISS DISTANCES WITHOUT THE MANEUVER.
*************************************************************
*     VARIABLES USED ARE:
*     FSRNG:          ARBITRARY LARGE RANGE VALUE
*     PALT,CALT:      ALTITUDES OF TCAS AND CONFLICTING AIRCRAFT
*     DX:             DISTANCE BETWEEN AIRCRAFT IN LONGITUDE (IN FEET)
*     DY:             DISTANCE BETWEEN AIRCRAFT IN LATITUDE  (IN FEET)
*     PLT,PLG:        TCAS AIRCRAFT LATITUDE AND LONGITUDE
*     CLT,CLG:        CONFLICTING AIRCRAFT LATITUDE AND LONGITUDE
*     PDZ:            TCAS AIRCRAFT VERTICAL VELOCITY FOR NO MANEUVER CASE
*     LALT:           REQUIRED LEVEL OFF ALTITUDE FOR TCAS CLIMB/DESCENT
*     RNG:            RANGE IN THE X,Y PLANE
*     SRNG:           RANGE IN THE X,Y,Z PLANE (MISS DISTANCE)
*     DZ:             ALTITUDE DIFFERENCE BETWEEN AIRCRAFT
*************************************************************
*     DEFINE VARIABLES
      CHARACTER*50 FORMI
      INTEGER TIME
*     DOUBLE PRECISION USED TO INCREASE THE ACCURACY OF THE CALCULATION
      DOUBLE PRECISION DX,DY,PLT,PLG,PALT,CLT,CLG,CALT,LALT,MLAT
      REAL RNG,SRNG,FSRNG,PI,DZ
*******ENTER THE LEVEL OFF ALTITUDE IF REQUIRED (LALT)
      DATA TIME,LALT,PI,FSRNG/1,10000.0,3.14159,99000.0/
*******THE NEXT LINE IS USED TO ENTER THE TCAS AIRCRAFT'S INITIAL
*******ALTITUDE AND CLIMB/DESCENT RATE IF EVALUATING NO MANEUVER CASE
      DATA PALT,PDZ/5000.00000,000.00/
10    FORMI='(10X,F9.5,1X,F10.5)'
      READ (20,FMT=FORMI,END=20)PLT,PLG
      FORMI='(30X,F11.4)'
*     THE FOLLOWING 3 READ STATEMENTS READ IN DATA FROM REMOTE FILES
*     CONTAINING SIMULATOR DATA
*******THE NEXT LINE IS DELETED WHEN EVALUATING THE NO MANEUVER CASE
***   READ (21,FMT=FORMI,END=20)PALT
      FORMI='(20X,F8.5,2X,F10.5,1X,F11.4)'
      READ (22,FMT=FORMI,END=20)CLT,CLG,CALT
*     THE NEXT 3 LINES CONVERT THE LAT/LONG DIFFERENCES TO DISTANCES
*     IN FEET BETWEEN THE TWO AIRCRAFT IN THE X AND Y PLANE.
      MLAT=ABS((PLT+CLT)/2.0)
      DX=(PLG-CLG)*60.0*6076.1033*COS((MLAT*PI)/180.0)
      DY=(PLT-CLT)*60.0*6076.1033
*     THE NEXT LINE COMPUTES THE ALTITUDE DIFFERENCE BETWEEN AIRCRAFT
      DZ=PALT-CALT
*     COMPUTE RANGE IN X,Y PLANE
      RNG=SQRT(DX**2+DY**2)
*     COMPUTE SLANT RANGE (MISS DISTANCE)
      SRNG=SQRT(RNG**2+DZ**2)
*     PRINT THE RESULTS
      PRINT*,'TIME=',TIME,'RNG=',RNG,'SRNG=',SRNG,'ALTD=',DZ
*     CHECK TO SEE IF RANGE IS DECREASING (IF IT IS NOT END PROGRAM)
      IF (SRNG.GT.FSRNG)GO TO 20
*     IF RANGE IS DECREASING LOOP TO OBTAIN MORE DATA
      FSRNG=SRNG
*     THIS IF STATEMENT ALLOWS THE USER TO LIMIT THE NUMBER OF DATA
*     POINTS USED OR TIME PERIOD EXAMINED
      IF (TIME.GE.90)GO TO 20
      TIME=TIME+1
*******THE NEXT LINE IS USED FOR THE NO MANEUVER CASE
      PALT=PALT+PDZ
*******THE NEXT 3 LINES ARE USED IF A LEVEL OFF RESTRICTION IS REQUIRED
***   IF(PALT.LE.LALT) THEN
***   PALT=LALT
***   END IF
      GO TO 10
15    CONTINUE
20    END
```

APPENDIX B

"LLTCAS" RESULTS

```
FILE: RESULTS  RESULTS  A1

*** SCENARIO 1 ***
FT2111  SCENARIO 1 WITHOUT MANEUVER (CONTINUED DESCENT)
TIME=          17 RNG=  733.958740     SRNG=  789.986328     ALTD= -292.203857
TIME=  ****    18 RNG=  297.052979     SRNG=  418.879150     ALTD= -295.329102
TIME=          19 RNG=  374.661865     SRNG=  479.005615     ALTD= -298.454346
FT2111  SCENARIO 1 WITH COLLISION AVOIDANCE MANEUVER
TIME=          17 RNG=  733.958740     SRNG=  988.836670     ALTD= -662.648193
TIME=  ****    18 RNG=  297.052979     SRNG=  746.444580     ALTD= -694.791260
TIME=          19 RNG=  374.661865     SRNG=  793.720215     ALTD= -699.728760

*** SCENARIO 2 ***
FT2111  SCENARIO 2 WITHOUT MANEUVER (CONTINUED LEVEL)
TIME=          19 RNG=  484.288330     SRNG=  514.309570     ALTD= -173.145493
TIME=  ****    20 RNG=  426.200439     SRNG=  443.175293     ALTD= -121.480499
TIME=          21 RNG=  721.542236     SRNG=  724.911621     ALTD= -69.8104858
FT2111  SCENARIO 2 WITH COLLISION AVOIDANCE MANEUVER
TIME=          19 RNG=  484.288330     SRNG=  1166.69531     ALTD= -1061.43457
TIME=  ****    20 RNG=  426.200439     SRNG=  1091.97485     ALTD= -1005.36719
TIME=          21 RNG=  721.542236     SRNG=  1184.10522     ALTD= -938.872803


*** SCENARIO 3 ***
FT2221  SCENARIO 1 WITHOUT MANEUVER (CONTINUED LEVEL)
TIME=           4 RNG=  11449.8398     SRNG=  11501.9609     ALTD=  1093.74023
TIME=  ****     5 RNG=  11411.9375     SRNG=  11460.2656     ALTD=  1051.37866
TIME=           6 RNG=  11419.7227     SRNG=  11464.2109     ALTD=  1009.01147
FT2221  SCENARIO 1 WITH COLLISION AVOIDANCE MANEUVER
TIME=           4 RNG=  11449.8398     SRNG=  11500.4609     ALTD=  1077.86523
TIME=  ****     5 RNG=  11411.9375     SRNG=  11458.0469     ALTD=  1026.89038
TIME=           6 RNG=  11419.7227     SRNG=  11460.8008     ALTD=  969.480225
NOTE: THIS IS A CASE WHERE THE COLLISION AVOIDANCE MANEUVER DECREASED
      THE SLANT RANGE AND ALTITUDE SEPARATION AT CPA.  THE TCAS COMMAND
      WAS "DESCEND TO CROSS".

*** SCENARIO 4 ***
FT2221  SCENARIO 2 WITHOUT MANEUVER  (CONTINUED DECENT)
TIME=          17 RNG=  9742.52344     SRNG=  9767.73437     ALTD=  701.328369
TIME=  ****    18 RNG=  9743.69531     SRNG=  9765.49219     ALTD=  652.132568
TIME=          19 RNG=  9765.95703     SRNG=  9784.55078     ALTD=  602.939453
FT2221  SCENARIO 2 WITH COLLISION AVOIDANCE MANEUVER
TIME=          17 RNG=  9742.52344     SRNG=  9888.92578     ALTD=  1695.32788
TIME=  ****    18 RNG=  9743.69531     SRNG=  9884.32031     ALTD=  1661.40039
TIME=          19 RNG=  9765.95703     SRNG=  9899.80078     ALTD=  1622.38550

*** SCENARIO 5 ***
FT2221  SCENARIO 3 WITHOUT MANEUVER (CONTINUED LEVEL)
TIME=          17 RNG=  1834.38843     SRNG=  1836.96973     ALTD= -97.3554993
TIME=  ****    18 RNG=  922.626953     SRNG=  926.148926     ALTD= -80.6923981
TIME=          19 RNG=  1214.73364     SRNG=  1216.53809     ALTD= -66.2470856
FT2221  SCENARIO 3 WITH COLLISION AVOIDANCE MANEUVER
TIME=          17 RNG=  1834.38843     SRNG=  1883.94629     ALTD= -429.272461
TIME=  ****    18 RNG=  922.626953     SRNG=  1016.03711     ALTD= -425.547852
TIME=          19 RNG=  1214.73364     SRNG=  1285.82690     ALTD= -421.632568

*** SCENARIO 6 ***
FT2221  SCENARIO 4 WITHOUT MANEUVER (CONTINUED DESCENT UNTIL LEVEL OFF)
TIME=          25 RNG=  5458.90625     SRNG=  5458.99219     ALTD=  30.5819855
TIME=  ****    26 RNG=  5423.91016     SRNG=  5423.99609     ALTD=  30.5819855
TIME=          27 RNG=  5443.53516     SRNG=  5443.62109     ALTD=  30.5819855
NOTE: REQUIRED LEVEL OFF AT 5000 FEET.
FT2221  SCENARIO 4 WITH COLLISION AVOIDANCE MANEUVER
TIME=          25 RNG=  5458.90625     SRNG=  5495.92187     ALTD=  636.788818
TIME=  ****    26 RNG=  5423.91016     SRNG=  5454.98828     ALTD=  581.476318
TIME=          27 RNG=  5443.53516     SRNG=  5469.09375     ALTD=  528.148193
```

FILE: RESULTS RESULTS A1

```
*** SCENARIO 7 ***
FT2312  SCENARIO 1 WITHOUT MANEUVER (CONTINUED LEVEL)
TIME=          13 RNG=  5121.67187      SRNG=  5175.57812      ALTD=  745.062256
TIME=  ****    14 RNG=  5084.64453      SRNG=  5133.06641      ALTD=  703.394287
TIME=          15 RNG=  5130.39844      SRNG=  5172.89453      ALTD=  661.718750
FT2312  SCENARIO 1 WITH COLLISION AVOIDANCE MANEUVER
TIME=          13 RNG=  5121.67187      SRNG=  5343.83984      ALTD=  1524.83569
TIME=  ****    14 RNG=  5084.64453      SRNG=  5309.26562      ALTD=  1527.98413
TIME=          15 RNG=  5130.39844      SRNG=  5351.39844      ALTD=  1522.00781

*** SCENARIO 8 ***
FT2312  SCENARIO 2 WITHOUT MANEUVER (CONTINUED DESCENT)
TIME=          35 RNG=  6339.27734      SRNG=  6347.21094      ALTD= -317.278076
TIME=  ****    36 RNG=  6313.62891      SRNG=  6325.22266      ALTD= -382.802979
TIME=          37 RNG=  6394.01562      SRNG=  6409.71094      ALTD= -448.326172
FT2312  SCENARIO 2 WITH COLLISION AVOIDANCE MANEUVER
TIME=          35 RNG=  6339.27734      SRNG=  6467.53906      ALTD=  1291.66089
TIME=  ****    36 RNG=  6313.62891      SRNG=  6429.51562      ALTD=  1215.22266
TIME=          37 RNG=  6394.01562      SRNG=  6495.19922      ALTD=  1142.00952

*** SCENARIO 9 ***
FT2312  SCENARIO 3 WITHOUT MANEUVER (CONTINUED LEVEL)
TIME=          17 RNG=  452.436523      SRNG=  457.608643      ALTD= -68.6063995
TIME=  ****    18 RNG=  402.323730      SRNG=  402.753906      ALTD= -18.6094055
TIME=          19 RNG=  651.105957      SRNG=  651.862061      ALTD=  31.3886871
FT2312  SCENARIO 3 WITH COLLISION AVOIDANCE MANEUVER
TIME=          16 RNG=  702.217773      SRNG=  891.712402      ALTD=  549.582764
TIME=  ****    17 RNG=  452.436523      SRNG=  834.801025      ALTD=  701.565430
TIME=          18 RNG=  402.323730      SRNG=  929.584717      ALTD=  838.011475

*** SCENARIO 10 ***
FT2312  SCENARIO 4 WITHOUT MANEUVER (CONTINUED DESCENT)
TIME=          29 RNG=  1515.23999      SRNG=  1518.67944      ALTD=  102.154572
TIME=  ****    30 RNG=  1479.34277      SRNG=  1482.28516      ALTD=  93.3535614
TIME=          31 RNG=  1500.91895      SRNG=  1503.29834      ALTD=  84.5521698
FT2312  SCENARIO 4 WITH COLLISION AVOIDANCE MANEUVER
TIME=          29 RNG=  1515.23999      SRNG=  1704.83105      ALTD=  781.343506
TIME=  ****    30 RNG=  1479.34277      SRNG=  1670.79638      ALTD=  776.577393
TIME=          31 RNG=  1500.91895      SRNG=  1687.18457      ALTD=  770.606934


*** SCENARIO 11 ***
FT2422  SCENARIO 1 WITHOUT MANEUVER (CONTINUED LEVEL)
TIME=          16 RNG=  9026.06641      SRNG=  9052.21875      ALTD=  687.607178
TIME=  ****    17 RNG=  9008.75391      SRNG=  9031.87109      ALTD=  645.810547
TIME=          18 RNG=  9020.71875      SRNG=  9040.92578      ALTD=  604.150146
FT2422  SCENARIO 1 WITH COLLISION AVOIDANCE MANEUVER
TIME=          16 RNG=  9026.06641      SRNG=  9029.12891      ALTD=  235.150299
TIME=  ****    17 RNG=  9008.75391      SRNG=  9009.84766      ALTD=  140.359390
TIME=          18 RNG=  9020.71875      SRNG=  9020.83203      ALTD=  44.9022980

*** SCENARIO 12 ***
FT2422  SCENARIO 2 WITHOUT MANEUVER (CONTINUED DESCENT)
TIME=          14 RNG=  2449.52026      SRNG=  2496.77344      ALTD=  483.456299
TIME=  ****    15 RNG=  2450.74170      SRNG=  2494.26562      ALTD=  463.926270
TIME=          16 RNG=  2536.18701      SRNG=  2574.82666      ALTD=  444.396240
FT2422  SCENARIO 2 WITH COLLISION AVOIDANCE MANEUVER
TIME=          13 RNG=  2469.16602      SRNG=  2560.50244      ALTD=  677.785889
TIME=  ****    14 RNG=  2449.52026      SRNG=  2545.76465      ALTD=  693.375000
TIME=          15 RNG=  2450.74170      SRNG=  2550.07986      ALTD=  704.817871

*** SCENARIO 13 ***
FT2422  SCENARIO 3 WITHOUT MANEUVER (CONTINUED DESCENT UNTIL LEVEL OFF)
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FILE: RESULTS  RESULTS  A1

TIME=          26 RNG=  1073.11841      SRNG=  1077.72632      ALTD=  99.5546875
TIME=  ****    27 RNG=  812.431641      SRNG=  818.508545      ALTD=  99.5546875
TIME=          28 RNG=  1014.82642      SRNG=  1019.69800      ALTD=  99.5546875
NOTE: REQUIRED LEVEL OFF AT 5000 FEET.
FT2422  SCENARIO 3 WITH COLLISION AVOIDANCE MANEUVER
TIME=          26 RNG=  1073.11841      SRNG=  1451.70239      ALTD=  977.679687
TIME=  ****    27 RNG=  812.431641      SRNG=  1253.86110      ALTD=  955.077981
TIME=          28 RNG=  1014.82642      SRNG=  1374.68750      ALTD=  927.304687


*** SCENARIO 14 ***
FT3111 SCENARIO 1 WITHOUT MANEUVER  (CONTINUED DESCENT)
TIME=          27 RNG=  1676.39966      SRNG=  1686.20435      ALTD= -181.576889
TIME=  ****    28 RNG=  1576.77344      SRNG=  1585.81201      ALTD= -169.076385
TIME=          29 RNG=  1740.63281      SRNG=  1747.66040      ALTD= -156.575699
FT3111 SCENARIO 1 WITH COLLISION ADVOIDANCE MANEUVER
TIME=          27 RNG=  1676.39966      SRNG=  1878.76562      ALTD=  848.201172
TIME=  ****    28 RNG=  1576.77344      SRNG=  1796.71899      ALTD=  861.385986
TIME=          29 RNG=  1740.63281      SRNG=  1944.79761      ALTD=  867.430908


*** SCENARIO 15 ***
FT3111 SCENARIO 2 WITHOUT MANEUVER  (CONTINUED LEVEL)
TIME=          25 RNG=  5309.11329      SRNG=  5316.22266      ALTD=  274.855469
TIME=  ****    26 RNG=  5236.97656      SRNG=  5243.30859      ALTD=  257.613281
TIME=          27 RNG=  5273.07812      SRNG=  5279.14453      ALTD=  253.064468
FT3111 SCENARIO 2 WITH COLLISION AVOIDANCE MANEUVER
TIME=          25 RNG=  5309.11329      SRNG=  5614.01172      ALTD= -1824.95288
TIME=  ****    26 RNG=  5236.97656      SRNG=  5559.34766      ALTD= -1865.59351
TIME=          27 RNG=  5273.07812      SRNG=  5592.95703      ALTD= -1864.35718


*** SCENARIO 16 ***
FT3111 SCENARIO 3 WITHOUT MANEUVER  (CONTINUED DESCENT)
TIME=          33 RNG=  5887.03516      SRNG=  5887.68359      ALTD= -87.4238129
TIME=  ****    34 RNG=  5858.81641      SRNG=  5860.27344      ALTD= -130.689819
TIME=          35 RNG=  5867.98047      SRNG=  5870.55859      ALTD= -173.951935
FT3111 SCENARIO 3 WITH COLLISION AVOIDANCE MANEUVER
TIME=          34 RNG=  5858.81641      SRNG=  6059.53125      ALTD=  1546.67285
TIME=  ****    35 RNG=  5867.98047      SRNG=  6045.48928      ALTD=  1454.20996
TIME=          36 RNG=  5915.00000      SRNG=  6065.91406      ALTD=  1344.65039


*** SCENARIO 17 ***
FT3111 SCENARIO 4 WITHOUT MANEUVER  (CONTINUED LEVEL)
TIME=          20 RNG=  293.120117      SRNG=  461.708984      ALTD=  356.729492
TIME=  ****    21 RNG=  93.8893585      SRNG=  419.052734      ALTD=  408.399414
TIME=          22 RNG=  349.162842      SRNG=  576.496338      ALTD=  458.730225
FT3111 SCENARIO 4 WITH COLLISION AVOIDANCE MANEUVER
TIME=          18 RNG=  939.338623      SRNG=  1982.65405      ALTD=  1746.01270
TIME=  ****    19 RNG=  604.302246      SRNG=  1955.93652      ALTD=  1860.24390
TIME=          20 RNG=  293.120117      SRNG=  1987.56006      ALTD=  1965.82715


*** SCENARIO 18 ***
FT3221  SCENARIO 1 WITHOUT MANEUVER  (CONTINUED DESCENT)
TIME=          25 RNG=  3165.98633      SRNG=  3166.26001      ALTD= -41.6446533
TIME=  ****    26 RNG=  2991.59351      SRNG=  2992.14844      ALTD= -57.6353607
TIME=          27 RNG=  3012.62476      SRNG=  3013.52417      ALTD= -73.6258698
FT3221  SCENARIO 1 WITH COLLISION AVOIDANCE MANEUVER
TIME=          25 RNG=  3165.98633      SRNG=  3336.09521      ALTD=  1051.69507
TIME=  ****    26 RNG=  2991.59351      SRNG=  3189.37939      ALTD=  1105.67139
TIME=          27 RNG=  3012.62476      SRNG=  3225.82153      ALTD=  1153.26416


*** SCENARIO 19 ***
FT3221  SCENARIO 2 WITHOUT MANEUVER (CONTINUED DESCENT UNTIL LEVEL OFF)
TIME=          28 RNG=  1702.82986      SRNG=  1703.42139      ALTD=  44.9257965
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FILE: RESULTS  RESULTS  A1

TIME=  ****    29 RNG=   1626.97389      SRNG=   1627.59375      ALTD=   44.9257965
TIME=          30 RNG=   1730.42383      SRNG=   1731.00659      ALTD=   44.9257965
NOTE: CLEARANCE REQUIRED LEVEL OFF AT 5000 FEET.
FT3221   SCENARIO 2 WITH COLLISION AVOIDANCE MANEUVER
TIME=          28 RNG=   1702.82886      SRNG=   1870.43311      ALTD=   773.682569
TIME=  ****    29 RNG=   1626.97388      SRNG=   1800.20142      ALTD=   770.508057
TIME=          30 RNG=   1730.42383      SRNG=   1894.23340      ALTD=   770.554687


*** SCENARIO 20 ***
FT3312   SCENARIO 1 WITHOUT MANEUVER (CONTINUED DESCENT)
TIME=          20 RNG=   631.507812      SRNG=   836.599854      ALTD= -548.723389
TIME=  ****    21 RNG=   365.420654      SRNG=   670.811523      ALTD= -562.543945
TIME=          22 RNG=   473.935791      SRNG=   746.197266      ALTD= -576.363770
FT3312   SCENARIO 1 WITH COLLISION AVOIDANCE MANEUVER
TIME=          20 RNG=   631.507812      SRNG=   1016.96655      ALTD= -797.131836
TIME=  ****    21 RNG=   365.420654      SRNG=   894.823730      ALTD= -816.809082
TIME=          22 RNG=   473.935791      SRNG=   957.734863      ALTD= -832.250488


*** SCENARIO 21 ***
FT3312   SCENARIO 2 WITHOUT MANEUVER  (CONTINUED DESCENT)
TIME=          25 RNG=   1350.83179      SRNG=   1368.52734      ALTD= -219.366943
TIME=  ****    26 RNG=   1126.99365      SRNG=   1152.04785      ALTD= -238.956940
TIME=          27 RNG=   1364.48242      SRNG=   1388.76123      ALTD= -258.546875
FT3312   SCENARIO 2 WITH COLLISION AVOIDANCE MANEUVER
TIME=          25 RNG=   1350.83179      SRNG=   1492.54395      ALTD=  634.777100
TIME=  ****    26 RNG=   1126.99365      SRNG=   1282.30811      ALTD=  611.718994
TIME=          27 RNG=   1364.48242      SRNG=   1469.71704      ALTD=  597.867187


*** SCENARIO 22 ***
FT3312   SCENARIO 3 WITHOUT MANEUVER  (CONTINUED DESCENT)
TIME=          16 RNG=   3618.11963      SRNG=   3817.74561      ALTD=   1218.35669
TIME=  ****    17 RNG=   3603.09229      SRNG=   3789.77905      ALTD=   1174.79858
TIME=          18 RNG=   3706.17114      SRNG=   3875.68628      ALTD=   1133.68506
FT3312   SCENARIO 2 WITH COLLISION AVOIDANCE MANEUVER
TIME=          16 RNG=   3618.11963      SRNG=   3877.70483      ALTD=   1394.92163
TIME=  ****    17 RNG=   3603.09229      SRNG=   3850.90161      ALTD=   1359.10620
TIME=          18 RNG=   3706.17114      SRNG=   3936.22705      ALTD=   1325.96387
NOTE: PILOTS DECREASED THEIR RATE OF DESCENT PRIOR TO THE RA USING
      INFORMATION PROVIDED BY THE TRAFFIC ADVISORY DISPLAY.


*** SCENARIO 23 ***
FT3422   SCENARIO 1 WITHOUT MANEUVER (CONTINUED LEVEL)
TIME=          14 RNG=   9094.44922      SRNG=   9121.75000      ALTD=   705.198975
TIME=  ***     15 RNG=   9071.60937      SRNG=   9095.84375      ALTD=   663.525146
TIME=          16 RNG=   9075.67578      SRNG=   9096.95703      ALTD=   621.861328
FT3422   SCENARIO 1 WITH COLLISION AVOIDANCE MANEUVER
TIME=          14 RNG=   9094.44922      SRNG=   9101.55859      ALTD=   359.648193
TIME=  ****    15 RNG=   9071.60937      SRNG=   9075.45312      ALTD=   264.173584
TIME=          16 RNG=   9075.67578      SRNG=   9077.23437      ALTD=   168.158188
NOTE: THIS IS A CASE WHERE THE COLLISION AVOIDANCE MANEUVER DECREASED
      THE VERTICAL SEPARATION BETWEEN THE TWO AIRCRAFT AT CPA.  THE
      TCAS COMMAND WAS "DESCEND TO CROSS".


*** SCENARIO 24 ***
FT3422 SCENARIO 2 WITHOUT MANEUVER (CONTINUED LEVEL)
TIME=           3 RNG=   1404.76587      SRNG=   1496.46289      ALTD= -515.785156
TIME=  ****     4 RNG=   1387.08325      SRNG=   1482.11768      ALTD= -522.182373
TIME=           5 RNG=   1389.24854      SRNG=   1486.40771      ALTD= -528.580566
FT3422   SCENARIO 2 WITH COLLISION AVOIDANCE MANEUVER
TIME=           3 RNG=   1404.76587      SRNG=   1503.35937      ALTD= -535.464844
TIME=   ****    4 RNG=   1387.08325      SRNG=   1495.76074      ALTD= -559.733398
TIME=           5 RNG=   1389.24854      SRNG=   1510.01587      ALTD= -591.724365
NOTE: PILOT DESCENDED AND LEVELED OFF AT 7000 FEET JUST PRIOR TO RA.
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FILE: RESULTS  RESULTS  A1

      CONFLICTING AIRCRAFT WAS AT 7500 FEET AND WAS NOT A THREAT UNTIL
      THE TCAS AIRCRAFT LEVELED OFF.

*** SCENARIO 25 ***
FT3422  SCENARIO 3 WITHOUT MANEUVER (CONTINUED DESCENT UNTIL LEVEL OFF)
TIME=          21 RNG=  2298.30396     SRNG=  2301.83911     ALTD=  127.523392
TIME=  ****    22 RNG=  2112.44629     SRNG=  2116.29175     ALTD=  127.523392
TIME=          23 RNG=  2187.60522     SRNG=  2191.31885     ALTD=  127.523392
NOTE: CLEARANCE REQUIRED LEVEL OFF AT 5000 FEET
FT3422  SCENARIO 3 WITH COLLISION AVOIDANCE MANEUVER
TIME=          21 RNG=  2298.30396     SRNG=  2476.17041     ALTD=  921.531006
TIME=  ****    22 RNG=  2112.44629     SRNG=  2300.98584     ALTD=  912.199463
TIME=          23 RNG=  2187.60522     SRNG=  2365.66724     ALTD=  900.425537


*** SCENARIO 26 ***
FT4111 SCENARIO 1 WITHOUT MANEUVER (CONTINUED LEVEL)
TIME=          23 RNG=  6659.12109     SRNG=  6672.10156     ALTD=  416.031250
TIME=  ****    24 RNG=  6616.39062     SRNG=  6626.97266     ALTD=  374.364990
TIME=          25 RNG=  6623.61328     SRNG=  6631.96094     ALTD=  332.689453
FT4111 SCENARIO 1 WITH COLLISION AVOIDANCE MANEUVER
TIME=          23 RNG=  6659.12109     SRNG=  6667.66406     ALTD= -337.439209
TIME=  ****    24 RNG=  6616.39062     SRNG=  6629.79297     ALTD= -421.365234
TIME=          25 RNG=  6623.61329     SRNG=  6642.64453     ALTD= -502.496094

*** SCENARIO 27 ***
FT4111 SCENARIO 2 WITHOUT MANEUVER  (CONTINUED DESCENT)
TIME=          34 RNG=  8441.61719     SRNG=  8442.37109     ALTD= -112.843079
TIME=  ****    35 RNG=  8387.00781     SRNG=  8389.05469     ALTD= -195.378479
TIME=          36 RNG=  8437.70312     SRNG=  8441.64844     ALTD= -258.046631
FT4111 SCENARIO 2 WITH COLLISION AVOIDANCE MANEUVER
TIME=          34 RNG=  8441.61719     SRNG=  8605.96484     ALTD=  1673.83472
TIME=  ****    35 RNG=  8387.00781     SRNG=  8547.53516     ALTD=  1644.77319
TIME=          36 RNG=  8437.70312     SRNG=  8591.90625     ALTD=  1620.51270

*** SCENARIO 28 ***
FT4221  SCENARIO 1 WITHOUT MANEUVER (CONTINUED LEVEL)
TIME=          40 RNG=  5815.05859     SRNG=  5822.60547     ALTD=  296.363037
TIME=  ****    41 RNG=  5803.01562     SRNG=  5810.64453     ALTD=  297.710937
TIME=          42 RNG=  5841.97656     SRNG=  5849.62500     ALTD=  299.048828
FT4221  SCENARIO 1 WITH COLLISION AVOIDANCE MANEUVER
TIME=          40 RNG=  5815.05859     SRNG=  6013.22266     ALTD= -1531.00000
TIME=  ****    41 RNG=  5803.01562     SRNG=  5998.60547     ALTD= -1519.30469
TIME=          42 RNG=  5841.97656     SRNG=  6031.99609     ALTD= -1502.09546

*** SCENARIO 29 ***
FT4221  SCENARIO 2 WITHOUT MANEUVER (CONTINUED DESCENT UNTIL LEVEL)
TIME=          69 RNG=  1254.30127     SRNG=  1593.25537     ALTD=  982.441895
TIME=  ****    70 RNG=  1245.79932     SRNG=  1586.57080     ALTD=  982.441895
TIME=          71 RNG=  1361.92285     SRNG=  1679.29297     ALTD=  982.441895
NOTE: REQUIRED LEVEL OFF AT 2500 FEET
FT4221  SCENARIO 2 WITH COLLISION AVOIDANCE MANEUVER
TIME=          69 RNG=  1254.30127     SRNG=  1610.98657     ALTD=  1010.94409
TIME=  ****    70 RNG=  1245.79932     SRNG=  1600.17187     ALTD=  1004.25879
TIME=          71 RNG=  1361.92285     SRNG=  1687.73364     ALTD=  996.801270

*** SCENARIO 30 ***
FT4221  SCENARIO 3 WITHOUT MANEUVER (CONTINUED DESCENT UNTIL LEVEL)
TIME=          17 RNG=  1522.29468     SRNG=  1525.98928     ALTD= -106.108887
TIME=  ****    18 RNG=  1383.01367     SRNG=  1387.02956     ALTD= -105.462585
TIME=          19 RNG=  1434.66919     SRNG=  1438.49269     ALTD= -104.816193
NOTE: REQUIRED LEVEL OFF AT 2000 FEET
FT4221  SCENARIO 3 WITH COLLISION AVOIDANCE MANEUVER
TIME=          17 RNG=  1522.29468     SRNG=  1589.63623     ALTD= -457.790273
TIME=  ****    18 RNG=  1383.01367     SRNG=  1455.57129     ALTD= -453.830811
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FILE: RESULTS  RESULTS  A1

TIME=          19 RNG=  1434.66919      SRNG=  1500.73755      ALTD= -440.384766


*** SCENARIO 31 ***
FT4221  SCENARIO 4 WITHOUT MANEUVER (CONTINUED DESCENT UNTIL LEVEL OFF)
TIME=          23 RNG=  4028.14673      SRNG=  4028.39282      ALTD=  44.5233917
TIME=  ****    24 RNG=  3870.27441      SRNG=  3870.53052      ALTD=  44.5233917
TIME=          25 RNG=  3875.35352      SRNG=  3875.60913      ALTD=  44.5233917
NOTE: REQUIRED LEVEL OFF AT 5000 FEET
FT4221  SCENARIO 4 WITH COLLISION AVOIDANCE MANEUVER
TIME=          23 RNG=  4028.14673      SRNG=  4063.96680      ALTD= -538.386719
TIME=  ****    24 RNG=  3870.27441      SRNG=  3909.56860      ALTD= -545.799062
TIME=          25 RNG=  3875.35352      SRNG=  3913.73926      ALTD= -546.800781


*** SCENARIO 32 ***
FT4312  SCENARIO 1 WITHOUT MANEUVER (CONTINUED LEVEL)
TIME=          25 RNG=  1231.13062      SRNG=  1245.50757      ALTD=  188.699188
TIME=  ****    26 RNG=  1131.76953      SRNG=  1147.39233      ALTD=  188.699188
TIME=          27 RNG=  1457.78882      SRNG=  1469.95068      ALTD=  188.699188
FT4312  SCENARIO 1 WITH COLLISION AVOIDANCE MANEUVER
TIME=          25 RNG=  1231.13062      SRNG=  1398.55103      ALTD=  663.523193
TIME=  ****    26 RNG=  1131.76953      SRNG=  1306.66870      ALTD=  653.055176
TIME=          27 RNG=  1457.78882      SRNG=  1594.83350      ALTD=  646.796875


*** SCENARIO 33 ***
FT4312  SCENARIO 2 WITHOUT MANEUVER (CONTINUED DESCENT)
TIME=          23 RNG=  8885.48437      SRNG=  8885.66016      ALTD=  55.9360657
TIME=  ****    24 RNG=  8878.41797      SRNG=  8878.54297      ALTD=  47.1d50586
TIME=          25 RNG=  8982.05469      SRNG=  8982.13672      ALTD=  39.4355621
FT4312  SCENARIO 2 WITH COLLISION AVOIDANCE MANEUVER
TIME=          23 RNG=  8885.48437      SRNG=  9026.69141      ALTD=  1590.39526
TIME=  ****    24 RNG=  8878.41797      SRNG=  9021.94922      ALTD=  1602.39429
TIME=          25 RNG=  8962.05469      SRNG=  9125.16016      ALTD=  1615.39478


*** SCENARIO 34 ***
FT4312  SCENARIO 3 WITHOUT MANEUVER (CONTINUED DESCENT UNTIL LEVEL)
TIME=          15 RNG=  2138.14185      SRNG=  2224.76538      ALTD=  614.761475
TIME=  ****    16 RNG=  2012.51123      SRNG=  2104.31274      ALTD=  614.761475
TIME=          17 RNG=  2028.63110      SRNG=  2119.73462      ALTD=  614.761475
NOTE: REQUIRED LEVEL OFF AT 2000 FEET.
FT4312  SCENARIO 3 WITH COLLISION AVOIDANCE MANEUVER
TIME=          15 RNG=  2138.14185      SRNG=  2276.44580      ALTD=  781.380859
TIME=  ****    16 RNG=  2012.51123      SRNG=  2155.73413      ALTD=  772.650879
TIME=          17 RNG=  2028.63110      SRNG=  2163.49219      ALTD=  766.168457


*** SCENARIO 35 ***
FT4312  SCENARIO 4 WITHOUT MANEUVER (CONTINUED LEVEL)
TIME=           8 RNG=  3754.19922      SRNG=  3874.01636      ALTD=  956.029053
TIME=  ****     9 RNG=  3672.79761      SRNG=  3784.90576      ALTD=  914.368896
TIME=          10 RNG=  3692.49487      SRNG=  3794.22266      ALTD=  872.701172
FT4312  SCENARIO 4 WITH COLLISION AVOIDANCE MANEUVER
TIME=           8 RNG=  3754.19922      SRNG=  3932.41797      ALTD=  1170.42749
TIME=  ****     9 RNG=  3672.79761      SRNG=  3858.14648      ALTD=  1131.46265
TIME=          10 RNG=  3692.49487      SRNG=  3880.61230      ALTD=  1193.58008


*** SCENARIO 36 ***
FT4422  SCENARIO 1 WITHOUT MANEUVER  (CONTINUED LEVEL)
TIME=          15 RNG=  5129.67187      SRNG=  5182.07422      ALTD=  742.058350
TIME=  ****    16 RNG=  5130.41406      SRNG=  5177.90625      ALTD=  699.695068
TIME=          17 RNG=  5152.21094      SRNG=  5193.97266      ALTD=  657.339844
FT4422  SCENARIO 1 WITH COLLISION AVOIDANCE MANEUVER
TIME=          14 RNG=  5167.03516      SRNG=  5299.38281      ALTD=  1176.95679
TIME=  ****    15 RNG=  5128.67187      SRNG=  5266.12500      ALTD=  1195.32788
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FILE: RESULTS  RESULTS  A1

TIME=          16 RNG=  5130.41406      SRNG=  5271.40875      ALTD=  1211.31250


*** SCENARIO 37 ***
FT4422  SCENARIO 2 WITHOUT MANEUVER  (CONTINUED DESCENT)
TIME=          15 RNG=  1032.84253      SRNG=  1251.84180      ALTD=  707.351318
TIME=  ****    16 RNG=  1031.47510      SRNG=  1220.65894      ALTD=  652.739258
TIME=          17 RNG=  1358.86133      SRNG=  1484.67212      ALTD=  598.120361
FT4422  SCENARIO 2 WITH COLLISION AVOIDANCE MANEUVER
TIME=          15 RNG=  1032.84253      SRNG=  1485.07031      ALTD=  1067.08569
TIME=  ****    16 RNG=  1031.47510      SRNG=  1474.10303      ALTD=  1053.11011
TIME=          17 RNG=  1358.86133      SRNG=  1710.65308      ALTD=  1039.14917


*** SCENARIO 38 ***
FT4422  SCENARIO 3 WITHOUT MANEUVER (CONTINUED LEVEL)
TIME=          23 RNG=  518.891113      SRNG=  729.418701      ALTD= -512.643799
TIME=  ****    24 RNG=  293.148926      SRNG=  588.921631      ALTD= -510.776367
TIME=          25 RNG=  328.109375      SRNG=  605.511230      ALTD= -508.908691
FT4422  SCENARIO 3 WITH COLLISION AVOIDANCE MANEUVER
TIME=          23 RNG=  518.891113      SRNG=  930.103271      ALTD= -771.909424
TIME=  ****    24 RNG=  293.148926      SRNG=  873.071777      ALTD= -822.385742
TIME=          25 RNG=  328.109375      SRNG=  936.962402      ALTD= -877.634766


*** SCENARIO 39 ***
FT4422  SCENARIO 4 WITHOUT MANEUVER (CONTINUED DESCENT)
TIME=          25 RNG=  4856.83594      SRNG=  4862.81250      ALTD=  241.048752
TIME=  ****    26 RNG=  4923.99609      SRNG=  4829.73047      ALTD=  235.338440
TIME=          27 RNG=  4977.47656      SRNG=  4882.87891      ALTD=  229.628937
FT4422  SCENARIO 4 WITH COLLISION AVOIDANCE MANEUVER
TIME=          25 RNG=  4856.83594      SRNG=  4918.21094      ALTD=  774.585449
TIME=  ****    26 RNG=  4823.99609      SRNG=  4885.31641      ALTD=  771.626465
TIME=          27 RNG=  4877.47656      SRNG=  4937.84375      ALTD=  769.768066


*** SCENARIO 40 ***
FT4422  SCENARIO 5 WITHOUT MANEUVER (CONTINUED LEVEL)
TIME=          25 RNG=  1400.62231      SRNG=  1401.94507      ALTD=  60.8944855
TIME=  ****    26 RNG=  1017.89844      SRNG=  1019.71826      ALTD=  60.8944855
TIME=          27 RNG=  1084.52563      SRNG=  1086.23340      ALTD=  60.8944855
NOTE: CREW WAS LEVELING AT 5000 FEET AT RA TIME.
FT4422  SCENARIO 5 WITH COLLISION AVOIDANCE MANEUVER
TIME=          24 RNG=  1400.62231      SRNG=  1495.21484      ALTD= -523.378662
TIME=  ****    25 RNG=  1017.89844      SRNG=  1148.79028      ALTD= -532.542969
TIME=          26 RNG=  1084.52563      SRNG=  1211.75586      ALTD= -540.515625
```

APPENDIX C

SUMMARY OF RA MANEUVER DATA

FILE: PLOT DATA A1

A	B	C	D	E	F	G	H
1	29	18	11	684.8	295.3	389.5	327.6
2	34	20	14	1005.4	121.5	883.9	648.8
3	25	5	20	1026.9	1051.4	-24.5	-2.2
4	32	18	14	1661.4	652.1	1009.3	118.8
5	19	18	1	425.5	80.7	344.8	89.9
6	42	26	16	581.5	30.6	550.9	31.0
7	27	14	13	1528.0	703.4	824.6	176.2
8	51	36	15	1215.2	382.8	832.4	104.3
9	32	17	15	701.6	18.6	683.0	432.1
10	66	30	36	776.6	93.4	683.2	188.5
11	30	17	13	140.4	645.8	-505.4	-22.0
12	35	14	21	693.4	463.9	229.5	51.5
13	42	27	15	955.1	99.6	855.5	435.4
14	46	28	18	861.4	169.1	692.3	210.9
15	39	26	13	1865.6	257.6	1600.0	316.0
16	52	35	17	1454.2	130.7	1323.5	185.2
17	34	19	15	1860.2	408.4	1451.8	1536.9
18	44	26	18	1105.7	57.6	1048.1	197.2
19	45	29	16	770.5	44.9	725.6	172.6
20	36	21	15	816.8	562.5	254.3	224.0
21	41	26	15	611.7	239.0	372.7	130.3
22	31	17	14	1359.1	1174.8	184.3	61.1
23	33	15	18	264.2	653.7	-389.5	-19.7
24	39	4	35	559.7	522.2	37.5	13.6
25	43	22	21	912.2	127.5	784.7	184.7
26	40	24	16	421.4	374.4	47.0	2.8
27	41	35	6	1648.8	185.4	1463.4	158.5
28	57	41	16	1519.3	297.7	1221.6	188.0
29	86	70	16	1004.3	982.4	21.9	13.6
30	34	18	16	453.8	105.5	348.3	68.5
31	40	24	16	545.8	44.5	501.3	38.0
32	42	26	16	653.1	188.7	464.4	159.3
33	40	24	16	1602.9	47.2	1555.7	143.4
34	43	16	27	772.7	614.7	158.0	51.4
35	25	9	16	1181.5	914.4	267.1	73.2
36	30	15	15	1195.3	699.7	495.6	88.2
37	20	16	4	1053.1	652.7	400.4	253.4
38	44	24	20	822.4	510.8	311.6	284.2
39	41	26	15	771.6	235.3	536.3	55.6
40	40	25	15	532.5	60.9	471.6	129.1

A = SCENARIO NUMBER
B = TIME FROM TA TO CPA FOR TCAS AIRCRAFT
C = TIME FROM RA TO CPA FOR TCAS AIRCRAFT
D = DIFFERENCE IN TIME BETWEEN TA AND RA
E = ALTITUDE DIFFERENCE BETWEEN THE 2 AIRCRAFT AT CPA WITH TCAS MANEUVER
F = ALTITUDE DIFFERENCE BETWEEN THE 2 AIRCRAFT AT CPA WITH NO MANEUVER
G = DIFFERENCE BETWEEN TCAS AND NO-TCAS ALTITUDE SEPARATION AT CPA
H = DIFFERENCE BETWEEN TCAS AND NO-TCAS SLANT RANGE AT CPA

APPENDIX D

EXPERIMENTAL RA DISPLAYS

0. IVSI VERTICAL SPEED: 0 FPM
   WARNING ARC: Red lights from -6000 FPM to +2000 FPM and/or green lights from +2000 FPM to +3000 FPM.
   REQUIRED RESPONSE: Climb
   NOTE: The first presentation in each set of 14 was this example display. The following 13 were presented in a random order.

1. IVSI VERTICAL SPEED: 0 FPM
   WARNING ARC: Red lights from -6000 FPM to +2000 FPM and/or green lights from +2000 FPM to +3000 FPM.

   REQUIRED RESPONSE: Climb

2. IVSI VERTICAL SPEED: 0 FPM
   WARNING ARC: Red lights from-6000 FPM to +1500 FPM and/or green lights from +1500 FPM to +2500 FPM.
   REQUIRED RESPONSE: Climb

3. IVSI VERTICAL SPEED: 0 FPM
   WARNING ARC: Red lights from -1500 FPM to +6000 FPM and/or green lights from -2500 FPM to -1500 FPM.
   REQUIRED RESPONSE: Descend

4. IVSI VERTICAL SPEED: 0 FPM
   WARNING ARC: Red lights from -2000 FPM to +6000 FPM and/or green lights from -3000 FPM to -2000 FPM.
   REQUIRED RESPONSE: Descend

5. IVSI VERTICAL SPEED: -1500 FPM
   WARNING ARC: Red lights from -6000 FPM to +1500 FPM and/or green lights from +1500 FPM to +2500 FPM.
   REQUIRED RESPONSE: Climb

6. IVSI VERTICAL SPEED: +1500 FPM
   WARNING ARC: Red lights from -1500 FPM to +6000 FPM and/or green lights from -2500 FPM to -1500 FPM.
   REQUIRED RESPONSE: Descend

7. IVSI VERTICAL SPEED: -1500 fpm
WARNING ARC: Red lights from -6000 FPM to -200 FPM and from +200 FPM to +6000 FPM and/or green lights from -200 FPM to +200 FPM.
REQUIRED RESPONSE: Climb

8. IVSI VERTICAL SPEED: +1500 fpm
WARNING ARC: Red lights from -6000 FPM to -200 FPM and from +200 FPM to +6000 FPM and/or green lights from -200 FPM to +200 FPM.
REQUIRED RESPONSE: Descend

9. IVSI VERTICAL SPEED: +1000 FPM
WARNING ARC: Red lights from -6000 FPM to +2000 FPM and/or green lights from +2000 FPM to +3000 FPM.
REQUIRED RESPONSE: Climb

10. IVSI VERTICAL SPEED: -1000 fpm
WARNING ARC: Red lights from -2000 FPM to +6000 FPM and/or green lights from -3000 FPM to -2000 FPM.
REQUIRED RESPONSE: Descend

11. IVSI VERTICAL SPEED: +2000 FPM
WARNING ARC: Red lights from +1000 FPM to +6000 FPM and/or green lights from 0 FPM to +1000 FPM.
REQUIRED RESPONSE: Descend

12. IVSI VERTICAL SPEED: -2000 FPM
WARNING ARC: Red lights from -6000 FPM to -1000 FPM and/or green lights from -1000 FPM to 0 FPM.
REQUIRED RESPONSE: Climb

13. THREE PREVENTATIVE RA DISPLAYS

13A. IVSI VERTICAL SPEED: +2000 FPM
WARNING ARC: Red lights from -6000 FPM to 0 FPM.
REQUIRED RESPONSE: No action required

13B. IVSI VERTICAL SPEED: -2000 FPM
WARNING ARC: Red lights from 0 FPM to +6000 FPM.
REQUIRED RESPONSE: No action required

13C. IVSI VERTICAL SPEED: 0 FPM
WARNING ARC: Red lights from +200 FPM to +6000 FPM and from -200 FPM to -6000 FPM.
REQUIRED RESPONSE: No action required

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3. Sperry Dalmo Victor Inc., Advertisement C-61-7200-21-00, TCAS II Traffic Alert and Collision Avoidance System, pp. 1-5, Printed in U.S.A., May 1987.

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