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TCAS II TESTING
CONFLICTS AND RESOLUTIONS

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ABSTRACT

The Federal Aviation Administration (FAA), following a congressional directive, has mandated the installation and operation of an airborne collision avoidance concept called the Traffic Alert and Collision Avoidance System (TCAS). All airline aircraft flying in U.S. airspace with more than 30 passenger seats must be equipped with TCAS by the end of 1993.

TCAS is an onboard avionics system developed to ensure safe air traffic separation. TCAS II is a category of TCAS created for installation in commercial aircraft and provides collision threat information and avoidance maneuver guidance. The system relies on transponders installed in commercial and most general aviation aircraft, allowing for an onboard collision avoidance system independent of the FAA Air Traffic Control system.

Boeing has conducted TCAS II ground and flight tests on model 737, 747, 757 and 767 airplanes. Testing was performed to technically evaluate TCAS II performance against the minimum design requirements and to demonstrate TCAS II performance for FAA follow-on certification. This paper describes the methods used to evaluate TCAS II performance, difficulties encountered, modified test techniques, and operational aspects of the TCAS II system.

NOMENCLATURE

AC	Advisory Circular
AGL	Above Ground Level
ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
CAS	Collision Avoidance System
EADI	Electronic Attitude Director Indicator (Artificial Horizon)
EHSI	Electronic Horizontal Situation Indicator (with Moving Map)
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FCC	Federal Communications Commission
nm	Nautical Miles
RA	Resolution Advisory (Indication Given by TCAS to Flight Crew)
SAFT	Semi-Automated Flightline Tester
TA	Traffic Advisory (Indication Given by TCAS to Flight Crew)
TCA	Terminal Control Area
TCAS	Traffic Alert and Collision Avoidance System
VSI	Vertical Speed Indicator

INTRODUCTION

In October of 1990, Boeing began ground and flight testing to evaluate TCAS II systems in preparation for FAA follow-on certification. The first tests were conducted on a Boeing Model 737-500 for three primary TCAS vendors and one intermixed combination of components. TCAS performance was evaluated per the guidance material published in AC 20-131A (1) for TCAS/ATC follow-on certification.

Based on test results, TCAS vendors incorporated modifications to improve system operation. Test techniques were modified to improve data quality, test efficiency and test safety. Boeing has since conducted evaluation tests on most currently produced models of Boeing aircraft. At the writing of this paper, two vendors' systems had been certified on several Boeing airplane models.

TCAS II SYSTEM DESCRIPTION

General Operation

TCAS II detects aircraft equipped with operating transponders using a procedure called "whisper/shout," and also by detecting Mode S squitter signals (2,3). TCAS interrogates the transponders of nearby aircraft and tracks them by their replies. It also computes and displays their range, bearing and relative altitude on cockpit displays.

The TCAS computer constructs two layers of protective airspace around itself for each detected aircraft (*target*) based on their range and closure rate. Figure (1) illustrates this concept. When an aircraft penetrates the outer protective layer, a *Traffic Advisory* (*TA*) is issued. The aural alert "Traffic, Traffic" is broadcast over cockpit speakers and symbology depicts the intruder as a TA on TCAS Traffic Displays. When an aircraft penetrates the inner protective layer, a *Resolution Advisory* (*RA*) is issued. Symbology on traffic displays identify the intruder as a collision threat. Vertical collision avoidance maneuver commands announce over cockpit speakers (e.g., "Climb, Climb, Climb") and pitch guidance cues appear on TCAS Resolution Displays. Resolution maneuvers are coordinated between TCAS equipped aircraft.

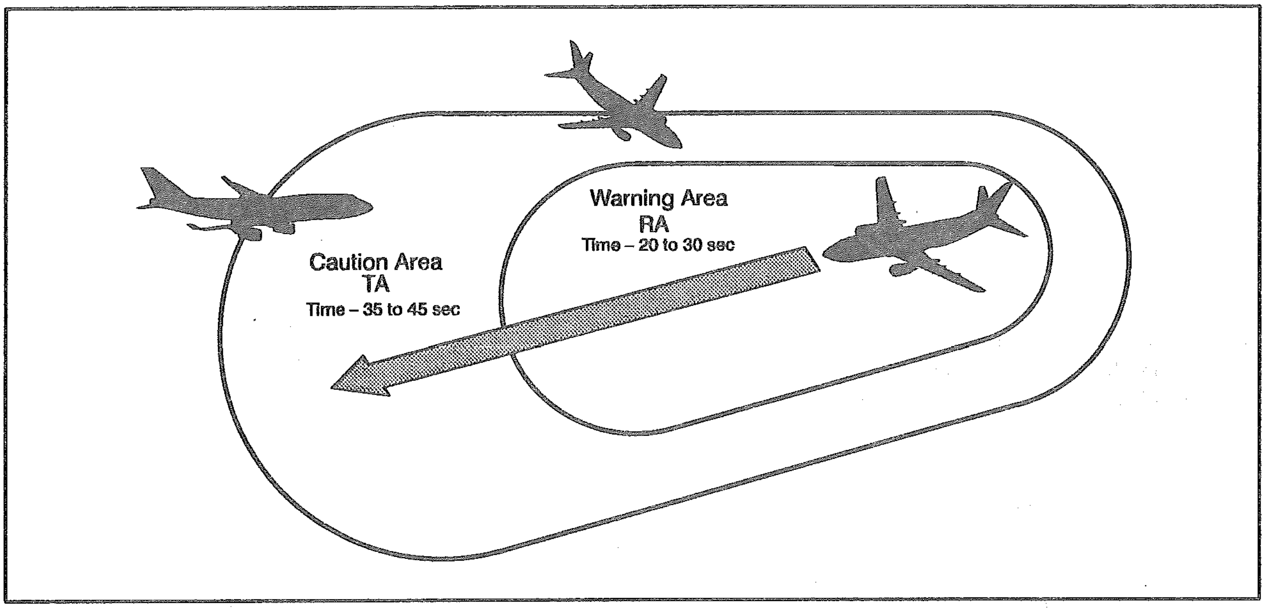

Figure 1 – TCAS II Protection

Traffic Displays

TCAS targets are displayed in the flight deck on traffic displays. To conserve already cramped instrument panel space, traffic displays have been integrated into existing cockpit instruments (although dedicated traffic displays are also available). Targets display in a "map" or plan-view format on flat panel Vertical Speed Indicators (VSIs), Electronic Horizontal Situation Indicators (EHSIs) and shared color weather radar displays. Figure (2) shows a representation of TCAS traffic on an EHSI.

Targets are depicted on traffic displays as symbols representing collision threat. Aircraft within the surveillance range of TCAS that are not considered a collision threat are designated as *other traffic* and depicted on traffic displays as hollow white diamonds. Aircraft within 6 nm and ±1,200 feet of the TCAS own aircraft are designated as *proximate traffic* and depicted on traffic displays as solid white diamonds. Aircraft that trigger TAs appear on traffic displays as solid yellow circles, and aircraft that trigger RAs are shown as solid red squares.

When altitude information is available from Mode C and Mode S transponder equipped aircraft, the target's symbol on the traffic display is accompanied by an altitude tag containing the target's relative altitude (in plus or minus hundreds of feet) and an up or down arrow if its climb or descent rate is greater than 500 feet per minute.

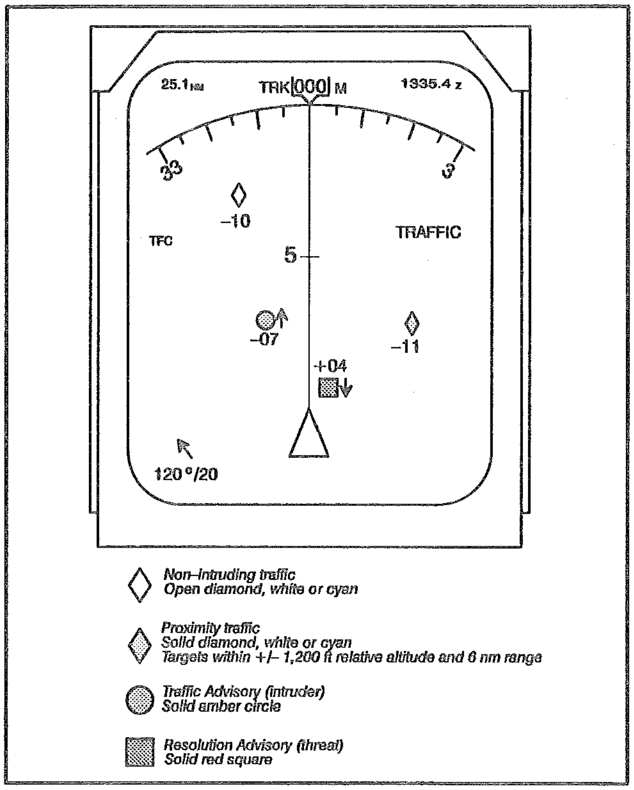

Figure 2 – TCAS Traffic on an EHSI Display

Resolution Displays

Resolution commands generated by TCAS are issued aurally over cockpit speakers and visually on resolution displays. The commands alert the flight crew to achieve (or maintain) a vertical rate to avert collision. Resolution displays are integrated into existing cockpit instruments. Command information may be displayed on flat panel VSIs or Electronic Attitude Director Indicators (EADIs). Resolution command information on flat panel VSIs is displayed in the form of red and green arcs indicating prohibited and desired vertical speed ranges, Figure (3). Resolution command information on EADIs are displayed as pitch attitude cues, Figure (4).

TEST OBJECTIVES

Tests are conducted to evaluate TCAS II performance per the guidance material published in AC 20-131A for FAA follow-on certification. This includes the following:

- Evaluation of the general arrangement and operation of TCAS controls
- Evaluation of TCAS self-test features and failure mode displays and annunciations
- Verification of TCAS system interfaces
- Evaluation of TCAS directional antenna bearing accuracy for 360° coverage at 30° intervals (with a maximum permissible error of ±15° for zones visible from the cockpit)
- Verification of proper TCAS inhibit operation
- Inflight encounters to demonstrate proper operation of TCAS traffic and resolution displays, annunciations and aural alerts

Most of the test objectives are accomplished during ground testing. Inflight encounters are demonstrated by flying against a projected target generated by ground based equipment.

TCAS GROUND STATION

Ground Station System

Boeing flies TCAS encounters and bearing accuracy tests against a stationary target generated by a ground based Mode C transponder. The system consists of two general aviation Mode C transponders adapted to electronically output desired test altitudes. One of the transponders is used as a "hot spare" during testing. The system is a self-contained rack mounted unit that operates on 110 VAC power converted to DC power for use by the transponders. Low-loss coaxial cable is used between the transponders and antenna to provide extra cable length for antenna positioning while maintaining line losses representative of a typical general aviation transponder installation. Transmitted altitude is set using thumbwheel switches on the face of the unit. TCAS equipped aircraft see the ground station target as an actual intruder at the altitude transmitted by the ground station.

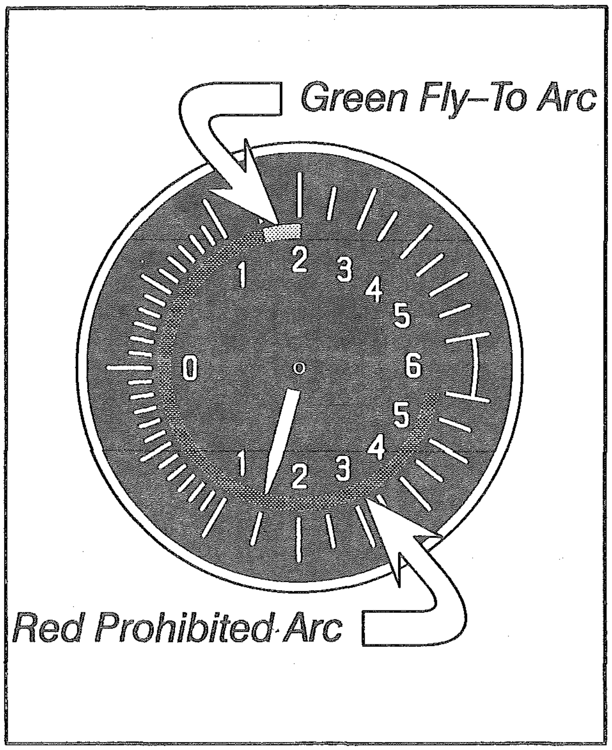

Figure 3 - Resolution Advisory on a VSI

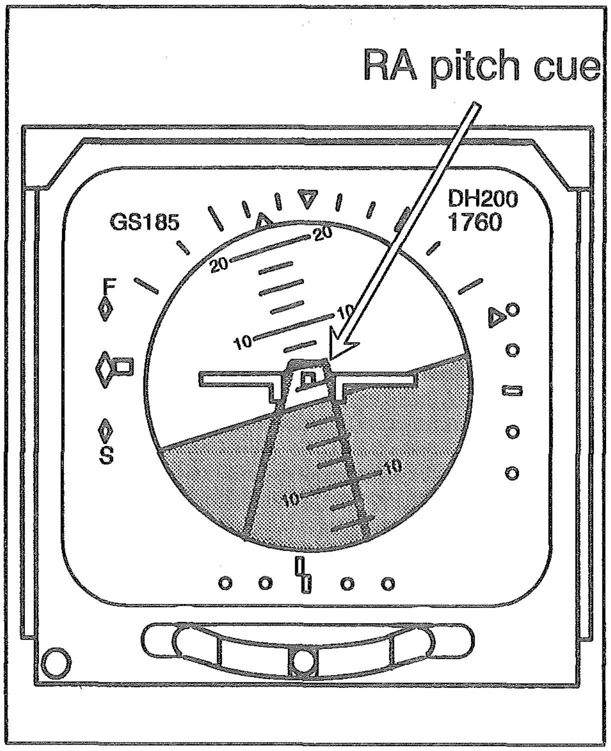

Figure 4 - RA Pitch Cue on EADI

Benefits

Several benefits are realized by flying encounters against a ground station generated target (as opposed to flying encounters against another airplane). One such benefit is fixed geometry. Actual intruder range, bearing and closure rate can be determined onboard the test airplane using visual landmarks and standard airplane avionics. Another benefit is safety. Encounters triggering TAs and RAs can be flown against the ground-station target without actual collision danger, thus permitting TCAS system evaluation in critical conflict scenarios. Additionally, test encounters with a ground-station target can be more easily planned, coordinated and flown.

Constraints

Generation of TCAS advisories using the ground-station target requires the test airplane to fly at low altitudes and high airspeeds. Encounters with the ground-station target are flown at approximately 4,500 feet above the ground station and at airspeeds ranging from 250 knots to V_{mo} (Boeing has a waiver to the Part 91 Federal Aviation Regulation for speed restrictions, allowing flight at airspeeds above 250 knots below 10,000 feet MSL).

Range to the ground-station target is the measured distance between the TCAS equipped airplane and the ground based transponder. The range to the ground-station target as depicted on the traffic display is, in effect, the slant range to the TCAS ground station. This means that the test airplane cannot get any closer to the ground-station target than its own altitude above the ground station, regardless of transmitted ground-station target altitude. Since the issuance of TCAS advisories is based on range and closure rate, it is desirable to minimize the slant range effect to allow the generation of these advisories. This is done by flying encounters at high airspeeds and low altitudes.

To avoid undesirable ground-station target dropouts, test passes flown are offset by one quarter nm from the TCAS ground station. A null signal area (cone-of-silence) exists above the ground station antenna. The cone widens with height above the ground station. At the altitudes the encounters are flown, the null signal area is much wider than would normally be experienced with an actual intruder at the same indicated relative altitude. This area needs to be avioded and further limits the closest point of approach obtainable. Flying encounters at low altitudes can minimize this effect.

Substantial general aviation traffic exists at the low altitudes required for testing. Even with TCAS in use, they present significant collision hazards if they do not have properly operating transponders installed.

FCC License

An FCC license was required for operation of the TCAS ground station. The application process took approximately one year. A Special Temporary Authorization was issued for the initial testing with five operational restrictions attached by the FAA. The restrictions are:

(1) Flights must be conducted during daylight hours under Visual Flight Rules (*a tough criterion for any flight conducted in the Pacific Northwest!*)

(2) Flights must be conducted on a noninterference basis to aviation operations in the National Airspace System.

(3) Advance notification of testing to the Air Route Traffic Control Center (ARTCC) must be made.

(4) Emergency procedures for immediate cessation of testing as directed by the ARTCC must exist.

(5) Transmitted altitude for the ground-station target is restricted to altitudes between 500 and 5,000 feet Above Ground Level (AGL), later raised to 15,000 feet AGL.

These restrictions may have been instigated because a "test code" for TCAS testing does not exist. The ground-station target appears as an actual intruder to all TCAS equipped aircraft, and therefore has the potential of triggering nuisance advisories.

Location

The TCAS ground station was originally set up in the Boeing-Everett radio tower. The tower resides on a corner of the Boeing 747/767 assembly plant (*the largest building in the world by volume!*) on the Snohomish County/Paine Field Airport, Everett, Washington. This site was primarily selected for proximity to Boeing test facilities. Co-locating it with an already existing facility eliminated the need to dedicate a crew to operate at a remote site. However, flight testing at this location revealed safety issues that resulted in the relocation of the ground station for subsequent TCAS testing.

Air traffic near the Paine Field Airport is dense at times. Shortly after the site was selected, Seattle-Tacoma International Airport approach and departure corridors were relocated to pass near Paine Field. At times during the test flights, up to 20 intruders could be observed on the traffic displays. Although flight testing was conducted within the 30 nm ring of the Seattle Terminal Control Area (TCA), where transponders are generally required per Federal Aviation Regulations (FARs), a few aircraft were in the area without operating transponders. These aircraft were totally invisible to TCAS and represented the greatest flight hazard.

Test and data considerations also contributed to the decision to relocate the ground station. Because of airspace constraints in the Paine Field area, resolution maneuvers generated by the ground-station target could not be flown to their full extent as desired. Also, identification of the ground-station target was complicated by the large number of targets cluttering the displays and creating additional data to sort through during post flight analysis.

The TCAS ground station was moved to the Mansfield Airport in Mansfield, Washington. The airport is located in the heart of a farming community. The land surrounding the airport is flat and contains no natural obstacles to block the ground station signal. The TCAS ground station equipment was modified to allow installation in a van for transportation to and from the remote site. The modification included adding generators to supply AC power for the ground station equipment, creating a stand-alone system. Although Mansfield is only 108 nm northeast of the Paine Field site (as the airplane flies), the drive traversing the frequently snow-covered Cascade Mountain passes during winter can take over five hours. During the summer months, the trip can be completed in three and a half hours. An FCC license was obtained for the new location.

Originally locating the TCAS ground station at the Paine Field site was not without its rewards. Flight testing conducted at this location identified what some pilots consider to be unacceptable aspects of TCAS operation.(4)

Boeing test pilots indicated that TCAS advisories received were often more distracting than useful. Airborne traffic not considered to be a factor by pilots frequently trigger TAs and RAs. The nuisance advisories are typically issued during the initial or final stages of a flight (shortly after takeoff and just prior to landing) when the demand on the pilot is the highest. Most of these advisories are triggered from aircraft in normal airport traffic patterns, either for the same runway or its parallel. Problems with TCAS over-sensitivity has put pressure on the FAA to modify the Collision Avoidance System (CAS) logic.

Also, due to the irregularity of the terrain surrounding some airports (including Paine Field), aircraft parked in taxi and tie-down areas with active transponders appear as actual airborne targets (and threats) to TCAS equipped airplanes. These parked aircraft frequently generate nuisance advisories to overflying or landing TCAS equipped aircraft. The FAA is now recommending that interim measures be taken during TCAS and ATC ground testing (such as antenna shielding) to curtail these kinds of nuisance advisories. A more permanent solution (such as designated test codes) is reportedly being developed by the FAA.

INSTRUMENTATION

First Test Airplane (737-500)

A large-scale flight test instrumentation system was installed on the first test airplane. Data was recorded selectively from 21 ARINC digital buses. Approximately 100 parameters from six of the buses were specifically used for TCAS analysis. Although an operational Airborne Data Analysis and Monitoring System (ADAMS) was on the airplane, it was not possible to monitor TCAS intruder data because each intruder uses the same label.(5) A special program to demultiplex TCAS intruder files had to be written for post-flight data reduction. TCAS targets frequently switched intruder numbers, making data analysis difficult.

Pertinent cockpit observations were recorded in manual notes taken during the tests. This data was sufficient for determination of proper TCAS operation and display accuracy. The data recorded by the instrumentation system was used for postflight verification of inflight observations and TCAS system troubleshooting.

A hand-held video camera was used during the first two flights to record specific observations on TCAS cockpit displays. A high resolution camera was mounted in the cockpit for subsequent test flights to record the First Officer's EHSI (TCAS traffic display). Aside from manual notes, the video tapes provided the most useful data collected.

Second Test Airplane (757-200)

A Portable Airborne Digital Data System (PADDS) was installed on the second test airplane. The system recorded eight ARINC buses. Unfortunately, the 100 millisecond time resolution of PADDS was insufficient for complete data analysis, and the portable system was replaced with a High Speed Pulse Code Modulation (HSPCM) data system.

Subsequent Test Airplanes

Cameras mounted in the cockpit for recording of TCAS Traffic and Resolution Displays is the only instrumentation presently used during TCAS testing. Figure (5) shows the camera installation in the flight deck. The video is tagged with IRIG time and has proven itself to be a valuable analysis tool.

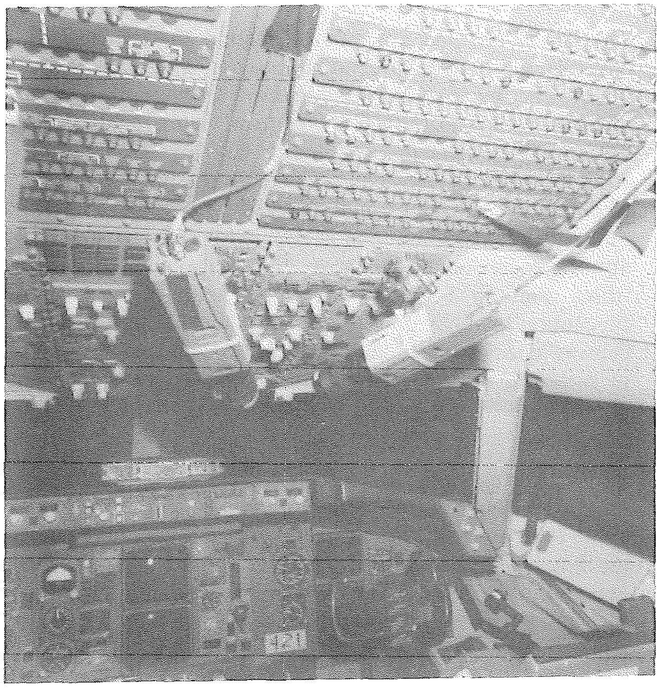

Figure 5 - Cockpit Camera Installation

TEST METHODS

Testing evaluates TCAS performance per the guidance material published in AC 20-131A for FAA follow-on certification. The testing is designed to verify accurate and continuous TCAS information on traffic and resolution displays, appropriate aural callouts and proper operation of TCAS inhibits.

Bearing Accuracy

TCAS intruder position information is computed using data collected from directional antennas. TCAS systems may have top directional and bottom omni-directional antennas or both top and bottom directional antennas. The systems installed on Boeing aircraft have the latter antenna configuration. Testing is conducted to evaluate bearing accuracy for both top and bottom directional antennas.

The top directional antenna is evaluated during ground testing. The airplane's top directional antenna is centered on a modified compass rose. A stationary target is simulated by a TCAS ramp test-set. The test-set is the size of a small suitcase and can simulate a variety of intruder parameters including altitude, range and range rate. The bearing of the test-set intruder on the traffic display is the actual bearing of the test-set antenna from the TCAS directional antenna as measured from the nose of the airplane. The test-set is moved on the compass rose around the top TCAS directional antenna in 30° increments for 360° of coverage. The relative bearing to the stationary target as observed on the traffic display is then compared with the actual relative bearing of the TCAS ramp test-set.

The top directional antenna is isolated for this test by covering the bottom directional antenna with a reflective hood. The inside of the hood is lined with a material that absorbs signals in the TCAS frequency range. Logic in some TCAS systems disregard bearing information received from the bottom directional antenna in certain airplane configurations or flight profiles. In those cases, the top directional antenna is isolated by configuring the aircraft accordingly. Because there is no way to verify which antenna TCAS is using, the hood is used as a precaution to verify only top antenna reception during all bearing checks. A high-lifter ("cherry picker") is used to raise the TCAS ramp test-set and operator to the elevation of the top antenna to obtain near-horizon target reception.

Initial bearing accuracy tests revealed that due to the forward location of the TCAS antennas, a conventional sized compass rose was not adequate. When conducting the bearing accuracy test, the test airplane's directional antenna is centered on the rose and all bearing measurements are taken relative to the antenna. Due to antenna location (several feet aft of the nose gear), the wings and empennage of the airplane hang over the edge of the compass rose markings, hindering precise positioning of the TCAS ramp tester. To provide accurate test points, an elliptical shaped azimuth marked in 30° increments (±0.1°) was painted for the bearing accuracy ground test.

Due to configuration induced multipathing (test-set signal reflections from engine cowlings, landing gear and landing gear doors) that cause target splitting and erroneous bearing data, it was predicted that the bottom directional antenna would need to be checked inflight. Attempts to check bottom antenna bearing accuracy on the ground confirmed this conclusion. Additionally, Boeing engineers felt that the bottom antenna would be used for targets sufficiently below the horizon to preclude ground testing, even if the aircraft could be supported on jacks.

Inflight bearing accuracy testing is conducted using the TCAS ground-station target. A 12-leg cloverleaf pattern is flown to evaluate the TCAS system bearing accuracy in 30° increments for 360° coverage. Figure (6) shows the cloverleaf pattern superimposed on a sectional chart. A point located approximately 5 nm from the ground station is used as the center point of the cloverleaf pattern. By flying over the pattern center point at known airplane headings, relative bearing to the ground station is known from simple geometry. The indicated bearing to the ground-station target is measured by laying the autopilot's Heading Select cursor over the target symbol on the map. When passing over the center point, the actual relative bearing is compared to the indicated bearing of the target on the traffic display to obtain a bearing error.

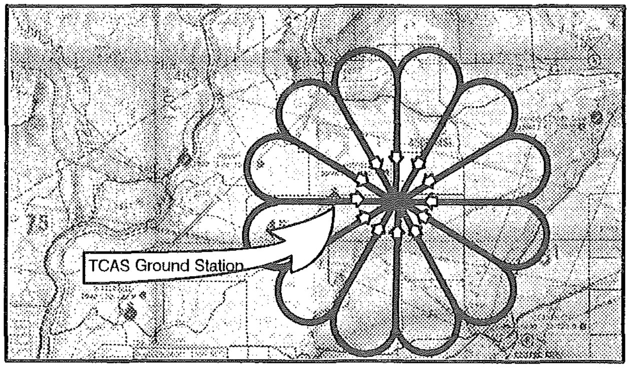

Figure 6 – Cloverleaf Pattern

TCAS Inhibits

There are several partial and complete TCAS inhibits. Ground proximity and windshear alerts inhibit all TCAS aural alerts and sets TCAS into a TA-Only mode (no resolution advisories can be issued in this mode). Several TCAS functions are inhibited below certain radar altitudes. For example, "Increase Descent" commands are inhibited below a radar altitude of 1,450 feet; "Descend" commands are inhibited below a radar altitude of 1,000 feet; and all RAs and TCAS voice alerts are inhibited below 400 feet. Increased climb RAs are inhibited in landing configuration at particular flap settings (varies with airplane model). Additional inhibits exist for "Climb" or "Increased Climb" commands above fixed barometric altitudes, depending on aircraft performance.

All of the inhibits are verified for proper operation during ground testing. Pressure and radio altitudes are simulated by a Boeing Semi-Automated Flightline Tester (SAFT) for activation and evaluation of TCAS inhibits.

TCAS Interfaces

The TCAS system interfaces with the Air Data Computers (ADC), Inertial Reference System (IRS), Air Traffic Control (ATC) transponders, Radio Altimeters, Ground Proximity Warning System (GPWS), and cockpit speakers (Figure (7)). SAFT simulated inputs are used to exercise and evaluate the interfaces. Failure mode annunciations and displays are checked by pulling interfacing system circuit breakers and verifying proper TCAS system response.

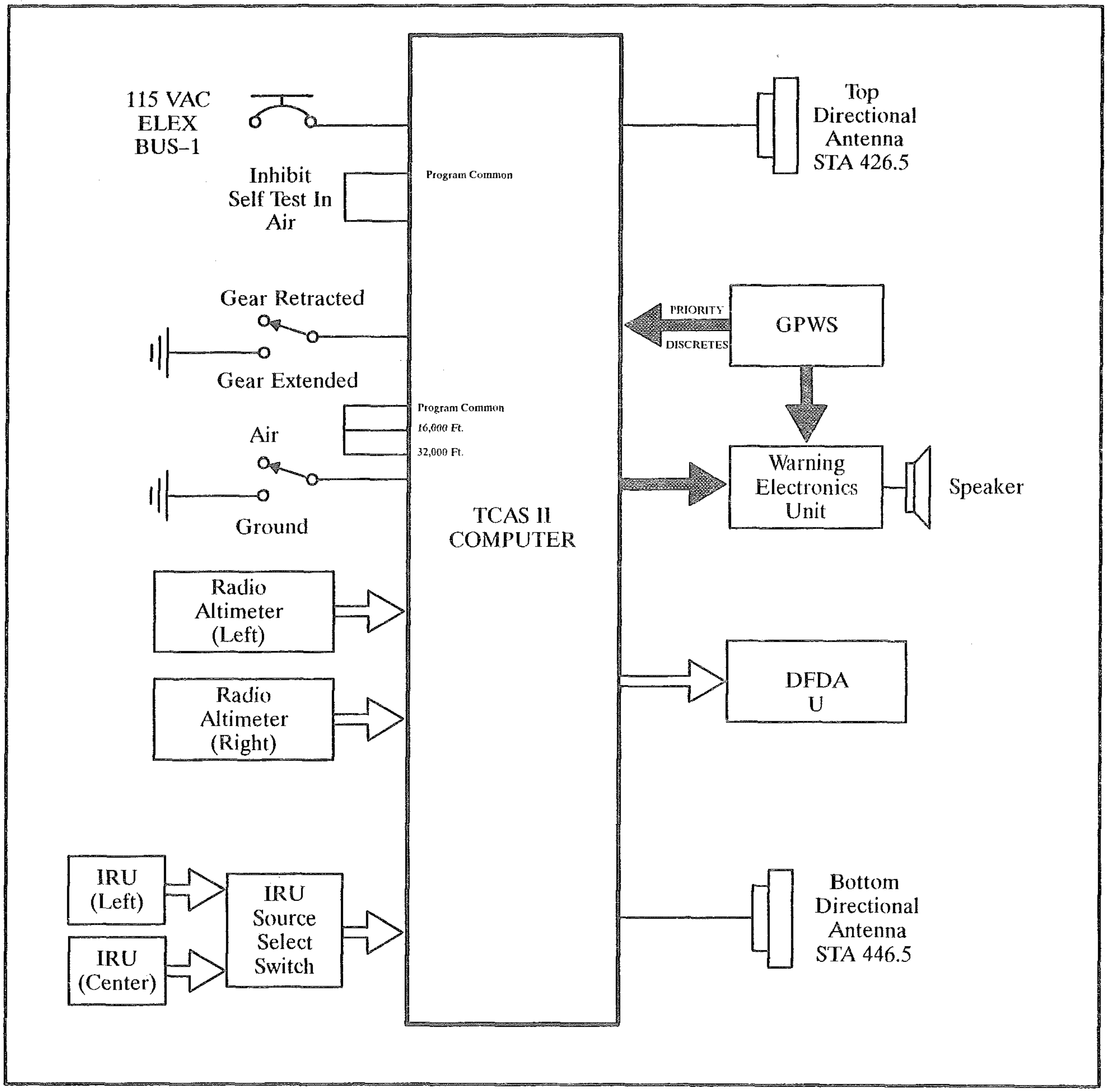

Figure 7 – 757/767 TCAS II System

TCAS Encounters

TCAS operation is evaluated in flight during encounters with targets of opportunity and planned encounters with the ground-station target. The encounters are used to confirm that appropriate aural alerts occur correctly with the TAs and RAs and to verify proper traffic symbology and altitude information on EHSI displays. Figure (8) depicts a TCAS II encounter. In most cases, the RAs are flown as displayed on the EADI. The displays are evaluated for accurate, complete and continuous TCAS information.

Head-on approaches with the TCAS ground station intruder are flown to generate TCAS advisories. Flight at or slightly above the ground-station target's transmitted altitude generates climb RAs. Flying slightly below the ground-station target's altitude generates descend RAs. By ignoring initial RA commands, increase climb or descend RAs can be provoked.

RESULTS AND DISCUSSION

Ground and flight tests have been conducted for each of three TCAS vendors and one intermix combination of components.

The initial TCAS testing identified areas for improvement of each system tested. Some of these areas included target splitting (due to multipathing) on the TCAS traffic display in flight, repeated TCAS computer failures and ear shattering TCAS aural volume levels.

Ground Test

The ground tests are typically 10 to 16 hours in duration, including the usual test setup (airplane positioning, test gear hookups and troubleshooting). The greatest source of frustration during the ground tests has been the operation of the TCAS ramp test-sets. A prototype unit was used for initial testing; it was finicky and the software was later upgraded to provide more dependable operation. Later units felt the wrath of Pacific Northwest weather as rain penetrated a misaligned seal in one of the test-sets, rendering it inoperative. Antenna cable connectors often wear loose, causing erratic and intermittent simulations. Improvements are being made with each subsequent unit, and their operation is becoming more reliable.

Bearing accuracy of the TCAS top directional antenna is typically within ±5° during the ground test. The largest errors are generally no greater than ±10°. One vendor's bearing accuracy deteriorated when installed on the 757-200 airplane with errors as high as ±35°. That TCAS system was modified and retested with satisfactory results.

As noted previously, bottom directional antenna bearing accuracy testing on the ground usually results in erroneous readings caused by signal multipathing.

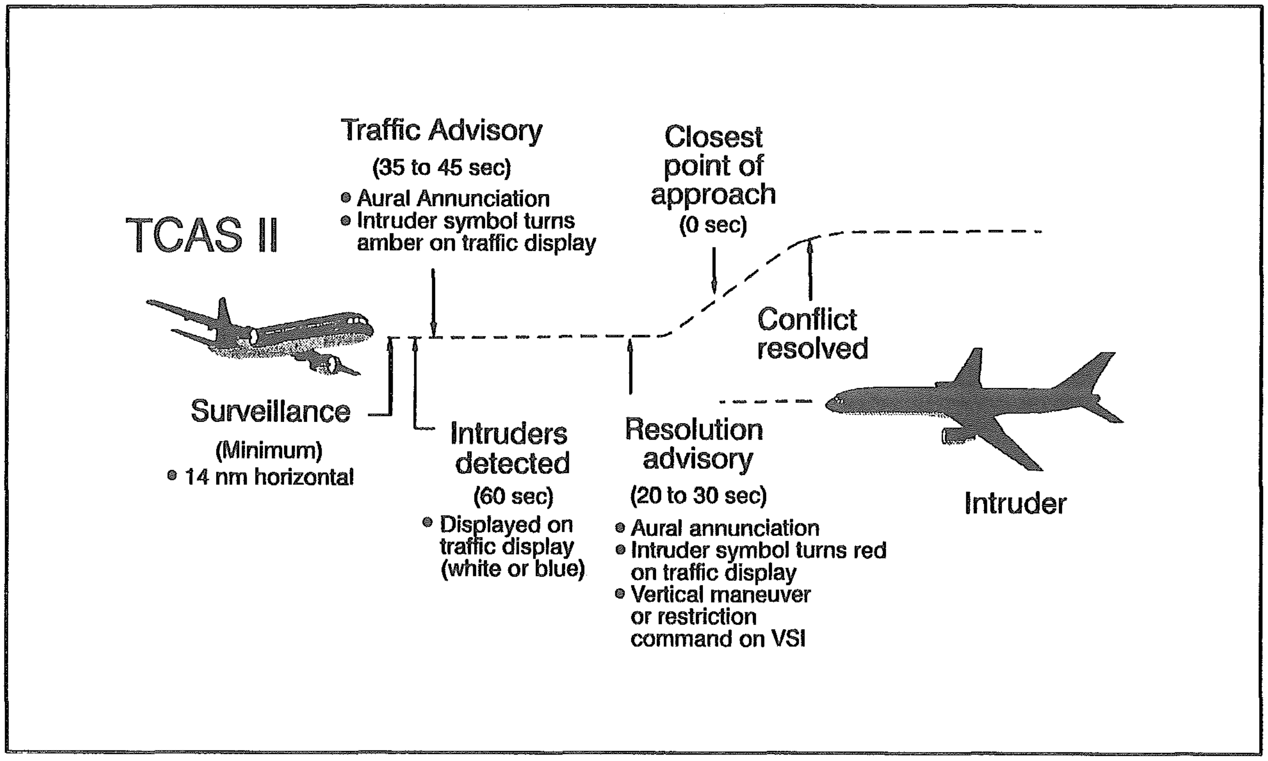

Figure 8 - TCAS II Encounter

Flight Test

TCAS flight tests are typically flown with ATC transponder tests. The flights are three to four hours in duration. One hour is dedicated to transponder testing. The TCAS system bearing accuracy cloverleaf pattern takes a little over an hour to fly. The rest of the time is used for planned encounters with the ground-station target and additional TCAS testing.

The cloverleaf pattern is physiologically distressing for some of the passengers. Flight at the low altitudes used for the pattern produces a bumpy and somewhat uncomfortable ride. Cloverleaf patterns flown at the Paine Field ground-station site used up to 60°of bank for maneuvering due to airspace and terrain considerations.

On nearly every test flight, TAs and RAs are issued while being vectored by ATC during departures from and approaches to Boeing Field, Seattle, Washington. Some of the advisories are generated by general aviation aircraft in normal traffic patterns for landing at the airport, several by approaching and departing helicopters, and some by other aircraft being vectored by ATC. Many of the RA commands are not followed if the intruders are in sight and determined not to be a factor. The flight test pilots occasionally find these advisories to be distracting and sometimes unnecessary.

Inflight bearing accuracy of the TCAS system is obtained during the cloverleaf pattern is typically within ±7°. Encounters with the ground-station target results in vertical displacements of three to five hundred feet in reaction to "Climb" or "Descend" resolution advisories.

CONCLUSIONS

The TCAS II tests conducted satisfactorily demonstrated TCAS II systems for FAA follow-on certification and were successful in identifying problem areas of TCAS operation.

Onboard data is limited and special programs are necessary for data reduction. Large analysis effort was required to sort out the ground-station target from other targets because its intruder number changed frequently. Relocating the ground station to a more remote test area with low air traffic densities minimized this effort. It also provided a greater margin of safety and allowed TCAS RAs to be flown to their full extent.

Cameras mounted in the flight deck to record TCAS Traffic and Resolution displays provided valuable post flight data for TCAS system analysis.

The success of TCAS operation will ultimately depend on pilot reaction to TCAS advisories. This means pilots must have confidence in the system. To build pilot confidence, nuisance advisories must be reduced. This will require modification of the Collision Avoidance System (CAS) logic to reduce TCAS sensitivity to aircraft in normal airport operations, development of test codes for maintenance activity on ground-based aircraft, and the equipping of aircraft with properly operating transponders.

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