

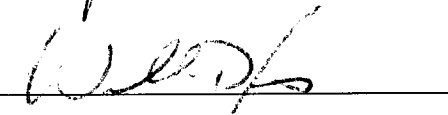
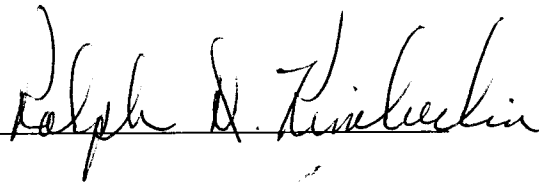
To the Graduate Council:

I am submitting herewith a thesis written by Edwin V. Odisho II entitled "An Evaluation of the Traffic Collision Avoidance System for T-1A Cell Formation Stationkeeping." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.



Dr. Frank Collins, Major Professor

We have read this thesis and recommend its acceptance:



Accepted for the Council:



Associate Vice Chancellor
and Dean of the Graduate School

AN EVALUATION OF THE TRAFFIC ALERT AND COLLISION
AVOIDANCE SYSTEM FOR T-1A CELL FORMATION
STATIONKEEPING

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Edwin V. Odisho II

December 1996

DISCLAIMER

The results contained within this thesis were developed at the Naval Air Warfare Center, Aircraft Division, Patuxent River, Maryland. The discussion of the data, conclusions and recommendations presented are the opinion of the author and should not be construed as an official position of the United States Department of Defense, the Naval Air Systems Command or the Naval Air Warfare Center.

ABSTRACT

The United States Air Force Headquarters Air Education and Training Command (HQAETC) desired the capability to accomplish limited cell formation training with the T-1A Jayhawk jet transport aircraft in instrument meteorological conditions (IMC), using the Traffic Alert and Collision Avoidance System (TCAS). Traffic Alert and Collision Avoidance System is a family of airborne devices that function independently of the ground-based air traffic control system, and provide collision avoidance for a broad spectrum of aircraft types.

Testing was conducted using two T-1A Jayhawks, provided by AETC. The general test objective was to evaluate the feasibility of using the TCAS to execute IMC trail formation procedures. Instrument meteorological conditions are defined when the prevailing visibility is less than three statute miles or the ceiling is observed to be less than one thousand feet. The ceiling is normally identified as the base of a cloud layer cover of more than fifty percent coverage of the sky. Cell formation stationkeeping is an maneuver where multiple aircraft fly in formation with each other while maintaining a set distance apart. For the purposes of this evaluation, cell formation required the aircraft to maintain a position one mile in trail of the lead aircraft and 500 feet below the lead aircraft's altitude. The TCAS system was evaluated during takeoff, climb, cruise, and descent. Seven formation sorties, totaling 25.5 flight hours, were flown during this evaluation. Overall, the TCAS system was satisfactory for use during IMC cell formation procedures in the T-1A Jayhawk.

System performance characteristics during cell formation procedures were satisfactory. The TCAS position accuracy was satisfactory, and there were no antenna blanking problems which would impact normal cell formation operations. Antenna blanking results from signal interference and precludes the receiver from receiving and processing the signal from the transmitter. A safe operational envelope, compatible with current cell formation procedures, was determined. The TCAS operation in a high density traffic environment was satisfactory. Workload during simulated and actual IMC ranged from light, during straight and level flight, to high during unannounced maneuvering. Unannounced maneuvering was defined as any maneuvering performed by the lead aircraft without broadcasting the intent of his impending maneuver.

It is recommend that the TCAS be incorporated into current AETC cell procedures for IMC operations. No evaluation of operational cell formation procedures was performed due to the lack of established AETC TCAS cell formation procedures. A published set of procedures is necessary for operational use of the TCAS system for cell formation in actual IMC and should be established prior to operational employment of the system. To minimize pilot workload, inter-aircraft communications should be established and maintained during IMC operations. In addition, several recommendations to improve the TCAS display, warnings and cues were made.

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LIST OF ABBREVIATIONS AND SYMBOLS

A/A	Air-to-Air
ADF	Automatic Direction Finding
AETC	Air Education and Training Command
AFB	Air Force Base
AFFTC	Air Force Flight Test Center
AGL	Above Ground Level
ASC	Aeronautical Systems Center
ATC	Air Traffic Control
CA	California
C/A	Coarse Acquisition
EPE	Estimated Position Error
GPS	Global Positioning System
HQ	Headquarters
IFF	Identification, Friend or Foe
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
KIAS	Knots Indicated Airspeed
MCT	Maximum Continuous Thrust
MFD	Multi-Function Display

N ₁	Percent engine speed in rotations per minute
OH	Ohio
PA	Pressure Altitude
SKE	Station Keeping Equipment
SWAT	Subjective Workload Assessment Technique
TA	Traffic Advisory
TACAN	Tactical Air Navigation
TCAS	Traffic Alert/Collision Avoidance System
TECCS	Technical Evaluation Command and Control System
TSPI	Time Space Position Information
TPS	Test Pilot School
USAF	United States Air Force
UTC	Universal Time Code
VMC	Visual Meteorological Conditions

CHAPTER I

INTRODUCTION

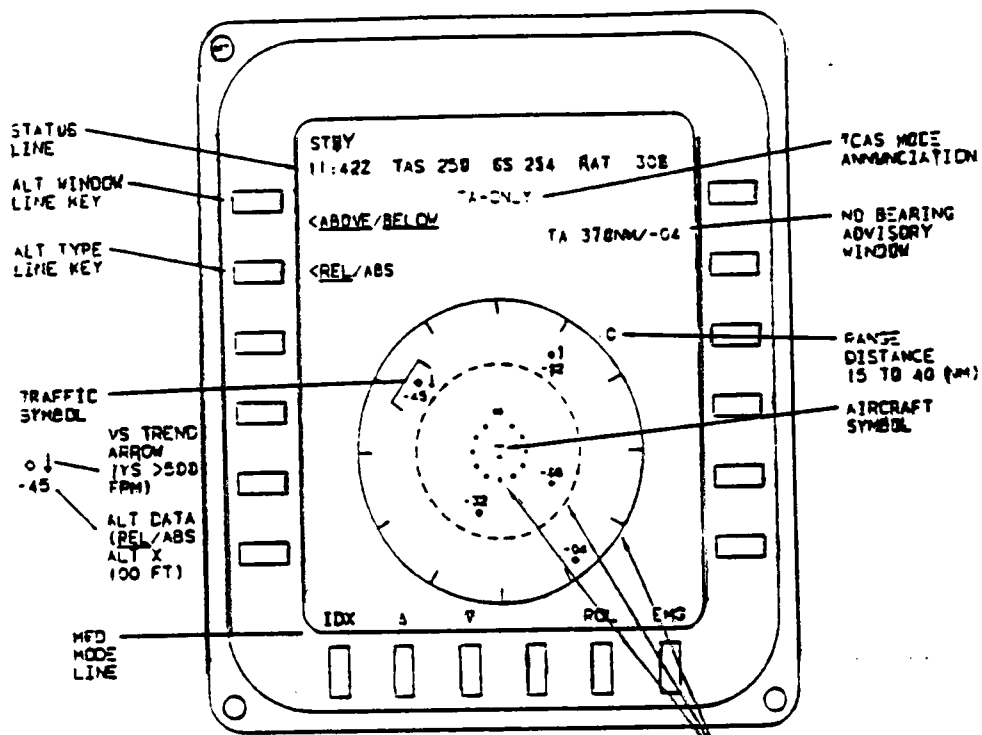
BACKGROUND

United States Air Force Headquarters Air Education and Training Command (HQ AETC) requested the United States Air Force Test Pilot School (USAFTPS) to investigate the station-keeping capabilities of the Traffic Alert and Collision Avoidance System (TCAS) for instrument flight rules (IFR) cell formations in the T-1A Jayhawk. Two T-1A Jayhawks (USAF serial numbers 90-0404 and 92-1633) provided by AETC were used in the testing. Seven formation sorties, totaling 25.5 flight hours, were flown during this evaluation.

Air Education and Training Command desired the capability to accomplish limited cell formation training with the T-1A Jayhawk in instrument meteorological conditions (IMC). Instrument meteorological conditions are defined when the prevailing visibility is less than three statute miles or the ceiling is observed to be less than one thousand feet. The ceiling is normally identified as the base of a cloud layer cover of more than fifty percent coverage of the sky. Cell formation stationkeeping is an maneuver where multiple aircraft fly in formation with each other while maintaining a set distance apart. For the purposes of this evaluation, cell formation required the aircraft to maintain a position one mile in trail of the lead aircraft and 500 feet below the lead aircraft's altitude. At the time, air-to-air Tactical Air Navigation (TACAN) was used only in visual meteorological conditions, but not in instrument meteorological conditions. Tactical Air Navigation is an

avionics system used in military aircraft to navigate from fixed base ground stations using both azimuth and distance measuring equipment. In the air-to-air mode, TACAN indicates distance between two aircraft in nautical miles. Distance is presented the aircrew in the form of a digital readout in nautical miles. In October 1994, Beechcraft Aircraft Company and the USAF accomplished a quick-look study using an enhanced TCAS display for T-1A cell formation station-keeping. The TCAS display is shown in Figure 1. During the single proof-of-concept flight test, the trail aircraft was able to maintain 1 nautical mile in-trail formation position with the lead aircraft using the TCAS system.

The TCAS system was evaluated during takeoff, climb, cruise, and descent. A T-1A instructor pilot occupied the right seat of each aircraft during all of the flights. The author was the project test pilot and flew both lead and wing positions during the test sorties. One flight was flown outside the local Edwards flight area, within the Los Angeles basin, in order to test the TCAS in a high density traffic environment. All flights originated from and ended at Edwards AFB California.



SYMBOLS (NOTE 1)

- (RED) = RA TRAFFIC
- (YELLOW) = TA TRAFFIC
- ◆ (CYAN) = PROXIMATE TRAFFIC
- (CYAN) = OTHER TRAFFIC

RANGE RINGS

- OUTER = 5 TO 40 NM
- MIDDLE = HALF SCALE
- INNER = 2 NM (NOTE 2)

NOTES

1. VS TREND ARROW AND ALT DATA SAME COLOR AS TRAFFIC SYMBOL
2. BLANKS WHEN SELECTED RANGE IS 40 NM

Figure 1
TRAFFIC COLLISION AND AVOIDANCE SYSTEM MULTIFUNCTION DISPLAY
Source: Beechcraft Corporation

TEST ITEM DESCRIPTION

Traffic collision alert avoidance system

Traffic Alert and Collision Avoidance System is a family of airborne devices that function independently of the ground-based air traffic control system, and provide collision avoidance for a broad spectrum of aircraft types. TCAS I provides proximity warning only, to assist the pilot in the visual acquisition of intruder aircraft. It is intended for use by smaller commuter aircraft and by general aviation aircraft. TCAS II provides traffic advisories and resolution advisories (recommended escape maneuvers to avoid collision) in a vertical direction to avoid conflicting traffic. Airline aircraft, and larger commuter and business aircraft use TCAS II equipment. TCAS III provides traffic advisories and resolution advisories in the horizontal as well as the vertical direction to avoid conflicting traffic.

The TCAS incorporated in the Beechcraft T-1A Jayhawk was the primary test item. The TCAS was an airborne device that functioned independently of the ground-based air traffic control (ATC) system, and provided collision avoidance protection. The TCAS was built by Collins Commercial Avionics-Rockwell. The TCAS actively interrogated the transponders of nearby aircraft and provided a warning when the proximity of an aircraft was determined to be a safety threat. The TCAS system was comprised of a multifunction display, the computer unit, a receiver/transmitter unit, a directional antenna located on the top of the aircraft, and an omnidirectional antenna located on the bottom of the aircraft. Surrounding traffic relative bearing and range information were displayed on

the multifunction TCAS traffic page. The TCAS computer unit computed the relative position of the surrounding traffic by using the directional antenna for bearing information and the time between the TCAS interrogation and the transponder reply of the surrounding traffic for distance information. Transponder Mode C (altitude information only) was transmitted along with the reply. A transponder is a piece of avionics equipment that provides aircraft identification to air traffic control via a beacon that replies to interrogations from a ground station.

The TCAS control panel controls all TCAS elements including the computer, Mode S transponder, and the display. Control information is provided to the TCAS computer via the Mode S transponder. The Mode S transponder performs the normal air traffic control functions of existing Mode A and C transponders. Because of its selective address capability, the Mode S transponder is also used to provide air-to-air data exchange between TCAS-equipped aircraft to ensure coordinated, complementary resolution advisories.

The TCAS computer unit performs airspace surveillance, intruder and own aircraft tracking, threat detection and resolution, and advisory generation. Pressure and radar altimeter inputs are used by the computer to control the collision avoidance logic parameters that determine the protection volume around the aircraft. The vertical dimensions of the protected volume are twelve hundred feet above and below the altitude of the aircraft. The horizontal dimensions are not based on actual distance, but on the time to the closest point of approach. The size of the protected volume depends on the

speeds and headings of the aircraft involved and also on the slant range. TCAS is designed to provide collision avoidance protection in the case of any two aircraft which are closing horizontally at any rate up to twelve hundred nautical miles per hour and vertically up to ten thousand feet per minute. If a tracked aircraft is a collision threat, the computer selects the best avoidance maneuver. An avoidance maneuver is a climb, turn, or a combination of both that an aircraft performs in order to avoid a collision with another intruder aircraft. The primary instrument used by the pilot to determine whether an adjustment in aircraft vertical rate is necessary to avoid a threat aircraft is the vertical speed indicator, modified to indicate the vertical rate that must be achieved to maintain safe separation from threatening aircraft. The display contains red and green eyebrow lights around the vertical speed scale, nominally segmented at five hundred feet increments from two hundred feet per minute to six thousand feet per minute. The decision of whether to maneuver or not is based on the position of the needle with respect to the lighted segments or eyebrow lights. If the needle is in the red segment, the pilot is to change the aircraft vertical rate until the needle falls within the green segment.

The antennas used by TCAS include a directional antenna which transmits interrogations on one thousand thirty megahertz at varying power levels in each of four ninety degree azimuth segments. Transponder replies are received on one thousand ninety megahertz and are sent to the TCAS computer unit. The directional antenna permits the partitioning of replies to reduce synchronous garbling. Synchronous garbling, or antenna blanking, occurs when Mode A and C transponders reply to a Mode C

interrogation. Because of the length of the reply, all Mode A and C equipped aircraft within a range difference of 1.7 nautical miles from the TCAS will generate replies which garble when received at the TCAS. Hardware degarblers can reliably decode up to three overlapping replies, and the combined use of variable power levels and suppression pulses reduces the number of transponders which reply to a single interrogation. This technique, which is known as whisper-shout, takes advantage of differences between the receiver sensitivity of transponders and the transponder antenna gains of the target aircraft. An omnidirectional transmitting and receiving antenna mounted on the bottom of the aircraft provides range and altitude data on targets that are below the TCAS aircraft.

The TCAS display depicts the position of the traffic relative to the TCAS aircraft, to assist the pilot in visually acquiring intruding aircraft, in discriminating between intruder threats, and other traffic, and in determining the horizontal position (range and bearing) of transponder-equipped aircraft. Relative altitude or, optionally, flight level is also shown for those targets reporting pressure altitude. The refresh rate is once per second. Targets of interest on the display are symbolized in various shapes and colors.

The production TCAS full-scale range was variable from 5 to 40 nautical miles on the TCAS traffic page. The TCAS units under test were modified to display a 2 nautical mile scope. This was the primary screen that was tested for station-keeping. Other than the 2 nautical mile range display modification, no software or hardware modifications were made, and the TCAS units used for this test were considered production representative.

Supporting aircraft

Two Beechcraft T-1A Jayhawks (USAF serial numbers 90-0404 and 92-1633) were flown for this evaluation. The T-1A was a swept-wing, high and low altitude, all-weather trainer. The normal training crew complement was three crewmembers (one instructor pilot and two student pilots). Two aft-mounted Pratt and Whitney JT15D-5B turbofan engines powered the T-1A. The T-1A also included speedbrakes, spoilers for roll control, a reversible flight control system, yaw damper, full span slotted Fowler flaps, retractable tricycle-type landing gear, nose wheel steering, and independent main gear anti-skid brakes. The T-1A test aircraft were modified by replacing the automatic direction finding (ADF) antenna with a global positioning system (GPS) blade antenna. Since the ADF was not required for navigation or other functions during this test, removal of the antenna did not impact normal aircraft operations. An antenna cable was routed from the GPS antenna to the passenger compartment. These modifications did not alter the aircraft's performance or handling qualities; therefore, the aircraft were considered production representative.

Instrumentation

Test instrumentation on each aircraft included a portable Garmin GPS100 GPS, incorporating coarse acquisition (C/A) code only, a NEC Versa E Series notebook computer, and either a VHS or 8 millimeter video camera. All of the instrumentation units were battery-powered. The Garmin GPS100 units were used in each aircraft to obtain reference position data during flight testing. Position and time data from the GPS units were archived inflight on the NEC Versa E Series notebook computers by using a serial

communication port. The data rate from the GPS was 1 sample every 2 seconds which proved adequate for meeting test objectives. The aircraft traveled a distance of approximately seven hundred thirty-five feet during two seconds. The video camera was used to record the TCAS multifunction-function display and aircraft intercom and radio transmissions.

TEST OBJECTIVES

The general test objective was to evaluate the feasibility of using the TCAS to execute IMC trail formation procedures in the T1-A Jayhawk.

The specific test objectives were to:

1. Quantitatively evaluate the T-1A TCAS system's performance when used for formation station-keeping procedures.
 - a. Evaluate the ability of the TCAS to display proper formation position within the area defined by the following limits: one nautical mile +/- 1/2 nautical miles aft of lead, 1,000 feet above to 1,000 feet below lead's position, and +/- 30 degrees lateral displacement.
 - b. Investigate in-trail positions for any regions of antenna blanking or performance degradations.
2. Qualitatively evaluate the ability to maintain in-trail formation position using TCAS in a high density traffic environment.

3. Qualitatively evaluate the TCAS display and warning cues for station-keeping operations.
4. Qualitatively evaluate pilot workload while using the TCAS for IMC station-keeping procedures.

All test objectives were met.

CHAPTER II

REVIEW OF THE LITERATURE

INTRODUCTION

In recent years, increases in the amount and changes in the distribution of air traffic have been very dramatic and are continuing. The need for changes in the current air traffic systems is clear. The impact of air traffic systems on the economic well being of a country can be demonstrated by the fact, in the United States alone, delays due to air traffic problems will result in losses in billions of dollars per year if dramatic changes are not made. As a result, extensive research is being conducted to discover new ways of modernizing and improving air traffic control systems.

The International Civil Aviation Organization (ICAO) has developed standards for airborne collision avoidance system for aircraft. TCAS is a piece of equipment, manufactured in the United States, and since January 1994, is mandatory for all aircraft with more than thirty seats and flying over the United States. The International Civil Aviation Organization evaluation conducted from 1990 to 1993 has highlighted the safety benefits which could be obtained from airborne collision avoidance systems. Training is essential for pilots and air traffic controllers for the best use of the system.¹ The number of TCAS equipped aircraft increases steadily, due to United States law mandating installation. Over five thousand aircraft within the United States and a large number of foreign aircraft commuting to and from the United States airspace are already TCAS

¹ Casaux 1995

equipped. Whenever TCAS declares a nearby aircraft to be a threat, it issues a resolution advisory (RA) to the pilot. Such an advisory can either be preventive or corrective and therefore can interfere with normal air traffic control.²

It is suggested that TCAS will evolve from its limited collision avoidance only role to become an integral part of the airspace management system. Benefits will be cooperative air traffic procedures, reduced separations, and independent routings.³

TCAS EFFECTS ON AIR TRAFFIC CONTROL

The effects of TCAS avoidance applications on pilot and controller interactions are analyzed, and strategies that could promote more harmonious human-technology interaction are suggested. It is found that TCAS has definitely enhanced flight safety and is widely supported by the commercial pilot community. TCAS applications have had an impact on the respective roles of the pilot and the controller. Behavior ramifications need to be fully evaluated in concert with ergonomic issues.⁴

The Federal Aviation Administration's future aviation surveillance systems fall into four categories: Automatic Dependent Surveillance (ADS) will be used in the oceanic environment; ADS-Broadcast (ADS-B) will be used in the domestic enroute environment; ADS-B will be used with a secondary radar backup in the terminal area; and ADS-B will be used with primary radar backup within the Airport Surface Traffic Automation system on the airport's surface environment. Two other systems introduced by Donohue are Cockpit Display of Traffic Information and Traffic Advisory and

² Kuegler 1994

³ Deckert 1992

Collision Avoidance System. All these systems will use navigational signals emitted by the GPS constellation of satellites.⁵ The next generation of the airborne collision avoidance system, TCAS IV, will improve upon the present TCAS II in several respects. In making use of accurate satellite-based position data and air to air data link on intent, TCAS IV will support superior collision threat detection and resolution. Operational applications making use of cockpit-displayed traffic information should facilitate more efficient and flexible flight.⁶ It is anticipated by the FAA that air carrier flights over both the Atlantic and Pacific Oceans between 1996 and 2005 will double and the oceanic air traffic control system will become far more sophisticated. By 2000, use of satellite-based communications, navigation, and surveillance, plus additional hardware and software in the aircraft and on the ground will allow for the vertical separation distance on oceanic routes to be reduced from two thousand to one thousand feet, the in-trail separation distance to be shortened from ten to fifteen minutes (eighty to one hundred twenty nautical miles) to four minutes (thirty nautical miles), the lateral separation distance on parallel tracks to be reduced from one hundred to thirty nautical miles, and properly equipped aircraft to no longer have to fly along standard routes. The planned use of the Global Positioning System and withdrawal of the Omega ground based navigation system in 1997 is mentioned, along with aircraft position surveillance techniques such as automatic dependent surveillance (ADS), which uses GPS-derived positions, and the use of ocean airspace meteorological data from various National Aeronautics and Space

⁴ Mellone and Frank 1993

⁵ Donohue 1995

Administration and weather satellites. In terms of avionics, it is pointed out that due to the high cost of obtaining ADS surveillance data through communications satellites, some time beyond 2000, TCAS and cockpit display of traffic and weather will likely become the primary means of separating aircraft on a tactical basis.⁷ Stead provides a status update on the TCAS Transition Program (TTP) which was established to monitor the operational performance and assist with the introduction of TCAS avionics into the National Airspace System (NAS). The update is provided by means of a qualitative performance comparison between the software logic initially fielded and the latest version developed to address various flight performance dynamics and interface issues between TCAS and the air traffic control system. The latest software logic has been in operation in all TCAS II equipped aircraft since January 1995.⁸

TCAS AND GPS COMBINED SURVEILLANCE

Flight testing of a new air surveillance concept, GPS-Squitter, began during 1994. GPS is a system concept that merges the capabilities of Automatic Dependent Surveillance and the Mode S beacon radar. It integrates GPS receivers with the existing secondary surveillance radar beacon equipment carried by most aircraft. Simple, inexpensive, nonscanning ground stations listen for GPS position reports broadcast by the Mode S beacon transponders on the aircraft and send them on to air traffic control facilities. In addition to its surveillance application, GPS-Squitter presents opportunities for enhancing other important functions such as collision avoidance systems and data link

⁶ Zeitlin 1995

⁷ Fee and Simpson 1995

services. System tradeoff studies are comparing range and altitude coverage with the cost and number of stations needed. Other issues are data link interference, multipath, total aircraft capacity, and unambiguous reporting range. The baseline system uses commercial off of the shelf components in order to ensure low production costs.⁹ Small aircraft have limited access to the sophisticated and relatively high cost TCAS system. Baldwin describes the concept, the development approach, and the requirements analysis of a small low cost system for collision avoidance, called Traffic Alert System, which is being developed for general aviation use. The TAS is aimed at enhancing air safety by combining Mode S and GPS technology.¹⁰

Lincoln Laboratory has investigated the possibility of increasing the capacity of the TCAS by incorporating the horizontal maneuvering of aircraft. Horizontal resolution advisories can be computed if the intruder horizontal miss distances at closest approach are known. Horizontal miss distances can be estimated with range and bearing measurements of intruders. With this method, however, large errors in calculating the horizontal miss distances may result. An improved method of determining the horizontal miss distances is to use the Mode S data link to obtain state data from the intruder aircraft.¹¹

HUMAN FACTORS

⁸ Stead and Gambarani 1995

⁹ Bayliss and Burrows 1994

¹⁰ Baldwin and Smith 1994

¹¹ Burgess and Altman 1994

The need for a safe and expeditious air traffic system, along with recent and rapid developments in advanced computer technology, has been associated with remarkable changes in airway systems operations and in the system decision making process. A key issue in air traffic systems concerns how new technologies should be used to maximize system performance and efficiency, without jeopardizing system safety. These decisions are quite simple for a few selected functions where human performance is superior, or in some instances inferior, to machines. The decisions become more critical in considering those functions where human and machine performance differences are subtle. These latter circumstances present the greatest challenge to the human factors professionals and system designers because of the potential human factors consequences.¹²

One of the more challenging questions in systems integration is the display format. More specifically, pilot and cockpit interface design issues include: determination of what modes of feedback are most appropriate; the merits of visual versus audio displays; and stand alone versus integrated displays. Cotton reviews various display issues relative to TCAS design. Attention is given to existing implementations, resolution advisories, and traffic advisories. Cotton points out that enhancements to TCAS logic are continuing and refinements to symbology to improve the information transfer to pilots have also been identified.¹³

Auditory Display Presentations

¹² Wise and Hopkin 1990

¹³ Cotton 1992

The use of spatialized audio techniques for head-up auditory displays for commercial aircraft has been investigated at the National Aeronautics and Space Administration Ames Research Center since 1989. Results from two completed studies are presented, where a spatialized audio TCAS was designed and evaluated in full mission simulation context. The advantage of a head-up auditory display for situational awareness was evaluated in an experiment designed to measure and compare the acquisition time for capturing visual targets under two conditions: standard head-down TCAS display and spatial audio TCAS presentation. The technology used for spatial audio presentation allows a stereo headphone user to potentially localize a sound at any externalized position in spatialized auditory space. Ten commercial airline crews were tested under full mission simulation conditions. Scenario software generated targets corresponding to aircraft that activated a spatial aural advisory or a standard, visual-audio TCAS advisory (map display with monaural audio alert). Results showed a significant difference in target acquisition time between the two conditions, favoring the spatial audio TCAS condition by five hundred milliseconds.¹⁴

SUMMARY

The need to find more efficient and safe ways to expedite the movement of air traffic is evident, both from a historical perspective and from the driving factor of modern commercial airline economics. What should now be considered is a way to implement existing technologies into the National Airspace System. As the current methods of air traffic control continue to cause costly delays, research clearly points to a future of

¹⁴ Begault and Pittman 1996

autonomous control for pilots and a new relationship with air traffic controllers. The use of TCAS needs to be expanded to include the new role of stationkeeping as well as continuing in the role of collision avoidance.

A trend in recent research indicates that advances in GPS data link capabilities can be combined with TCAS to greatly improve information available to pilots and air traffic controllers. The information available to the human operators should be investigated for accuracy and reliability. In addition, pilot machine interface issues should be examined to discover what improvements need to be made to the existing avionics hardware and software in order for the TCAS to be safely used in an expanded role in the air traffic control system. It is therefore useful to select a current transport system to determine system and human performance while using TCAS in this role.

CHAPTER III

METHODS

TEST PROCEDURES

General Data Collection

Testing was conducted using a buildup approach. Ridley time space position information (TSPI) data were obtained during the first flight to demonstrate the GPS accuracy. The Ridley radar facility is a range tracking facility at Edwards Air Force Base used to accurately determine the position of air vehicles. The GPS position data were used to determine the TCAS position accuracy and define areas of TCAS degradation or antenna blanking. The TCAS traffic prioritization logic was investigated with formation aircraft opening and closing maneuvers. In addition, one flight was conducted in a high-density traffic area to investigate potential interference problems that may be caused by other transponder-equipped aircraft. The TCAS displays and warning cues were evaluated during takeoff, turns, maneuvering, and simulated transponder failure. To assess pilot workload, the TCAS system was used by the trailing aircraft to maintain position on the lead aircraft while using an instrument flight rules (IFR) hood and performing IMC station-keeping procedures.¹⁵ In addition, an operationally representative mission was flown in actual IMC. Pilot comments were recorded on

¹⁵ DOAF 1993

questionnaires and the actual workload was quantified using the Subjective Workload Assessment Technique.¹⁶

The author flew the test sorties as project pilot. He conducted preflight briefings and specifically determined the order in which the test points would be used to gather data. The project pilot stabilized on conditions and called “stable” over the radio. He also made qualitative comments on the TCAS and provided workload assessments in flight.

TCAS Accuracy Data Collection

Portable Garmin GPS100 GPS units (coarse acquisition code only) were used in each aircraft to obtain reference position data during flight testing. Position and time data from the GPS units were archived inflight on NEC Versa E Series notebook computers, using the GARMIN PC100 software at one sample every two seconds. The GPS estimated position errors were calculated and recorded. GPS satellite status was determined prior to each flight. A GPS relative position error was found to be less than one hundred twelve feet and estimated position error values were determined to be less than twenty percent. In addition, battery-operated video cameras were used to record the TCAS multifunction-function display and aircraft intercom and radio transmissions.

The Ridley Mission Control Center (RMCC) FPS-16 range radar was used on the first flight to demonstrate that the GPS units were capable of providing accurate position data. Ridley provided the test team with a post mission file containing universal time code (UTC) time, latitude, longitude, and altitude information at approximately two

¹⁶ Reid and Nygen 1987

samples per second for both aircraft. The GPS relative position accuracy was evaluated by comparing GPS position and time data with RMCC radar TSPI. The RMCC radar TSPI data were accurate to within approximately fifty feet using skin tracking.

For TCAS accuracy testing, a battery-operated video camera was used to record the TCAS multifunction and the aircraft intercom and radio transmissions. The video camera was used with the time-on-tape feature to correlate flight events in UTC time between the two aircraft. The GPS units provided position reference information for evaluating TCAS position accuracy. The TCAS position accuracy was evaluated by comparing TCAS relative range, bearing and time information with GPS position and time data.

The TCAS in both aircraft were set up in the traffic advisory (TA) mode with the two nautical mile range display. Both aircraft barometric altimeters were set to 29.92 inches of mercury. The lead aircraft called the base heading and stabilized at 250 KIAS $\pm$ 10 knots and 20,000 feet pressure altitude (PA) $\pm$ 500 feet. To maintain a stable airspeed and altitude, the lead aircraft engaged the autopilot. When the wingman called "Stable" over the radio, data were recorded for that stable point. Criteria for recording a stable point, were that both aircraft were within speed and altitude tolerances for a period time at least five seconds in duration. The airspeed and altitude tolerances for both lead and the wingman were $\pm$ 5 knots and $\pm$ 100 feet, respectively. The tolerances for the wingman were $\pm$ 1000 feet in-trail and $\pm$ 5 degrees of azimuth from the desired stable position. The TCAS system was designed so that if it stopped receiving transponder replies from a displayed traffic target, the TCAS would enter a coast mode for that

aircraft. After 6 seconds of coasting with no transponder replies, the target would disappear from the display. The TCAS gave no indication to the aircrew when it was operating in the coast mode. To ensure potential blanking was not masked by the TCAS coast feature, the wingman stabilized on test conditions for 15 seconds. Each aircraft recorded the time when stable, GPS positions, GPS estimated position error values, aircraft magnetic headings, barometric altitude, and TCAS relative altitude. The enroute stable point depiction is shown in Figure 2. In addition, the TCAS displays were videotaped. The magnetic variation for the region of testing was applied to the wingman's magnetic heading to determine the aircraft true heading. The wingman's true heading and GPS position

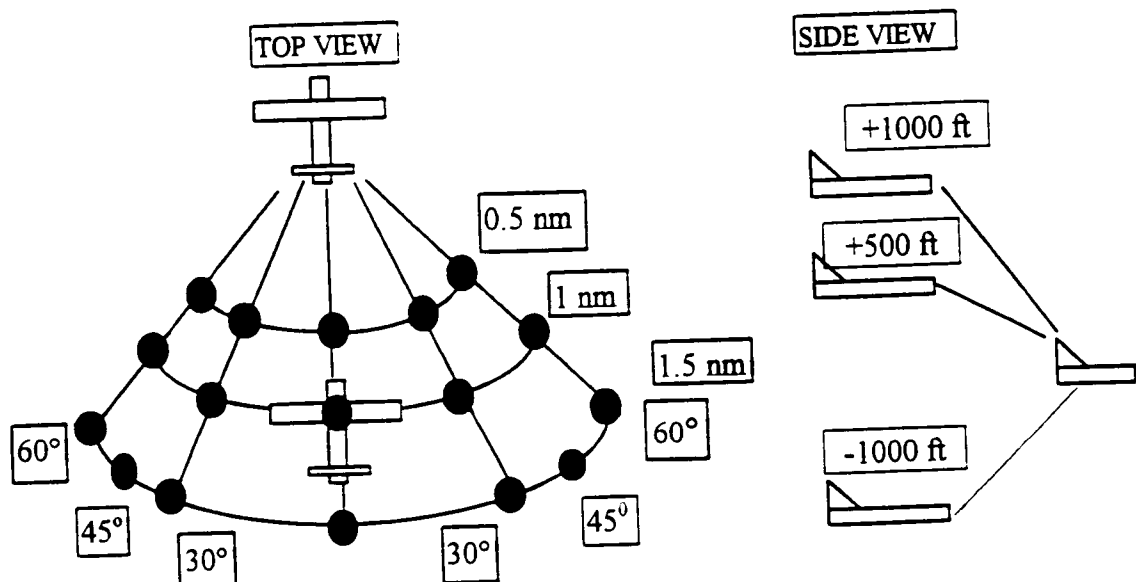


Figure 2
T1A JAYHAWK ENROUTE STABLE POINT DEPICTION

data were used to determine the bearing and range between the aircraft. The TCAS display video of the stable points were converted into still photographs for post mission analysis. The bearings and ranges depicted on the TCAS display photographs were compared to the GPS data, and the difference between the lead and wingman barometric altitudes were compared to the TCAS relative altitude.

Antenna blanking Data Collection

Antenna blanking and performance degradation were investigated during climb, enroute cruise, and enroute descent. Maximum continuous thrust (MCT) minus five percent N_1 (percent engine fan speed in rotations per minute) in-trail formation climbs were performed from 7,000 to 20,000 feet PA. The TCAS in both aircraft were set up in the TA mode with the two nautical mile range display. Both aircraft barometric altimeters were set to 29.92 inches of mercury. The tolerances for the wingman were $\pm 1,000$ feet in-trail and ± 5 degrees of azimuth from the desired stable position. To ensure potential blanking was not masked by the TCAS coast feature, the wingman maintained stable test conditions for fifteen seconds.

The lead aircraft called the climb base heading and climbed at 220 KIAS. The data band was ± 5 knots with a ± 3 knot tolerance. To maintain a stable climb airspeed, the lead aircraft engaged the autopilot. The lead aircraft made altitude calls every one thousand feet. Once at the desired position, the wingman called "Stable" over the radio. Each aircraft recorded the time when stable, GPS positions, GPS estimated position error

values, and videotaped the TCAS displays. The GPS position data were used to define precisely the wingman's relative position from lead if antenna blanking occurred.

While performing TCAS accuracy testing, straight and level enroute cruise antenna blanking was also investigated. In addition to the TCAS accuracy test points, the wingman stabilized one nautical mile abeam (both left and right) and co-altitude with lead. Then, the wingman stabilized one nautical mile abeam (both left and right) and 1,500 feet above and below lead. Finally, the wingman stabilized 1,500 feet directly above and below lead. The TCAS in both aircraft were set up in the TA mode with the two nautical mile range display. Both aircraft barometric altimeters were set to 29.92 inches of mercury. The lead aircraft called the base heading and stabilized at 250 KIAS $\pm$ 10 knots and 20,000 feet PA $\pm$ 500 feet. To maintain a stable airspeed and altitude, the lead aircraft engaged the autopilot. Climb and descent stable point depictions are shown in Figures 3 and 4 respectively. To ensure potential blanking was not masked by the TCAS coast mode, the wingman maintained on conditions for fifteen seconds. Each aircraft recorded the time when stable, GPS positions, GPS EPE values, and videotaped the TCAS displays. The GPS position data were used to define precisely the wingman's relative position from lead if antenna blanking occurred.

In-trail turns using twenty, thirty, and forty-five degrees of bank were performed to investigate antenna blanking while maneuvering. The TCAS in both aircraft were set up in the TA mode with the two nautical mile range display. Both aircraft barometric altimeters were set to 29.92 inches of mercury. The lead aircraft announced the turn over

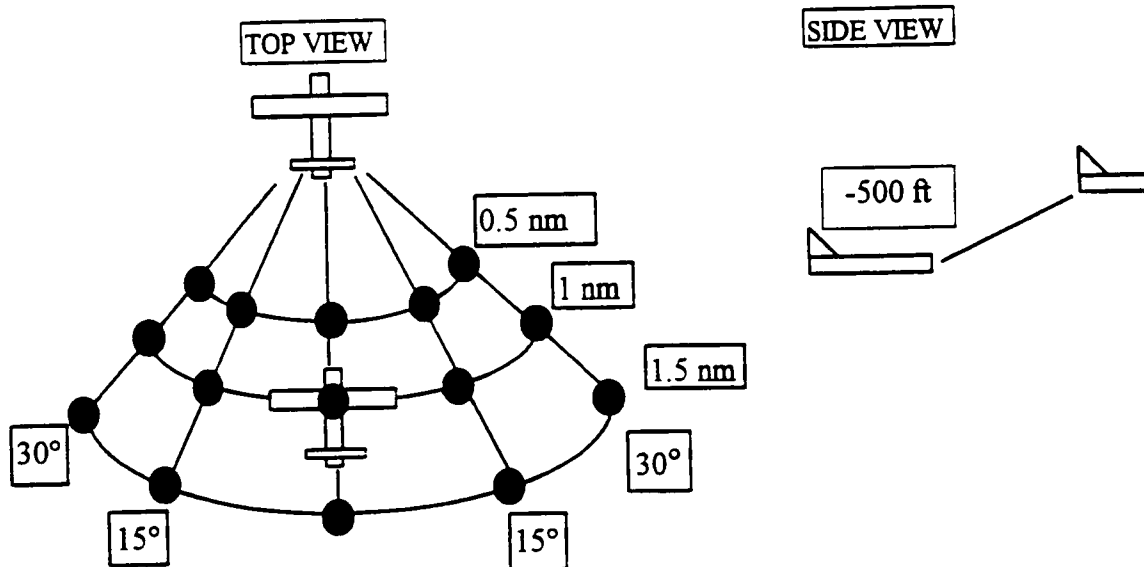


Figure 3
T1A JAYHAWK CLIMB STABLE POINT DEPICTION

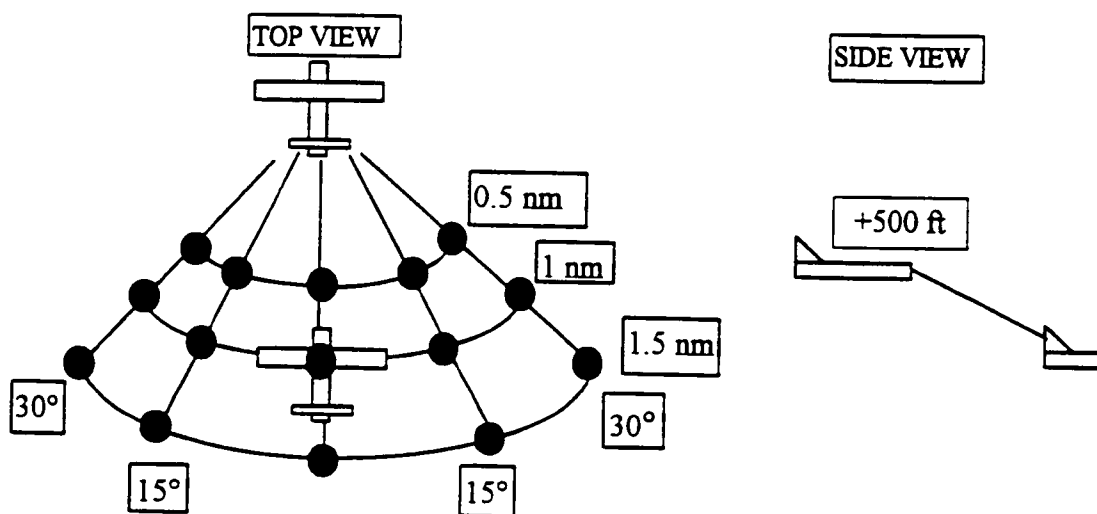


Figure 4
T1A JAYHAWK DESCENT STABLE POINT DEPICTION

the radio by stating the angle of bank and direction of the turn. Both ninety and one hundred eighty degree turns were performed at 20,000 feet PA $\pm$ 500 feet and 250 KIAS $\pm$ 10 knots. With twenty and thirty degrees of bank, the lead aircraft either hand-flew or used the autopilot to accomplish the turns. Forty-five degree banked turns were hand-flown. The wingman delayed the turn based on true airspeed and in-trail distance from the lead aircraft. Each aircraft recorded the turn start time, GPS positions, and videotaped the TCAS displays.

Enroute descents were accomplished from 20,000 to 7,000 feet PA to investigate antenna blanking. The TCAS in both aircraft were set up in the TA mode with the two nautical mile range display. Both aircraft barometric altimeters were set to 29.92 inches of mercury. The tolerances for the wingman were $\pm$ 1000 feet in-trail and $\pm$ 5 degrees of azimuth from the desired stable position. To ensure potential blanking was not masked by the TCAS coast mode, the wingman maintained stable test conditions for fifteen seconds.

The lead aircraft called the base heading, set power to sixty percent N_1 , and maintained 250 KIAS. During the descent the data band was $\pm$ 5 knots with a $\pm$ 3 knot tolerance. To maintain a stable descent airspeed, the lead aircraft engaged the autopilot. The lead made altitude calls every one thousand feet. Once at the desired position, the wingman called "Stable" over the radio. Each aircraft recorded the time when stable, GPS positions, GPS EPE values, and videotaped the TCAS displays. The GPS position data

were used to define precisely the wingman's relative position from lead if antenna blanking occurred.

Prioritization testing, high density environment Data Collection

Opening and closing maneuvers were flown to investigate the TCAS traffic prioritization logic. The opening maneuvers are executed to open, or increase the distance between the two aircraft and the closing maneuvers are executed to decrease the distance and develop a closure rate between the two aircraft. The logic functions which are used by TCAS to perform the collision avoidance task are based on many special conditions relating to encounter geometries, thresholds, and aircraft performance.

Using surveillance reports each second, the computer tracks the slant range and closing speed of each target aircraft, to determine the time in seconds to the closest point of approach. If the target is equipped with an altitude-coding transponder, the computer also tracks the altitude reports to project the altitude of the target at the closest point of approach. The logic determines the vertical rate of the target by measuring the time it takes to traverse successive one hundred foot increments of altitude. The computer uses the data from its own aircraft pressure altimeter either directly from the altitude encoder or as processed by an air data computer, to determine own aircraft altitude, vertical rate, and relative altitude of each target. This data is then used to determine the traffic advisory and threat detection information to the pilots.

The TCAS in both aircraft were set up in the TA mode with the two nautical mile range display. Both aircraft barometric altimeters were set to 29.92 inches of mercury for

prioritization testing and to local altimeter setting for high density environment testing. Using the autopilot, the lead aircraft maintained 250 KIAS $\pm$ 10 knots and 20,000 feet PA $\pm$ 500 feet. The wingman started 0.5 nautical miles aft and one thousand feet above lead, and then decelerated to twenty-five knots of opening velocity by slowing down. The maneuver was terminated when the wingman reached 1.5 nautical miles aft of lead. Each aircraft videotaped the TCAS display to observe potential degradations or formation aircraft dropouts. The opening maneuver was repeated at fifty knots of opening velocity. Next, closing maneuvers were performed. As in the opening maneuvers, the TCAS in both aircraft were set up in the TA mode with the two nautical mile range display, and the lead aircraft used the autopilot to maintain 250 KIAS $\pm$ 10 knots and 20,000 feet PA $\pm$ 500 feet. The wingman started 1.5 nautical miles aft and 1,000 feet above lead, and then accelerated to twenty-five knots of closure. The air-to-air TACAN relative velocity was used to monitor the closure rate. The maneuver was terminated when the wingman was 1,000 feet aft of lead. The closing maneuver was repeated at thirty-five and fifty knots of closure. Each aircraft videotaped the TCAS display.

Air Education and Training Command cell formation procedures (wingman one nautical mile aft and five hundred feet above lead) were used while flying in the Los Angeles approach low-altitude airway structure. Emphasis was placed on the wingman's ability to recognize the lead aircraft and investigate any interference from other traffic. The wingman used the TCAS display in the two nautical mile range, while the lead aircraft used the forty nautical mile range to aid in traffic clearing. The wingman pilot

flew the mission with an instrument flight rules (IFR) hood. The TCAS displays in each aircraft were videotaped. RMCC provided a videotape and computer printouts showing traffic summaries of the mission.

Data Analysis (Displays, warning cues)

For takeoff, the TCAS in both aircraft were set up in the TA mode with the two nautical mile range display. Both aircraft barometric altimeters were set to 29.92 inches of mercury. Also, the air-to-air (A/A) TACAN systems were set up between the aircraft to backup the TCAS information and to use the A/A TACAN relative velocity function. For the runway lineup, the lead T-1A was positioned on the right side of the runway, while the wingman T-1A was positioned on the left side of the runway. The nose of the wingman was aligned with the tail of the lead aircraft with at least thirty feet of lateral wingtip clearance. Lead called for engine run-up to eighty percent N_1 . When the wingman signaled ready, lead released brakes. The wingman started the takeoff roll twenty seconds after lead's brake release. A twenty second interval was chosen to reduce the time required for the wingman to rejoin one nautical mile in-trail. Each aircraft recorded the GPS estimated position error values at takeoff. After weight-off-wheels in each individual aircraft, timing was started to determine when the formation appeared on the TCAS displays. In addition, the wingman in-trail spacing was recorded at the point when the formation appeared on the TCAS display. The delay in display data was due to weight-on-wheels switch which disables the Mode S until airborne. The purpose of determining the delay in display was to determine if takeoffs could be performed in close

formation to the lead aircraft. If the delay was excessive enough to prevent tracking of the lead aircraft when penetrating clouds, then an operating limitation would have been instituted. During the initial climb-out, altimeters were set to 29.92 inches of mercury. Lead accelerated to 220 KIAS and climbed to 7,000 feet PA. The wingman rejoined to one nautical mile in-trail at 6,000 feet PA. If the wingman established position prior to the lead aircraft reaching 7,000 feet PA, then the climb to 20,000 feet PA was started immediately. For the first three sorties, takeoffs were accomplished with the wingman using the TCAS, A/A TACAN, and outside visual cues to rejoin on the lead aircraft. On subsequent missions, the wingman pilot used an IFR hood after passing 300 feet above ground level (AGL) to simulate IMC.

The TCAS display lateral displacement resolution was evaluated by the lead aircraft maintaining $250 \text{ KIAS} \pm 10 \text{ knots}$ and $20,000 \text{ feet PA} \pm 500 \text{ feet}$ using the autopilot. The TCAS in both aircraft were set up in the TA mode with the two nautical mile range display. Both aircraft barometric altimeters were set to 29.92 inches of mercury. The wingman set up one nautical mile aft and 500 feet above lead. The wingman used five degrees of bank to start a slow lateral movement. Timing was started when the maneuver was initiated, and timing was stopped when movement was recognized on the TCAS display. The maneuver was accomplished in both directions. The TCAS display was videotaped, and GPS position data were recorded. A similar procedure was performed to evaluate the utility of the TCAS display for turn recognition.

Both ninety and one hundred eighty degree turns were performed at 20,000 feet PA $\pm$ 500 feet and 250 KIAS $\pm$ 10 knots using twenty, thirty, and forty-five degrees of bank. The lead aircraft announced the turn over the radio by stating the angle of bank and direction of the turn. With twenty and thirty degrees of bank, the lead aircraft pilot either hand-flew or used the autopilot to accomplish the turns. Forty-five degree banked turns were hand-flown. The wingman started timing when the lead aircraft announced "Turning" and timing was stopped when lead's turn was recognized on the TCAS display. The maneuver was accomplished in both directions. The wingman delayed the turn based on true airspeed and in-trail distance from the lead aircraft. Each aircraft recorded the turn start time, turn end time, GPS positions, and video-taped the TCAS displays. Unannounced turns were performed also to evaluate the wingman's ability to maintain formation using only the TCAS display.

Wingman opening and closing maneuvers were flown to investigate the TCAS display update rate. First, opening maneuvers were performed. The TCAS in both aircraft were set up in the TA mode with the two nautical mile range display. Both aircraft barometric altimeters were set to 29.92 inches of mercury. Using the auto-pilot, the lead aircraft maintained 250 KIAS $\pm$ 10 knots and 20,000 feet PA $\pm$ 500 feet. The wingman started 0.5 nautical miles aft and one thousand feet above lead, and then decelerated to twenty-five knots of opening velocity. The air-to-air TACAN relative velocity vector was used to monitor the opening rate. The accuracy of the TACAN was determined to be less than three hundred feet. Each aircraft video-taped the TCAS display. The maneuver was

terminated when the wingman reached 1.5 nautical miles aft of lead. The opening maneuver was repeated for fifty knots of opening velocity. Next, closing maneuvers were performed. As in the opening maneuvers, the TCAS in both aircraft were set up in the TA mode with the two nautical mile range display, aircraft barometric altimeters were set to 29.92 inches of mercury, and the lead aircraft used the auto-pilot to maintain 250 KIAS $\pm$ 10 knots and 20,000 feet PA $\pm$ five hundred feet. The wingman started 1.5 nautical miles aft and one thousand feet above lead, and then accelerated to twenty-five knots of closure. The A/A TACAN relative velocity was used to monitor the closure rate. The maneuver was terminated when the wingman reached one thousand feet aft of lead. The closing maneuver was repeated for thirty-five and fifty knots of closure. Each aircraft video-taped the TCAS display.

TCAS failure was simulated by the lead aircraft turning off the transponder for thirty seconds. Prior to turning the transponder off, the TCAS in both aircraft were set up in the TA mode with the two nautical mile range display. Both aircraft barometric altimeters were set to 29.92 inches of mercury. The lead aircraft maintained 250 KIAS $\pm$ 10 knots and 20,000 feet PA $\pm$ 500 feet using the auto-pilot. The wingman stabilized one nautical mile directly aft and five hundred feet above the lead aircraft. At the lead's call, the lead's transponder was turned off, and timing was started. The time between turn-off and when lead's symbol disappeared from the wingman's TCAS screen was recorded in the wing aircraft. Each aircraft video-taped the TCAS displays to observe the target dropout and any warning cues.

Data Analysis (Workload Assessment)

Pilot workload was assessed for all operationally representative maneuvers. The two test pilots were both former operational C-130 pilots. One had extensive experience in Station Keeping Equipment (SKE) formation procedures. These procedures were similar to the station-keeping procedures used in this test. The author had no SKE or formation station-keeping experience.

Pilot comments were recorded and the actual workload was quantified using the Subjective Workload Assessment Technique (SWAT). The SWAT was developed by the Workload and Ergonomics Branch of the Armstrong Laboratories at Wright-Patterson in the early 1980s. It was a systematically developed and validated subjective measure specifically designed to assess mental workload.¹⁷

Mental workload was proposed to be a multidimensional construct comprised of three component factors: time load, mental effort load, and psychological stress load. In addition, SWAT further defined three levels for each of the component factors roughly corresponding to high, medium, and low loading. The component factors were defined as:

Time Load: That fraction of the total time the pilot was busy.

Mental Effort Load: The amount of attention and concentration required to perform the task.

Psychological Stress Load: The presence of confusion, frustration, or anxiety which caused a need for greater concentration and determination.

¹⁷ Reid and Nygen 1987

A card sort procedure was accomplished by the two test pilots prior to flying the first mission. There were 27 cards which corresponded to each combination of workload rating. These cards were ordered according to which component factor the subject believed contributed most significantly to his perception of mental workload. The net result was an interval workload scale ranging from zero to one hundred. The SWAT card sort performed by the two test pilots revealed that psychological stress load was the most significant factor in their perception of workload.

The SWAT card sort was analyzed using the SWAT computer program. Group scaling was achieved from the results. For group scaling, the card sort data from the pilots were averaged together, and analysis derived a single scale for the group based on a statistic known as Kendall's Coefficient of Concordance. In order for the use of group scaling to be valid, the Kendall's statistic was required to be greater than 0.75. Prior to flight test, the Kendall's statistic for the two test pilots was 0.99; therefore, their perception of mental workload was very closely aligned.

To determine the pilots' perception of workload, the test pilots provided a SWAT rating for individual operationally representative tasks. The SWAT rating was converted to a SWAT value determined from the interval workload scale produced by the computer program. Research has indicated that the "red line" measure for SWAT is between thirty and fifty. This means that depending upon the amount of time required to complete the task (called dwell time), performance degradation will occur at or around this point over time.

An entire mission profile was flown in simulated and actual IMC for workload assessment. No video cameras or GPS unit were used for the flight in IMC to ensure that the profile was as representative as possible to an operational mission.

For takeoff, the TCAS in both aircraft were setup in the TA mode with the two nautical mile range display. Also, the A/A TACAN system was set up between the aircraft to back up the TCAS information and use the A/A TACAN relative velocity function. For the runway lineup, the lead T-1A was positioned on the right side of the runway while the wingman T-1A was positioned on the left side of the runway. The nose of the wingman was aligned with the tail of the lead aircraft with at least thirty feet of lateral wing tip clearance. Lead called for engine run-up to eighty percent N_1 . When the wingman signaled ready, lead released brakes. The wingman started the takeoff roll twenty seconds after lead's brake release. The wingman pilot used an IFR hood after passing three hundred feet AGL to simulate IMC. Pilot workload was assessed for all simulated IMC takeoffs using the SWAT rating system. During the climbout, altimeters were set to 29.92 inches of mercury. Lead accelerated to 220 KIAS and climbed to seven thousand feet pressure altitude. Wing promptly rejoined to one nautical mile in-trail, six thousand feet pressure altitude. If the wingman established position prior to the lead aircraft reaching seven thousand pressure altitude, then the climb to twenty thousand feet pressure altitude was started immediately.

Next, a maximum continuous thrust (MCT) minus five percent N_1 in-trail formation climb was performed from seven thousand to twenty thousand feet pressure altitude.

During the climb, the wingman maintained one nautical mile in-trail and five hundred feet below lead's altitude using the TCAS and air-to-air TACAN. The tolerances for the wingman were ± 1000 feet in-trail and ± 5 degrees of azimuth. The lead aircraft called the climb base heading and climbed at 220 KIAS. The data band was ± 5 knots with a ± 3 knot tolerance. To maintain a stable climb airspeed, the lead aircraft engaged the autopilot. The lead made altitude calls every one thousand feet. Pilot workload was assessed with the SWAT rating system. The actual level-off altitude was determined by height of the cloud decks.

Once in IMC, the lead aircraft leveled off and maintained 250 KIAS ± 10 knots. The wingman maintained one nautical mile in-trail and 500 above lead's altitude. The tolerances for the wingman were ± 1000 feet in-trail, ± 100 feet for altitude, and ± 5 degrees of azimuth. The tolerances were based on readings from the aircraft flight instruments and used for data band limits. A data band is a target interval of certain parameters used to determine acceptable tolerances for data accuracy. The data band is used to distinguish acceptable data points. The lead aircraft performed announced and unannounced in-trail thirty degree banked turns. The wingman used timing and the TCAS to maintain formation position. Pilot workload was assessed with the SWAT rating system.

Finally, an enroute descent to seven thousand pressure altitude was accomplished in IMC. The lead aircraft called the base heading, set power to sixty percent N_1 , and descended at 250 KIAS. The data band was ± 5 knots with a ± 3 knot tolerance. To

maintain a stable descent airspeed, the lead aircraft engaged the auto-pilot. The lead made altitude calls every one thousand feet. The wingman maintained one nautical mile in-trail and five hundred above lead's altitude using the TCAS and A/A TACAN relative velocity information. The tolerances for the wingman were ± 1000 feet in-trail and ± 5 degrees of azimuth. Pilot workload was assessed with the SWAT rating system.

CHAPTER IV

RESULTS

All test objectives were met. The TCAS was satisfactory to execute IMC trail formation procedures for the T-1A Jayhawk. The TCAS accuracy in displaying aircraft relative position within the normal cell formation envelope was satisfactory. Regions of blanking were found only on the lead's display when the wingman was within 0.8 miles aft and eight hundred feet or more below lead. No blanking occurred on the wingman's display. The TCAS display and warning cues were satisfactory for station-keeping operations, although some minor areas of improvements for displays and cues were identified. The pilot's ability to maintain cell formation position using the TCAS in a high density environment was satisfactory. Pilot workload was satisfactory while using TCAS for IMC stationkeeping procedures. Incorporate the use of TCAS into current AETC cell procedures for IMC penetration.

No evaluation of operational maneuvers was accomplished due to the lack of established procedures for station-keeping using the TCAS. The current AETC cell formation procedures were used whenever feasible during the course of testing. A set of established procedures are required for operational use of this system in actual IMC. Establish procedures for T-1A cell formation using the TCAS in IMC.

Other recommendations to improve the performance and human factors integration of the TCAS system were also made. The general order that the recommendations are

presented in indicates the priority given to the recommendation. The first two recommendations are the most important and should be implemented together. The other recommendations address potential areas of improvement which, while not necessary for safe operation of the system, would enhance the system's operational utility.

QUANTITATIVE RESULTS

GPS relative position accuracy

The GPS position was accurate to within ± 112 feet relative range and ± 0.54 degrees relative bearing

TCAS Accuracy

The position accuracy of the TCAS display symbology was satisfactory for use during cell formation station-keeping. The accuracy of the relative displacement of the aircraft symbology was such as to provide a correct representation of the time, space, and position as determined by the GPS. The TCAS range and bearing accuracy were determined by comparing photos of the TCAS display to GPS position data obtained during the stable points. The TCAS altitude accuracy was determined by comparing TCAS-displayed relative altitude with aircraft barometric altimeter readings. The barometric altimeters are accurate to within ± 75 feet of each other.

a. Bearing Accuracy -- Analysis of the TCAS bearing points show accuracies within two degrees.

b. Range Accuracy -- Analysis of the stable points indicated a TCAS range error of less than six hundred feet for all test points. This was the largest range error recorded and

was considered worst case. In order to operate safely with this error, all recommendations should be considered for use while flying formation using TCAS. If large closure rates are not promptly corrected and the data signal is lost, causing TCAS to enter the coast mode, the potential for midair collision is increased. The reader is reminded that the TCAS should alert the crew of any impending collision threats between the formation aircraft.

c. Altitude Accuracy -- Altitude accuracy was determined by comparing the TCAS-computed relative altitude, displayed on the TCAS multifunction display during the stable points, and a reference altitude difference computed by subtracting the two aircrafts' barometric altimeter readings. Both altimeters were set to 29.92 inches for the stable points. Data were plotted for all stable points, with relative altitudes ranging from -1,000 to +1,000 feet.

The aircraft symbology as represented on the TCAS display was an accurate depiction of actual aircraft relative position and was satisfactory for station-keeping in cell formation. The three-dimensional position accuracy is depicted in Figure 5.

Antenna blanking

No antenna blanking or degradations which would impact using TCAS for cell formation station-keeping were observed. For the purposes of this evaluation, antenna blanking, or "blanking" was defined as a situation wherein either aircraft's TCAS symbol disappeared from the other's screen with TCAS and IFF transponders operating normally. The TCAS system exhibited no antenna blanking for the wing aircraft during

normal trail operations, including climbs, turns, and descents. However, blanking was noted on the lead aircraft's display when the wingman approached close to and below the lead's position, and only when both aircraft were very stable. The safe operational envelope is depicted in Figure 6. If the wingman was between 700 and 1,500 feet below lead and within 0.5 nautical mile, as soon as either aircraft established a relative position rate, the TCAS symbol reappeared on lead's screen. However, if the wingman was more than 1,500 feet below lead, the

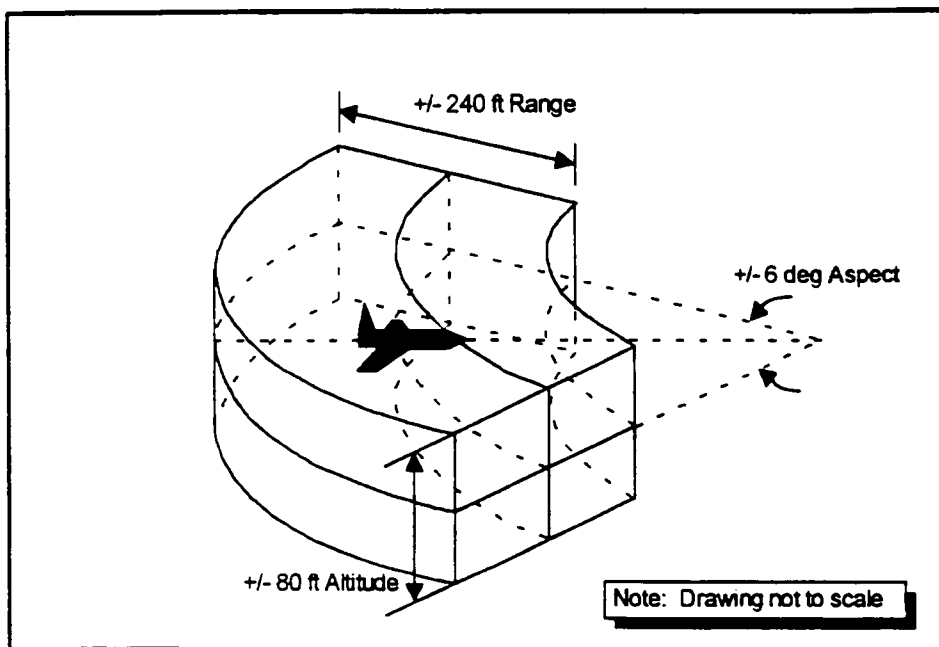


Figure 5
T1A JAYHAWK THREE DIMENSIONAL POSITION ACCURACY DEPICTION

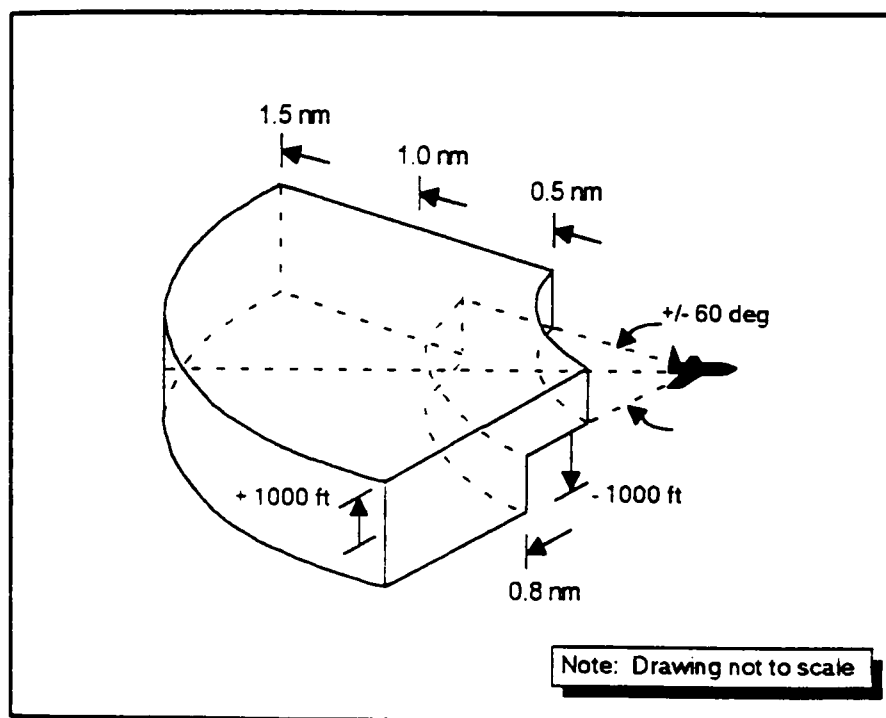


Figure 6
TRAFFIC COLLISION AND ALERT AVOIDANCE SYSTEM SAFE ENVELOPE OF
OPERATION

TCAS symbol did not reappear. The only time the lead aircraft disappeared from the wingman's TCAS screen was during the position limits test, when the wingman was one thousand five hundred feet directly above lead. Overall, the TCAS system exhibited safe, consistent operation within a trail envelope defined by the position limits shown in Table 1.

Table 1. TCAS Safe Operational Envelope

Wingman Altitude Relative to Lead	Safe Operational Cone
1,000 to 0 feet	>0.8 nm, +/-60° aspect
0 to 1,000 feet	>0.5 nm, +/-60° aspect

Prioritization testing, high density environment

The TCAS prioritization characteristics and operation during high density traffic conditions were satisfactory. The wing aircraft performed several opening and closing maneuvers using various rates to evaluate the update and prioritization characteristics of the TCAS system. The refresh rate of the TCAS system was adequate for all of the airspeeds tested -- up to fifty knots of closing velocity. There were no dropouts or anomalies observed in the lead or wing aircraft during this portion of the testing. The TCAS prioritization system was of some concern because the system was built for traffic avoidance, and the software logic was built around the idea that an aircraft that is a potential conflict would get the most attention from the system. This software logic was tested at various times while in the local Edwards Air Force Base area. On three separate occasions, the formation was the target of an interception run by a fighter aircraft. In each

situation, the fighter aircraft passed by the formation in relatively close proximity at high airspeeds. While the refresh rate of the TCAS screen was inadequate to continuously display the fighter traffic, at no time were any problems found with the wingman's ability to identify and track the lead aircraft.

The formation was flown within the Los Angeles Class B airspace at sixteen thousand feet pressure altitude to evaluate the effects of a high density traffic environment on TCAS station-keeping utility. The formation was flown across the top of Los Angeles International Airport between 0745 and 0830 hours local time. A composite radar track of the entire flight was recorded by Ridley Mission Control in cooperation with Los Angeles Center air traffic control (ATC) facility. A depiction of the traffic scenario is shown in Figure 7. The traffic density reached up to sixteen aircraft inside of a thirty nautical mile radius at certain times during the flight. A traffic density of greater than thirty aircraft inside of a thirty nautical mile radius of the formation was desired because the Collins TCAS was designed to track no more than thirty aircraft. Although the desired traffic density was not seen during testing, the traffic density experienced was as high or higher than the T-1A aircraft were expected to encounter during training operations; therefore, the flight was considered successful, and test objectives for this area were met.

QUALITATIVE RESULTS

Displays, warning cues

Using the TCAS display, the pilot's ability to accurately maintain normal cell position was satisfactory. The display size was adequate with good resolution of symbols and characters. Display location was adequate and clearly accessible to both pilots. The display lighting was adequate during the daylight evaluation. Display location prevented the sunlight from washing out the lighting under most flight conditions. Color coding of the traffic was useful in prioritizing traffic scan but was not used extensively for station-keeping. Traffic information content was generally adequate, with bearing information and altitude separation the most useful. The TCAS display was very user friendly and greatly contributed to increased pilot situational awareness.

Traffic information format was arranged logically, with vital information clearly and concisely presented. Altitude differential was placed appropriately above or below the target symbol to indicate qualitatively the target's position, and the actual altitude separation was presented digitally on the display in hundreds of feet. This feature allowed for a quick scan to determine relative aircraft position. The concentric range distance scale was very useful while monitoring formation aircraft relative range. An OFF SCALE warning provided cues even if an aircraft's relative range was beyond the selected scale. The range scale could be changed quickly to a forty nautical mile scale with a single push-button actuation for a quick look at the overall traffic environment.

System failure indications were generally lacking with only a TCAS FAIL warning displayed if power was removed from the transponder. No indications were provided in the event of system anomalies or dropouts within the cell formation. When system failures were simulated, the TCAS coast mode continued to present target information for six seconds before the target symbol disappeared from the screen with no warning or caution indications. Improved TCAS system degradation and failure indications would be desired to provide the pilots with increased confidence and situation awareness during cell formation station-keeping. Implement a caution/warning indication of lead/wingman signal loss or TCAS malfunction.

Traffic warning information was adequate, with the color coding and aural warnings particularly useful. The aural indication of "Traffic, Traffic" was a good method of keeping lead aware of unexpected closure or position changes in the cell formation, but it could be distracting when communicating with ATC or inter-cockpit. A capability similar to deselecting a voice radio guard channel would be useful to reduce the potential of crew distraction and decreased situation awareness. Incorporate a selective muting capability to the TCAS aural warning system.

No relative range or altitude rate information was provided by the TCAS to the pilot. The A/A TACAN was useful as a cross check for range rate, with closure rates presented in knots. The closure information was useful in station-keeping duties and decreased pilot workload, although A/A TACAN range and range rate accuracies were not specifically evaluated. AETC IMC cell formation procedures should recommend the use

of A/A TACAN as a cross-check tool during station-keeping. Accurate relative range rate and altitude rate information provided by TCAS would be very useful to the pilot while prioritizing specific aircraft for potential evasive action or directing formation position changes to avoid high threat traffic. Add the capability to selectively display position rates between lead and wingman on the TCAS MFD. Another useful enhancement would be the capability to positively distinguish between cell formation aircraft and other TCAS-equipped aircraft, either through color coding or different symbology. Implement the capability to independently distinguish lead or wingman, possibly by using color coding or unique symbology.

System response time and symbol movement rate was satisfactory to track traffic. Lead or wingman could distinguish discrete relative movements, which proved especially useful for unannounced turn recognition. The display refresh rate was satisfactory for station-keeping but marginal for extremely high closure rates (over 200 knots). Numerous interceptions of the T-1As in the local Edwards area by rapidly closing fighter aircraft were observed, and the TCAS refresh rate was marginal to track the fighters. These closure rates did not affect TCAS performance, degrade presentation of the cell formation aircraft, or impact the utility of using TCAS for station-keeping.

Specific mission scenarios were flown using operationally representative maneuvers, and the pilot in the wingman aircraft flew with an "IFR hood" obstructing his vision of outside references. This test procedure was intended to simulate IMC flight. The display cues were appropriate for takeoff in IMC. The lead aircraft appeared on the

TCAS screen an average of five seconds after takeoff (range was from 2.4 - 6.0 seconds). The delay in display data was due to weight-on-wheels switch which disables the Mode S until airborne. The purpose of determining the delay in display was to determine if takeoffs could be performed in close formation to the lead aircraft. If the delay was excessive enough to prevent tracking of the lead aircraft when penetrating clouds, then an operating limitation would have been instituted. The 20-second spacing used on takeoff worked well for helping the wingman attain a one-nautical mile spacing immediately upon takeoff.

The ability to accurately maintain normal in-trail position using the two nautical mile range scale on the T-1A TCAS in a high density traffic environment was satisfactory. The display gave appropriate cues and warnings to the wing pilot which enabled him to maintain an appropriate formation position throughout the flight. There were no dropouts or anomalies observed on the TCAS screen during the entire flight on either the lead or wing aircraft. With the two nautical mile range scale set on the screen, there were no problems with the pilot in the wing aircraft keeping positive identification of the lead aircraft at all times. The two nautical mile range screen display algorithm incorporated an altitude filter which displayed only targets within two thousand seven hundred feet relative altitude with the host aircraft, so even in the presence of relatively high density traffic, maintaining track of the lead aircraft's position was easy.

The lead aircraft operated on a forty nautical mile range scale while in the high density traffic environment, enabling the lead pilot to maintain situational awareness of the traffic

in the area around the formation. This procedure worked well. The lead aircraft was able to monitor large movements of the wingman and keep track of any potential traffic conflicts for the formation at the same time. If a more precise view of the wingman's position was needed, two pushes of the up arrow button changed the display to the two nautical mile range screen, and back to the forty nautical mile range.

Workload assessment

The results of the pilot surveys shown in Table 2 indicated satisfactory workload requirements. Workload evaluations were categorized according to flight phase and flight conditions such as VMC, simulated IMC, and actual IMC. Workload was light during all VMC and simulated IMC testing, as well as for actual IMC straight and level station-keeping. Workload was moderate during climb and descent, and high during maneuvering, especially for unannounced turns.

Pilot workload was dependent not only on weather conditions but also on crew coordination and communications. Pilot comments indicated workload decreased when the nonflying pilot assisted the flying crewmember with radio communications, navigation, and configuration changes (speed brakes during descents). The flying crewmember could devote more time to maintaining proper position and scanning the TCAS for position changes or lead maneuvers.

Positive two-way communications between aircraft greatly reduced pilot workload. When lead announced a maneuver, the wingman was able to anticipate the maneuver and react quickly to movement on the TCAS display. The higher SWAT ratings reflected the

trend of increased pilot workload during unannounced maneuvering, as experienced during the high density traffic test point. This problem was magnified in simulated and actual IMC when the pilot found that an effective instrument scan was difficult while reacting to symbol movement on the TCAS display. AETC IMC cell formation procedures should include the requirement to confirm operational inter-aircraft communications prior to entering IMC.

Twenty-nine SWAT ratings were gathered during this test. The SWAT ratings ranged from zero (meaning virtually no impact on workload) to fifty-nine point eight (generally regarded as high workload). The SWAT ratings, corresponding values and task averages are presented in Table 2. In the case of the in-trail descents, the SWAT average went down due to a smaller sample size and an increase in pilot proficiency.

Table 2. SWAT Ratings

MANEUVER	SWAT AVERAGE*	# OF DATA POINTS	RANGE
VMC	9.05	2	0-18.1
SIM IMC T/O	40.37	4	28.8-50.3
1000 FT/MIN CLIMB	28.8	1	(None)
<u>MCT-5% CLIMB</u>			
--SIM IMC	40.23	3	28.8-59.8
TURN RECOGNITION	0	1	(None)
<u>TIMED TURNS</u>			
--VMC	21.5	2	21.5 (All)
--SIM IMC (Unannounced)	81.0	1	(None)
--SIM IMC (Announced)	0	1	(None)
--ACTUAL IMC (Announced)	50.3	1	(None)
TCAS INTERFERENCE	21.5	1	(None)
IN-TRAIL DESCENTS			
--SIM IMC	39.55	2	28.8-50.3
--ACTUAL IMC	32.1	1	(None)
STRAIGHT & LEVEL			
ACTUAL IMC	21.5	1	(None)

*Average is valid if the maneuver conditions, aircraft and flight conditions were very close to identical for the two test pilots.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Overall, the Traffic Alert/Collision Avoidance System (TCAS) was satisfactory for use during instrument meteorological conditions (IMC) cell formation procedures in the T-1A Jayhawk.

System performance characteristics during cell formation procedures were satisfactory. TCAS position accuracy was adequate. There were no antenna blanking or degradation problems which would impact normal cell station-keeping operations. A safe operational envelope was determined as 0.5-1.5 nautical miles aft and 60 degree aspect when wingman was co-altitude to 1,000 feet above lead; 0.8 to 1.5 nautical miles aft and 60 degree aspect when wingman was co-altitude to 1,000 feet below lead.

The TCAS operation in a high density traffic environment and prioritization characteristics were satisfactory. A two-ship cell formation was flown through the Los Angeles basin with traffic densities reaching up to sixteen aircraft within a thirty nautical mile range. There were no problems maintaining positive identification of lead on the TCAS screen and maintaining desired cell formation. High-speed intercepts flown by fighter aircraft toward the flight formation caused no problems with dropouts or with maintaining lead identification.

Finally, workload during simulated and actual IMC ranged from light (straight and level flight) to high (unannounced maneuvering). Overall, workload was satisfactory for

using TCAS to maintain cell formation during IMC procedures. Incorporate TCAS into current AETC cell procedures for IMC penetration.

No evaluation of operational maneuvers was accomplished due to the lack of established procedures for station-keeping using the TCAS. The current AETC cell formation procedures were used whenever feasible during the course of testing. A set of established procedures are required for operational use of this system in actual IMC. Establish procedures for T-1A cell formation using the TCAS in IMC.

Other recommendations were made which would improve the performance and human factors integration of the TCAS system. The first two recommendations are the most important and should be implemented together. The rest of the recommendations are areas of improvement which, while not necessary for safe operation of the system, would enhance pilot performance.

In general, workload associated with using TCAS for station-keeping during IMC cell formation procedures was satisfactory. Workload was light during straight and level cell formation flight, for both visual meteorological conditions (VMC) and IMC. However, during the Los Angeles basin high density test point, inter-aircraft communication was severely limited due to the excessive radio traffic, so all maneuvering was performed unannounced. Maneuvering without prior notification raised workload levels to moderate and high. Inter-aircraft communication should be considered a requirement for using TCAS for cell formation station-keeping during IMC. AETC IMC cell formation

procedures should include the requirement to confirm operational inter-aircraft communications prior to entering IMC.

The TCAS displays, warnings, and cues were satisfactory. The display symbology and screen layout were logical and useful for station-keeping. A useful enhancement would be the capability to positively distinguish between cell formation aircraft and other transponder-equipped aircraft, either through color coding or different symbology. Implement the capability to independently distinguish lead or wingman, possibly by using color coding or unique symbology.

The TCAS provided no system failure indications in the event of TCAS anomalies or formation aircraft dropout. Such information would be useful to the pilot for increased confidence in using the TCAS for station keeping procedures. Implement a caution/warning indication of lead/wingman signal loss or TCAS malfunction.

In the absence of position rate information on the TCAS multifunction display (MFD), air-to-air (A/A) TACAN was useful to cross-check relative rate and should be incorporated into AETC procedures for IMC cell formation. AETC IMC cell formation procedures should recommend the use of A/A TACAN as a cross-check tool during station-keeping. While recognizing that GPS is the future navigation system that will be used to convey precise aircraft position information, a viable alternative to A/A TACAN would incorporate the data link capability inherent to GPS to present a rate management system to the pilot.

TCAS lacked the ability to display range rate and altitude rate between formation aircraft. Position rate information would be a useful enhancement to aid the pilot during station-keeping procedures. Add the capability to selectively display position rates between lead and wingman on the TCAS MFD. A rate management system should provide the pilot a simple, easy to use method of flying the aircraft in TCAS formation while precisely controlling the rate of closure between the formation aircraft. When pilot and TCAS interface issues are being investigated, workload and display format should be similar to the type of fly-to guidance that is used while flying instrument landing system (ILS) approaches. A qualitative display format showing rate of closure information and control guidance would greatly assist the pilot in maintaining a stable formation position and give the pilot timely warning cues in case closure rates are increasing. The inherent capability of the TCAS would be optimized in the case of collision avoidance and traffic alerting when specific closure rates parameters are exceeded.

Aural warning tones were helpful, but during extended periods of operation in high density traffic, the option of muting aural warnings was not provided with the current system. This option would be desired to reduce the potential of crew distraction and improve the training effectiveness during station-keeping procedures. Incorporate a selective muting capability to the TCAS aural warning system.

The United States still possesses the safest, most efficient, and busiest air traffic control system in the world, but there is room for great improvement and many new technologies are being explored as viable methods of improving the current system.

Many safety concerns are raised by the planned transition from an ATC system controlled from the ground to the collaborative pilot/controller decision-making of air traffic management. Too much information presented in a complicated format can create traffic management pitfalls that must be avoided. While exploring new ways of efficiently managing air traffic with existing technologies, two premises must remain: the pilot is responsible for the safety of the flight and the air traffic controller is responsible for the safe, efficient flow of traffic. Using TCAS to give the pilot a more autonomous approach to controlling his flight path and relative position to traffic in close proximity will provide challenges to the air traffic controller to maintain positive control of traffic flow. Pilots must accept this role while continuing to work with air traffic controllers to coordinate the safe, expeditious movement of air traffic.

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