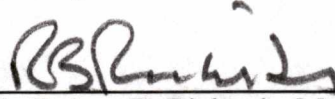


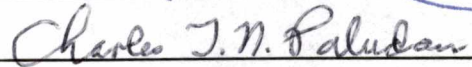
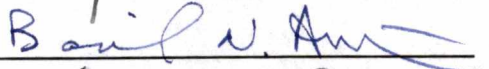
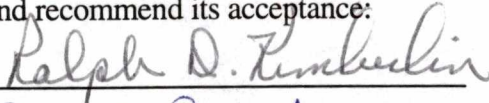
To the Graduate Council:

I am submitting herewith a thesis written by Michael Andrew Wettlaufer entitled "The Evaluation of the Cockpit 21 Modification to the T-45A Jet Trainer: Developmental Flight Testing." 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.



Mr. Robert B. Richards, Major Professor

We have read this thesis
and recommend its acceptance:



Accepted for the Council:



Associate Vice Chancellor
and Dean of the Graduate School

**THE EVALUATION OF THE COCKPIT 21 MODIFICATION
TO THE T-45A JET TRAINER:
Developmental Flight Testing**

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Michael Andrew Wettlaufer

December, 1995

DEDICATION

This thesis is dedicated to the hard working and diligent test pilots and engineers who ensure the taxpayer receives the product for which the government has paid.

ABSTRACT

Thesis statement: The objective of this thesis is to detail aspects of the developmental testing of the Cockpit 21 (CP21) modified prototype of the T-45A aircraft, specifically relating to its suitability as a flight trainer for the United States Navy Jet Training syllabus.

The CP21 system is considered a "glass cockpit" modification to the standard cockpit layout, replacing analog primary flight instruments in each cockpit with two, side by side, multi-function displays with associated system processing hardware. In March 1995, following 12 months of initial developmental testing of the CP21 system through 24 Operational Flight Program (OFP) software loads, a final Navy flight test evaluation was conducted utilizing OFP 2E-5. The evaluation focused on the capability of CP21 to provide an adequate flight training platform without degradation from the analog T-45A displays. Flight test maneuvers included basic instrument training, instrument navigation, familiarization flight, aerobatics, formation flight, air-to-ground weapon delivery, air combat maneuvering, and carrier landing practice.

This thesis describes the Navy's developmental flight test evaluation of CP21, as well as some specific results. Recommendations for system software and component modifications are included, where appropriate.

In summary, the CP21 modification has proven to be unsatisfactory for Navy Undergraduate Jet Training due to improper and inadequate implementation of system software, display functionality and symbology. Specific major deficiencies included: the lack of usable trend indications for altitude and airspeed, uncommanded blanking of the primary flight reference displays, and severe display latencies in the primary attitude reference.

PREFACE

This thesis is based upon approximately 150 developmental test flights, countless hours of laboratory testing, discussions with numerous test pilots, as well as flight test engineers, personal experience, and opinion. No published reports exist documenting the results or outcome of the completed testing, however, identified deficiencies discussed have been documented by the United States Navy flight test team. The information content, discussion of results, conclusions, and recommendations herein are the author's personal opinion and in no way reflect the United States Navy's or the Naval Air Warfare Center's points of view.

Due to the technical content of this thesis, a list of applicable and commonly referred to abbreviations and terms is included in a glossary. Human factors design deficiencies came to the forefront during the flight test evaluations especially concerning pilot to controls and displays interface. Many texts have been written containing in-depth discussions of ergonometics and human factors engineering. For a more comprehensive discussion of those areas, the reader should utilize the references available commercially or in the library.

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LIST OF ABBREVIATIONS

A/A - Air-to-Air
A/G - Air-to-Ground
ADI - Attitude Direction Indicator
ADR - Airborne Data Recorder
AGL - Above Ground Level
AOA - Angle of Attack
AOB - Angle of Bank
AV BIT - Avionics Built In Test Advisory
BIT - Built In Test
BNGO - Bingo, or Minimum, Fuel Setting
CCIP - Continuously Computed Impact Point
CNATRA - Commander of Naval Aviation Training
CP21 - Cockpit 21
CQ - Carrier Qualification
CR - Cruise Configuration
CRS - Navigation Course Entry
DATA - CP21 Navigation Data Page Format
DEP - Data Entry Panel
DEU - Display Electronics Unit
DOD - Department of Defense
ENG - Engine
FCLP - Field-Carrier Landing Practice
FLOLS - Fresnel Lens Optical Landing System
fpm - Feet Per Minute

ft - Feet

FTI - Flight Training Instructions

GCA - Ground Controlled Approach

GINA - Global Positioning System/Inertial Navigation Assembly Navigation Assembly

HDG - Commanded Heading Entry

HSI - Horizontal Situation Indicator

HUD - Head Up Display

IFR - Instrument Flight Rules

ILS - Instrument Landing System

IMC - Instrument Meteorological Conditions

ITF - Integration Test Facility

KIAS - Knots Indicated Airspeed

LAC - Lead Angle Computing A/A reticle

LAW - Low Altitude Warning

lbs - Pounds

MDA - McDonnell Douglas Aerospace

MDL - Mission Data Loader

MFD - Multi-Function Display

MIP - Main Instrument Panel

MRT - Military Rated Thrust

ms - Millisecond

MSL - Mean Sea Level

mux bus - Military Standard 1553 Multiplex Data Bus

NAS - Naval Air Station

NATOPS - Naval Air Training Operational Procedures Standardization

NAV - Navigation (refers to a processor Master Mode)

NAVAIRSYSCOM - Naval Air Systems Command

OFP - Operational Flight Program

PA - Power Approach Configuration

PAR - Precision Approach Radar

PCM - Pulse Code Modulation

PIO - Pilot Induced Oscillations

RALT - Radar Altimeter

RGG - Raster Graphics Generator

RPTR - Repeater MFD Option

SADS - Stability Augmentation Data Sensor

SAHRS - Standard Attitude Heading Reference System

SNA - Student Naval Aviator

SRT - Standard Rate Turn

STRS - CP21 Stores Page Format

TM - Telemetry

TRNG - CP21 Training Page Format

USN - United States Navy

VMC - Visual Meteorological Conditions

VREC - CP21 Video Recording Page Format

VV - Velocity Vector

WYPT - Navigation Waypoints

INTRODUCTION

INTRODUCTION

BACKGROUND

The United States Navy (USN) jet pilot training program is designed to teach basic flight techniques and to prepare the Student Naval Aviator (SNA) for subsequent assignment to a tactical aircraft based aboard an aircraft carrier or forward deployed as air support for the Marines. The jet training program follows primary flight training in a propeller driven airplane where general flight instruction in basic familiarization and instrument flight takes place. The students earning the highest grades during primary flight training are usually assigned to jet training with the ultimate goal of receiving their wings upon successful completion of the training syllabus. Once in jet training, the focus of the program is to teach the SNA basic and advanced instrument flight techniques, familiarization flying, including aerobatics, formation flight, basic tactical weapon delivery and air combat techniques, low level navigation and, finally, landing qualification aboard an aircraft carrier at sea.

The T-2C "Buckeye" and TA-4J "Skyhawk" have been the intermediate and advanced jet training aircraft, respectively, for the USN since the early 1970's. With the advanced age of the training aircraft, the end of their structural flight life draws near. Additionally, training costs have increased dramatically for both replacement parts and fuel consumption. The T-45A "Goshawk" jet trainer aircraft was chosen by the USN in 1988 to be a modern, low cost replacement for both the aging T-2C and TA-4J aircraft. With the one for two replacement, savings in training time are certainly realized by eliminating the need for redundant training phases in the intermediate and advanced stages of jet training. Since January 1994, SNA's have been undergoing jet flight training in the T-45A and receiving their wings upon successful completion.

Cockpit design and instrumentation in the T-2C, TA-4J, and T-45A all incorporate analog attitude gyros and navigation displays as primary flight references, making the Goshawk an easy fit into the proven flight training syllabus. The older T-2C and TA-4J utilize fixed reticle gunsights for air-to-air (A/A) gunnery and air-to-ground (A/G) ordnance delivery training. The T-45A provides a basic Head Up Display (HUD) which, in addition to the fixed reticle sight for A/G weapon delivery, incorporates a moving, aircraft-to-target predicting type A/A reticle, a constantly computed impact point A/G reticle, as well as aircraft attitude, and dynamic flight information. The basic techniques and habit patterns learned during flight training are used throughout the pilot's career, becoming the framework for the safe and successful employment of his tactical aircraft in the fleet.

STUDENT NAVAL AVIATOR TRAINING

The stages for SNA jet training are defined by the Commander of Naval Aviation Training (CNATRA) in the Flight Training Instructions for Undergraduate Jet Pilot Training (FTI, 1994), with the stated mission to provide Navy strike flight training. That mission requires a training system that includes a high performance jet aircraft and provides the capability to qualify the SNA for a standard instrument rating and to train the SNA in basic strike mission areas, as well as initial carrier qualification. The training syllabus attempts to develop important habit patterns, confidence and good judgment required for safe and effective operation of carrier based Naval aircraft.

The training syllabus can be broken down into four general areas, as follows: instrument flight, familiarization and formation flight, basic tactical employment, and carrier landing qualification. Training includes ground schools at various stages to teach the basics of weather, air traffic control interface, aircraft systems and procedures.

Simulators are used extensively to reinforce procedures and as an adjunct for each training stage. The most extensive use of simulators occurs during instrument flight and procedures training.

Before progressing to the familiarization flight stage in the front seat of the trainer, the SNA must complete an extensive period of instrument training. Instrument training begins with numerous simulator periods and includes many flights in the rear seat of the aircraft with an instrument hood installed. The instrument hood covers the inside of the rear cockpit canopy, eliminating any outside horizon reference and thus simulating flight in clouds, also known as Instrument Meteorological Conditions (IMC).

The instrument phase provides the foundation for the remainder of flight training. In this stage, the SNA learns how to fly by effectively scanning his flight instruments and properly interpreting them without visual reference to the outside world while coordinating control and throttle inputs. The initial simulator rides and flights focus on capturing and maintaining the basic parameters of aircraft heading, altitude, and airspeed. Maneuvers include takeoff, constant airspeed climbs and descents, constant rate climbs and descents, constant Angle of Bank (AOB) turns, constant rate turns, and patterns combining those basic maneuvers, including transitions to and from the landing configuration.

In addition to the basic maneuvers, the SNA is exposed to confidence maneuvers, such as aerobatics utilizing only the cockpit flight instruments, unusual attitude recoveries and stalls. Performing aerobatic maneuvers while "heads down", or concentrating on the cockpit instruments in lieu of the outside horizon, teaches the SNA to trust and properly scan his flight instruments. Unusual attitude training forces the SNA to quickly recognize and recover the aircraft from undesirable and possibly dangerous flight conditions, such as excessive combinations of pitch, AOB and airspeed which may occur in the event the pilot loses situational awareness while looking down

to change the radio channelization or inadvertent entry into IMC. Aerodynamic stalls in both the Power Approach configuration (PA), with landing gear, flaps and slats extended, and in the Cruise configuration (CR) with landing gear, flaps and slats retracted, are conducted to help the SNA recognize and recover from those conditions. Instrument interpretation is essential for unusual attitude and stall recovery.

Once the basic maneuvers have been introduced, the SNA progresses to radio instruments and airways navigation. Radio instrument and airways navigation flights utilize the Tactical Air Navigation (TACAN) receiver and the Very High Frequency Omnidirectional Receiver (VOR). The SNA learns to interpret and analyze the aircraft's position in relation to the navigation aids on the ground. The SNA performs non-precision and precision terminal approaches using radio instruments as well as communication with air traffic controllers on the ground. Precision terminal approaches are accomplished utilizing the T-45A's integral Instrument Landing System (ILS) display or through Ground Controlled Approaches (GCA) with Precision Approach Radar (PAR) guidance. The procedures and flight instrument interpretation required to successfully complete the initial stages of instrument training are carried forward into all subsequent phases of flight training and beyond.

When basic and radio instrument training is complete, the SNA progresses to familiarization and formation training while still involved in airways navigation flights. The familiarization and formation stages of training require the SNA to take knowledge of instrument flight and incorporate that with the view outside of the cockpit. These stages build confidence in the ability to maneuver the aircraft to any desired position or parameter, to conduct those maneuvers precisely and in concert with other aircraft, and to safely land the airplane. The SNA learns the basic performance aspects of the T-45A and to perform aerobatics and stalls under Visual Meteorological Conditions (VMC). In formation training, the SNA is taught to fly in various formation positions, to

rendezvous with other aircraft, and to fly instrument approaches as both a wingman and leader of a formation. Formation training is essential since all following training stages incorporate formation flight.

Once formation training is complete, the syllabus trains the SNA in A/A gunnery, tactical formation, basic Air Combat Maneuvering (ACM), A/G weapon delivery, and low level navigation. In A/A gunnery, the SNA must learn to place the HUD A/A reticle on a towed banner to accomplish a minimum score of "hits" from a simulated aircraft mounted gun while flying a precise pattern with three other aircraft and avoiding the banner and towing aircraft. HUD video recording is utilized to score A/A gunnery. Smooth and precise positioning of the HUD A/A reticle on the banner while maneuvering the aircraft is essential to succeed in this stage.

Tactical Formation and ACM flights teach the SNA to maneuver a two plane formation and to engage that formation with an enemy aircraft. Additionally, basic ACM offensive and defensive principles, in addition to basic A/A weapon envelopes are taught. The SNA learns to recognize and maneuver the aircraft at its performance boundaries in order to successfully engage and defeat an enemy aircraft.

During A/G weapon training, the SNA experiences basic weaponeering and delivering of bombs, rockets and simulated gun strafing from his airplane onto a ground target in concert with his formation flight. The bomb and rocket deliveries are from standardized patterns of altitude, airspeed, and dive angle which the SNA must attempt to capture, maintain, and correct to in order to deliver his weapons on target. The HUD A/G reticle can be positioned for each weapon and its delivery parameters of dive angle and release airspeed. The SNA learns to successfully maneuver the aircraft for weapons release while maintaining safe separation from the rest of the aircraft in his formation.

During low level navigation training, the SNA must learn to interpret 1:500,000 area charts depicting terrain and cultural features and navigate over a preselected track.

Once the ability to complete single plane low levels has been demonstrated, the SNA must then direct a formation flight for the same purpose. The formation low level incorporates some of the techniques learned in the A/G ordnance training as the SNA must direct a two plane flight on simulated attacks of targets along the low level route.

Throughout all of the previously discussed training phases, the SNA continues to practice carrier type landings to the runway at the end of each training mission. The culmination of USN jet training is in Carrier Qualification (CQ), that is, completion of landings aboard an aircraft carrier at sea. In preparation for CQ, the SNA has training flights dedicated to landing practice, called Field-Carrier Landing Practice (FCLP), during which, numerous touch and go landings are accomplished. The FCLP landing pattern requires the SNA to fly an instrument turn through approximately 145 degrees, until he visually acquires the Fresnel Lens Optical Landing System (FLOLS), next to the runway. Once the FLOLS is visually acquired, the pilot attempts to maintain the proper glideslope, referencing the FLOLS, while maintaining a precise Angle of Attack (AOA) and intercepting runway centerline. The FLOLS is set to a precise glideslope that, when flown correctly, at the target AOA, will guide the airplane to the desired touchdown point on the runway or, eventually, to a successful arrestment aboard ship during CQ.

Upon satisfactory completion of the training syllabus, the SNA is designated a Naval Aviator and assigned for training in a fleet aircraft.

WHY COCKPIT-21?

Today's modern tactical aircraft cockpits, such as the F/A-18 "Hornet" and F-14D "Tomcat", incorporate HUD and digital cockpit multi-function displays (MFD's) for primary aircraft attitude presentation and dynamic flight information. But, since the task of operating these aircraft is not limited to controlling only the stick and throttle,

their HUD's and MFD's provide controls and displays which allow aircrew interface with the myriad of sensors, weapons, and navigation systems which are an integral part of the tactical system that multi-role carrier based jet aircraft have become. In addition, the MFD's allow for selection of a wide range of display formats, effectively expanding the aircraft's capabilities and providing for growth in various mission areas.

With the expansion in capabilities, aircraft, such as the Hornet and Tomcat, have become multi-role platforms, fulfilling both A/A and A/G missions. In order to effectively operate each aircraft, the aircrew must routinely change MFD displays to access, control, and monitor the large volume of information and data presentations available, from A/G and A/A radar to navigation information and weapon targeting data. The cockpit MFD menus and displays must be organized in logical and useful patterns to facilitate quick access to the desired presentation. As mission tasking for each airframe increases, the pilot's task has evolved from one primarily focused on flying the aircraft to one requiring a good deal of cockpit management skills. Future aircraft, such as the F/A-18E/F "Super Hornet" currently in developmental flight test, incorporate more advanced control and display systems, with more reliance on their HUD and MFD's in lieu of analog displays.

With the continuing expansion in cockpit management skills required to effectively employ current and future Naval aircraft, the Naval Air Systems Command (NAVAIRSYSCOM) contracted with McDonnell Douglas Aerospace (MDA), to develop a major system upgrade for the T-45A known as Cockpit-21 (CP21). The CP21 avionics integration attempts to replace the analog cockpit with a number of digital displays selectable on MFD's. CP21 is designed to improve the long-term effectiveness of the T-45A and to more closely emulate modern fleet crew stations, thus exposing SNA's to a modern avionics architecture in a training environment prior to flying tactical aircraft in the fleet.

DESCRIPTION OF TEST AIRPLANE

GENERAL T-45A DESCRIPTION

The T-45A, manufactured by McDonnell Douglas Aerospace, is a tandem seat, light weight, high performance, fully aircraft carrier compatible version of the British Aerospace Hawk. The Goshawk is an all-weather, high altitude, trainer aircraft equipped with a non-after burning turbofan engine and is capable of flight up to 40,000 feet (ft) mean sea level (MSL), load factors in excess of 7, and speeds in excess of Mach 1. A complete description of the airplane is available in the Preliminary NATOPS (Naval Air Training And Operating Procedures Standardization) Flight Manual Navy Model T-45A (1994).

T-45A COCKPIT

The analog or baseline T-45A cockpit incorporates the attitude direction indicator (ADI) as the primary attitude reference and the horizontal situation indicator (HSI) as the primary navigation reference. The cockpit layout is presented in Figure 1. Both the ADI and HSI receive attitude and heading information from the Standard Attitude Heading Reference System (SAHRS). In addition to headings and AOB indications, the ADI provides ILS glideslope and azimuth steering needles for instrument approach. The HSI is equipped with the TACAN and VOR/ILS bearing indicators, a TACAN distance display, a course deviation indicator, a slewable command heading marker, a selectable course steering knob and an ILS glideslope pointer.

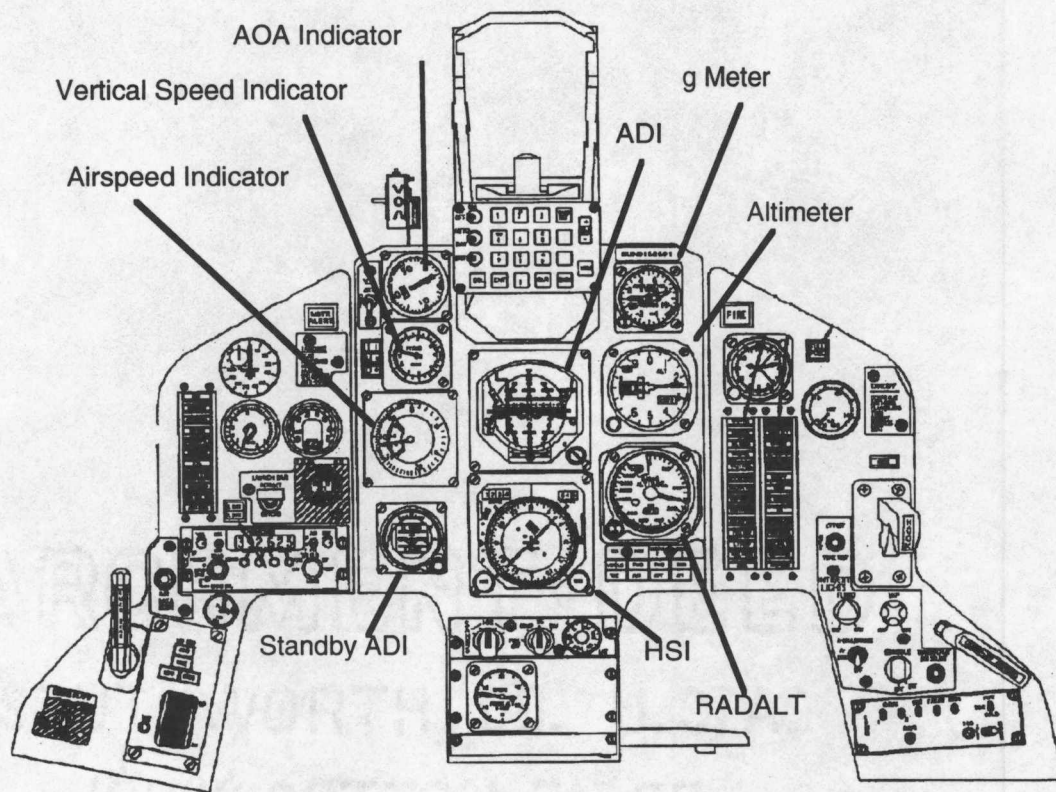


Figure 1. T-45A Analog Cockpit.

Source: Adapted from Preliminary NATOPS Flight Manual Navy Model T-45A (A1-T45AB-NFM-000) with Interim Change 11. (1994). Philadelphia, PA: Chief of Naval Operations.

The pressure instruments (altimeter, airspeed indicator, and vertical speed indicator) in both cockpits are driven by the pitot static system. The stability augmentation data sensor (SADS) converts pressures from the pitot static system into discreet voltages which are sent to the Display Electronics Unit (DEU). The DEU processes that data along with SAHRS data and presents aircraft attitude, as well as digitized altitude, airspeed, vertical speed, Mach number, and normal acceleration on the HUD. The pilot may use the Data Entry Panel (DEP) to enter local barometric pressure and airfield height, wind direction, wind speed, and target height for A/G weapon delivery and set A/G reticle depression angles. Aircraft engine and flight parameters are

recorded on the airborne data recorder (ADR) which has a capacity to record up to approximately 6 hours of flight.

Three aircrew selectable master modes of operation are available; Navigation (NAV), A/A, and A/G. When selected, the HUD display format is optimized for the selected mode. The master modes will be discussed later.

COCKPIT-21

The CP21 prototype test airplane was T-45A serial number 163635 (A037) with the cockpit layout shown in Figure 2 and a detailed description of avionics system changes

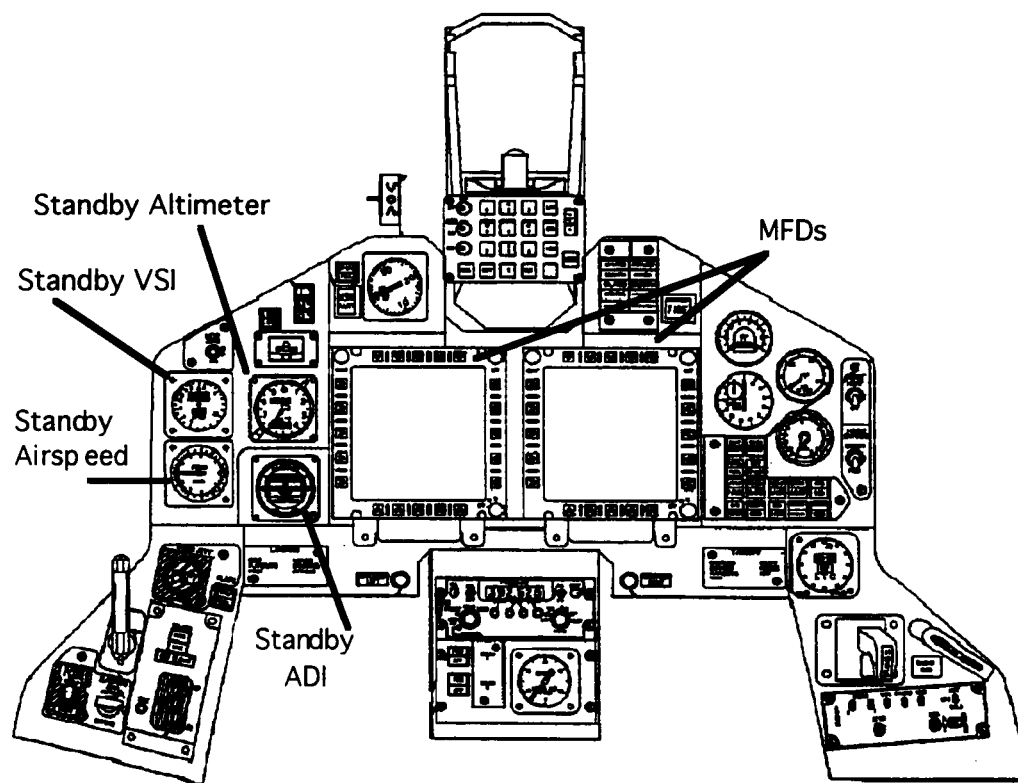


Figure 2. Cockpit 21 Cockpit Configuration

Source: Adapted from Preliminary NATOPS Flight Manual Difference Data With Cockpit 21 Installed Navy Model T-45A Prototype Aircraft 163635 (PS 1471-1). (1995). St. Louis, MO: McDonnell Douglas Aerospace.

provided in the Preliminary NATOPS Flight Manual Difference Data With Cockpit 21 Installed Navy Model T-45A Prototype Aircraft 163635 (1995). The digital cockpit incorporates two monochrome MFD's in each crew station, replacing the HSI and ADI and performing additional functions. Each MFD incorporates 20 individual pushbuttons to allow for aircrew selection of various display functions. The display and instrument arrangement within the cockpit was primarily driven by space.

The limited depth available behind each cockpit main instrument panel (MIP) and the limited choice of commercially available MFD's led to the selection of the five inch, raster graphics, MFD's and their side by side arrangement. The standby pressure and engine instruments were selected from 2 inch gauges either available in T-45A production or already in the Navy's avionics procurement system. This allowed the use of previously approved and tested components, lowering component qualification costs.

The analog airspeed indicator, altimeter, and vertical speed indicator, replaced with the 2 inch gauges, were located on the left side of MIP in the standby instrument cluster, along with an analog turn needle and sideslip indicator and the standby gyro. The production modifications add 90 lbs to the gross weight of the analog T-45, yielding an airplane weight of approximately 10,560 lbs for the two aircrew configuration and 10,610 with one pilot and the flight test instrumentation pallet installed in the aft cockpit.

Other avionics system modifications were required to facilitate CP21 system integration. The DEU was upgraded with additional circuit capacity, acting as a mission computer and display computer, while controlling a military standard 1553 multiplex data bus (mux bus). As shown in Figure 3, the mux bus interfaces with the ADR, mission data loader (MDL), and global positioning system (GPS)/inertial navigation

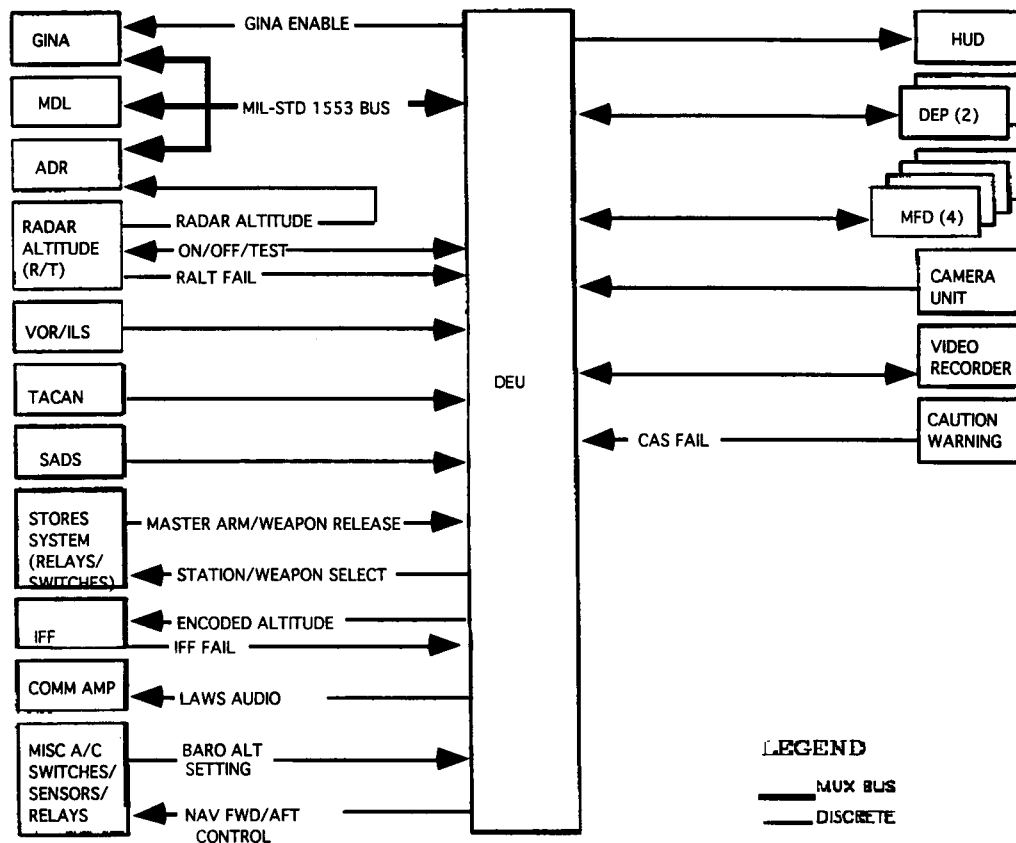


Figure 3. Display Electronics Unit (DEU) Interface.

Source: Adapted from Preliminary NATOPS Flight Manual Difference Data With Cockpit 21 Installed Navy Model T-45A Prototype Aircraft 163635 (PS 1471-1). (1995). St. Louis, MO: McDonnell Douglas Aerospace.

assembly (GINA) The DEU has hardware interfaces with the TACAN and VOR/ILS for navigation data, the SADS for air data, and other selected systems for built in test (BIT) and other miscellaneous functions.

DISPLAYS DESIGN

The display presentations were designed by MDA with input from USN personnel, including representatives from CNATRA, through a design review process known as the Aircrew Systems Advisory Panel (ASAP). The ASAP's were presented

with display designs on paper with system layout and functionality being verbally described. In a risk reduction effort during the design phase, simulation in a reconfigurable mockup was used. The mockup allowed the ASAP members to view instrument and display layout for the MIP on a large, cockpit size screen. Only limited interaction capability with the mockup was available and the display resolution was not representative of actual CP21 MFD's and instruments. Three ASAP's were held with the final one occurring in December 1993 with most display designs agreed upon by the end of that event.

CONTROLS AND DISPLAYS

As a display driver, the DEU interprets aircrew commands from the four MFD's and two DEP's to generate the appropriate response or display on the HUD and MFD's. The display format selection hierarchy is shown in Figure 4. The two display channels

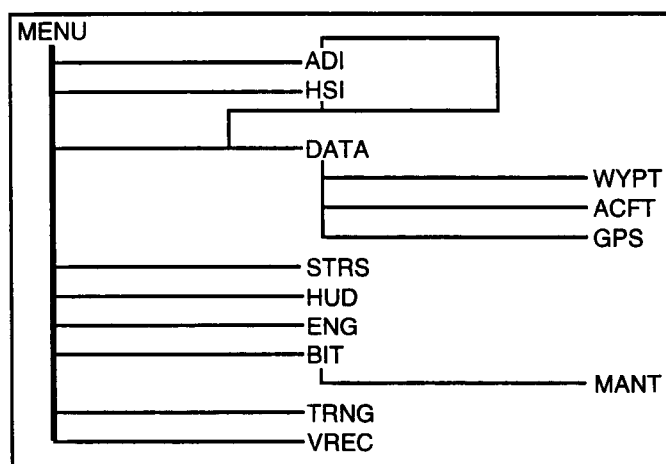


Figure 4. Multi-function Display (MFD) Format Hierarchy.

Source: Adapted from Preliminary NATOPS Flight Manual Difference Data With Cockpit 21 Installed Navy Model T-45A Prototype Aircraft 163635 (PS 1471-1). (1995). St. Louis, MO: McDonnell Douglas Aerospace.

were designed to allow independent control and display selection between cockpits and MFD's, and selection of the repeater option (RPTR) to repeat displays in the opposite crew station.

Primary Display Options

A menu page (MENU) is available and MENU options are presented on each display, around the outside edge, in four letter characters, allowing aircrew selection via the adjacent MFD pushtile. Each MFD display may be changed or altered depending upon the selected option. The ADI and HSI pages are available for selection from any display page, permitting quick access without going back to the MENU page, shown in Figure 5.

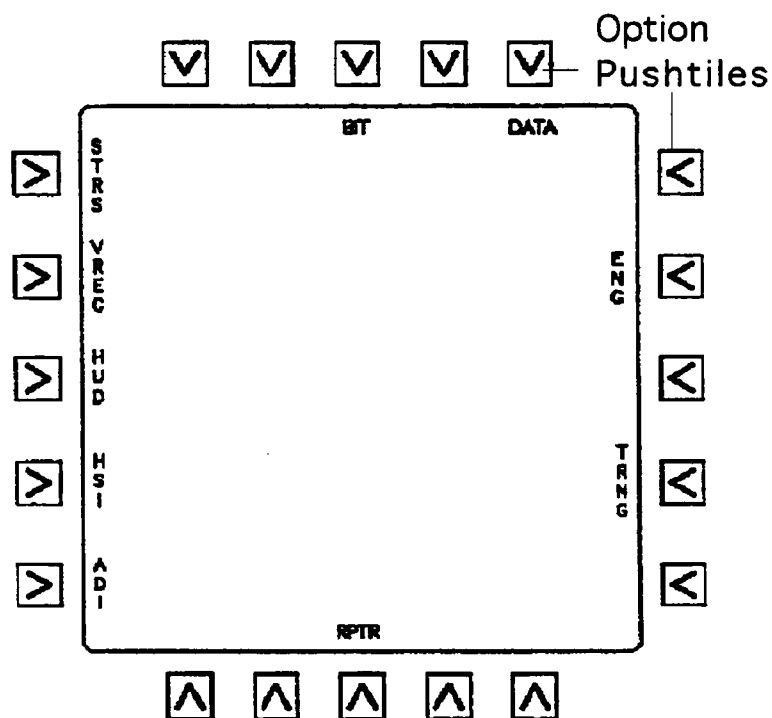


Figure 5. MENU Display Page.

Source: Preliminary NATOPS Flight Manual Difference Data With Cockpit 21 Installed Navy Model T-45A Prototype Aircraft 163635 (PS1471-1). (1995). St. Louis, MO: McDonnell Douglas Aerospace.

The presentation of primary flight references are on the ADI and HSI pages. Referred to as dynamic displays, the ADI and HSI must be constantly updated since they depict moving attitude and heading references along with digital presentations of critical flight data. The ADI and HSI displays are shown in Figures 6 and 7, respectively.

The ADI page presents the primary attitude reference, a digital depiction of an analog attitude indicator with pitch and bank angle indices, as well as digital airspeed, Mach number, AOA, load factor, altitude, and vertical speed. Additionally, a vertical speed caret is displayed on the right side of the ADI ball, with a range of +1500 feet per

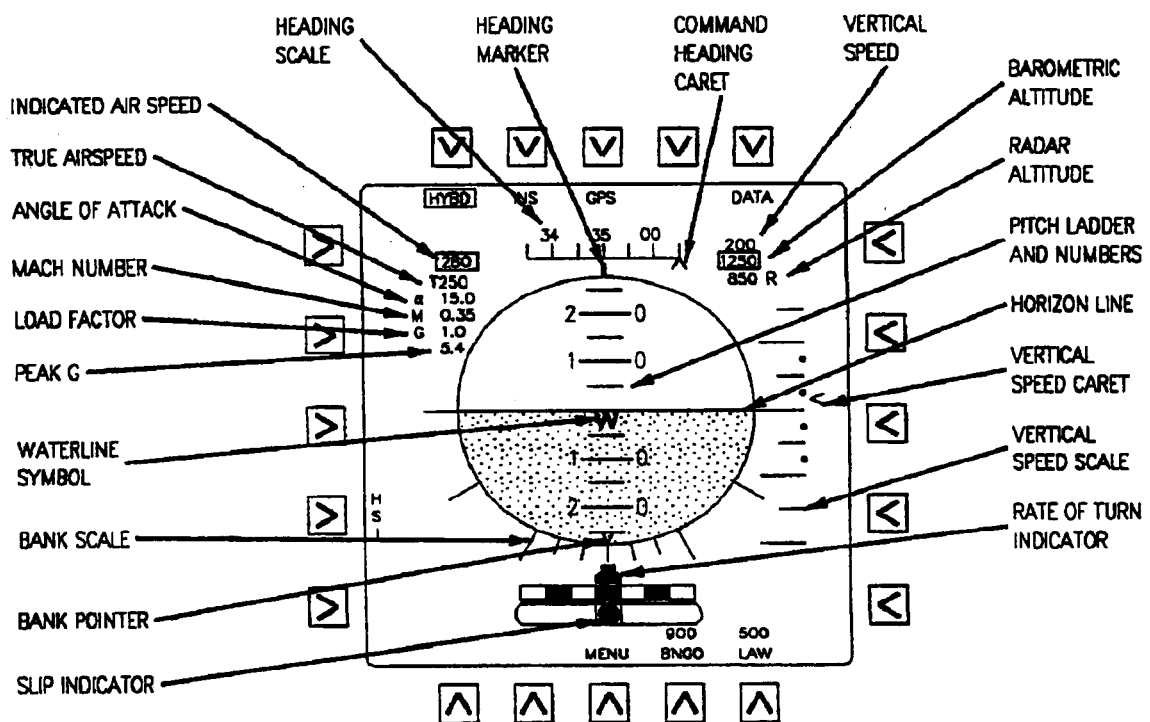


Figure 6. ADI Display Page.

Source: Preliminary NATOPS Flight Manual Difference Data With Cockpit 21 Installed Navy Model T-45A Prototype Aircraft 163635 (PS1471-1). (1995). St. Louis, MO: McDonnell Douglas Aerospace.

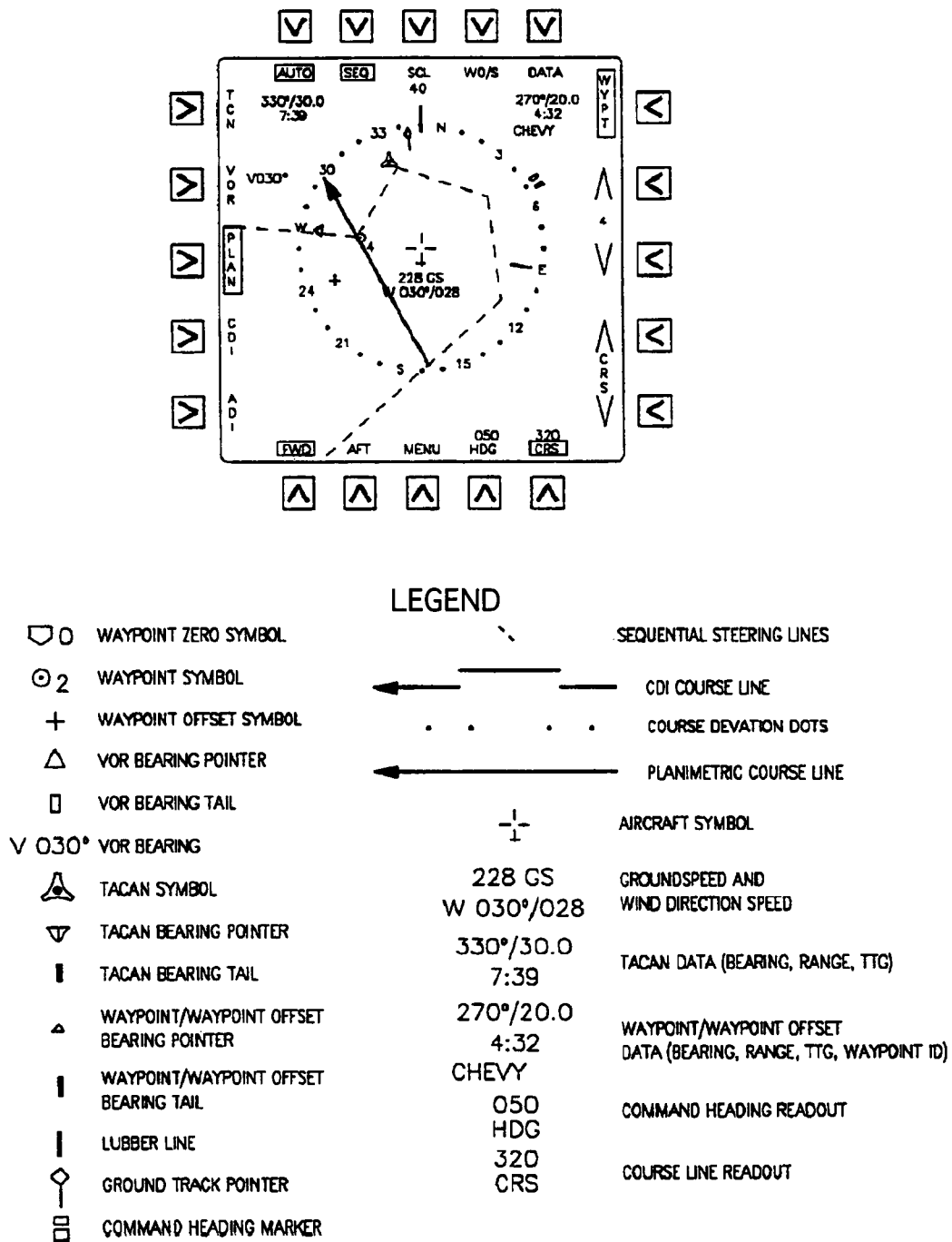


Figure 7. HSI Display Page: PLAN Mode.

Source: Preliminary NATOPS Flight Manual Difference Data With Cockpit 21 Installed Navy Model T-45A Prototype Aircraft 163635 (PS1471-1). (1995). St. Louis, MO: McDonnell Douglas Aerospace.

minute (fpm) to -2000 fpm. Aircraft heading data derived from the Global Positioning System/Inertial Navigation Unit Navigation Assembly (GINA) and navigation data derived from the ILS is sent via the DEU for presentation on the ADI display.

The HSI display replicates a standard compass, providing digital presentations of additional navigation data derived from the GINA, TACAN, VOR, ILS or MDL sent via deviation indication (CDI) mode, shown in Figure 8. In the case of the HSI, only one cockpit at a time may command changes on the HSI display by selecting either the FWD or the AFT legend on the HSI page.

The HUD is only present in the forward cockpit. The HUD projects flight and weapon delivery information in symbolic form into the pilots instantaneous field of view

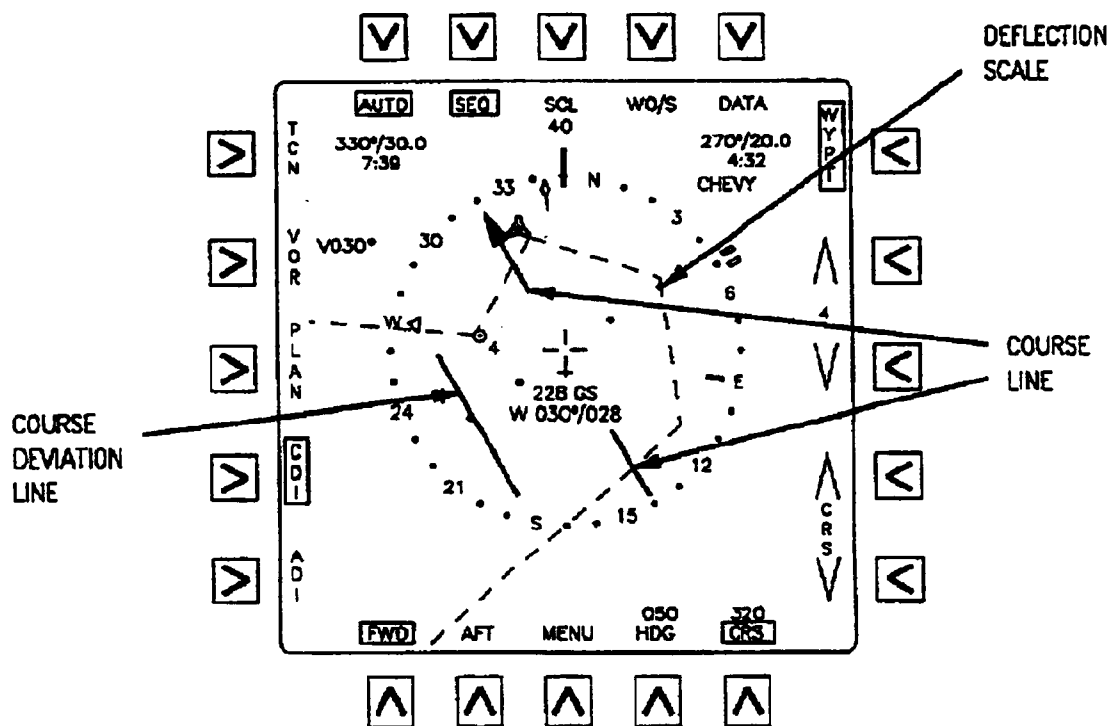


Figure 8. HSI Display Page: CDI Mode.

Source: Preliminary NATOPS Flight Manual Difference Data With Cockpit 21 Installed Navy Model T-45A Prototype Aircraft 163635 (PS1471-1). (1995). St. Louis, MO: McDonnell Douglas Aerospace.

on a combining glass. The HUD is directly controlled by the DEU which converts inputs from the various systems into symbology and digital numerics for display. The HUD display includes a pitch ladder, velocity vector and bank angle pointer as attitude references. The HUD symbology in the Navigation master mode is shown in Figure 9.

A/A and A/G HUD master modes are available with selection via the DEP or the stores page (STRS). Depression of the DEP master mode selection button scrolls through the three available modes. The HUD and DEP are presented in Figure 10. The DEP is utilized to select low altitude warning (LAW) entries for the radar altimeter (RALT), to select desired course (CRS) or heading (HDG) selections for navigation reference, to enter required data for GINA navigation waypoints (WYPT), to adjust A/G or A/A reticles, and to declutter the HUD display in any master mode. Any time DEP entries requiring numeric inputs are selected, a scratch pad appears on all displays

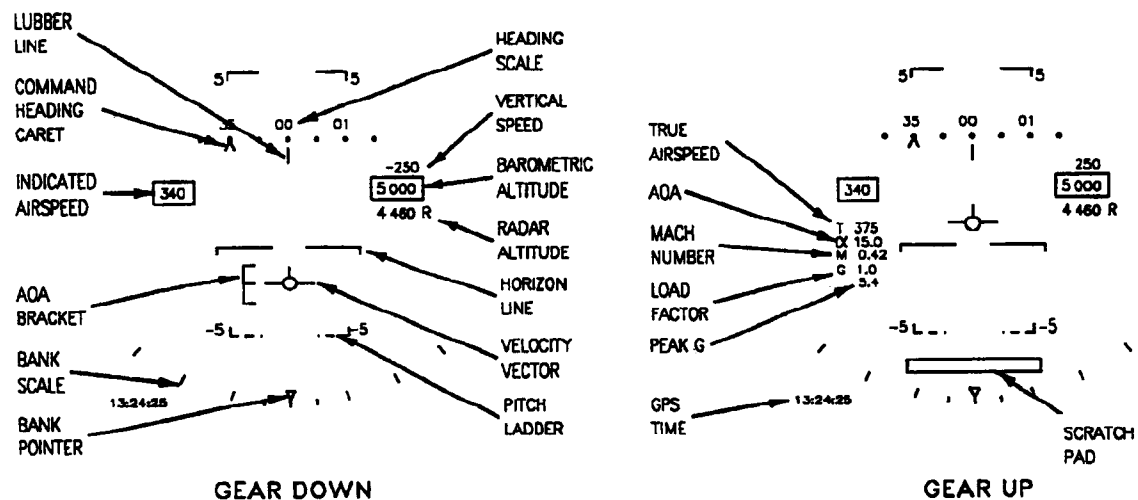


Figure 9. Head Up Display (HUD) Navigation Master Mode.

Source: Preliminary NATOPS Flight Manual Difference Data With Cockpit 21 Installed Navy Model T-45A Prototype Aircraft 163635 (PS1471-1). (1995). St. Louis, MO: McDonnell Douglas Aerospace.

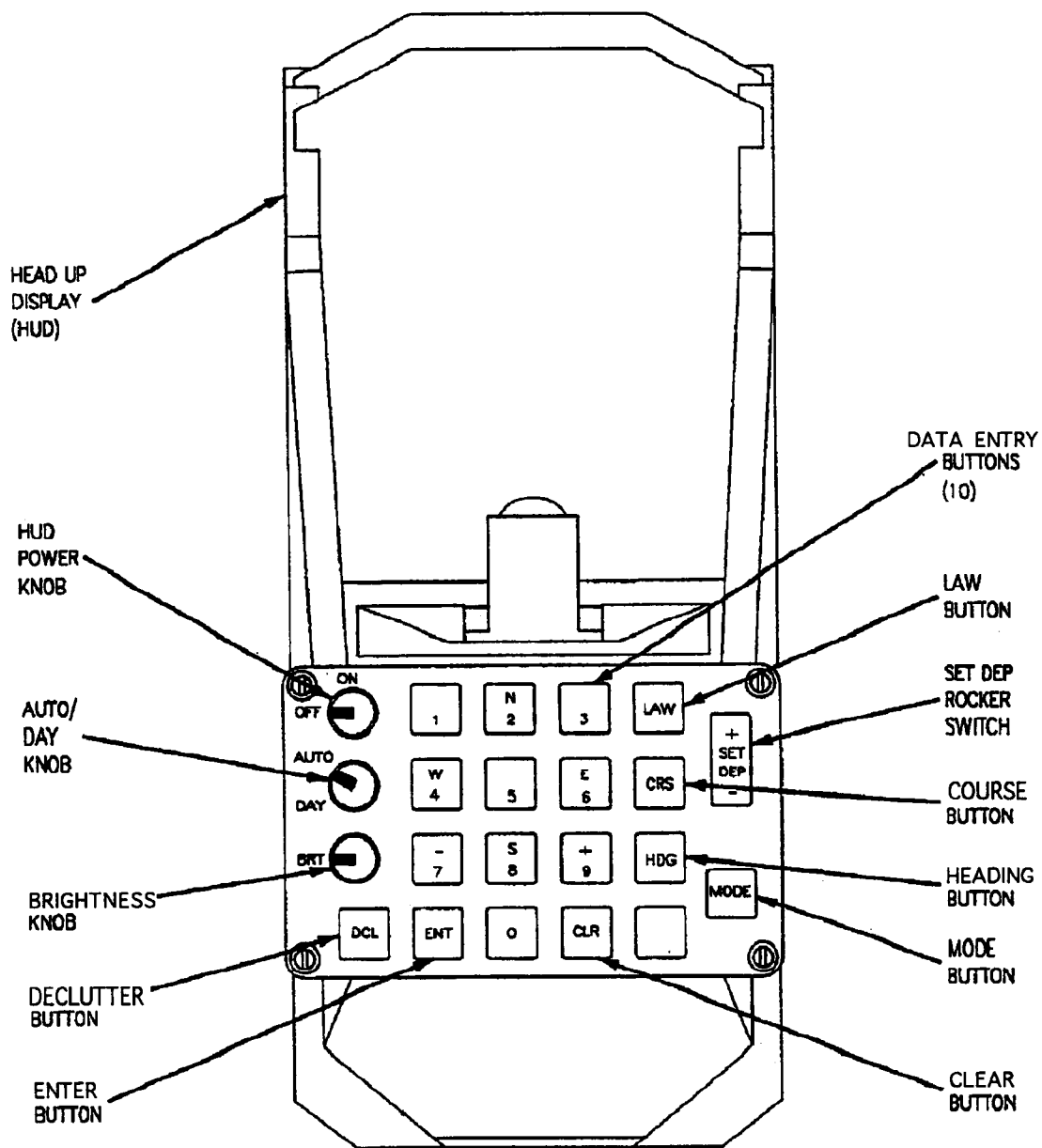


Figure 10. Head Up Display (HUD) and Data Entry Panel (DEP).

Source: Preliminary NATOPS Flight Manual Difference Data With Cockpit 21 Installed Navy Model T-45A Prototype Aircraft 163635 (PS1471-1). (1995). St. Louis, MO: McDonnell Douglas Aerospace.

showing the selected numerics until the enter option is depressed on the DEP and the DEU accepts the entry. Entries with excessive digits or unacceptable entries will cause the scratch pad to remain displayed until the entry is corrected or approximately 1 minute elapses following the last DEP button selection.

The DEU functions in any one of three mutually exclusive master modes. Master mode selection to NAV, A/A, or A/G optimizes the HUD display for the selected option. With the A/A and A/G HUD displays, the appropriate aiming reticles are presented while some symbology is removed. The removal of symbology through master mode selection essentially optimizes the HUD for the desired training mission. Additionally, selection of A/A or A/G enables the Stores (STRS) page display functions briefly discussed in the next section.

Additional Displays and Capabilities

The discussion of flight test results will mainly focus on the ADI, HSI and HUD controls and displays. However, a brief description of the various MENU options and CP21 displays is presented here in an attempt to provide balance and depth to the entire CP21 system and capabilities. As shown in Figure 5, the menu tree provides for selection of DATA, STRS, HUD, VREC, TRNG, BIT and engine (ENG) pages. Because of the proprietary nature of some features, depictions of most display options will be omitted.

The DATA MENU option allows the pilot to monitor or input navigation system data. The DATA sub-pages are ACFT, GPS, and WYPT, permitting the aircrew to check the GINA alignment following start, view GINA position information including GPS accuracy, check any of the 11 WYPT entries, interface with the MDL to transfer any of its 200 stored waypoints into the 11 accessible by the DEU, and to enter WYPT

positions or sequences. Additionally, the pilot may select the shipboard GINA alignment option.

The STRS page, permits master mode selection via the MFD pushtiles. When A/A is selected, the A/A reticle appears on the HUD. The reticle is positioned on the HUD for either maneuvering or nonmaneuvering targets at an optimum range of 1000 ft for attempting simulated A/A gunnery on a towed banner or opposing aircraft during ACM training, respectively. The only A/A weapon option is the gun (GUN). When A/G is selected, GUN, bomb (BMB), and rocket (RKT) weapon options appear. With any A/G weapon selected, the fixed reticle sight appears at a default depression setting appropriate to the weapon. A Continuously Computed Impact Point (CCIP) reticle option is also available for any of the weapons. When BMB or RKT are selected, weapon quantity selection (QTY) becomes available with default settings of 6 and 7, respectively. Each depression of the weapon release button on the control stick decrements the displayed weapon quantity.

The HUD MENU option selects the HUD video for display on any MFD. The display is presented from the HUD camera field of view and is too small to be utilized as a flight reference. The purpose of the display is to facilitate critique of SNA performance during any training phase, particularly, A/A and A/G.

The VREC page permits selection of any MFD or the HUD for video recording on the 8 mm video recorder mounted in the aft cockpit right console. Video recording aids in post flight debriefing of SNA performance.

The TRNG page allows the instructor pilot to fail any or all of the available displays or systems in the opposite crew station. Once the TRNG page has been selected in either cockpit, the other cockpit cannot access it until any initiated failures have been cleared and the display is deselected.

The built in test display (BIT) provides a status display for various avionics systems. The display is based on discreet status monitoring via the mux bus or the ON/OFF position of the control switch on the individual component control panels being monitored. Any time a BIT code status changes to indicate a degrade, an avionics built in test (AV BIT) advisory is displayed on each MFD. The AV BIT remains displayed until the BIT page is selected. When the airplane is on the ground and the DEU is receiving the weight on wheels discreet, tests of various avionics components may be initiated from the BIT page. Additionally, from BIT, the GINA or RALT power may be turned on or off. A maintenance (MANT) display option is also available from the BIT page. The MANT page permits aircrew or maintenance personnel to access system sensor codes, check system software, determine if the ADR data bank is full and enter a SADS barometric altimeter correction, if required.

An ENG display page provides digital readouts of various engine operating and fuel parameters. Engine parameters not provided on cockpit analog gauges but required for maintenance functions are available on the ENG page.

AIRPLANE MODIFICATIONS FOR FLIGHT TEST

As described in the T-45A Cockpit 21 Avionics Integration Evaluation Test Plan (1994), the airplane was equipped with an Aydin-Vector MMP-900 data system mounted on an instrumentation pallet in place of the aft cockpit seat. This was a time division multiplexing system with programmable read only memory format definition. The pulse code modulation (PCM) system had 10 bits per word and a bit rate that was variable from 32 Kbps to 1.024 Mbps in 6 binary steps. Modular remote multiplexing units were used to insert analog and digital data into the data stream. The PCM signal with time and pilot voice had the capability to be transmitted for real time monitoring.

The data system was also equipped with a Sonix FM system for high frequency data collection. A maximum of six chassis could be installed, each capable of recording up to 6 measurands. The chassis signals were sent directly to the tape recorder tracks. The PCM and FM data streams were both recorded on a 10 inch Mars 2000 tape recorder with a one hour run time at 15 ips.

A video camera was mounted on the instrumentation pallet to allow external recording of the aft cockpit MFD's. Provisions allowed the camera to be moved to the front cockpit, above and behind the pilots left shoulder, to record the standby pressure and attitude instruments or the left MFD.

The controls for TM and on board tape were located on the right console in the forward cockpit. Additionally, the HUD tape recording system was utilized for data collection. No modifications were required for HUD recording.

A DEU power, or reset, switch was mounted in the forward cockpit, left console. In the event of system failure or degrade, the DEU reset switch was available to restart the DEU as a last resort for eliminating encountered anomalies.

FLIGHT TEST DEVELOPMENT

GENERAL CONCEPT

Although no simulator was available for developmental testing, CP21 program risk was seen as low. Most components incorporated were modified T-45A avionics system hardware. The incorporation of the mux bus and MFD's were not considered high risk since they were previously tested and approved avionics components being utilized in other military aircraft. The software risk was deemed low mainly because the system requirements were simple. Because of the low risk nature of the project, only 17 to a maximum of 34 test flights were envisioned by MDA. The first flight of CP21 was scheduled for February, 1994.

As described up to this point, the avionics system changes required to incorporate CP21 in the T-45A were not extensive. However, the CP21 avionics upgrade yielded a primary display array dramatically changed from the analog cockpit. The battery of tests required to insure system functionality was extensive, including intra- and inter-system electromagnetic compatibility tests. I will limit this discussion mainly to the flight testing performed to ensure CP21 avionics integration functionality and utility. In addition, I will briefly describe the software release plan and the software safety of flight testing.

SCHEDULED SOFTWARE RELEASE PLAN

The original software development plan consisted of two Operational Flight Program (OFP) releases during the integration program, with a third OFP release scheduled for production incorporation. Development OFP releases were to be broken

down into sub-releases. OFP-1A was to incorporate basic navigation functions with the lack of BIT, MDL, STRS and TRNG page functions. OFP-1B was superseded by an early release of OFP-2A-1 prior to completion of tests on 1B. OFP-2A-1 incorporated BIT, RPTR, and MDL functionality. OFP-2A incorporated STRS and TRNG page functionality and included some additional navigation functions. Finally, OFP-2B was to incorporate enhancements and required changes identified during OFP-1 and OFP-2A testing. The completion of the process was planned for August 1994.

SPECIFIC METHODS OF TEST

LABORATORY TESTING

OFP Evaluations were conducted using MDA's Integration Test Facility (ITF). The ITF consisted of four integrated test stations: DEU, GINA, ADR/SADS, and TACAN/VHF/VOR/ILS stations. In addition, MDA modified a radar altimeter and transponder for integration with the system. Each station was designed to be part of the ITF, or as a stand alone test bench that could be taken to the flight line for trouble shooting, if required. Each station used actual CP21 avionics, but also had the capability to support a real-time simulated flight mode.

The simulation (SIM) mode was accessed through desk-top computers located at the DEU, GINA, and ADR/SADS stations. A generic flight model was utilized to provide the simulated flight environment. In the SIM mode, the computer-generated 1553 data (consisting of serial, synchro, analog, and discrete signals) was transmitted through a common 1553 interface from the DEU to the other on-line stations. In this manner, the ITF was used as an initial test bed for each OFP prior to loading it into the airplane. The ITF was then "flown" in an attempt to recreate a certain flight scenarios where problems were expected or encountered.

TEST PROCEDURES

The testing was divided into two areas, system functionality and mission profile testing. Functionality testing was performed in the ITF and then the airplane on the ground. Approximately two days were required in each of those phases to perform the full system check outs. Following the ground tests, the OFPs were functionally tested in the airplane during flight.

Functionality testing consisted of activating each MENU display option and every function on each display page. Additionally, each possible system entry via the DEP or MFD pushtiles was attempted. This time consuming process was necessary to access the basic performance of each successive OFP. Initially, functionality testing was performed with the instrumentation pallet installed. When tests using the RPTR and TRNG functions were required, the aft ejection seat was installed and two pilot flights were performed.

Once functionality was tested, test flights progressed to mission profiles. The mission profile maneuvers and procedures were taken from the FTI (1994) and included the following:

- A. Basic Instrument Flight with the instrument hood installed.
- B. Radio Instruments and Airways Navigation
- C. Familiarization Maneuvers including aerobatics and stalls
- D. Day and Night Formation Flight
- E. Simulated A/A Gunnery and ACM
- F. Simulated A/G Weapon Delivery Maneuvers
- G. Low Level Navigation
- H. FCLPs

The FTIs were used as a flight test maneuver guide to ensure CP21 system integration would not interfere with the SNA's ability to perform the various missions. Pertinent maneuver profiles are described in the Detailed Method of Test, appendix B.

GINA functional performance and integration testing was conducted concurrently with all the ground and flight tests. No cryptographic codes were loaded into the GINA GPS receiver for flight test. Dedicated GINA flight tests were not originally planned.

Flight Tests

Approximately 153 test flights were flown in either two pilot or single pilot configurations. The flight test team initially consisted of one Navy and one MDA test pilot. Aircrew for mission profile maneuvers flown at NAS Patuxent River and on cross country flights usually consisted of two Navy test pilots. I was the principle Navy CP-21 test pilot, flying 101 flights and 129 flight hours. During the final Navy evaluation, additional Navy test pilots flew in the aft cockpit and were used to evaluate CP21 during instrument and ACM mission profiles.

Test Conditions

Flight test in the prototype CP21 T-45A was limited to flight under VMC, either day or night. The airplane instrumentation wiring was to remain dry so flight in visible moisture was avoided as much as was practical. Flight tests were conducted from and between MDA, in St. Louis, MO, and NAS Patuxent River, MD.

Test Envelope

The CP21 aircraft has been cleared to full T-45A envelope limits. Minimal performance impact was expected, and no performance testing was planned. There were no flying qualities or propulsion impacts with the incorporation of CP21. Approximately 90 lbs. was added to the forward CG of the baseline aircraft (less than 2% forward CG shift from baseline). CG travel was well within the limits tested during T-45A Full Scale Development.

Test Loadings

With the exception of 5 carrier suitability test flights, all flights were conducted in the clean configuration. The carrier suitability test flights were flown with a Drodipod on the centerline pylon for real time monitoring of sink rates and loads. Gross weight varied from approximately 10,800 to 13,600 pounds. Center of gravity position varied from approximately 16% to 20% Mean Aerodynamic Chord (MAC), which was within the limits of 12% to 21% MAC.

Test Configurations

Test configurations are presented in Table 1. Thrust requirements varied for the test conditions.

Table 1
TEST CONFIGURATIONS

Configuration	Landing Gear	Flaps	Speed Brakes
Takeoff (TO)	Down	Half	In
Power Approach (PA)	Down	Full	Out
Cruise (CR)	Up	Up	In

INSTRUMENTATION

Flight test data, display video, and audio were recorded by on board tape recorders in the instrumentation pallet and the HUD video recorder. Specific system interface and integration test points as well as mission profile maneuvers were listed on pilot cards which were used for handwritten notes. TM was recorded by the ground station at MDA in St. Louis, MO, and at the Chesapeake Test Range, NAS Patuxent River.

TEST STANDARDS

The CP21 avionics upgrade to the T-45A was evaluated for its suitability to fulfill the requirements of the undergraduate jet training mission. Specified requirements included the capability to perform the maneuvers described in the FTI (1994) in compliance with the TEMP (1994) and compliance with Human Engineering Design Criteria for Military Systems, Equipment and Facilities, Military Standard (MIL-STD-1472C) (1983).

CHRONOLOGY OF EVENTS

Flight tests commenced in March 1994 with a final USN test period in March 1995. Table 2 contains a basic chronology of the evaluation with the date and flight number for first flight of each OFP, where applicable.

Table 2

CP21 FLIGHT TEST: OFP FLIGHT TEST CHRONOLOGY

Software Release	Flight Number	Flight Date ⁽¹⁾
OFP 1A	1	19 March 1994
OFP 1B	Laboratory Only ⁽²⁾	
OFP 2A-1	5	26 May 1994
OFP 2A-2	Laboratory Only	
OFP 2A	11	27 May 1994
OFP 2A-3	Laboratory Only	
OFP 2B	13	13 July 1994
OFP 2C	44	1 September 1994
OFP 2D-1	50	15 September 1994
OFP 2D-2	66	4 October 1994
OFP 2D-2-1	69	6 October 1994
OFP 2D-3	71	12 October 1994
OFP 2D-3-1	Laboratory Only	
OFP 2D-3-2	72	17 October 1994
OFP 2D-3-3	Laboratory Only	
OFP 2D-3-4	73	21 October 1994
OFP 2E	91	1 December 1994
OFP 2E-1	100	12 January 1995
OFP 2E-2	102	24 January 1995
OFP 2E-3P	Laboratory Only	
OFP 2E-3	106	8 February 1995
OFP 2E-3S	Laboratory Only	
OFP 2E-4	Laboratory Only	
OFP 2E-5	128	6 March 1995

Notes: (1) No dates are listed for laboratory only OFP tests.

(2) Laboratory Only refers to testing in the Integrated Test Facility (ITF) only.

FLIGHT TEST RESULTS

GENERAL

CP21 flight test commenced in March 1994 with a final USN evaluation conducted in March 1995. Every function and every maneuver were not flight tested with every OFP. Generally, after the first five OFPs, flight test focused on corrected functionality or areas where problems were expected following laboratory testing. The first flight of each OFP was used as a quick look, with the pilot testing or exploring specific functions. After the first few flights, the system was evaluated during mission maneuvers for functionality and utility.

Each test flight was preceded by a thorough briefing covering pertinent OFP changes, problems encountered in the laboratory, functionality expectations, and tests to be performed. Consequently, following each flight, a debrief was conducted utilizing video review of the display recordings for each test point or event. With the instrumentation pallet installed, the engineering team would examine TM or onboard data tapes for specific events where problems were noted.

When functionality anomalies or other problems were identified, the flight test engineers would define the problem for the software writers. The corrections were incorporated during the next available OFP release for further testing. The lack of a CP21 simulator probably led to delays in identification and definition of many problems. This was especially evident when the prototype airplane was undergoing serious maintenance difficulties in June and July of 1994.

Although the setbacks at that early stage certainly caused significant delays in corrections for many identified problems, OFP releases came fairly quickly. The

number of problems identified, defined, and scheduled for correction was fairly large, but the process seemed to be rolling along quite well. Unfortunately, problems identified in one OFP and corrected two releases later would often reappear in a following load.

From the first flight of CP21, system functionality was fairly good, with some minor miscues encountered. However, unexplained system anomalies and display perturbations occurred routinely, requiring more data gathering and investigation. Additionally, a few serious pilot to system interface problems were identified. Many problems were most likely the result of a lack of understanding of the desired utility on the part of the software code writers. Others were probably due to poor system design, with a large number caused by display response lags and poor MFD resolution.

The result of the large number of system and display problems was an excessive number of individual corrective actions demanded of the software designers with little apparent design control or configuration management. The snowballing effect was a degradation in the planned OFP release sequence and a long series of regressions encountered with the growing number of OFPs. The discussion of test results will be divided into two parts. The first part will detail a few of the major problems identified through the first 23 OFPs, prior to the final USN developmental flight test evaluation. The second part will deal with some of the final results from the USN evaluation of OFP 2E-5. All deficiencies were documented by the USN test team (Wettlaufer, Vinson, & O'Hara, 1995).

OPERATIONAL FLIGHT PROGRAM EVOLUTION

In the early stages of flight test, some of the most glaring problems were encountered in the HUD display, the MFD pushbutton input to display response

mechanization and timing, the digital nature of the ADI page, and the lack of smooth symbology transitions on the ADI and HSI displays. I will briefly touch on some of the specifics.

THE HEAD UP DISPLAY

The HUD display, shown in Figure 9, was modeled after the baseline T-45A HUD with the addition of the velocity vector (VV) and the HDG caret. The VV was designed to provide the pilot with a symbolic representation of the airplane's roll attitude, as well as climb or dive angle, when interpreted relative to the pitch ladder symbology. The two main problems encountered with the HUD display initially were the lack of a smooth VV transition at certain angles of bank and excessive jitter in the VV and pitch ladder.

Velocity Vector Jumping

VV jumping was identified during normal in flight maneuvering at bank angles greater than 90 degrees left or right. The condition occurred at all altitudes and airspeeds flown from approximately 5,000 to 25,000 ft MSL and 150 to 480 knots indicated airspeed (KIAS). The problem was then defined during 360 degree aileron rolls.

As a 360 deg AOB roll was initiated from a slightly nose up attitude and wings level flight, the VV should have moved up from the center of the HUD, followed by a transition to the lower portion of the HUD (at approximately 90 or 270 deg AOB) and then back toward the center again, assuming a return to level flight. The pitch ladder was supposed to be constantly positioned about the VV during its transitions. Unfortunately, the display did not provide a smoothly transitioning VV. The result was a display that appeared to have a vertical hold problem since the VV would instantly

disappear from the top of the HUD and reappear at the bottom during a 360 degree roll. In the first OFP load, the VV jump was coupled with a pitch ladder that would essentially split apart into separate pitch ladder lines, yielding a nonsensical display as airplane roll attitude passed through approximately 90 and 270 deg AOB. The pitch ladder break up anomaly was corrected fairly quickly but, the VV transition jump remained for a number of OFP loads, finally being corrected prior to OFP 2E-3.

Velocity Vector Jitter

In benign flight conditions with low levels of airplane pitch rate, the VV symbol position changed fairly smoothly and consistently. However, as pitch rate was increased at any AOB, the VV appeared to jitter. It was most apparent on the back side of a loop with low airspeed and a high pitch rate or under normal accelerations greater than approximately 2.0 g. The jitter, although not at a constant rate, was predictable and caused the VV to blur. The VV jitter also affected the HUD pitch ladder. When jitter was encountered, the pitch ladder rungs would appear to double write, causing a smeared looking display.

The jittering VV and pitch ladder caused eye fatigue and resulted in low confidence in the display presentation. HUD display jitter was investigated throughout the flight test evolution. The cause was not identified until after March 1995 and will be discussed later.

MULTI-FUNCTION DISPLAY PUSHTILE FUNCTIONS

In the original design, the main pilot to system function interface for the low altitude warning (LAW) function, low fuel or bingo (BNGO) setting, HDG and CRS set functions was through selection of display legends by depression of the adjacent MFD

pushtiles. LAW and BNGO were provided on the ADI page, while HDG and CRS were on the HSI page. As shown in Figures 6 and 7, the legends were collocated with a numeric indicating the current setting of that parameter. When the MFD pushtiles corresponding to LAW, BNGO, CRS or HDG legends were actuated, the legend became boxed and the two lower right side pushtiles on the MFD became active, with arrowhead symbols displayed, for scrolling the appropriate numeric up (increasing the numeric) or down (decreasing the numeric) to the desired setting. The LAW numeric setting range was from 10 to 4,950 ft above ground level (AGL), in 10 foot increments with a maximum scroll rate of approximately 400 feet per second. The HDG and CRS setting ranges were 000 through 359 degrees in 1 degree increments at a maximum scroll rate of 25 degrees per second. The BNGO numeric setting range was from 0 to 3000 pounds of fuel in 100 pound increments and had a maximum scroll rate of approximately 500 pounds per second.

The scroll rate varied with time of pushtile actuation. Upon the first depression of the selected incrementing pushtile, the numeric would change by the smallest increment. After 1 second of depression, the numeric would start to scroll at an increasing rate up to approximately 4 seconds when it would reach its maximum scroll rate. In an attempt to decrease the time required to make any changes in the parameters with this mechanization, the scroll rate ramp up was removed and timing was altered slightly in OFP 2D-3. In following OFPs, after approximately 1/2 second of pushtile depression for incrementing LAW, BNGO, CRS or HDG, the maximum scroll rate commenced without a ramp.

Although the BNGO function was not provided in the baseline T-45A, LAW, CRS, and HDG were available. The LAW setting was accomplished on the radar altimeter gauge through movement of a pointer on the display face facilitated by rotating a weighted knob. The pointer was positioned at the altitude, from 0 to 5,000 ft AGL,

that the pilot desired for a low altitude warning. The same mechanization for HDG and CRS were provided on the analog HSI. A rotating knob was used to move the HDG caret on the HSI compass card and another knob was utilized to input the desired CRS, from 001 to 360 degrees, which rotated the HSI course line and changed the CRS display numerics.

The use of the LAW, HDG, and CRS functions occur constantly throughout every flight. The standard USN practice is to adjust the LAW setting to approximately 10 percent below the desired flight altitude when airplane altitude is below 5,000 ft AGL and set it to 5,000 ft AGL when above that level. The HDG and CRS functions are used during instrument flight to assist the pilot by providing cues after receiving air traffic control instructions and during instrument approaches, as well as during low level navigation and any time the pilot desires to maintain a specific heading or course. LAW, CRS, and HDG set functions as well as BNGO were utilized during every test flight.

In the baseline T-45A, the movement of the LAW and HDG carets or the CRS display window setting and course line were predictable through manual rotation of the respective knobs. Therefore, setting those parameters merely required the pilot to locate the appropriate knob while noting the current setting, then rotate the knob the approximate amount without looking at the display, followed by a quick fine adjustment to the desired setting. Minimal time off of the control stick or throttle was required for the pilot's hand to perform those functions.

In CP21, changing any of the above numeric displays by significant amounts required excessive time with the pilot's hand off either the control stick or throttle. Changing the LAW setting from 500 to 3,000 ft during an instrument climb required the LAW legend to be manually boxed followed by depression of the increment pushtile for approximately 8 seconds until the desired value was reached. Because of the mechanization, the pilot was unable to anticipate the display numerics arriving at the

desired setting, requiring scan concentration on the selected display as the numerics changed in order to attempt to stop at the desired setting. During approaches and in formation flight, each LAW depression attempt required the pilot to release either the control stick or throttle for excessive periods of time while staring "heads down" at the changing LAW numerics. The results were gross position deviations in formation flight and aborted LAW entry attempts for what should otherwise be a quick, easy task. Similarly, during CRS and HDG adjustments, the pilot was required to watch the scrolling numerics, moving course pointer, or command heading caret to anticipate the arrival at the desired value.

An additional problem aggravated the above conditions. A significant delay was evident when the pilot depressed the pushtile on initial actuation or released the pushtile while any numerics were scrolling. The delay was approximately 1/3 second resulting in an 8-10 degree continuation of a scrolling HDG or CRS display after pushtile release. Even when the pilot concentrated solely on the scrolling numerics, attempts to anticipate arrival at the desired setting resulted in an overshoot or undershoot and required the pilot to make up to 10 additional single pushtile inputs to set the desired value.

As a further aggravation to the response delay, the MFD pushtiles had poor tactile feedback. The pushtiles were flat and did not snap when depressed. Depressions of the pushtiles at the corners did not yield display responses. Often, the pilot would sense that a pushtile had been actuated and move his hand back to the control stick or throttle only to notice at a later time that his attempted input had not been accepted.

Because the pilot to MFD interface created significant problems with the utility of the often used LAW, CRS, and HDG functions, the DEP keypad, shown in Figure 10, was integrated for those functions. Three spare buttons on the DEP were made available for LAW, CRS, and HDG actuation. In order to quickly enter the desired value instead of using the scroll function, the DEP keypad was made available for numeric entries in

those functions. Therefore, OFP 2E-5 was evaluated with DEP keypad functionality for LAW, CRS, and HDG incorporated.

THE ATTITUDE DIRECTOR INDICATOR PAGE

Instrument Scan

Aircraft flight instruments are divided into three categories according to their specific function: control instruments, performance instruments, and position instruments. The ADI is the primary control instrument that enables the pilot to provide a proper combination of pitch, roll, and yaw control to achieve the desired airplane performance (FTI, 1994). It is the central point of the instrument scan.

The performance instruments indicate how the airplane is performing as a result of control changes. The airspeed indicator, vertical speed indicator, heading indicators, AOA indicator, clock, turn needle and altimeter are performance indicators. Along with being a performance indicator, the altimeter is also a position instrument, conveying the aircraft's location in space and helping to provide an indication of what control and performance changes are required to achieve the desired flight parameters. Other position instruments include the ILS steering bars on the ADI and the radio instrument needles on the HSI.

During instrument flight, the pilot must divide his attention between the control, performance, and position instruments. The proper timing of the scan and sequence of instruments scanned varies depending upon the maneuver being performed. During flight training, the SNA learns what factors to consider when executing various maneuvers that determine how he will divide his attention properly between the flight references and which symptoms will enable him to recognize correct and incorrect scan patterns and techniques. The instrument scan, centered on the ADI, must allow the pilot

to quickly monitor altitude, airspeed, vertical speed, and navigation information. Common errors include having no instrument scan, omitting an instrument from the scan, or fixating on a single instrument (FTI, 1994).

The Digital ADI

In the baseline T-45A, all the primary flight references are positioned on separate instrument displays. In CP21, the primary flight reference, which includes the control, performance and position instruments, is the ADI page. The scan of flight instruments in the analog cockpit was much larger than that required in CP21. However, the analog instruments, with their infinite resolution, provided the pilot with moving pointers as reference indicators for altitude, airspeed, and vertical speed. With analog instruments, the pilot did not necessarily have to focus on the face of the gauge to determine his exact airspeed or altitude. Since the pilot is familiar with the face of each instrument and the delineations on it, the pilot only had to recognize the pointer's vicinity on the instrument face, its direction of movement, and rate of movement in order to quickly scan his performance and position indications.

Unlike the ADI display in Figure 6, the original design did not incorporate the fixed scale, moving pointer VSI on the right side. All flight parameter information on the primary display was in digital form. In order to understand the digital presentation, the pilot must not only determine what the displayed values are but, he must also determine where it is going and how fast it is changing.

The ADI page was evaluated during all flight test events but, problems with the display were especially evident during instrument flight training maneuvers. The maneuvers were flown from both the front and aft cockpits. The instrument hood was utilized to simulate IMC for pilots in the aft seat. The basic instrument maneuvers

performed included constant rate climbs and descents, constant AOB and constant rate turns, "S" patterns of defined combinations of timed climbing, descending, and turning flight, level speed changes, turn pattern, slow flight maneuver, and instrument approaches. Cockpit display arrangement was normally the ADI page on the left MFD and the HSI page on the right MFD. The altitude display had a resolution of 20 ft while the resolution of the VSI, originally 50 ft per minute prior to OFP 2C, was 10 ft per minute.

During normal instrument scan, changes in digital readouts were noted, but the pilot was forced to stare at the changing values to determine whether they were increasing, decreasing, or alternating between two values. Rates of change and trends could not be determined from a normal scan of the digital altitude and airspeed, making it extremely difficult to capture and maintain constant speed climbs and descents within ± 10 KIAS, constant rate climbs within ± 400 fpm, or altitudes within ± 200 ft. Attempts at basic instrument maneuvers resulted in scan fixation and ultimately scan breakdown. Attempts to capture and maintain glide slope and heading during precision approaches with the instrument hood installed resulted in excessive pitch attitude, airspeed, descent rate, and AOA deviations and subsequently poor glide slope control throughout the approaches.

Digital Update Rate

As mentioned previously, the resolution of the VSI digital readout was originally 50 fpm. The resolution was increased to 10 fpm in an attempt to provide better trend data to the pilot. Additionally, low update rates for critical flight parameters were a consistent problem.

During instrument flight, the primary flight displays provide the pilot with rate of change information that he uses to make control inputs, enabling smooth and timely capture and maintenance of desired flight parameters. Update rates on the ADI for altitude, airspeed, and VSI were low, at less than 2 Hz, initially. The rate of change of the numerics during any dynamic condition were too slow to present the scrolling numerics that were required for the pilot to perceive rates of change properly.

The result of the low update rates was an ADI display page that only provided "snap shots" of critical flight parameters. For instance, in shallow descending flight at approximately 15 degrees nose down pitch attitude, the altimeter numerics changed in 100 foot increments and the VSI did not scroll to indicate a rate of change of the rate of descent as airspeed increased. The airspeed numerics did not scroll either, but changed in apparently randomly sized increments during accelerations and deceleration's. During basic instrument maneuvers, attempts to capture and maintain desired combinations of airspeed, altitude, and vertical speed were extremely difficult, requiring the pilot to stare at the displayed numerics for excessive periods of time while attempting to decipher the leaps in each parameter.

The ADI attitude ball and the HSI compass rose displays update rates were designed to be approximately 25 Hz. The digital data update rate on the those displays was designed for 3 Hz. After achieving and then determining that the 3 Hz design update rate was inadequate for instrument flight, the update rate for the digital numerics on the ADI page were targeted for increases with each successive OFP release. The update rates for the numeric parameters reached 15 to 17 Hz in OFP 2E-5.

ATTITUDE DIRECTOR INDICATOR AND HORIZONTAL SITUATION INDICATOR SYMBOLOGY MOVEMENT

The primary symbology on the ADI page, the attitude ball, and the HSI page, the compass rose, represent the analog instruments in the baseline T-45A. The movement of the analog instruments is essentially smooth and free of discrete steps, possessing infinite resolution. On the other hand, representation of those displays on the CP21 MFD's presents some inherent difficulties.

The MFD display screens consist of discrete pixels which are illuminated selectively to present the symbology desired. Since the dimensions of each pixel are fixed, a lower limit exists on the thickness of any line and thus any symbol. Additionally, with the arrangement of the pixels on the display, a straight line can only be drawn straight across, straight up and down, and at 45 degree angles to the sides of the screen. Any rotation of a line on the display causes the line to segment, giving a stairstep appearance.

For instance, the horizon line on the ADI attitude ball is straight when flying a wings level attitude. As soon as the AOB changes to a value other than 0, the horizon line segments in the center. With small increases in AOB, the number of segments or breaks in the horizon line increases. The same occurs with each line on the ADI ball and any line symbol on the HSI. A similar problem exists when symbols must be translated across the screen.

When the ADI attitude ball numerics or dots, letters, and numbers on the HSI compass rose move, they are unable to transcribe an arc and, so, do not move smoothly. Instead, the symbol movements ratcheted. When a dot on the compass rose moves as the airplane turns, the symbol may have to move up one pixel and over two as the compass rotates. That movement appears disjointed or unnatural for a compass. Because the same situation exists for all the symbols on the compass or attitude ball at

the same time, all of the display movements were corrupted, resulting in individually moving symbology pieces with a disjointed swimming motion.

Effects Of Ratcheting Displays

During the flight test evaluations, the movement of symbology on the ADI and HSI display formats appeared discontinuous and ratcheting. During small AOB changes of less than 5 deg, the ADI horizon line and pitch bars separated into a series of moving line segments. The segmenting horizon line implied larger AOB deviations to the pilot, which diverted the instrument scan and resulted in a trained response to correct unnecessarily for the perceived flight path deviations. During small AOB changes about a level flight condition, the segmented horizon line resulted in excessively large and often incorrect or opposite step or pulsing lateral control inputs as the pilot attempted to maintain wings level flight.

The sliding heading scale in the upper portion of the ADI page did not present a smoothly transitioning compass display, clicking in 1 deg increments as the airplane heading changed. During attempts to maintain a precise heading within 1 degree using the ADI display, clicking or ratcheting of the heading scale forced the pilot to input larger than required lateral control inputs to recapture the desired heading because initial small inputs did not result in timely or smooth heading scale changes. Additionally, the HSI compass rose numerics and markings did not rotate smoothly during turns. Instead, the compass rose symbology appeared to ratchet and rotated in a manner not representative of typical HSI type instruments or display representations.

During attempts to maintain a heading from a small, 1 to 2 degree deviation required the pilot to make small lateral control inputs, the heading indications would not change as expected. So, the pilot would increase the magnitude of his control input and

the display would "click" too far yielding an overshoot and requiring the pilot to make another attempt. The frustrating process would continue until the pilot finally achieved his desired heading or accepted the deviations. The overall effect of the ratcheting primary flight displays caused the pilot to fixate his scan on the ratcheting symbology as he attempted to control that parameter and led to poor control of altitude, vertical speed, airspeed, and pitch attitude during instrument flight.

THE FINAL EVALUATION: OPERATIONAL FLIGHT PROGRAM 2E-5

The first flight for OFP 2E-5 was in early March, 1995. After initial flight tests to confirm functionality and implemented corrections, A037 was flown to NAS Patuxent River, MD, for the evaluation. A series of test flights covering the pertinent training mission profiles and including most of their FTI described maneuvers was conducted. The main concentration of the flight test effort was toward instrument flight since most problems had manifested themselves in that area.

Corrections for some problems identified prior to OFP 2E-5 were mentioned in the previous section. They included incorporating the DEP for pilot interface and control of LAW, CRS, and HDG functions, the VSI fixed scale, moving pointer symbology for trending information on the ADI page, and increases in the update rate for some flight critical digital data numerics on the ADI page. Those changes in the system design and displays were improvements but did not eliminate other important avionics integration deficiencies.

A few additional problems with the CP21 avionics integration identified during the flight test evaluation of OFP 2E-5 will be discussed here. Along with those still existing in the system prior to OFP 2E-5, like the lack of trend information for critical flight parameters and the ratcheting display symbology, additional problems included

DEP keypad interface problems, velocity vector positioning errors, excessive response lags on the primary flight references, and uncommanded MFD display blanking.

TREND INDICATIONS

As noted previously, the VSI scale and caret on the ADI page were added to the display prior to OFP 2E-5 in an attempt to provide a trend indication that would allow effective instrument flight training. The vertical speed was still displayed digitally but the addition of the fixed scale, moving pointer VSI symbology provided a presentation that would allow the pilot to more precisely control that parameter. The scale limits were 1,500 fpm rate of climb to 2,000 fpm rate of descent.

In spite of the addition of the VSI display, the same problems with airplane control occurred in instrument flight. Digital readouts of altitude and airspeed did not provide enough trend information to the pilot to effectively accomplish basic instrument training maneuvers. The result was scan breakdown. Again, attempts to capture and maintain glideslope and heading during precision instrument approaches with the instrument hood installed resulted in excessive pitch attitude, airspeed, and AOA deviations and subsequently poor glide slope control.

RATCHETING SYMBOLOGY

In an attempt to eliminate the horizon line segmentation problem, the horizon line went through some symbology changes. The solid line was changed to dotted. The dotted line was barely noticeable and effectively eliminated the horizon line as a usable flight reference. Additionally, the attitude ball pitch ladder lines movements were tied together in pairs to try to correct the swimming motion of the display symbology. Unfortunately, the symbology movements were the same, but in larger pieces. The

same method was unsuccessfully used in attempting to correct the HSI compass rose symbol swimming.

The avionics system did not possess enough memory or throughput to allow for changes in the raster graphics generator software to compensate for the low MFD resolution. In order to present finer symbols and smoother movement in the raster scan displays, a symbol anti-aliasing technique was required. The process of anti-aliasing consists of varying individual pixel brightness within the pixels illuminated to present a symbol in order to prevent the stairstep of lines and swimming motion associated with ratcheting in the displays. Basically, anti-aliasing would improve the resolution of the MFD's. The design engineers determined that only a hardware change to the avionics system would permit the implementation of anti-aliasing. Unfortunately, avionics system hardware changes would require more time and money than were available. MDA hoped that enhancements in other areas would lessen the severity of this problem.

DATA ENTRY PANEL KEYPAD

The utilization of the DEP for LAW, CRS, and HDG entries mimics modern tactical aircraft, like the F/A-18, which incorporate an up front controller keypad for pilot interface with a number of systems. Implementation of the DEP for entering LAW, CRS, and HDG data reduced the time required to set those parameters, especially for large changes. The BNGO function was not incorporated into the DEP since large changes in its value are not normally necessary, possibly only being reset 1 to 2 times during a flight.

With the use of the DEP to set LAW, CRS, and HDG parameters during all flights, another problem came to light. This problem manifested itself mainly in attempts to utilize the LAW set function. Quick, successive depressions of the same

keypad button were often not displayed. For example, when the pilot attempted to enter a LAW setting of 2,000 ft AGL, at a normal frequency of 2-3 inputs per second, the actual LAW setting resulting from the entry attempt was 200 ft. Contributing to the numerous erroneous LAW entries was an extremely poor tactile feedback in the DEP buttons and a lack of tactile feel on the DEP keypad.

The depression of the LAW DEP keypad button caused a scratch pad data field to be displayed on all MFD's and the HUD. To verify a LAW entry attempt before selecting enter, the pilot was required to look head down to view the scratch pad on the MFD or, in the front cockpit, refocus from the DEP to the HUD scratch pad (approximately 12-15 inches). The change in focal distance contributed to a overall poor pilot to DEP interface for data entries.

During instrument maneuvers from the aft cockpit, the MFD scratch was the only means to verify DEP entries since the HUD was only present in the forward crew station. During formation flight, attempts to input DEP entries resulted in gross position deviations and aborted DEP entry attempts, as experienced previously with MFD interface. Similar problems occurred when attempting DEP CRS and HDG entry attempts during instrument approaches.

VELOCITY VECTOR POSITIONING

Although VV and pitch ladder jitter were reduced up through OFP 2E-5, significant jitter was still apparent at higher pitch rates. The VV positioning errors encountered were not the result of jitter, but were caused by a smoothing function implemented as a fix for the VV jumping present in earlier versions. The caged position of the VV along a vertical line in the center of the HUD led to this problem.

Normally, when caged, most HUD VVs are allowed some lateral movement, possibly up to approximately ± 2 degrees. This lateral movement allows the VV position to more truly reflect actual climb and dive angle and to smoothly transition across the HUD during rolling maneuvers when caged. In an attempt to smooth the VV jump from the top to bottom on the HUD, a position error was incorporated into the VV positioning algorithm. Simply put, the more bank angle, the greater the position error allowed. ITF testing indicated that the VV was positioned incorrectly in relation to the horizon line by 0.2 deg at 30 deg AOB, by 1.2 deg at 40 deg AOB, and by 3.3 deg at 60 deg AOB. Positioning errors both above and below the pitch ladder horizon line were experienced.

The result of allowing position error in the HUD VV was to present erroneous climb or dive angle presentations as the airplane was banked. Rates of climb or descent of up to approximately 600 fpm were experienced with the velocity vector positioned on the wrong side of the HUD horizon line. When referencing the HUD velocity vector, the pilot was unable to maintain desired altitude in banked turns. No warnings, cautions or advisories were presented to the pilot at any time. Erroneous velocity vector positioning was displayed on the HUD until the pilot changed wing attitude to less than approximately 30 degrees AOB (Wettlaufer, Vinson, and O'Hara, 1995).

EXCESSIVE DISPLAY RESPONSE LAGS

Many corrections for OFP problems were attempted prior to OFP 2E-5 testing. The pilots noted what appeared to be excessive response lags on both ADI and HUD attitude displays. Roll response lag was most noticeable during aggressive bank angle correction and capture tasks such as aileron rolls and attempts at precise reticle placement during simulated A/G weapon delivery maneuvers. The pilots were unable to quickly

capture a wings level attitude in either case by using the primary attitude reference. Laboratory testing confirmed the lag with a time of approximately 170 milliseconds (ms).

With OFP 2E-5, all maneuvers requiring both fine control of flight parameters and aggressive control inputs proved difficult when scanning either the ADI or HUD. Excessive roll lag was noted on the ADI when maneuvering under all flight conditions. Attempts to make either small, slow or quick, aggressive corrections for heading deviations were unsuccessful as the attitude ball on the ADI page grossly lagged actual aircraft motion.

Laboratory testing recorded an ADI response delay of 377.5 ms during 100 degree per second rolls. During flight testing, attempts to capture wings level at the completion of a 360 degree aileron roll consistently resulted in overshoots of 45 to 60 degrees AOB. Attempts to make small, slow inputs to correct for even small changes in heading or AOB consistently resulted in under or over shooting of the desired heading or bank angle. The display response latency was also evident in pitch on the ADI attitude ball and on the HSI compass rose movement, rendering instrument flight extremely difficult.

MULTI-FUNCTION DISPLAY BLANKING

During normal display interface, the pilot may access various display formats to assess navigation data, check the BIT page, or interact with the STRS page during an A/G mission. The pilots noted that the cockpit MFD's would momentarily blank during some display changes. Momentary display blanking occurred in both cockpits and within the same cockpit on opposite displays.

When one of the front cockpit MFD formats was changed, both of the aft MFD's displays would go blank. When an aft cockpit MFD was changed from a nondynamic to a dynamic display, the opposite MFD in the same cockpit would blank and then return. After approximately 1 second, the blanked display would then return. The return of the previously displayed format would occur in a rebuilding fashion with the display page's base format returning first, followed by the display numerics and then the moving symbology.

During instrument flight with the instrument hood installed, the pilot's scan was focused on the MFD's. The blanking displays caused distrust of the MFD's and often resulted in the pilot altering his scan to the standby flight instruments.

The blanking MFD's occurred throughout flight test. Prior to OFP 2E-5, display formats were often changed following a blanking event. With OFP 2E-5, the display blanking, although more predictable, still presented a serious problem.

CONCLUSIONS

DEFICIENCIES

CP21 deficiencies were difficult to individually define as they had overlapping effects on pilot performance during flight test. For example, when ADI symbology ratcheting is coupled with excessive response lags during high workload tasks, such as precision instrument approaches, it is hard to determine which is more severe. As pilot gains increased or tight control of flight parameters was attempted, the negative effects of the combination of deficiencies increased, inhibiting task performance in every phase of flight.

The CP21 avionics integration failed the provisions of the TEMP (1994) in that the FTI (1994) could not be satisfactorily completed. With the problems discussed in the previous section, the failure of CP21 to meet the requirements for undergraduate jet pilot training can be classified into two main areas; compromise of flight safety and poor instrument flight training capability.

FLIGHT SAFETY

The VV positioning errors, excessive display response lags on the primary attitude reference, the uncommanded blanking of the primary displays are all considered safety of flight deficiencies. Although the HUD is considered by CNATRA to be a secondary flight instrument in the T-45A, pilots in any phase of flight will be presented with an incorrect flight path angle display which may result in dangerous flight conditions. The display response lag and blanking on the primary flight references contribute to poor instrument flight training but, more importantly, they significantly degrade any pilot's ability to safely fly in IMC.

Velocity Vector Positioning

HUD symbology is utilized for A/A gunnery, ACM, and A/G weapon delivery training. The presence of airspeed, altitude, VSI, and bank angle information of the HUD and its location in the center of the pilot's field of view for most mission phases will result in the pilot attempting to utilize the information presented. Therefore, I believe that the HUD VV presentation will be used as a flight reference, whether or not it is considered primary or secondary.

When conducting landing practice in FCLPs, during instrument approaches, and A/G or low level navigation training, inaccurate positioning of the velocity vector on the HUD may result in ground impact and subsequent loss of aircraft and aircrew. The erroneous DEU algorithm for HUD VV positioning that was intended to correct previous VV anomalies encountered at 90 and 270 degrees AOB is the cause of the positioning errors (Wettlaufer, et al., 1995). The VV does not comply with the Specification (MIL-STD 1472C, 1983) in that it fails to provide clear and unambiguous guidance to the operator and the quality of the VV is not consistent with pilot needs for a flight reference which displays stable, predictable, and reliable indications. Because of the VV positioning errors, CP21 fails to comply with the TEMP (1994) in that the system can not be effectively employed in teaching A/G weapon delivery training or high speed, low level navigation training during day VMC as solo.

Display Response Lag

Display and control response lags in excess of 250 ms have been linked to poor pilot performance, nausea, vertigo, loss of situational awareness, and mishaps (Knotts, Ball, & Parag, 1992). Although research and studies by the Flight Research Department

at CALSPAN Corporation (Knotts et al., 1992) focus on advanced airplane control systems, the essence of their findings concern time delays which relate to both display and airplane response delays. Their studies indicate that pilots need to either feel or see immediate results from control inputs. Delay in response causes inappropriate inputs and leads to pilot induced oscillations (PIO) requiring the pilot to devote more attention to input compensation, which, when focused on display response, causes scan fixation and ultimately results in loss of situational awareness. Another serious consequence of the display response lag is a measurable degradation in the handling qualities of the airplane, resulting in poor control of all flight parameters.

The excessive display lags in CP21 severely degrade the ability of any aviator to fly safely in IMC and is a significant degradation from the baseline T-45A. The cause of the excessive lags is most likely a combination of slow computational data rates and poor software scheduling (Wettlaufer et al., 1995). The CP21 system fails the Specification (MIL-STD-1472C, 1983) in that feedback to the pilot is not provided as rapidly as possible and that displayed information is inconsistent and incompatible with the operators expectations. The excessive time lag between pilot control inputs and display presentation of aircraft response was not consistent with safe and efficient flight operations. In addition, CP21 failed to comply with the TEMP (1994) in that the system will not be able to be effectively employed in teaching the basic or radio instrument training phases which require that the SNA develop a flight instrument scan adequate to control the aircraft without reference to a visual horizon and apply that scan to aircraft operations in instrument flight rule (IFR) environments.

Display Blanking

I feel that uncommanded changes or blanking of the primary flight reference displays is an unacceptable characteristic in any aircraft, no matter the duration of the event. Display blanking in either cockpit of CP21-equipped T-45A aircraft during any flight phase is a major distraction from the training mission and will result in negative training and a loss of confidence in the primary flight references. Momentary blanking of the primary flight references during instrument flight, especially at night or in IMC, will distract the pilot and degrade performance in a critical phase of flight (Wettlaufer et al., 1995).

The cause of the display blanking is the combination of poor software throughput availability and the implementation of the two raster graphics generators (RGG) to drive four independent displays. An interruption in the display generation of the ADI or HSI pages by another MENU selection on any MFD causes the display to be corrupted on the other MFD serviced by the same RGG. Due to this problem, CP21 does not comply with the Specification (MIL-STD-1472C, 1983) in that the displays are not updated and managed in a synchronous manner, and that uncommanded display blanking provides a system response which is not consistent with the operational requirements of the aircraft. CP21 also fails to comply with the TEMP (1994) in that the blanking of the displays interfere with developing a flight instrument scan adequate to control the aircraft without reference to a visual horizon.

INSTRUMENT FLIGHT

Instrument flight requires the pilot to precisely control his airplane through interpretation of the cockpit displays. Instrument approaches, both precision and non-precision, require the pilot to follow voice commands from ground controllers and

published flight parameters in order to maintain safe separation from obstacles on the ground, safe separation from other aircraft, and to successfully find the runway during IMC. On precision approaches, the pilot must maintain the assigned heading within 1 degree and maintain the published glideslope within the safe parameters of that particular approach.

The problems encountered in testing the CP21 avionics integration negatively affect the pilot's ability to effectively conduct instrument flight and to train for instrument flight. In addition to the safety of flight deficiencies discussed concerning velocity vector positioning errors, display response lags and display blanking, they also contribute to degradation of the instrument flight worthiness of CP21. The paucity of trend information and ratcheting symbology presentation on the primary flight references, as well as the system interface problems, heap additional difficulty on instrument flight and the instrument flight training mission.

Trend Indications

The basic instrument training maneuvers are the basis upon which all subsequent training is built. These maneuvers demand a quick and concise instrument scan pattern that will allow the pilot to readily determine and precisely control aircraft flight parameters. CP21 does not provide easily discernible trend indications for altitude or airspeed with the digital presentations on the ADI page. Additionally, the VSI trend indicator, the fixed scale, moving pointer VSI symbology, has only limited range. The CP21 primary flight references do not allow the pilot to readily determine trends in the critical performance and control flight parameters and will prevent the successful completion of instrument flight training, adversely affect instrument flight in IMC, and are degraded from the baseline T-45A cockpit.

The cause of the poor trending information is the lack of analog indicators to provide easily scanned references for altitude and airspeed. Analog presentations allow immediate recognition of both the actual parameter value, by the position of a pointer, and the rate of change of that parameter, by the rate of movement of the pointer. With only the digital numerics for those parameters, the pilot is forced to attempt to interpret scrolling digits and anticipate their rates of change during flight.

With the lack of trend indicators on the ADI page, CP21 fails to comply with the Specification (MIL-STD-1472C, 1983) in that scale indicators should be used to display quantitative information in combination with qualitative information, such as trend and direction of motion. CP21 also failed to comply with the TEMP (1994) in that the system will not be able to be effectively employed in teaching the basic or radio instrument training phases which require that the SNA develop a flight instrument scan adequate to control the aircraft without reference to a visual horizon and apply that scan to aircraft operations in IFR environments.

Display Symbolology Ratcheting

The ratcheting movement of the symbolology on the ADI and HSI pages caused the pilot to input unnecessary, erroneous, and impulse attitude corrections and heading adjustments in response to the primary flight reference presentation (Wettlaufer et al. 1995). The resulting pilot control inputs were not well timed or smooth, which aggravated the perceived attitude deviations, resulting in instrument scan breakdown. The ratcheting symbolology will prevent successful instrument flight training and is a degradation from the baseline T-45A cockpit displays.

The cause of the display symbolology ratcheting is a combination of the raster display resolution limitations, symbol generation techniques, and asynchronous data

transfer from the GINA to the DEU and the MFD's. Because of these problems, the CP21 system fails to comply with the specification in that the display indicators fail to clearly guide the correct control response and that the displayed information fails to allow the pilot to perform the intended mission, providing inaccurate and misleading cues. Additionally, CP21 failed to comply with the TEMP (1994) in that the system will not be able to be effectively employed in teaching the basic or radio instrument training phases which require that the SNA develop a flight instrument scan adequate to control the aircraft without reference to a visual horizon and apply that scan to aircraft operations in IFR environments.

Data Entry Panel Keypad

The use of the DEP keypad for making LAW, CRS, and HDG inputs was implemented to permit ease of use during high workload flight phases. The pilot interface via the DEP keypad led to inadvertent inputs of incorrect LAW, CRS, and HDG selections. The incorrect entries were due to a low DEU sample rate of the DEP keypad, lack of tactile feel and tactile feedback, as well as the lack of a scratch pad display near or attached to the DEP keypad.

Over time, as improper acceptances of desired DEP entries are experienced, I believe that the pilot will most likely abandon the task, especially during high workload phases of flight, such as instrument approaches. The result will be degraded situational awareness because of the lack of cues for low altitude warning, navigation course, and commanded heading. The DEP keypad interface problems fail to meet the requirements of the Specification (MIL-STD-1472C, 1983) in that the DEP button sample rate fails to meet the precision and speed required of the system to support normal operation, the button surfaces are not tactually distinct from the face of the DEP, and that no positive

indication of control activation, like a snap feel, is provided. In addition, CP21 fails TEMP compliance in the system will not be able to be effectively employed in completing instrument flight training.

RECOMMENDATIONS

GENERAL

As the flight test program became bogged down in successive OFP releases, it became evident that the CP21 system was not robust enough to facilitate the properly functioning integration that the USN desired. Numerous regressions in display functionality and response anomalies were encountered as the program continued under increasing schedule pressures. Although the USN test team made recommendations for hardware upgrades to increase memory capacity and data throughput on a number of occasions, the program continued to proceed with successive attempts to correct the identified problems with OFP releases.

As fixes for identified problems were incorporated into the OFPs, the display response lags increased. Every fix seemed to eat up more capacity. With some input combinations, the DEU would freeze up, either blanking all displays or preventing any new interface with the system, requiring the pilot to use the flight test DEU reset switch or reset the airplane generator.

SPECIFIC

In order to correct the utility, functionality, and design deficiencies identified during CP21 testing, a number of recommendations for system modifications were made by the USN test team. The modifications would require new software to provide

smoother and sharper display presentations, hardware modifications to provide increased capacity within the DEU and MFD's, and modifications to the DEP keypad. The USN test team recommended expansion of system memory and throughput by adding processing capacity in the DEU as an obvious choice to provide the capability to correct many of the identified problems.

Additionally, to provide capacity and capability to enhance the resolution of the MFD's, the only plausible solution was to provide individual channels for each MFD and incorporate anti-aliasing in the generation of dynamic symbology on the ADI and HSI pages. Advanced Anti-aliasing Raster Graphics Generators (AARGG) could be installed to allow anti-aliasing and provide individual display channels for the MFD's. The importance of separate channels for each MFD is to allow independent generation of the desired displays, eliminating the display blanking deficiency. An additional benefit of the AARGG's is to allow some software computations to be off loaded from the DEU, hopefully creating more throughput availability and decreasing system latencies.

A new DEP keypad design was suggested by the USN test team. In the absence of incorporating some concavity on each keypad button, they should be separated with raised ridges between them or on the outer edges of the buttons. Additionally, the buttons should incorporate a diaphragm to provide minimal resistance and tactile feedback when they are depressed. This type of change was successfully incorporated on the MFD pushstiles at my insistence during flight test because of their lack of tactile feel and feedback.

Following the final USN test period, the engineers uncovered an asynchronous data transfer problem. The data flow rates between the GINA and DEU were not compatible, causing some data transfer delays which probably increased already high latencies. To compensate for the data rate differences, MDA system engineers identified time tagging of the GINA output as the proper corrective action. Simply put, time

tagging would allow the DEU to only pick up the most recent data for display generation, permitting it to ignore old information. The time tagging of GINA data may eliminate the jitter and double writing of HUD symbology as well as some other deficiencies.

Further flight testing of an enhanced CP21 avionics integration is scheduled to begin in 1996.

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APPENDIX

DETAILED METHOD OF TEST

GENERAL

The maneuvers described in this appendix were taken from the Flight Training Instructions for Undergraduate Jet Pilot Training (FTI, 1994). Although the FTI are directed to the analog T-45A, they were used as a guide for flight maneuvers in order to ensure that realistic flight tests were conducted and training areas were not overlooked. Flight test was not limited to the maneuvers described here or listed in the complete FTI. This list of basic instrument maneuvers is not complete, but the following descriptions are provided to assist the reader in understanding some of the deficiencies described in the text.

SPECIFIC

INSTRUMENT FLIGHT TRAINING

Basic instrument flight maneuvers were performed utilizing the instrument training hood in the aft cockpit to simulate IMC. Tolerances were as follows: heading maintenance within 1-2 degrees, pitch attitude within 1 degree, bank angle within 1-2 degrees, airspeed within 5 KIAS, altitude within 50-100 ft, VSI within 200 fpm and, qualitatively, being able to easily correct for deviations in those parameters using the appropriate primary flight references.

1. Constant airspeed climbs and descents

Beginning at 250 KIAS, maintain heading and advance the throttle to military rated thrust (MRT) or full forward. Simultaneously establish a nose up attitude of 8 to 10 degrees on the ADI to maintain 250 KIAS. During the climb, use small nose attitude changes to maintain airspeed and trim inputs as required. The ADI is used for pitch and

bank control and the airspeed indicator for airspeed information in the scan during climb initiation and maintenance. When the aircraft reaches a lead point of 10% of VSI prior to the level off altitude (e.g. if the climb rate is 3000 fpm, initiate the level off 300 ft prior to reaching the desired altitude), simultaneously reduce power to maintain 250 KIAS, set pitch attitude to maintain level flight, and retrim.

The constant rate descent mirrors the climb, with the throttle and pitch attitude being reduced and decreased, respectively. Beginning from 250 KIAS, reduce the throttle to idle and smoothly establish a nose down attitude of 3-6 degrees to maintain 250 KIAS. Maintain airspeed by making small pitch attitude changes. Use a lead point of 10% of the VSI for leveling off by smoothly increasing power, establishing a level flight pitch attitude and retrimming.

2. Constant rate climbs and descents

Enter these maneuvers from 200 KIAS at a specified altitude and heading.

Initiate a 1000 fpm climb by advancing the throttle and establishing approximately 2-3 degree nose up pitch attitude while maintaining 200 KIAS. Maintain heading by monitoring the ADI. During the climb, control airspeed with pitch attitude and rate of climb with power. Accomplish the transition to level flight while maintaining 200 KIAS using the 10% VSI lead point.

Initiate a 1000 fpm descent by reducing the throttle and establishing a nose down pitch attitude of approximately 1-2 degrees on the ADI to maintain 200 KIAS. Maintain heading on the ADI. As with the climb, control airspeed with pitch attitude and rate of descent with power. Accomplish the transition to level flight while maintaining 200 KIAS using the 10% VSI lead point.

3. Level turns

For constant AOB turns: for turns of less than 30 degrees of heading change, use a bank angle that equals that change. If the heading change is 30 degrees or greater, use a bank angle of 30 degrees. As the airplane is rolled into a bank angle, a power addition may be required to maintain airspeed with some back stick to maintain altitude. Use a lead point of approximately 1/3 of the AOB for initiating the roll out on the desired heading while slightly reducing power and decreasing pitch attitude to maintain airspeed and level flight. Retrim.

For 1/2 a standard rate turn (SRT), the target turn rate is 1 1/2 degrees per second. A heading change of 30 degrees requires 20 seconds to complete. For SRT, the target turn rate is 3 degrees per second. To accomplish the targeted turn rate at different airspeeds, bank angle must vary. As a general rule of thumb, a bank angle equal to approximately 10% of the airspeed will yield a 1/2 SRT and at approximately 20% of airspeed will result in a SRT. Roll in and out of the turns as described in the description of constant AOB turns, above. Once the AOB is established, attempt to time all turns by referencing the clock sweep second hand while monitoring the turn rate indicator below the ADI attitude ball. Make small adjustments in bank angle to correct the rate of turn when deviations from the desired rate are detected. Maintain level flight and constant airspeed.

4. Level speed changes

Since pitch attitude must continuously change to maintain constant altitude during the speed change, altitude control through pitch attitude and trim are the primary focus. Set the power to that required for the target airspeed when changing less than 20 KIAS. For speed increases greater than 20 KIAS, use MRT and lead the desired airspeed by 5 KIAS for resetting the throttle position. For speed decreases, the throttle

is reduced below that required for the desired airspeed. Reset the throttle using the 5 KIAS lead. When making large or rapid airspeed decreases, the throttle is reduced to that required for the desired airspeed and the speed brakes are extended with the 5 KIAS lead point used for speed brake retraction. Maintain altitude and heading as required.

Speed changes are required throughout all flight regimes. Practice speed changes are conducted between 200 and 250 KIAS.

For level speed changes in 1/2, the procedures for level speed changes and 1/2 SRT are combined. As airspeed changes, AOB must be adjusted to maintain turn rate and pitch attitude must be adjusted to maintain altitude.

5. S patterns

“S” patterns are intended to build and add speed to the instrument scan, requiring the SNA to capture and maintain targeted rates of climb and descent, make transitions between them and include other flight instruments in the scan to control the parameters of heading, airspeed, turn rate, time, and bank angle.

a. S-1: The S-1 pattern consists of a 1000 fpm descent for 1000 ft followed by a 1000 fpm climb for 1000 ft, with the sequence repeated. The maneuver is flown on a constant heading and constant airspeed of 200 KIAS.

The S-1 is initiated at 200 knots and level flight by reducing power and decreasing pitch attitude approximately 1-2 degrees, 3 seconds before the clock sweep second hand reaches the 12 o'clock position. Capture and maintain a 1000 fpm descent for 1000 ft. Transition to a 1000 fpm climb 3 seconds or 100 ft prior to the end of the descent by adding power and increasing the pitch attitude to approximately 2-3 degrees up on the ADI. Following the climb, repeat the maneuver sequence to return to level flight at the original altitude and 200 KIAS after 4 minutes have elapsed. During the climbs and descents, cross check the altimeter with the clock every 250 ft and 15

seconds. Use power to control rate of climb or descent and pitch attitude to control airspeed.

b. S-3: The S-3 pattern combines the climbs and descents of the S-1 pattern with a 1/2 SRT and a reversal after 180 degrees at the beginning of the 2nd descent. Because the 1/2 SRT yields a turn rate of 1 1/2 degrees per second, a heading change of 90 degrees for each 1000 foot climb or descent. Begin the maneuver by initiating a 1/2 SRT as the descent is started. The turn direction is maintained as the transition to a climb is made. At the start of the 2nd descent, the direction of turn is reversed. After 4 minutes, the maneuver is completed on the original heading and altitude at 200 KIAS. The same cross checks used in the S-1 maneuver also apply to the S-3 with the addition of a heading cross check for 30 degrees every 20 seconds.

6. Turn pattern

The turn pattern consists of 2 pairs of left and right turns. The purpose is to practice smoothly performing a series of linked turns at a constant altitude and airspeed. Begin the maneuver by initiating a 30 degree AOB turn for 60 degrees with a reversal. After the 2nd 60 degree turn, reverse the turn direction at a 45 degree AOB for 90 degrees of turn with a reversal to the original heading. Execute the turn reversals with no straight and level legs. 250 KIAS should be maintained throughout the maneuver and a constant altitude.

7. Stalls in PA and CR

a. CR stalls: CR stalls are performed with the gear up, speed brakes in, flaps and slats retracted, and are initiated from 200 KIAS. To commence the maneuver, retard the throttle to idle, keep the wings level and maintain altitude. As the airspeed decreases, increase back stick pressure to maintain altitude but do not trim below 150 KIAS.

Maintain altitude and pitch attitude until the rudder shaker is activated, heavy buffet is encountered, and a sudden, uncommanded wing drop is encountered at the stall. At the stall, advance the throttle to MRT and lower the pitch attitude to attain 20-21 units AOA. Maintain 20-21 units AOA and a wing level attitude until a positive rate of climb develops.

b. PA stall: When configured in PA at 150 KIAS, retard the throttle to idle and maintain altitude and as the airplane decelerates. Maintain wings level and increase back stick to hold altitude and pitch attitude. Do not trim below the 17 unit AOA airspeed. Maintain altitude through rudder shakers and into the onset of buffet. The stall is characterized as a sharp wing drop, as in the CR stall. Recover by simultaneously advancing the throttle to MRT, retracting the speed brakes and decreasing the pitch attitude to 23-24 units AOA. Maintain 23-24 units AOA and wings level until a positive rate of climb is achieved.

8. Unusual attitude recoveries

Unusual attitudes are any aircraft attitudes encountered inadvertently. They may result from inattention to scan, instrument failure, vertigo, turbulence, or a combination of factors. Although the severity of the unusual attitudes encountered during instrument flight will not usually be as extreme as those that occur during tactical maneuvering, the recovery techniques are basically the same. The basic rules that apply to all unusual attitude recoveries are neutralize the flight controls, analyze and evaluate the situation before initiating recovery. Then, if the airplane is in a dive, reduce power and extend the speed brakes to aid in airspeed control, then roll the airplane in the shortest direction to wings level. Finally, if the airplane pitch attitude is high, hold the wing attitude while putting the throttle to MRT, retracting the speed brakes, if extended, until the pitch attitude is below the horizon and airspeed reaches at least 150 KIAS.

a. **Nose High Recovery:** When recovering from a nose high unusual attitude, the primary concern is to maintain AOA between 5 and 10 units. Additionally, do not input uncoordinated control inputs at slow speed as they may cause a departure from controlled flight.

The instructor will assume control of the airplane and direct the SNA to close his eyes while maneuvering is commenced. When the SNA is given control of the airplane, simultaneously neutralize the controls and analyze the flight instruments to determine attitude, AOA, altitude, and airspeed. To recover from the nose high condition, advance the throttle to MRT and retract the speed brakes to minimize loss of airspeed.

If the airplane attitude is upright, maintain neutral aileron and rudder and smoothly push the nose over to maintain AOA between 5 and 10 units. Maintain that AOA until the airplane nose falls through the horizon and accelerates to 150 KIAS. Then roll to a wings level attitude and return to level flight.

If inverted, maintain neutral aileron and rudder and pull the nose through the horizon while maintaining 17 units AOA. When the aircraft accelerates to 150 KIAS, level the wings in the shortest direction, pull the nose to the horizon, and adjust the throttle for level flight. Do not exceed 17 units AOA and use care not to stall the airplane when recovery is initiated from low airspeeds.

b. **Nose Low Recovery:** The first step is to neutralize the controls and analyze the flight instruments. Recognition of the nose low unusual attitude from the pitch attitude on the ADI accompanied by increasing airspeed and decreasing altitude. If airspeed is rapidly approaching 250 KIAS, retard the throttle. If airspeed is approaching or has exceeded 300 KIAS, extend the speed brakes. These procedures should control airspeed and altitude loss. Roll the airplane to wings level in the shortest direction and smoothly pull the nose up to the horizon. Complete the recovery in level flight.

VITA

Michael Andrew Wettlaufer was born in Alexandria, Virginia on March 14, 1960, and was, without a doubt, the best looking baby in the nursery. He attended various public schools across the country and graduated from Cherry Creek High School in Englewood, Colorado in June, 1978. In 1985 he received a Bachelor of Science in Microbiology from Colorado State University. He was commissioned an Officer in the United States Navy in May, 1986 and received his Navy Wings of Gold in March, 1988. He was assigned to fly the A-6 Intruder airplane while attached to Attack Squadron Eighty-Five on board the USS America. He completed three major deployments to the Mediterranean Sea, Red Sea, Indian Ocean and Persian Gulf, including Operation Desert Storm. In January, 1993, he reported to the United States Naval Test Pilot School with Class 104. Since graduation in December, 1993, he has served at the Naval Strike Aircraft Test Squadron as an A-6, F/A-18, and T-45 test pilot for carrier suitability, flight systems, and mission systems developmental testing.