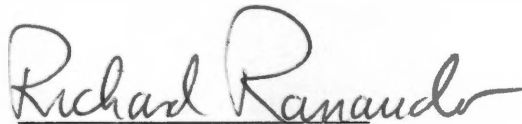


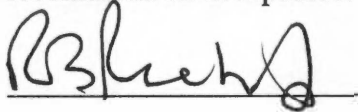
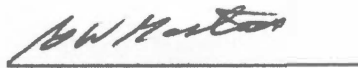
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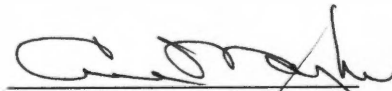
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Vice Chancellor and Dean of
Graduate Studies

HUMAN FACTORS EVALUATION OF
PORTABLE ELECTRONIC DEVICES
IN TACTICAL AIRCRAFT

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

Martin Bernard Fuerst
August 2005

Thesis

2006

.F84

DEDICATION

My father once said that behind every great man stands an even greater woman. In my life, I have been blessed with two outstanding women to whom I wish to dedicate this thesis to.

The first is my mother, Sandra Fuerst, who was a constant light who guided me through my early years. Her relentless sacrifice, overwhelming support, and endless love were her eternal gifts to my siblings and myself. If it were not for her, I probably would have never realized the accomplishments and successes that I know today. Unfortunately, my mother passed away several years ago after long and courageous battle with cancer. While she may never read this thesis, I know she was always with me as I wrote it.

I have also been blessed with a truly wonderful and loving wife, Becky. As a Navy wife, she has had to deal with long deployments and time away from home. Still, she has never complained a single time. As a newly wed and on shore duty when we were supposed to relax from the rigors of sea duty, she often played second fiddle to allow me to complete my classes and this paper. Again, to her I am extremely grateful for her love, patience, and support.

ACKNOWLEDGEMENTS

I would like to thank the many people who have helped me with this thesis and completing all of the classes required for this degree: Prof. Ranaudo who served as my thesis advisor and provided excellent guidance and recommendations that were invaluable in helping me write this paper. Dr. Masters and Dr. Richards who served on my thesis committee. The UTSI staff at Tullahoma and Patuxent River, especially Betsy Harbin, who assisted with registering for classes, submitting homework assignments, proctoring tests, and mailing video tapes. To Randy Smith, Kevin Johnson, Dave DeMauro, and Steve Stearns for critiquing this paper.

I would also like to several individuals who provided information and technical reports that were used in this document: Vince Parisi, Gary Milhoan, LtCol Fiebig, Divya Chandra, Heather Howell, LT Chris Bahner, and Art Fabbri.

Finally, a special thanks to all my family and friends who have been extremely helpful and supportive in making this paper a reality.

ABSTRACT

As the service life of aging military aircraft are extended and these aircraft are tasked with new missions they were never designed to support, military aircraft are constantly being upgraded with new systems and avionics. Additionally, many legacy aircraft have poor cockpit layouts or incorporate older displays that are not compatible with or require extensive modification to support these new technologies. Unfortunately, many acquisition programs do not have the luxury of an unlimited budget and schedule to complete the required upgrades. One alternative is to incorporate a portable electronic device or PED into the cockpit. These devices can provide moving maps, real time intelligence information, or simply transition to a paperless cockpit. Adding a PED can be a cheaper and easier alternative than redesigning the entire cockpit. Although PEDs have some cost and schedule benefits, the human factors concerns can often overshadow the money and time saved using these devices.

This paper investigates the human factors and aircrew systems design considerations when integrating laptop, pentablet, and personal digital assistant (PDA) type devices into attack and strike-fighter fixed wing aircraft. The range of issues that human factors engineers must consider with any potential PED is wide ranging, from display readability to operator training and from user interface to degraded system operation. This paper focuses on the hardware integration requirements for PEDs in tactical fixed wing aircraft. While software functionality and aircrew workload are important factors that must be considered for any system, these issues are outside the scope of this paper. When integrating a PED system, there are six critical operational issues (COI) every system must meet before it can be considered operationally effective and suitable for the cockpit environment. The six PED COIs are:

- The display must be easily readable under all anticipated lighting conditions ranging from direct sunlight to night time operations. Also, the display must have adequate off axis readability if the display is not in the pilot's primary field of view or if shared by two crew members.

- The display lighting must be compatible with existing cockpit lighting, including night vision imaging systems (NVIS). Lighting compatibility affects both internal and external cockpit vision and the ability to shift focus from outside to inside the cockpit and vice versa.
- The input devices and controls must allow for fast, accurate data entry and system optimization to present mission critical information in the desired format at the appropriate time.
- The PED must be integrated into the cockpit so it is easily accessible to the pilot while not restricting the pilot's access to other cockpit controls and displays.
- If the PED is used as an electronic kneeboard, it must be properly secured so the device remains firmly in place and is comfortable to wear, especially during dynamic maneuvering and extended combat missions.
- The PED must not interfere with normal and emergency ingress and egress, including the ejection process. Also, the PED should not increase the risk of injury during an emergency egress scenario.

For each COI, military and Federal Aviation Administration (FAA) human factors, cockpit guidelines, and specifications are outlined and applied to PED use in a military cockpit. This paper examines several fielded systems used in both commercial and military aviation, as well as potential Commercial Off the Shelf (COTS) systems. Ground and flight test reports for fielded and developmental PEDs provide examples as to how these guidelines and specifications apply to PED integration into the cockpit. Finally, the author, a Navy test pilot with experience employing PEDs in tactical cockpits, provides an aviator perspective to these guidelines and specifications in a combat environment.

Based on the PED COIs, military specifications presented, and lessons learned from currently deployed PED systems, five conclusions were made when conducting this evaluation:

- Pentablet computers are preferred over laptops and PDAs.
- PEDs should not serve as the primary indicator of safety of flight or mission critical information.
- Integrating COTS systems does not guarantee cost and schedule savings.
- Touch screens and reprogrammable push buttons are the optimum control option.
- PEDs should be mounted on kneeboards vice the instrument panel.

PEDs have excellent potential to fulfill many roles in the tactical cockpit, including electronic checklists, navigation charts, and real time weapon system control. While PEDs may not be the perfect solution to many system integration problems, they are viable options that deserve further consideration by any program manager or acquisition professional.

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ABBREVIATIONS

AMLCD	Active Matrix Liquid Crystal Display
ARM	Airport Restriction Manual
BIT	Built in Test
CIE	International Commission on Illumination
COI	Critical Operational Issue
COTS	Commercial Off The Shelf
CR	Contrast Ratio
CRT	Cathode Ray Tube
CTP	Critical Technical Parameters
EGPWS	Enhanced Ground Proximity Warning System
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
fc	Foot Candles
fL	Foot Lambert
FOD	Foreign Object Damage
GPS	Global Positioning System
HOTAS	Hand on Throttle and Stick
HSD	Horizontal Situation Display
HUD	Heads Up Display
JSSG	Joint Service Specification Guideline
L	Luminance
LC	Luminance Contrast
LCD	Liquid Crystal Display
Lil HAL	Little High-end Airborne Laptop
MEL	Minimum Equipment List
MRAD	Milliradian
NAVAIR	Naval Air Systems Command
NAWCAD	Naval Air Warfare Center – Aircraft Division
NOTAM	Notice to Airmen

NR	Night Vision Imaging System Radiance
NVD	Night Vision Device
NVIS	Night Vision Imaging Systems
ODM	Operation Data Manual
PDA	Personal Digital Assistant
PED	Portable Electronic Device
SVGA	Super Video Graphics Array
TCAS	Traffic Collision Avoidance System
UHF	Ultra High Frequency
VHF	Very High Frequency
VSM	Vehicle Subsystem Management
WCA	Warning, Caution, Advisory

INTRODUCTION

As cockpits have evolved from a few simple flight and engine instruments to modern, multifunction color and helmet-mounted displays, information management has become an increasingly important task for the military aviator. In order to successfully complete a dynamic and continually evolving combat mission, the military aviator must fuse together multiple sources of information, both internal and external to the aircraft, to build situational awareness about the developing battle. Internal to the aircraft, the pilot is presented with an array of aircraft and weapon system displays, including navigation and on board sensors like radar and imaging systems. Most modern aircraft have at least two UHF/VHF radios as well as satellite and data link voice capabilities to communicate with other aircraft and theatre commanders. Additionally, new data links fuse on and off board sensors to allow the pilot to see the threats other aircraft have detected and are actively engaging. While it is easy for the pilot to become fixated on aircraft displays, the pilot must also scan outside the cockpit to monitor formation position, look for surface to air missile threats, and locate targets on the ground.

While the newest generation of tactical aircraft incorporate many crew systems innovations to improve information management, there are many older, tactical aircraft in the U.S. military inventory that have cockpit controls and displays that can not adequately support these modern military systems. As military planners look to extend the service life and add new missions to these older aircraft, integrating new weapon systems in many cases will be limited by the lack of available cockpit “real estate” required for additional controls and displays. Even modern cockpits may eventually require upgrades to support evolving technologies. As shrinking acquisition budgets and schedules preclude expensive cockpit modernization programs, systems engineers must find innovative ways to integrate new weapon systems into tactical aircraft. One way is through the use of portable electronic devices or PEDs.

PEDs are characterized as laptop, pentablet computer, and personal digital assistant (PDAs) type devices that are not permanently installed in the aircraft. These devices are also commonly known as electronic kneeboards and electronic flight bags. PEDs can be Commercial Off The Shelf (COTS) products that take advantage of existing hardware and software or they can be systems specifically designed for military applications. Commercial and general aviation have been using PEDs for many years and their use is widely accepted within their respective aviation communities. On the other hand, the military has only recently begun integrating these systems into their aircraft and several PEDs have been successfully used in combat. However, there are many important integration issues that must be resolved before PEDs become commonplace in military aircraft.

In many ways, PEDs present an excellent option for integrating new weapon systems, reducing aircrew workload, and increasing mission effectiveness. A PED can play many roles in the cockpit including moving map navigation displays, updated weather, and free text and data link connectivity to provide the most recent intelligence and threat data. At a minimum, these devices allow the military aviator to transition to a paperless cockpit by replacing pocket checklists, navigation and instrument approach procedures, and mission kneeboard cards with electronic versions. Prior to each mission, a PED can be quickly loaded with the latest weather, target photos, and intelligence updates and carried straight to the aircraft. Furthermore, a PED can present this information in an organized and easy to locate manner.

This paper investigates the human factors issues relating to system hardware and functionality when integrating a PED into a tactical fixed wing aircraft. These issues include display readability and lighting compatibility, controls and input options, aircrew and cockpit compatibility, and normal and emergency egress. Aside from the hardware issues, PEDs pose other human factors concerns such as software crew vehicle interface, aircrew workload, and training. While these areas are important concerns that must be addressed, they are outside the scope of this paper. This paper focuses on human factors

issues specific to fixed wing tactical aircraft. While many of the concerns presented also apply to helicopters and transport aircraft, fixed wing aircraft have unique human factors issues due to differences in cockpit layout, crew size, and mission environment and requirements.

Section 1 provides an introduction to PED characteristics and system description, commercial and military applications, and system requirements. Sections 2-5 address each hardware functional area to include task descriptions and mission impacts. Military and commercial aviation human factors standards and specifications related to each area are outlined, including the rationale behind the requirements. Results from Naval Air Systems Command (NAVAIR) and Air Force Research Laboratory PED ground and flight tests are provided to highlight potential deficiencies found in current fielded systems. The final section of this paper provides specific conclusions and recommendations for integrating PEDs in tactical aircraft cockpits.

SECTION 1: PED DESCRIPTION

1.1 COMMERCIAL AND GENERAL AVIATION APPLICATIONS

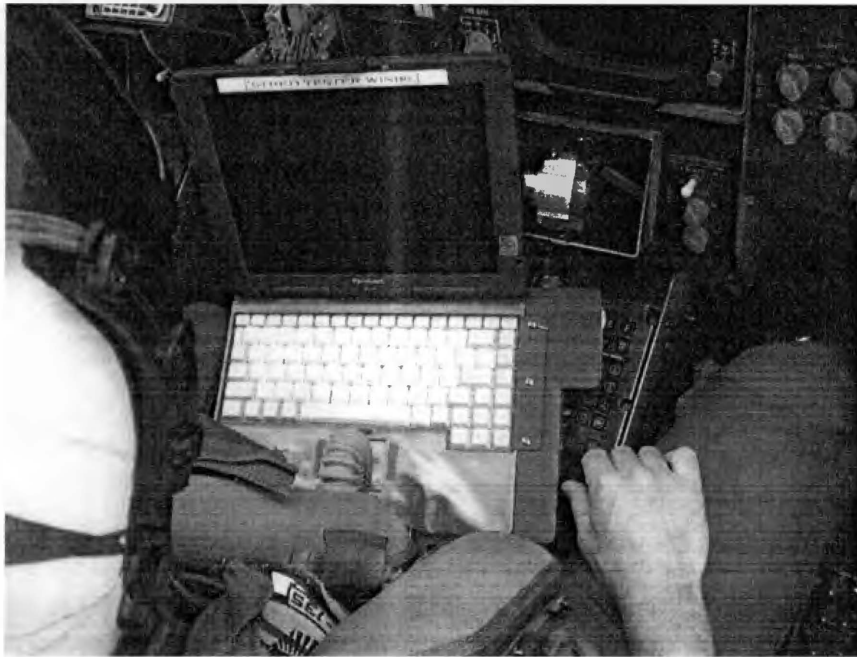
PEDs were first used in commercial and general aviation aircraft. Their primary purpose was to transition to a paperless cockpit and reduce the number of publications carried to the aircraft. The typical commercial pilot flight kit weighs approximately 25 pounds and contains numerous large publications like minimum equipment lists (MEL), operation data manuals (ODM), airport restriction manuals (ARM), charts, maps, and approach plates for the entire national airspace structure. As early as 1991, FedEx started using the Hewlett Packard Omnibook to calculate take off airspeeds. More recently, FedEx replaced the Omnibook with the Sprinet Systems' "pilot access terminal" on their MD-11 and Airbus A310 aircraft. In addition to take off calculations, the system contains an onboard server that transmits fault reports to FedEx's ground facilities, decreasing aircraft maintenance and turn around time. Jet Blue airlines has been carrying electronic flight manuals since 1999, although they will continue to use paper navigation charts until the FAA certifies the use of electronically displayed navigation publications. Several other airlines, including Delta and United, are either currently developing or are already using electronic devices. Airlines are also considering PEDs to incorporate enhanced ground proximity warning systems (EGPWS) and traffic collision avoidance systems (TCAS).

Many hardware and software manufacturers have recognized the need for electronic flight bags and other aviation oriented PEDs. These devices range from simple handheld personal digital assistants (PDAs) with electronic checklists to specialized displays that are integrated into the aircraft's navigation and fault reporting system. As these systems have evolved from stand alone devices performing simple calculations to managing aircraft functions, the Federal Aviation Administration (FAA) started certifying PEDs in Advisory Circular AC-120-76A, *Guidelines for the Certification, Airworthiness, and Operational Approval of Electronic Flight Bag Computing Devices*, reference A. The FAA's Volpe National Transportation Center has also published an excellent reference

for PED design, entitled *Human Factors Considerations in the Design and Evaluation of Electronic Flight Bags*, reference B. While these publications pertain to commercial and general aviation, many of the human factors issues are applicable to military aircraft with little or no modification.

1.2 MILITARY APPLICATIONS

Military aviation has lagged behind civil aviation incorporating PEDs. However, the Air Force, Army, and the Navy are now fielding systems or are developing research programs to investigate the potential of PEDs in helicopters, transport, and strike-fighter aircraft. One of the first military applications of a PED was the EA-6B Prowler which incorporated a Panasonic CF-25 Toughbook laptop computer in the aft cockpit as the primary crew vehicle interface for electronic warfare systems. The Panasonic Toughbook is shown in figures 1 and 2. Currently, several electronic kneeboards are integrated or undergoing testing for installation in the A-10, AH-64, and H-60 variant helicopters. Most military systems involve COTS designs that have been modified for tactical aircraft, like the Itronix Go Book for the UH-60 and EA-6B. The Go Book, shown in figure 3, is a pentablet computer with an 8.4 inch, 800 x 600 Super Video Graphics Array (SVGA) touch sensitive screen. The Go Book dimensions are 10.6 x 7.2 x 1.7 inches and weighs a little less than 4 pounds. The Go Book, combined with an external Global Positioning System (GPS) antenna, is undergoing testing as a moving map display for Army helicopters. The Go Book is also scheduled to replace the Panasonic Toughbook in the EA-6B. Some systems, like the Raytheon Air Warrior for the Army helicopters, are specifically designed for military applications. The Air Warrior, shown in figure 4, measures 9.0 x 5.0 x 1.1 inches in size and weighs just 2.5 pounds. It contains a 6.4 inch, 640 x 489 touch sensitive display as well as reprogrammable hard keys arranged around the display. The Air Warrior is currently deployed with Army helicopters and has been used in combat during Operation Iraqi Freedom. The Air Force Research Laboratory is testing the Little High-end Airborne Laptop, known as Lil HAL. Lil HAL, shown in figure 5, is a research program that combines a portable computer with a digital kneeboard and a



Source: USQ-113 Independent Safety Risk Assessment

Figure 1: Panasonic CF-25 Laptop in EA-6B Prowler (Top View)



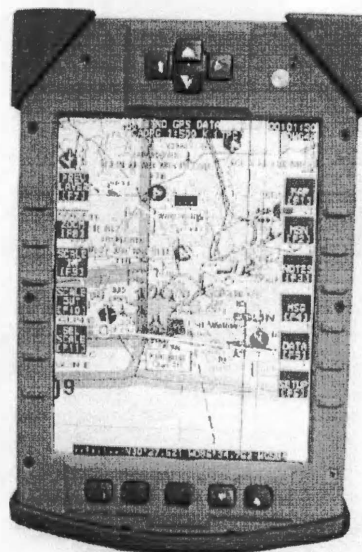
Source: USQ-113 Independent Safety Risk Assessment

Figure 2: Panasonic CF-25 Laptop in EA-6B Prowler (Side View)



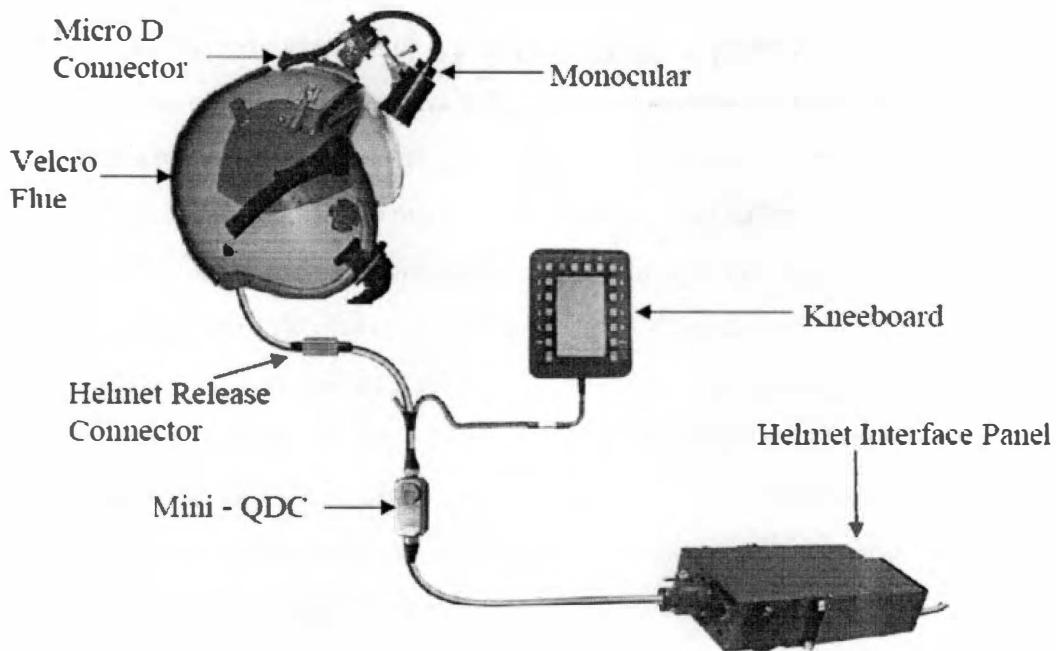
Source: Go Book Tablet PC Brochure

Figure 3: Itronix IX 300 Go Book Pentablet



Source: Air Warrior Electronic Data Manager Brochure

Figure 4: Raytheon Air Warrior Electronic Data Manager



Source: Safe-for-Flight Determination for Helmet-Mounted Little High-end Airborne Laptop

Figure 5: Little High-end Airborne Laptop (Lil HAL)

helmet-mounted display for use in the A-10. This system is specifically designed for use in a tactical cockpit and can be worn during an ejection.

1.3 SYSTEM CHARACTERISTICS

The human factors issues presented herein are limited to laptops, pentablet computers, and PDAs. While some portable systems, like handheld GPS units, have unique aviation applications, these systems tend to be small, handheld devices and are found in military aircraft on a limited basis. PEDs can be generally described in terms of size and weight, display type and size, input devices, and software applications. The following paragraphs discuss these system characteristics.

1.3.1 SIZE AND WEIGHT

Most PEDs designed for cockpit applications are either handheld, strapped to the knee, or mounted to the instrument panel. Overall system size and weight are significant factors when integrating PEDs into tactical cockpits. Smaller systems are easier to integrate into the cockpit and are generally strapped to the pilot's leg. However, smaller systems contain smaller displays, which limits the amount and type of data presented. Small handheld devices, like PDAs, are typically 2 x 4 inches and less than ½ inch thick. Pentablets and laptops are considerably larger and are more difficult to manage in a tactical cockpit. The largest laptops can be up to 10 x 7 x 2 inches in size. Weight can range from several ounces for handheld devices to up to 5 pounds for pentablet computers. Any additional power chords or attachment devices increases the overall size and weight of the apparatus. Given the small size of modern cockpits and limited space available for additional systems, system size must therefore be matched to the available cockpit space.

1.3.2 DISPLAY TYPE AND SIZE

Display type and size will determine the amount and type of information that can be presented. Most pentablets have 8.4 inch diagonal displays although display sizes up to 10.4 inches are available. The standard resolution is 800 x 600 SVGA for most pentablets. Display type also affects display resolution, number of available colors, and daylight and night time readability. The most common display type is the liquid crystal display (LCD). Laptop computers normally employ back-lit LCD displays that use a florescent light behind the screen to brighten the display. Active matrix LCDs (AMLCD) are newer versions of the common LCD display that have a faster reset rate per pixel, thus improving video quality. Additional display considerations include luminance, contrast, off-axis readability, and night vision device (NVD) compatibility, which will be discussed later in detail.

1.3.3 DATA INPUT DEVICES

One advantage of PEDs is they can be removed from the aircraft and loaded with premission planning data through a docking station or computer connection. However, once installed in the aircraft, the pilot requires some way to interact with the device to configure the system and display the required information. The input device is dependent on the type and amount of data that is entered as well as how the device is mounted in the aircraft. Majority of PDAs and pentablets have touch screens with a stylus for use with soft keypads and shorthand data entry methods. Laptops contain full size QWERTY keyboards while some smaller systems may have small, collapsible keyboards. A keyboard is very useful for entering text very quickly, but typing errors and operator fatigue can increase without a way to stabilize the hand. Most systems contain hard keys that perform specific functions or are software controlled multifunctional keys that can be programmed depending on the software application currently in use. Other control options include tracks balls and finger joysticks. Regardless of the type of input device used, the control must allow for fast and accurate data entry, or the system will increase aircrew workload or distract the pilot. This is especially true during dynamic maneuvering or turbulence.

1.3.4 AIRCRAFT INTEGRATION

Aircraft integration describes PED interaction with aircraft navigation, electrical, and weapon systems. Integration options range from battery powered, handheld devices to systems that rely on aircraft power and are tied into navigation and weapon system buses. Wireless systems are also viable options and the Air Force Research Laboratory at Wright Patterson AFB has completed testing on a wireless display. The test results are reported in reference C. While the wireless display test results look promising, there are several issues, such as battery life, secure data links, and electromagnetic interference, that must be resolved. The FAA certification standards for electronic flight bags, reference A, defines three hardware configurations based on how the PED is integrated and tied into the cockpit and aircraft systems.

Class 1: Class 1 systems are portable devices that are not attached to an aircraft mounting cradle or apparatus and are generally handheld. These systems may use aircraft power as either the primary power source or to charge batteries. A Class 1 system can tie into aircraft avionics to provide read-only data access, but cannot be used to transmit and receive messages over aircraft communication systems and buses. If the device is connected to aircraft electrical buses through a power chord, the connection will require a quick disconnect fitting to allow for easy ingress and egress.

Class 2: Class 2 systems are portable devices that are attached to an aircraft mounting cradle. Additionally, Class 2 systems can interact and communicate with other aircraft systems and therefore require additional certification to ensure airworthiness of the mounting device, data connectivity, and power sources.

Class 3: Class 3 systems are non-portable systems that are permanently installed in the cockpit. Class 3 systems are outside the scope of this paper.

1.3.5 SOFTWARE APPLICATIONS

Software applications impact system processor, hard drive size, display type, and aircraft interface requirements. If the intended function is to present flight operation manuals, the system requires a larger hard drive to store all of the publications and a display with sufficient resolution for reading text and images. However, if the device is used for real time navigation, the system requires a faster processor and display refresh rates. Most processors employ a standard operating system like Microsoft Windows or Palm OS, but some systems may use a proprietary operating system. The FAA certification standards for electronic flight bags, reference A, classifies software applications into three types. Most PEDs will run Type A and Type B software applications, however, moving map displays and other system status displays require Type C software.

Type A: Type A software applications are limited to “*pre-composed, fixed presentations currently presented in paper form.*” These applications do not perform calculations or display aircraft status. Examples of Type A software applications include flight operations manuals; fixed, non-interactive performance charts; minimum equipment lists; captain’s logs; Notice to Airman (NOTAM); and aircraft flight and maintenance records.

Type B: Type B software applications include “*dynamic, interactive applications that can manipulate data.*” Examples of Type B software applications include take off, cruise, and landing performance data calculated by system software; normal and emergency procedures, non-interactive approach plates, and weather and aeronautical data.

Type C: Type C software applications include primary flight displays, navigation, and aircraft status displays.

1.4 CRITICAL OPERATIONAL ISSUES

Regardless of the size and type of display, input device, or software used, the PED must meet several operational requirements in order to increase pilot situational awareness and mission effectiveness. These requirements can be defined as critical operational issues (COI) that determine the PED’s effectiveness and suitability to complete its intended mission in a combat environment. There are numerous military specifications that set specific, quantifiable requirements or critical technical parameters (CTP) that play a key role in meeting these COIs. It is possible for a PED to fail to meet a CTP yet still be an extremely useful tool to the pilot. However, failure to meet one of the COIs will significantly degrade operational effectiveness and suitability.

When integrating a PED into a tactical cockpit, there are six COIs that must be met:

- The display must be easily readable under all anticipated lighting conditions ranging from direct sunlight to night time operations. The display must also have

adequate off axis readability if the display is not in the pilot's primary field of view or if shared by two crew members.

- The display lighting must be compatible with existing cockpit lighting, including night vision imaging systems (NVIS). Lighting compatibility affects both internal and external cockpit vision and the ability to shift focus from outside to inside the cockpit and vice versa.
- The input devices and controls must allow for fast, accurate data entry and system optimization to present mission critical information in the desired format at the appropriate time.
- The PED must be integrated into the cockpit so it is easily accessible to the pilot while not restricting the pilot's access to other cockpit controls and displays.
- If the PED is used as an electronic kneeboard, it must be properly secured so the device remains firmly in place and is comfortable to wear, especially during dynamic maneuvering and extended combat missions.
- The PED must not interfere with normal and emergency ingress and egress, including the ejection process. Also, the PED should not increase the risk of injury during an emergency egress scenario.

1.5 HUMAN FACTORS SPECIFICATIONS AND GUIDELINES

When evaluating PEDs from a human factors standpoint, each system must be individually evaluated taking into consideration the cockpit it will be integrated with, the functions the system will perform, and the mission environment in which it will operate. Some human factors considerations have unique quantifiable requirements, like text size and control spacing. There are other issues, such as cockpit egress, where only general requirement statements can be made. Currently, there are no military specification or standards for PEDs in tactical aircraft. Therefore, one must combine several applicable military specifications and human factors guidelines to determine system requirements. Display readability and lighting requirements are outlined in the *Military Handbook for Electronically/Optically Generated Airborne Displays* (MIL-HDBK-87213) and the

Military Standard for NVIS Compatible Interior Aircraft Lighting (MIL-L-85762A), references D and E respectively. Cockpit integration guidelines are contained in the *Military Standard for Location, Arrangement, and Actuation of Aircrew Station Controls and Displays for Fixed Wing Aircraft* (MIL-STD-203G) and the *Military Standard for Aircrew Station Geometry for Military Aircraft* (MIL-STD-1333B), reference F and G respectively. Another excellent reference for military design guidance is the Joint Service Specification Guideline (JSSG), reference H. This document combines numerous military specifications into a single reference. This document must apply to all services across a wide range of the military components and presents design considerations vice specific requirements. Unfortunately, this document contains export controlled information and the design guidance it contains can not be referenced in this paper for security concerns. When military specifications do not exist, one may apply civil aviation human factors guidelines for integrating PEDs. The FAA's Volpe Center has published a comprehensive paper on human factors considerations for PEDs, reference B. Federal Aviation Regulation (FAR) Part 23 cockpit design requirements are outlined in reference I. FAA PED airworthiness certification guidelines are contained in reference A.

SECTION 2: DISPLAYS

This section addresses the first two COIs: display readability and lighting compatibility. These issues are broken down into smaller subsections, such as resolution, luminance, color, and dimming. For each subsection, the human factors considerations and applicable specifications are discussed. Where applicable, results from the Itronix IX 300 Go Book lighting tests will be cited. Go Book testing was performed by the Naval Air Warfare Center –Aircraft Division (NAWCAD) Crew Station Electro-optic Branch at NAS Patuxent River, MD during initial developmental testing. Testing included display luminance uniformity, chromaticity shift, contrast, reflectivity, and NVIS radiance. The Go Book test results are contained in reference J.

2.1 DISPLAY FUNCTIONALITY

MIL-STD-87213, reference D, defines four different types of displays: primary flight displays, situation displays, vehicle subsystem management (VSM) displays, and warning, caution, and advisory (WCA) displays. Primary flight displays provide airspeed, altitude, heading, and attitude information to the pilot. These critical displays present safety of flight information and must be placed in the pilot's primary field of view. PEDs are generally unsuitable for primary flight displays, unless the PED is designed as an electronic backup to the primary flight displays. Situation displays present the aircraft position in relation to the intended flight plan, threats, and other aircraft. Examples of situation displays include Horizontal Situation Displays (HSD) and moving map displays. These types of displays are well suited for PEDs as long as the display size and graphics can support complex images and fast update rates. VSM displays contain propulsion, electrical, hydraulic, and weapon system status and Built in Test (BIT) results. If the PED provides a VSM display, this requirement will impact PED location, e.g. fuel displays should be located close to fuel management controls. Likewise, VSM displays require the PED to be integrated into the aircraft's status monitoring bus, which will increase the complexity of the system integration. WCA displays are used to alert the pilot of any potential unsafe condition. These displays can range from engine fire lights to system

level fault detection. Like primary flight displays, PEDs should not be the primary indicator for warnings and cautions. However, if used as a secondary indicator, the PED must support the color and audio alerts appropriate for the warning or caution level.

2.2 DISPLAY SIZE

Display size will determine the type and amount of data that can be presented, but the size will be limited by the amount of cockpit space available. If the screen is too large, it may interfere with the pilot's access to flight controls or obscure other cockpit displays. If the screen is too small, detail will be lost, the amount of information will be limited, and the pilot may not be able to read the display. Factors that must be considered when determining the display size is the function it performs and the importance of the task it supports. A safety of flight display should be larger than a system status display. If the system presents radar or imaging system video, the PED requires a larger screen to provide sufficient image resolution. Applications used on small displays that require readable text, like electronic checklists, might be designed for a certain size display. These applications can be enlarged and presented on a larger display, but shrinking the data for use on a smaller display size may make the text and symbols unreadable. A small display size can be overcome by software that allows the operator to expand the image to allow greater detail when required but zoom out when detail is not important.

2.3 DISPLAY RESOLUTION

In addition to screen size, display resolution has a significant impact on the type and amount of data that can be presented on a PED. Display resolution is a physical display quality that determines the amount of detail in the image or text. Resolution is dependant on display brightness, contrast ratios, and viewing distance. Resolution also determines font size and selection to ensure the text can be read at the anticipated viewing distance and lighting conditions. Some applications, like a moving map, may have specific resolution requirements to ensure the display can present the image or text with the required level of detail. For an imaging system, the display resolution should have least the same resolution as the sensor to prevent the overall system from becoming display

resolution limited. For example, if a radar can differentiate two buildings spaced 100 feet apart, the display should have sufficient resolution or pixel size and numbers to present two distinct targets instead of combining the two targets into one. To improve display resolution, most displays will incorporate anti-aliasing techniques that smooth diagonal and curved lines by adding additional pixels of similar colors and brightness.

There are numerous recommendations for what is considered sufficient resolution. The General Aviation Manufacturers Association Flight Deck Design Guidelines, reference I, requires cockpit cathode ray tubes (CRT) displays to have resolutions outlined in table 1. While most PEDs do not use CRT type displays, these numbers represent one reference design recommendation. The Air Force Institute for Information Technology Applications presented a technical paper on electronic flights bags, reference K, where the recommended PED display resolution was 120 elements/inch for text, but only 86 elements/inch for images when viewed at 24 inches. AMLCD displays, common on most pentablets and laptops, have resolutions up to 120 elements/inch. This resolution supports most home and office advanced graphics applications. Many PED military applications have similar resolution requirements. Therefore, AMLCD displays should have sufficient resolution for most military applications.

Table 1: Display Resolution Guidelines

Graphics	Minimum Resolution
Alphanumeric	40 elements/inch (1.6 elements/mm)
High speed reading alphanumeric	90 elements/inch (3.5 elements/mm)
Complex symbols and graphics	100 elements/inch (3.9 elements/mm)

Source: GAMA Publication No. 10, Section 7.1.3.6

2.4 DISPLAY TYPE

The display type, whether LCD or AMLCD, will significantly impact display readability. LCD displays generally have poor off-axis reading characteristics, especially for color displays where the colors tend to blend together as the off axis angle increases. Backlit LCD screens, common to laptop computers, also tend to wash out when viewed in direct sunlight and large glare sources. Reflective LCD displays use a mirror to reflect ambient lighting that improves sunlight readability. Off axis and daylight readability are important if two aircrew are dependant on the information from the same electronic device. If the application relies on color coding to highlight important or critical information as in alert displays, the ability to discern colors during off-axis viewing becomes more important.

Many PEDs employ touch screens that rely on a stylus or aircrew finger to enter data and manipulate the system. The stylus may scratch or mar the glass or plastic cover, decreasing display readability. Fingerprints and smudges can distort the image or create distracting colors. This problem is also relevant to non-touch screen displays that will accumulate substances on the screen. A protective cover may be employed to help reduce abrasion and decrease the amount of dirt build up on the display that is inherent to normal, every day use. Systems that use glass or plastic covers may become broken or cracked, creating a potential foreign object damage (FOD) hazard in the cockpit.

2.5 DISPLAY LIGHTING

Most PEDs are independently lighted and do not require dedicated cockpit lighting. Thus, display lighting issues focus on brightness, dimming, and contrast. These characteristics are a function of the type of display used and can be controlled to some extent through hardware and software controls such as manual or automatic dimming. Display lighting is critical for two reasons. First, the display must be readable over a wide range of cockpit lighting conditions from direct sunlight to low lux night operations.

Second, the PED display must be compatible with adjacent cockpit displays and light levels so as not to degrade the pilot's interior and exterior vision.

2.5.1 ILLUMINATION

MIL-HDBK-1908B, reference L, defines illumination as “*the amount of light falling on a surface*” and is expressed in the units of foot candles (fc). From a human factors standpoint, illumination levels directly apply to daylight readability. When the sun is shining directly into the cockpit, the PED may have its display washed out. One must also be concerned with light reflecting off aircrew flight equipment and clouds creating a large glare source that might also wash out the display. Poor daylight readability can affect the location of the device in the cockpit, require a glare shield for the PED, or require an antireflective coating be applied to the display.

Tactical cockpits with bubble canopies have the highest illumination levels due to direct sunlight and glare off aircrew equipment and clouds. When discussing illumination levels in cockpits, most crew systems engineers use diffuse illumination levels to account for light losses due to canopy transmission. Cockpit illumination levels are outlined in MIL-HDBK- 87213, reference D. For bubble canopies in ambient sunshine, a diffuse illumination level of 10,000 fc is recommended for optimally placed displays where the sun is outside of 30 degrees perpendicular to the display. The 10,000 fc recommendation includes a 2,000 foot-Lambert (fL) glare source to account for light reflecting off of aircrew flight equipment. Light reflecting off of a white cloud, a larger glare source, has a luminance of 10,000 fL. Adding the additional glare from clouds, cockpit illuminance levels in ambient sunshine at high noon at high altitude can be as high as 14,300 fc. If a glare shield covers the PED, the illuminance level requirement will drop significantly to 300 fc.

2.5.2 LUMINANCE

MIL-HDBK-1908B, reference L, defines luminance (L), or display brightness, as the “*amount of light flux (power) per unit area per solid angle emitted or reflected from a surface*” and is expressed in units of foot-Lambert (fL). As a baseline, an average computer monitor in an office setting has a luminance of 496 fL.¹ When determining luminance, the ambient illumination level must be prescribed, which is generally set at 10,000 fc.² Likewise, display luminance is measured referencing specific colors, usually the primary colors or the International Commission on Illumination (CIE) color scale. Display luminance must be considered from three aspects. First, the display luminance must be consistent across the entire display. This makes the display both easy to read and ensures the pilot doesn’t miss critical data. Secondly, display contrast, or the difference between the maximum and minimum simultaneous display luminance, will impact the ability to discern text and images on the display. Finally, the display brightness must be adjustable to be compatible with ambient light levels and with adjacent displays.

2.5.2.1 DISPLAY LUMINANCE UNIFORMITY

Display luminance uniformity ensures that text, symbols, and images have a uniform brightness across the display, making the entire display easier to read. While the FAA and military use the same design recommendations contained in MIL-HDBK-87213, reference D, they differ in the rationale behind the design considerations. MIL-HDBK-87213 specifically states that luminance uniformity makes the display pleasing to look at but doesn’t necessarily impact mission effectiveness. However, the FAR Part 23 cockpit design guidelines, reference I, points out that “*lack of uniform brightness and unbalanced display characteristics can lead to the pilot missing critical data on a display.*” While software will determine display layout and set specific brightness levels, the hardware must have luminance uniformity across the screen to allow information to be placed anywhere on the screen and not restrict the software designer. Additionally, the display

¹ Meyer et al

² MIL-HDBK-87213

luminance uniformity must be consistent under all lighting conditions, dimming settings, and off-axis reading conditions.

Luminance uniformity guidelines for CRT displays are outlined in MIL-HDBK-87213, reference D. Large area uniformity guidelines are as follows:

“The difference in luminance between any point and the average within any circle whose diameter is one-fourth the display’s minimum dimension shall not exceed $\pm 20\%$ of the average value. Total variation across the display shall not exceed $\pm 40\%$.”

While this requirement is set for CRT displays, the requirement for PEDs should not be more restrictive because the eyes are not sensitive to brightness variations over large areas, however abrupt edges and discontinuities should be avoided. Some systems can have up to a 50% non-uniformity rate but still be considered acceptable. Small area uniformity guidelines are as follows:

“The difference in luminance between any point and the average within any 10 mm circle shall not exceed $\pm 10\%$.”

To illustrate some of the lighting issues associated with PEDs, the results of the NAWCAD Crew Station Electro-optics Branch evaluation of the Itronix Go Book are presented. Luminance uniformity measurements were taken with a spectrometer in the maximum and minimum display intensity settings with white, red, green, blue, and black flat field colors. In each color and intensity setting, 49 data points, spread evenly throughout the display, were measured and recorded. To calculate luminance non-uniformity, the NAWCAD Crew Station Electro-optics Branch used the following equation:

$$\text{Luminance Uniformity} = ((L_{\max} - L_{\min}) / L_{\max}) * 100$$

The results of the Go Book display luminance uniformity tests are presented in table 2.

The Go Book luminance non-uniformity specification was $\leq 30\%$, for which the display

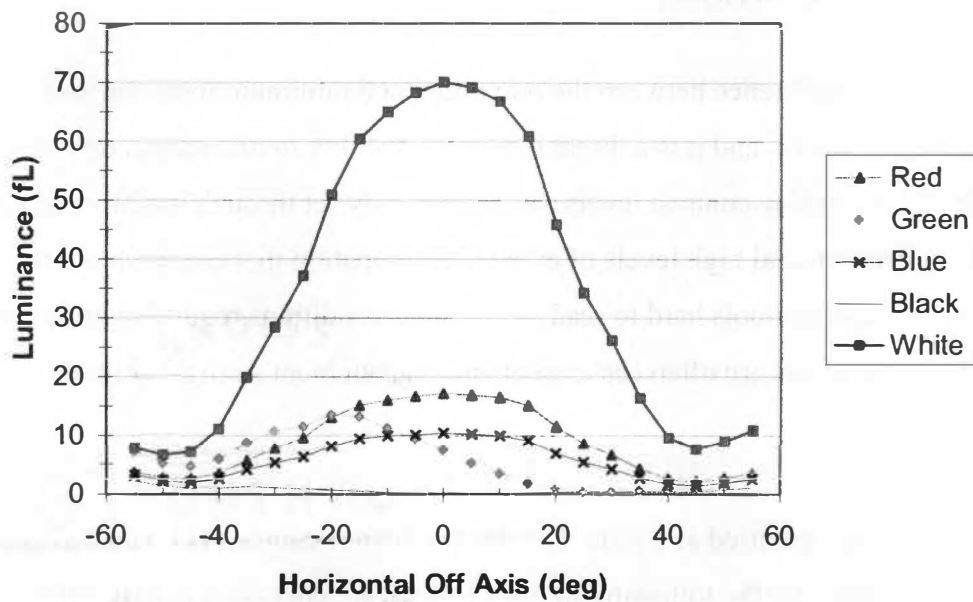
Table 2: Itronix IX 300 Go Book Luminance Uniformity Data

Intensity	Color	Average Luminance (fL)	Non-uniformity (%)
Maximum	White	67.0	23
	Red	16.0	23
	Green	6.7	32
	Blue	9.5	24
	Black	0.1	37
Minimum	White	0.9	38
	Red	0.2	40
	Green	0.1	41
	Blue	0.1	41
	Black	0.002	44

Source: EA-6B Itronix Go Book Pentablet PC Test Report

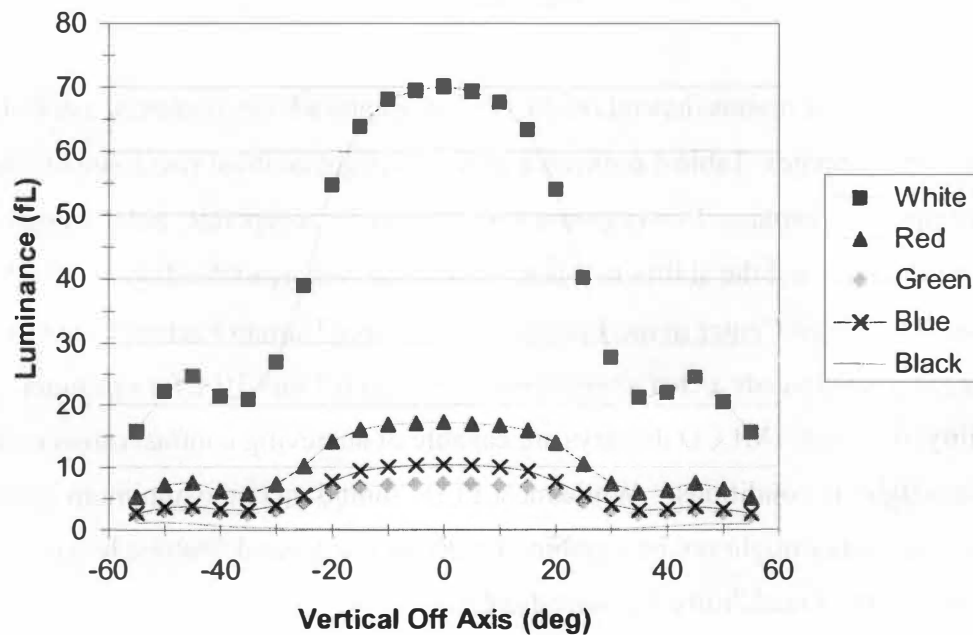
failed for all colors at the minimum intensity and for black and green at the maximum intensity.

Additional Go Book testing was completed to calculate off-axis display luminance shift. For this test, luminance measurements were taken at the center of the display while the horizontal and vertical off-axis angle was increased to ± 55 degrees in 5 degree increments. Figures 6 and 7 summarize horizontal and vertical off axis luminance shift data. For all colors except black, the luminance tended to decrease as the off axis angle increased. Green had the maximum luminance shift with a 94% decrease for the horizontal axis. It is also interesting to note that green in the horizontal axis had the highest luminance at approximately 20 degrees off center. For the color black, both the horizontal and vertical off axis luminance measurements actually increased by 95% and 90% respectively. Based on these results, the NAWCAD Electro-optics branch concluded that the Go Book may not be readable at extreme off-axis angles, which may limit the location of the Go Book in the cockpit.



Source: EA-6B Itronix Go Book Pentablet PC Test Report

Figure 6: Itronix IX 300 Go Book Horizontal Off Axis Luminance Shift



Source: EA-6B Itronix Go Book Pentablet PC Test Report

Figure 7: Itronix IX 300 Go Book Vertical Off Axis Luminance Shift

2.5.3 DISPLAY CONTRAST

Contrast is the difference between the maximum and minimum instantaneous luminance on a screen, and it is a direct indicator of ability to distinguish text and symbols. While display contrast levels can be manually set through hardware or software controls, reflections and high levels of external illumination that can wash out the display and make text and symbols hard to read. Also, night conditions require higher contrast levels, but these levels are often easier to obtain than ambient sunlight contrast requirements.

Contrast is often specified as a ratio. Display luminance contrast (LC) and contrast ratio (CR) are calculated by the following formulas which are contained in MIL-HDBK-1908B, reference L:

$$LC = (L_{\max} - L_{\min}) / L_{\min} \text{ or } (L_{\max} - L_{\min}) / L_{\max}$$

$$CR = L_{\max} / L_{\min}$$

Contrast ratio requirements depend on the type of graphics (text, numbers, symbols) and the size of the graphics. Table 3 outlines ambient daylight contrast requirements for NVIS compatible displays. Lower contrast levels may be acceptable, but the display may appear washed out and the ability to quickly and accurately read the display may be degraded. The Volpe Center in the Electronic Flight Bag Human Factors Considerations, reference B, recommends a character contrast between 6:1 and 10:1 for optimum readability. Average AMLCD displays are capable of achieving contrast ratios up to 6:1 in ambient lighting conditions.³ While most PEDs should meet the minimum contrast requirements, many might not be capable of meeting the desired contrast levels, which translates into poor readability for most displays.

³ Chandra

Table 3: Ambient Daylight Contrast Requirements

Graphics	Required Contrast ⁽³⁾	Desired Contrast ⁽⁴⁾
Numbers only ⁽¹⁾	≥1.5	2-20
Alphanumeric ⁽¹⁾	≥2.0	3-20
Symbols and alphanumeric	≥3.0	3-20
Video ⁽²⁾	≥4.6	20-50

Notes: (1) For a character height where $h = 0.2$ in and character stroke width (SW) where $0.12h \leq SW \leq 0.2h$. Assumes a 30 in viewing distance.

(2) For six level gray scale in worst case ambient lighting

(3) MIL-L-85762A

(4) MIL-HDBK-87213

Table 4: Itronix IX 300 Go Book Contrast Data

Color	Contrast	Illumination (fL)
White	0.12	369
Red	0.01	331
Green	0.01	330
Blue	0.00	327

Source: EA-6B Itronix Go Book Pentablet PC Test Report

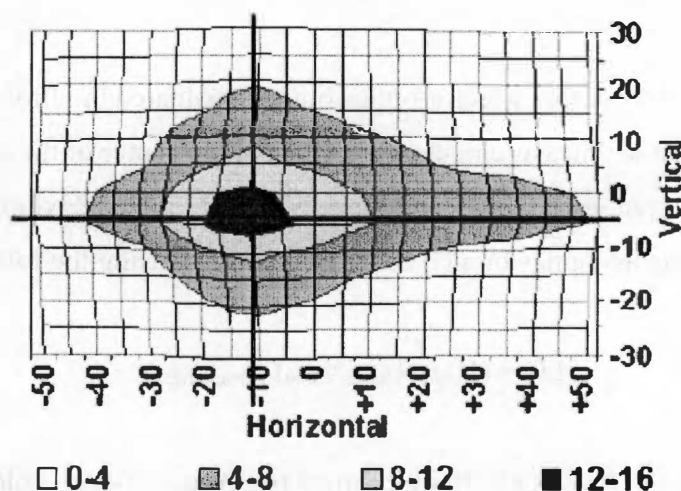
The NAWCAD Crew Station Electro-optics branch evaluated the Itronix Go Book for display contrast. Contrast measurements were taken at the center of the display using flat field colors of white, red, green, blue, and black with a simulated daylight environment. The Crew Station Electro-optics branch calculated contrast using the following formula:

$$LC = (L_{\text{color}} - L_{\text{background}}) / L_{\text{background}}$$

Table 4 summarizes the Itronix Go Book contrast test results. For all colors, the display failed to meet the NVIS compatible display requirements outlined in MIL-L-85762A, reference E. The NAWCAD Electro-optics branch concluded the Go Book may not be suitable for certain types of text or symbols, which affects the type of applications the

device can support in a cockpit environment. These results also indicate that the display may also have daylight readability problems, especially under direct sunlight.

In another display evaluation, the Air Force Research Laboratory at Wright Patterson AFB conducted a lighting evaluation of the Panasonic Toughbook 07, which had a wireless, 6.75 x 5.125 inch AMLCD display. The test results were reported in the paper “Evaluation of Portable Computer with Wireless Transflective Display for Use in Avionics Cockpits,” reference C. For contrast lighting tests, the system displayed a contrast ratio at approximately 7.5 under typical office lighting conditions. During some tests, peak contrasts up to 13.4 were measured. The maximum contrast was observed when viewing the display from 10 degrees left of center as shown in figure 8. From these results, it appears that the contrast ratio is optimized for right hand users who make up majority of the population. While this design feature may be suitable for office use, it may impact the ability to use this device in a tactical aircraft, especially if the display will be located on the left side of the pilot or if shared by two crew members.



Source: Evaluation of Portable Computer with Wireless Transflective Display for use in Aviation Cockpits

Figure 8: Panasonic Toughbook 07 Contrast Ratio Vs. Viewing Angle

2.5.4 REFLECTIVITY

Display reflections are classified as either specular or diffuse. Specular reflections are mirror like reflections that occur when the viewing angle approximates the angle of incidence. Diffuse reflections come from broken or scattered light sources. Display contrast is adversely affected by reflections that obscure text and displays, degrading daylight readability. The specification guidelines for electronic displays contained in MIL-HDBK-87213, reference D, outline specific contrast requirements, but only provide recommendations for acceptable reflectivity levels. The rationale for setting contrast vice reflectivity requirements is that reflections reduce display contrast and contrast requirements are set high enough to account for any reflections that may degrade readability. MIL-HDBK-87213 recommends a maximum reflectivity level of 0.5 percent for displays used in ambient lighting conditions with an anti-reflective coating applied to the screen.

The NAWCAD Electro-optics branch conducted display reflectivity tests on the Itronix IX 300 Go Book. The tests, outlined in MIL-L-85762A, reference E, required that reflectivity measurements be taken under lighting conditions containing 10,000 fc diffuse illumination and a 2,000 fL specular glare source. For this condition, the Itronix Go Book had a display reflectivity of 1.25% and 9.9% for the 10,000 fc and 2,000 fL lighting sources respectively. Based on the high reflectivity of the Go Book displays, the NAWCAD Electro-optics branch recommended an anti-glare coating be applied to the Go Book's display.

2.5.5 DISPLAY BRIGHTNESS RANGE

The previous display lighting issues revolve around one central theme: the display must be readable under all lighting conditions. Unfortunately, optimizing PED readability may impact the ability to read other cockpit displays or look outside the cockpit. A perfect example would be night operations where a bright screen may be easier for the pilot to read but degrades external night vision. Thus, the PED display brightness must be

adjustable such that the eye perceives all displays at equal light levels. Many cockpit displays have brightness controls with day and night settings, while some displays have AUTO dimming capabilities. Additionally, most cockpit displays and lighting brightness levels are set by a single lighting control. However, most PEDs are not tied into the cockpit lighting controls and require individual dimming capabilities. This requirement is consistent with FAA Volpe Center's electronic flight bag design guidelines, reference B, which recommends that PEDs should be controlled independently of other cockpit displays. If the PED display uses an automatic brightness control, there are several requirements that must be met. The brightness range must be adjustable to a wide range of ambient lighting conditions, generally from 100 to 10,000 fc.⁴ The system should employ multiple sensors so the screen does not constantly change brightness settings due to rapid fluctuations in cockpit lighting during aircraft maneuvering. A sensor is also needed to measure external lighting conditions in addition to the cockpit lighting conditions so that bright lighting conditions outside the cockpit do not dim the cockpit displays. Finally, the automatic brightness control must be sensitive enough to respond to subtle lighting changes, especially during sunrise and sunset where the automatic dimming controls can be most valuable to the pilot.

For military cockpits, brightness levels for heads down displays are generally not specified provided that adequate dimming controls are provided. Likewise, the FAA Volpe Center's design guidance for electronic flight bags, reference B, does not specify a desired dimming range. Most dimming requirements are primarily related to dark adaptation of the human eye or "night vision." When maximum dark adaptation is required, MIL-STD-1472, reference M, recommends red lighting at a luminance level of 0.02 – 0.10 fL.⁵ However, at this light level, aircrew may not have complete dark adaptation to view scenes outside the cockpit. Some of the newer displays can be dimmed to 0.01 fL, which still allows critical information to be viewed without degrading night vision or creating distracting canopy reflections but is too dim to see well.⁶ In bright

⁴ MIL-HDBK-87213

⁵ MIL-STD-1472F

⁶ MIL-HDBK-87213

sunlight, this same display must also be easily readable. MIL-HDBK-87213, reference E, recommends that the luminance shift between a cockpit display and bright sunlight white cloud (10,000 fL) should be limited to approximately 20:1. With today's technology, it is possible to achieve ratios up to 50:1, which equates to a display luminance of 200 fL. For a display that is low in the cockpit where the pilot's vision is focused entirely inside the cockpit and the bright external light is outside the pilot's field of view, a smaller display luminance of 100 fL is recommended.

2.5.6 CANOPY REFLECTIONS

One final luminance consideration is the PED should not create large reflections on the canopy that degrade aircrew ability to see outside the cockpit. Canopy reflections may distract the aircrew, especially when the reflections are in their peripheral vision where motion is easily detected. General human factors design considerations for display reflections on canopies are outlined in MIL-STD-1472F, reference M, by the following statement:

Displays shall be constructed, arranged, and mounted to prevent reduction of information transfer due to reflection of the ambient illumination from the display cover. Reflection of instruments and consoles in windshields and other enclosures shall be avoided. If necessary, techniques (such as use of shields and filters) shall be employed to ensure that system performance will not be degraded.

Canopy reflections, including the size and location of the reflections, are highly dependant on the size and shape of the aircraft's canopy and the location of the PED in the cockpit. A display should be dimmable to avoid creating reflections but still allow the pilot to easily read the display. Filters and glare shields for console mounted PEDs can further reduce canopy reflections.

2.6 COLOR

Color displays can significantly enhance both display readability and aircrew situational awareness. The appropriate use of color can quickly alert a pilot to an aircraft malfunction requiring immediate attention or allow the pilot to quickly read and comprehend mission status displays. While color can be an extremely useful and enhancing tool, it can also degrade display readability and cause aircrew confusion if not implemented properly. Most PEDs incorporate displays that are capable of supporting over 256 different colors, however some systems have greater capabilities. Regardless, most display design guidelines recommend a maximum of six colors with specific meanings.⁷ More colors can be used in a display, especially with maps and imagery, however these colors should not have specific meanings. Additionally, the colors must be discernable under all lighting conditions and for off axis readability.

2.6.1 COLOR CODING

General human factors convention assigns specific meanings or situations to colors. Table 5 outlines common color coding definitions. While color can play a critical role in presenting information, it should not be the sole means to differentiate information. Color should be combined with different fonts, text sizes or animations, like flashing symbology. Regardless of the number of colors employed, each color should be easily identifiable to avoid confusion. Certain color combinations, like red/magenta, yellow/amber, and cyan/green, should be avoided because these combinations may be difficult to distinguish. The color blue should not be used for small symbols and text due to poor night time readability.⁸ Caution should also be used when bright colors are used for backgrounds or large areas, which can cause eyestrain. Flashing colors can be used to quickly capture the pilot's attention, but the frequency and duty cycle of the flash pattern must not overly distract the pilot. Red warning indications should flash between 3-5 Hz with a 50% duty cycle. Yellow caution indicators should have a slower flash rate around

⁷ Chandra

⁸ Ibid

Table 5: Color Definitions

Color	Meaning
Red	Warnings or cautions of hazardous situations that require immediate pilot attention or action
Yellow/Amber	Indication of marginal conditions or situations that require the pilot's attention
Green	System or condition is within operating limits or functioning properly
White	Used to indicate non-safety or operational information
Blue	Should be used as an advisory color

Source: GAMA Publication No. 10, Sect 7.16

2 Hz with a 30% duty cycle.⁹ Finally, the use of color should be consistent between the PED and other cockpit displays.

2.6.2 CHROMATICITY SHIFT

Chromaticity shift refers to color changes that occur due to off axis reading angles. If the colors are not distinguishable under these conditions, the display becomes unreadable and causes the pilot to miss vital information. Most PED displays have very little chromaticity shift at small, off axis viewing angles. However, at large off axis angles, the colors tend to become washed out, making color differentiation extremely difficult.

The Itronix Go Book was evaluated for chromaticity shift by the NAWCAD Electro-optics branch. A spectrometer was used to measure display color using white, red, green, and blue display flat field colors. The CIE color coordinates were used to define the color settings. Color measurements were taken at the center of the display at the maximum brightness setting. The NAWCAD Electro-optics Branch used the following formula to calculate chromaticity shift where u' and v' represent CIE color coordinates:

$$\Delta u'v' = [(u'_{ref} - u')^2 + (v'_{ref} - v')^2]^{1/2}$$

⁹ MIL-STD-1472F

Off axis chromaticity measurements were made in 5 degree increments in both the horizontal and vertical axis up to ± 55 degrees off axis. The maximum chromaticity shifts are presented in table 6. While display specifications do not contain specific requirements for the maximum allowable chromaticity shift, these test results showed that the largest chromaticity shifts, with the exception of green, were observed at the extreme off axis viewing angles. Green had a large shift at 30 degrees off axis which might imply limiting the use of the color green or placing the device in the cockpit such that the off axis viewing angle is minimized.

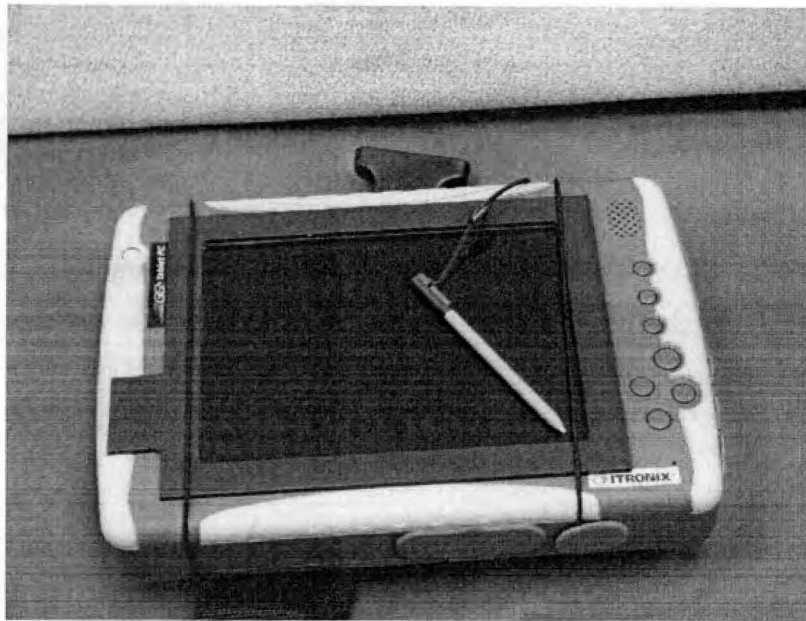
2.7 NIGHT VISION DEVICE COMPATIBILITY

Majority of the tactical aircraft in the U.S. military's inventory are night vision device compatible. As such, any potential PED should also be NVD compatible. Unfortunately, most devices are COTS systems primarily intended for the commercial market and are not compatible with NVDs. Therefore, many devices must be modified with a NVIS filter, which usually consists of a thin plastic sheet placed over the display. The Itronix IX 300 Go Book requires such a filter. The prototype filter is designed to cover the display area as well as four indicator lights at the top of the device. The filter is held in place by two elastic straps. Figure 9 shows the prototype NVIS filter and how it is attached to the Itronix Go Book. While NVIS filters are a viable option for modifying

Table 6: Itronix IX 300 Go Book Off Axis Chromaticity Shift

Color	Horizontal Axis		Vertical Axis	
	Max Shift ($\Delta u'v'$)	Off Axis Angle (deg)	Max Shift ($\Delta u'v'$)	Off Axis Angle (deg)
White	0.015	-45	0.027	-55
Red	0.136	-55	0.032	-55
Green	0.095	30	0.047	-55
Blue	0.105	-55	0.070	-55

Source: EA-6B Itronix Go Book Pentablet PC Test Report



Source: EA-6B Itronix Go Book Pentablet PC Test Report

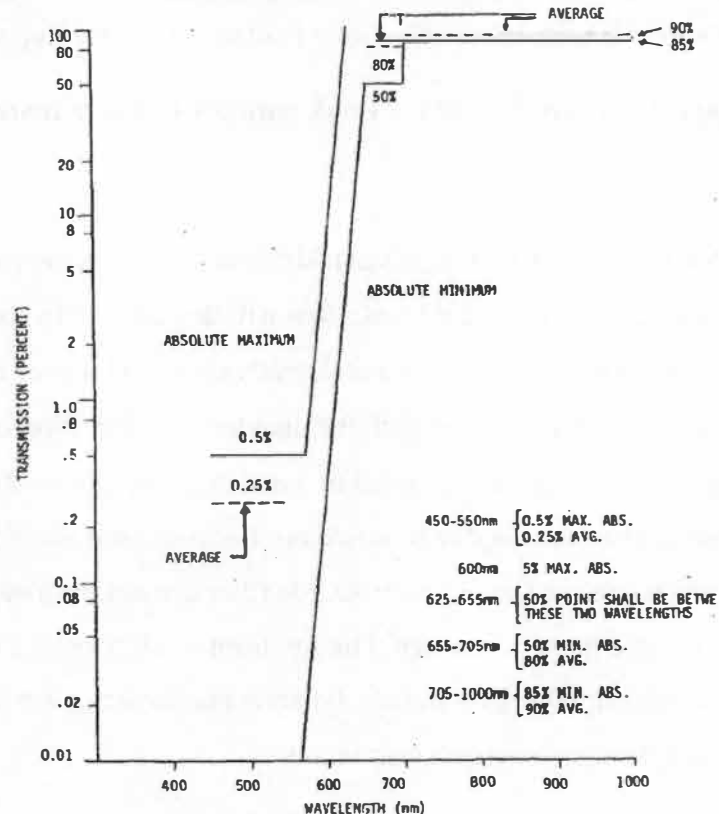
Figure 9: Itronix IX 300 Go Book with NVIS Filter Installed

COTS displays, the use of the filters involves additional crew systems considerations. The installed filters must not allow light leaks that will degrade NVIS compatibility. When the filter is installed, the filter must not degrade the brightness or contrast of the screen, making the display hard to read with the unaided eye. The filter can not create unnecessary reflections affecting the unaided or aided eye. The covers should not become distorted or damaged when the display is turned on. Because most electronic devices employ a touch screen or have lighted controls, the filter can not obstruct these buttons or degrade the ability to use the touch screen. Finally, from a safety point of view, the filters must be secured to prevent falling off during dynamic maneuvering but also be easily removed if need be during an emergency situation.

2.7.1 RADIANCE

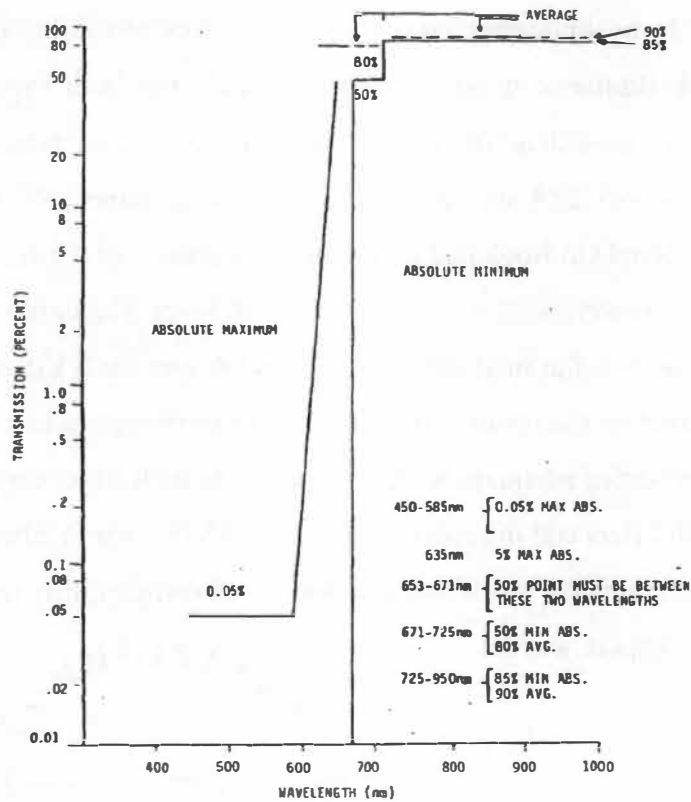
NVIS radiance (NR) is defined in MIL-L-85762A, reference E, as “*the amount of energy emitted by a light source that is visible through NVIS systems.*” NVIS radiance is calculated by integrating the curve of the spectral radiance of the light source multiplied

by the relative spectral response of the system as a function of wavelength. The NVIS class is determined by the wavelength of the filter employed. A Class A system employs a 625 nm filter while a Class B system uses a 665 nm filter. Figures 10 and 11 show the transmission specifications for each class of system. A Class A system is not red light compatible because the system is sensitive to the red light wavelength. A Class B system is compatible with certain filtered red lights and color displays. The radiance specification for Type I color electronic displays is contained in table 7.



Source: MIL-L-85762A

Figure 10: Class A NVIS Transmission Requirements



Source: MIL-L-85762A

Figure 11: Class B NVIS Transmission Requirements

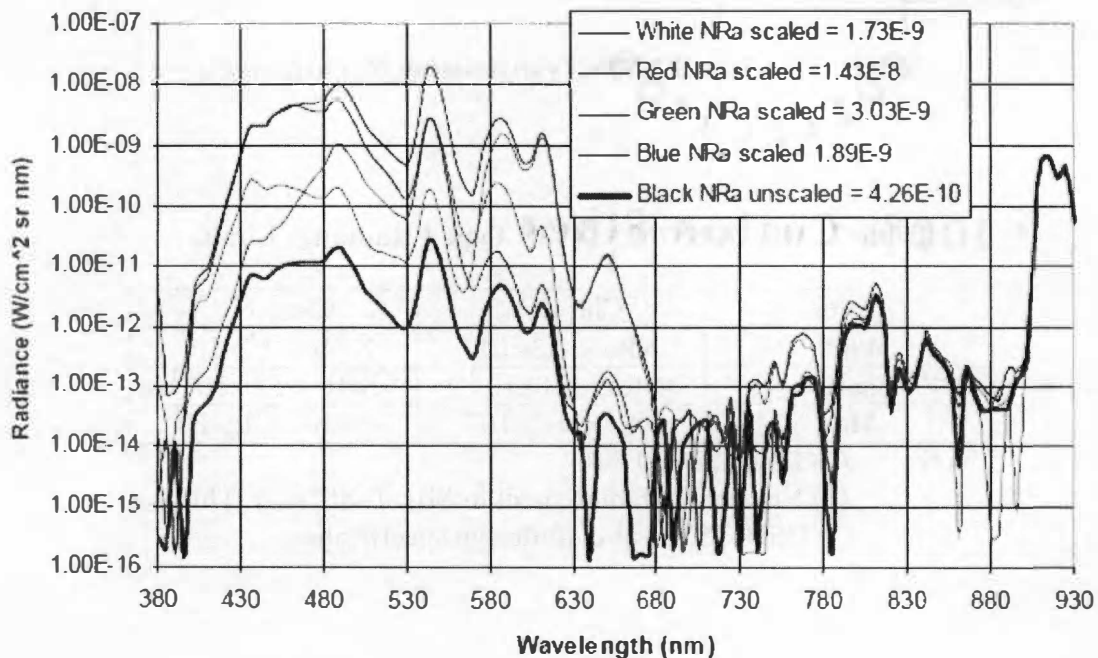
Table 7: MIL-L-85762A NVIS Type I Radiance Limits

Color	Class A ⁽¹⁾	Class B ⁽¹⁾
White	$NRa < 2.3 \times 10^{-9}$	$NRb < 2.2 \times 10^{-9}$
Black ⁽²⁾	$NRa < 5.0 \times 10^{-11}$	$NRb < 5.0 \times 10^{-11}$
Max	$NRa < 1.2 \times 10^{-8}$	$NRb < 1.1 \times 10^{-8}$

Note: (1) Luminance 0.5 fL

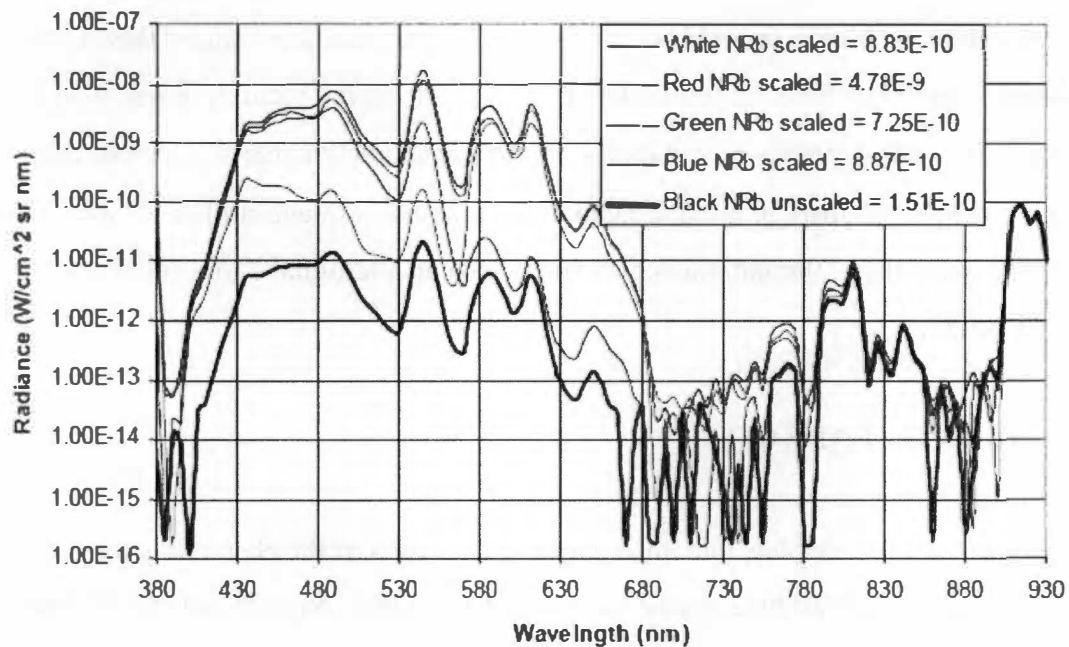
(2) No specific requirement in MIL-L-85762A. This is a USN/USMC aircraft design specification.

The NAWCAD Electro-optics branch conducted NVIS compatibility lighting tests on the Itronix Go Book. Radiance measurements were made with both Type A and Type B filters installed as well as with no filter installed and the results are presented in figures 12 and 13. The MIL-L-85762A specification for radiance requires a 0.5 fL luminance setting, but the unfiltered Go Book had a minimum luminance of 0.8 fL. Therefore, the radiance measurements were scaled down to the 0.5 fL level. The unfiltered radiance test confirmed that for the five flat field colors, the Go Book was not NVIS compatible and required a filter. Based on the results, the NAWCAD Electro-optics branch concluded that the Go Book exhibited adequate NVIS compatibility with the exception of the black background for both filters and the color red with the NVIS Type A filter. The black background had high radiance levels that affected NVIS compatibility regardless of how bright the Go Book display was set.



Source: EA-6B Itronix Go Book Pentablet PC Test Report

Figure 12: Itronix IX 300 Go Book Spectral Radiance with NVIS A Filter



Source: EA-6B Itronix Go Book Pentablet PC Test Report

Figure 13: Itronix IX 300 Go Book Spectral Radiance with NVIS B Filter

2.8 DISPLAY FLICKER, JITTER, AND NOISE

Display and image stability can significantly impact the effectiveness and suitability of any PED. Flicker, jitter, and noise can increase eye fatigue, reduce display readability, and make the display unpleasing to look at. The JSSG, reference H, defines flicker as *“the undesirable rapid temporal variation in display luminance of a symbol or group of symbols.”* The JSSG also defines jitter as *“rapid spatial movement of a displayed image, element, or symbol discernable to the human eye.”* Jitter involves frequencies greater than 0.25 Hz, while lower frequencies relate to image stability. Jitter and image stability are dependant on display refresh rate, which should not be noticeable to the human eye. LCD displays require a refresh rate of 75 Hz, which is higher than CRT displays due the display voltage requirements.¹⁰ Some types of display can use a slower update rate, like moving map displays, which can be supported by a 1 Hz update rate. However, safety of

¹⁰ GAMA Publication No. 10

flight information like airspeed and altitude require update rates greater than 15 Hz.¹¹ To minimize jitter problems, general human factors design guidelines require that an image or element move less than 0.2 milliradian (mrad) or 41 degree seconds in less than 1 second.¹² For image dimensional stability, the image should change by no more than ± 2 %. For symbols less than 50 mrad in height, the maximum image shift is ± 7 mm. For symbols greater than 50 mrad, the requirement adds an additional 7 mm for every 50 mrad in height.¹³

2.9 DESIGN TRADE OFFS

When evaluating a display, one must consider how each of the characteristics previously discussed combine to provide a readable display. As with reflectivity and contrast, negative reflectivity characteristics can be overcome by improved contrast ratios. Display brightness, which is directly related to ambient lighting conditions, can be controlled by cockpit placement and brightness controls. Some hardware pitfalls can be overcome by software. Poor display brightness may require larger fonts and symbols. Off axis chromaticity shifts may preclude using certain colors for specific applications, which may also limit some functions of the PED. Most important, the display must be readable for all lighting conditions and off axis reading angles. Hardware and software trade offs must be made such that discrepancies in one area can be offset by other system attributes.

¹¹ MIL-STD-1472F

¹² MIL-HDBK-87213

¹³ Chandra

SECTION 3: PED CONTROLS

3.1 CONTROL OPTIONS

Aircrew need a way to quickly and accurately input data and manipulate a PED to present the mission information required for each stage of the flight. The range of available control options are varied and diverse, and each type of control has its own advantages and disadvantages. Control and input options include full size QWERTY and mission specific keyboards, styluses and pointing devices, and hard and reprogrammable soft keys. This section discusses several control options commonly incorporated in PEDs, including the human factors and design considerations and specification for each option. The specifications for common controls and input devices can be found in MIL-STD-1472F, reference M.

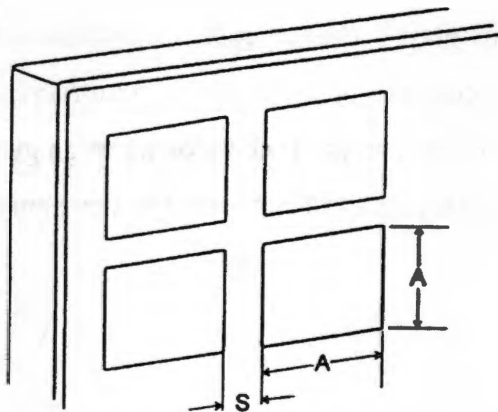
There are several important human factors considerations that are pertinent to all input devices and controls. First, the input device must be matched to the type and frequency of the data to be entered. A standard keyboard is desirable for quickly entering large amounts of alphanumeric data while soft keys are better suited for complex software applications with numerous functions. A suitable hand rest that allows the aircrew to stabilize their hand when entering data will reduce aircrew fatigue and improve the speed and accuracy of data entry. All controls, especially reprogrammable soft function controls, must be labeled to indicate the function of the button. These labels may be abbreviated but should not confuse the aircrew about the function or purpose of the control. Control labeling should be consistent for all PED displays and across the entire cockpit to the maximum extent possible. Control actuation must provide sufficient feedback that allows the aircrew to know that the input was recognized. Controls should be close to the display they interact with and the most common controls should be positioned where they can be easily located and actuated. Finally, control placement, shape coding, and proper control spacing should minimize inadvertent control activation. This specification details every aspect of the control, including size, spacing, feedback, and labeling.

3.2 TOUCH SCREENS

The FAA electronic flight bag human factors design guide, reference B, contains a comprehensive list of commercially available PEDs marketed for aviation applications. Of the 15 PED examples listed, 14 systems incorporate a touch screen as one of the control options. Touch screens offer a wide array of flexible input options, including digital keyboards and pointing devices. However, there are some unique considerations when employing touch screens. Touch screens, especially for pentablet computers with large display areas, can be extremely sensitive to inadvertent actuation. To avoid this problem, some touch screens, such as the Itronix Go Book, require a special stylus device with a magnet in the tip. The Go Book is not sensitive to fingers and will not allow inadvertent actuations if accidentally brushed by aircrew flight equipment. When the aircrew intends to enter data, the screen should provide some type of positive feedback to let the aircrew know his input was recognized by the system. Some devices rely on an audible click sound, which may not be heard in a loud cockpit environment or with a helmet on. Most devices also use a physical change to the display image, like an increase in symbol size or brightness, to indicate control actuation. Regardless of the type of feedback, the response time to the actuation should be less than 100 msec.¹⁴ For critical tasks, a confirmation control actuation should be incorporated to preclude accidentally shutting off essential systems or entering incorrect control settings. Finally, the touch screen must be durable and not become scratched or damaged due to constant use. Use of the stylus, repeated wear on commonly used controls, and finger oils should not mar or distort the touch screen, causing the screen to become hard to read.

There are several human factors guidelines and specifications for touch screen target areas, which are contained in reference B. For military applications, human factor guidelines for touch screen target areas are outlined in MIL-STD-1472F, reference M, and presented in figure 14. The touch sensitive areas should be symmetrical and equilateral in shape.” If color or shape coding is used, the coding should

¹⁴ Chandra



Requirement	ALPHANUMERIC / NUMERIC KEYBOARDS		
	A (Actuation Area)	S (Separation) ⁽¹⁾	Resistance
MINIMUM	—	0	250 mN (0.9 oz)
PREFERRED	13 x 13 mm (0.5 x 0.5")	—	—
MAXIMUM	—	6 mm (0.25")	1.5 N (5.3 oz)

Requirement	OTHER APPLICATIONS		
	A (Actuation Area)	S (Separation) ⁽¹⁾	Resistance
MINIMUM	16 x 16 mm (0.65 x 0.65")	3 mm (0.13 in)	250 mN (0.9 oz)
MAXIMUM	38 x 38 mm (1.5 x 1.5")	6 mm (0.25")	1.5 N (5.3 oz)

Note: (1) For touch screens that use a “first contact” actuation strategy, separation between targets should be not less than 5 mm (0.2”). For touch screens that use a “last contact” strategy, separation between targets may be less than 5 mm (0.20”), but not less than 3 mm (0.12”) for applications other than alphanumeric/numeric keyboards.

Figure 14: MIL-STD-1472F Touch Screen Specification

be consistent through the display.¹⁵ The target area should be sufficiently large to allow for accurate data entry in a confined area and during minor aircraft maneuvering or turbulence. The Boeing Company established its own design guidelines for the Boeing 777 aircraft, requiring the target area to be at least 3/8 inch square with 1/2 inch spacing.¹⁶

3.3 KEYBOARDS

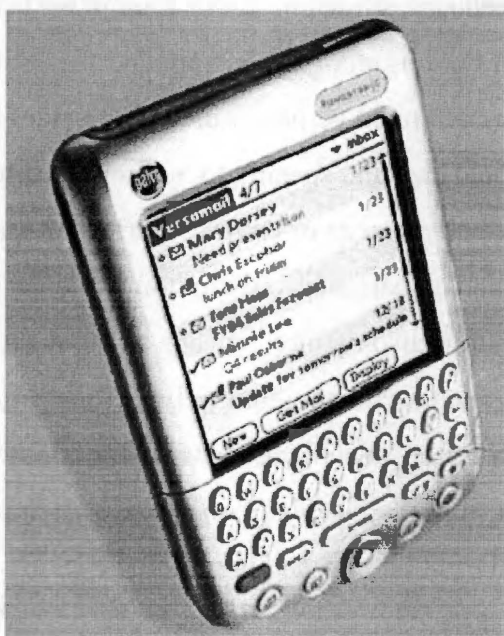
Most PEDs employ either a physical or software generated keyboard to allow for data entry. Laptop devices contain full size QWERTY keyboards. Most pen tablets and PDAs use a soft keypad with a stylus or a pointing device. An important factor when examining the type of keyboard used is the type and frequency of the data to be entered. When large amounts of text are required, a full size keyboard for use with both hands is considered optimum. When smaller amounts of text or both hands are not available for typing, an alphanumeric keypad may be acceptable. For numeric entry, a dedicated keypad is recommended, although the keypad may be integrated into the larger keyboard device. Some systems may not have room for a full size keyboard, so smaller, thumb keypads, as seen in figure 15, or detachable keypads may be employed. If a soft keyboard is used, the key size should match the target size for touch screens. If a hard keyboard is employed, table 8 outlines keyboard specifications contained in MIL-STD-1472F, reference M. Based on the keyboard guidelines, thumb keyboards and some foldable keyboards may not have sufficient key sizes and spacing to allow a pilot wearing flight gloves to adequately enter text without delaying data entry or having numerous typing errors.

3.4 PUSH BUTTONS

All PEDs contain some type of push button. At a minimum, these controls are used to turn the system on and off and control display brightness and contrast. These hard keys may have unique, specific functions or they may be multifunction, soft keys that are

¹⁵ Ibid

¹⁶ Chandra



Source: Palm Tungsten C Brochure

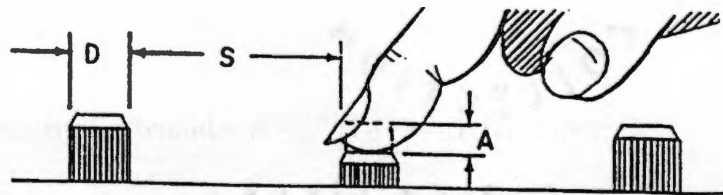
Figure 15: Thumb Keypad on PDA

Table 8: MIL-STD-1472F Keyboard Specifications

Specification ⁽¹⁾	Dimensions (in)	Resistance (oz)	Separation (in)
Minimum	0.4	9.9	-
Preferred	-	-	0.5
Maximum	1.0	23.7	-

Note: (1) For vehicle operation

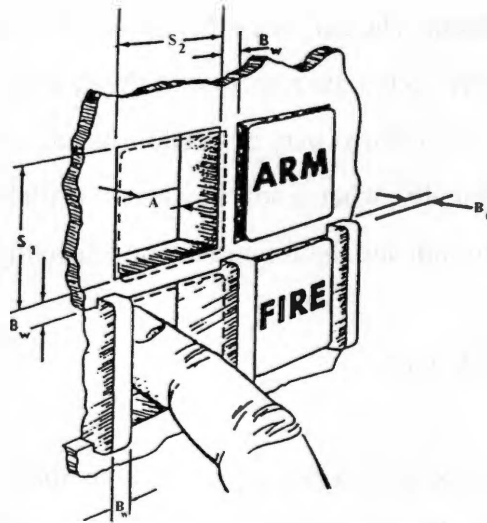
reprogrammable based on the software application being used. The Raytheon Electronic Data Manager Digital Kneeboard, shown in figure 4, employs both hard and soft keys. The hard keys include four buttons along the bottom and four arrow keys across the top. The reprogrammable keys are arranged vertically along both sides of the display. These pushbuttons require sufficient size and spacing to be usable while wearing flight gloves. The buttons must be sufficiently spaced or employ barriers or spacers between each key to allow aircrew to locate and actuate a specific button while not inadvertently selecting an adjacent button. The buttons also require a means to avoid accidental actuation if the button is hit by flight equipment, which might imply a minimum actuation force or some type of barrier. The human factors specifications will depend on whether the keys are push buttons (protrude out from the faceplate) or legend switches (flush with faceplate). The specifications for both push buttons and legend switches are contained in figures 16 and 17 respectively.



Specification	Diameter ⁽¹⁾ (D) (in)	Spacing ⁽¹⁾ (S) (in)	Displacement ⁽¹⁾ (A) (in)	Resistance ⁽¹⁾ (oz)
Minimum	0.75	1.0	0.08	10
Maximum	-	-	0.25	40

Note: (1) Gloved finger

Figure 16: MIL-STD-1472F Push Button Specification



Specification	Size ⁽¹⁾ (S1 and S2) (in)	Barrier ⁽²⁾ (Bw) (in)	Barrier ⁽²⁾ (Bd) (in)	Displacement (in)	Resistance ⁽³⁾ (oz)
Minimum	1.0	0.125	0.2	0.125	40
Maximum	1.5	-	-	0.250	60

Notes: (1) Gloved finger
 (2) Switch separation
 (3) Assumes moving vehicle

Figure 17: MIL-STD-1472F Legend Switch Specification

3.5 SOFT KEYS

Smaller PEDs heavily rely on reprogrammable soft keys to overcome limited space available for hard keys. The functions of these keys depend on the software application. When employing soft keys, there are several design guidelines that should be followed in addition to the key size, spacing, and displacement requirements outlined in section 3.4. Soft key design guidelines can be found in *Human Factors Considerations in the Design and Evaluation of Electronic Flight Bags*, reference B. Soft keys must be labeled with their current function, and the label must be consistent through the application. If a function can be found on different menus of the software matrix, this function should be placed in the same location on each software stick. The labels should be easily interpreted

to avoid aircrew confusion. The soft key labels should be positioned around the edges of the display and not cover up the main section of the display. Ideally, the labels should be in horizontal text, but vertical text may be used if the label does not extend into the primary display area. Finally, when a soft key is not available, the key should either not be labeled or marked to indicate the function is not currently available.

3.6 POINTING DEVICES

Even if a device does not incorporate a touch screen, most systems employ Windows type software that normally relies on a pointing device to select information on the display. Several pointing device options are available, ranging from a simple stylus to track balls to finger operated joysticks. Even the finger can be a suitable pointing device depending on the size of the target and accuracy requirements. However, different types of pointing devices are better suited for certain control functions, i.e. track balls work well for placing the cursors on a target but are not recommended for drawing graphics. Table 9 outlines control options and their suitability for specific functions.

Table 9: Control Suitability for Display Applications

Control Type	Display Application			
	XY Data Pickoff	Continuous Tracking	Free-Drawn Graphics	Setting Cross Hairs
Track Ball	Good	Fair	Poor	Good
Isometric Joystick	Good	Good	Fair	Fair
Displacement Joystick	Good	Good	Good	Fair
Free moving XY controller	Good	Not Recommended	Not Recommended	Fair
Stylus	Good	Fair	Good	Fair

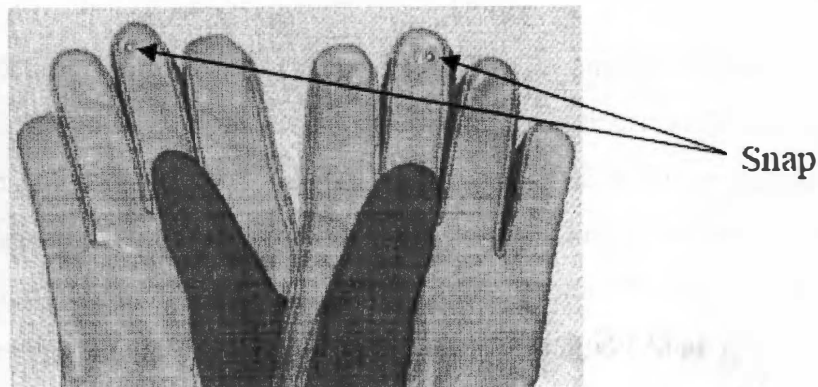
Source: DOD Human Factors Pocket Guide

3.6.1 STYLUS

Styluses are extremely common for pentablet and PDA systems. While a stylus may be ideal for home and office use, it has unique requirements for cockpit use. Stylus specifications can be found in MIL-STD-1472F, reference M. The stylus dimensions should be 4.7 – 7.1 inches in length, between 0.3 – 0.8 inches in diameter, and weigh approximately 0.350 – 0.875 ounces. The force required to use the stylus on the touch screen should be less than 2.9 ounces. The stylus should have a slip resistant surface and must be permanently attached using a string or chord to prevent it from being dropped or lost in the aircraft. When the stylus is applied to the touch screen, a follower (mark, bug, or hook) should be presented on the display at the same coordinates as the stylus. The follower should continue to display the stylus location until the stylus is moved, at which time, the follower coordinates should continuously and smoothly match the stylus location. When not in use, the stylus should have a storage area to preclude it from injuring the aircrew or becoming lodged in flight controls during abrupt maneuvering or emergency egress scenarios.

3.6.2 FINGERTIP

The stylus represents a potential FOD hazard and must be secured at all times. In lieu of the stylus, the fingertip may provide a suitable option for touch screen control. However, aircrew are required to wear fireproof flight gloves while flying in military aircraft. These gloves may not be suitable for touch screen use because they may be too large for target areas. Also, some touch screens are not sensitive to a gloved fingertip and require a special pointing device. To overcome these limitations, the Air Force Research Laboratory at Wright Patterson AFB devised an innovative solution while testing the Lil HAL system. The engineers modified the fingertips of the aviator flight gloves with the male portion of a common snap, as shown in figure 18. This button performed like a small stylus attached to the fingertip, which improved pointing accuracy while still maintaining adequate fire protection and FOD prevention.

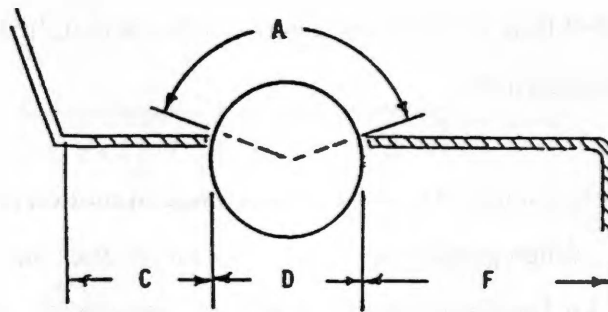


Source: Safe to Fly Determination for Lil HAL System

Figure 18: Lil HAL Modified Aviator Flight Glove

3.6.3 TRACK BALLS

Track balls also represent potential control input options. Track balls are generally found on older laptop computers. Track ball specifications can be found in MIL-STD-1472F, reference M. The ball moves in both the x and y axis and is useful for selecting items on the display. Track ball manipulation should allow for both fast, large control movements and small, fine control adjustments. A follower indicator should be used with track balls and the follower should move proportionally to the track ball displacement. When a track ball is used, wrist or hand support is required to allow for fine control adjustment. Track ball dimensions, resistance, and clearance limits are presented in figure 19. It is possible to use smaller track balls than prescribed in figure 19, however this should be reserved for situations where space is limited and small, precise control inputs are not critical. Track balls are highly susceptible to inadvertent control inputs. This limitation is a major concern, especially for electronic kneeboards, where the track ball can be easily brushed by aircrew flight equipment. Increasing the track ball break out force may be an option but increased forces will make small control adjustments more difficult. Placing a cover over the track ball might not be practical due to the size of the shield.



Specification	Dimensions		Resistance ⁽¹⁾		Clearance	
	Diameter (D) (in)	Surface (A) (deg)	Precise Control (oz)	Vibration/ Acceleration (oz)	Ball to Display (C) (in)	Ball to Front (F) (in)
Minimum	2.0	100	0.9	-	2.0	4.75
Preferred	4.0	120	1.1	-	-	-
Maximum	6.0	140	5.4	6.0	-	10.0

Note: (1) Initial resistance should range from 0.9 to 1.4 oz

Figure 19: MIL-STD-1472F Track Ball Specification

3.6.4 JOYSTICKS

Many laptop computers contain small, finger-operated joysticks that are normally located in the center of the keyboard. A large handheld joystick would be impractical due to the increased potential for inadvertent actuation and snag and impale hazards during emergency egress. A finger operated joystick device may be more suitable. This is true especially if the joystick can be integrated into a throttle, hand controller, or control stick common to most tactical aircraft. Joystick specifications and design guidelines can be found in MIL-STD-1472F, reference M. There are two types of joystick options available: isotonic or isometric. Isotonic joysticks reference joystick displacement while isometric joysticks have little or no movement and use force to guide the follower device. Isotonic, or displacement, joysticks work best where position accuracy is more important than speed and work very well for selecting data or drawing freehand graphics. Isometric joysticks are better suited for applications that require immediate return to center characteristics and for tasks where feedback is primarily visual instead of tactile. Isometric joysticks are not recommended for tasks that require a constant force to be held

for an extended period of time or when there is no feedback that the maximum allowable control input has been exceeded.

Displacement joysticks should have a maximum range of motion of 45 degrees from center in all directions. When placing the cursor on a target, the control ratio and force required should allow for fast, large control inputs and fine, precise cursor placement with no noticeable cross coupling or excessive overshoots. The delay from control input to follower movement should be less than 0.1 second. To avoid inadvertent actuation and provide improved control, displacement joysticks should be recess mounted into the console or keyboard. If mounted on a hand controller, displacement joysticks should be easily manipulated using a normal handgrip and not require excessive forces. Regardless of the type of joystick employed, the joystick should not be mounted on a device or handgrip that also serves as a joystick to avoid inadvertent control coupling. Also, some type of hand or wrist rest is required to stabilize the hand and improve control input accuracy.

SECTION 4: COCKPIT INTEGRATION

The section examines PED cockpit integration and addresses relevant location issues. The fourth COI requires a PED to be easily accessible and not obstruct the pilot's ability to see and use existing cockpit displays and controls. An obvious choice would be to strap the PED to the pilot's leg as an electronic kneeboard. This location is easily accessible and viewable, and aircrew are already familiar with placing mission critical information on a kneeboard. The electronic kneeboard option has a unique COI requirement that the kneeboard be securely attached to the pilot's leg to prevent the device from distracting the pilot or causing discomfort due to size, weight, and temperature. If the PED is not used as an electronic kneeboard, a mounting device must be provided to securely hold it in place across the entire flight envelope, including dynamic combat maneuvering. The primary military specifications for cockpit integration can be found in the requirements for aircrew station geometry (MIL-STD-1333B), reference G, and fixed wing aircrew station controls and displays location and arrangement (MIL-STD-203G), reference F. In addition to the crew station requirements, this section presents several real world examples of PED integration and discusses the advantages and disadvantages of each.

4.1 COCKPIT LOCATION

The military specification for fixed wing aircrew controls and displays, MIL-STD-203G, reference F, lists nine factors to be considered for control and display location:

1. Frequency of use
2. Criticality
3. Sequence of use
4. Size
5. Type and number of controls
6. Interlinkage of controls
7. Control operating envelope
8. Visual display on control panel
9. Functional reach zones

A control or display that is consistently used should be placed in an easily accessible location. PED frequency of use will depend on the role the system will play. As an example, a PED used primarily for checklists should be readily available at aircraft start up, shut down, and during emergency situations, but can be stowed when not in use. The criticality of the information presented will likewise determine the location of the PED. A device that displays safety of flight information must be located within the pilot's primary field of view to allow the pilot to readily monitor critical flight parameters. Sequence of use relates to how the display or control is used in relation to other cockpit controls and displays during normal and emergency procedures. An example is placing the landing gear handle close to the flap lever to allow the aircrew to simultaneously raise and lower the landing gear and flaps for take off and landing. PEDs used with weapon systems should be located in the vicinity of master arm or weapon select controls. The size, type, and number of controls are critical to ensure the aircrew can easily locate and actuate the controls.

4.1.1 FUNCTIONAL REACH ZONES

Functional reach zones for controls are directly tied to the criticality and frequency of use of the control. Functional reach zones and the type of controls that should be located in each zone are outlined in references F and G. Safety of flight or mission critical controls must be easily located and manipulated. These controls are required to be in the Restraint Harness Locked - Functional Reach Zone, or Zone 1, where the aircrew is fully restrained and does not stretch the arm or shoulder muscles. Specifically, *"this zone defines the maximum limit allowed for the placement of emergency escape system controls and the forward most operation limit of primary flight and propulsion controls."*¹⁷ Flight and mission essential controls that allow the aircraft to be flown in a degraded mode, but allow the aircraft to be safely flown and the mission successfully accomplished should be located in the Restraint Harness Locked – Maximum Functional Reach Zone, or Zone 2. This functional reach zone is similar to Zone 1, but allows for the maximum possible reach of the aircrew with the harness locked. Zone 2 defines the

¹⁷ MIL-STD-1333B

maximum limit for the placement of emergency controls except for emergency escape controls. All other controls not defined as flight or mission critical or essential can be placed in Zone 3, or the Restraint Harness Unlocked – Maximum Functional Reach Zone, which allows the restraint system and arms to be fully stretched. A PED should be placed in a functional reach zone appropriate for its intended use.

4.2 ELECTRONIC KNEEBOARDS

The use of a PED as an electronic kneeboard in a tactical cockpit has several important considerations, which include the cramped confines of the cockpit, the dynamic flight environment, and requirements for aircrew flight and survival equipment. The electronic kneeboard must not interfere with the flight controls, throttles, and other safety of flight items. It must also be comfortably secured but still be easily attached and removed. Finally, the potential for spatial disorientation from looking heads down in the cockpit, must be evaluated based on kneeboard use during various mission phases.

4.2.1 KNEEBOARD ATTACHMENTS

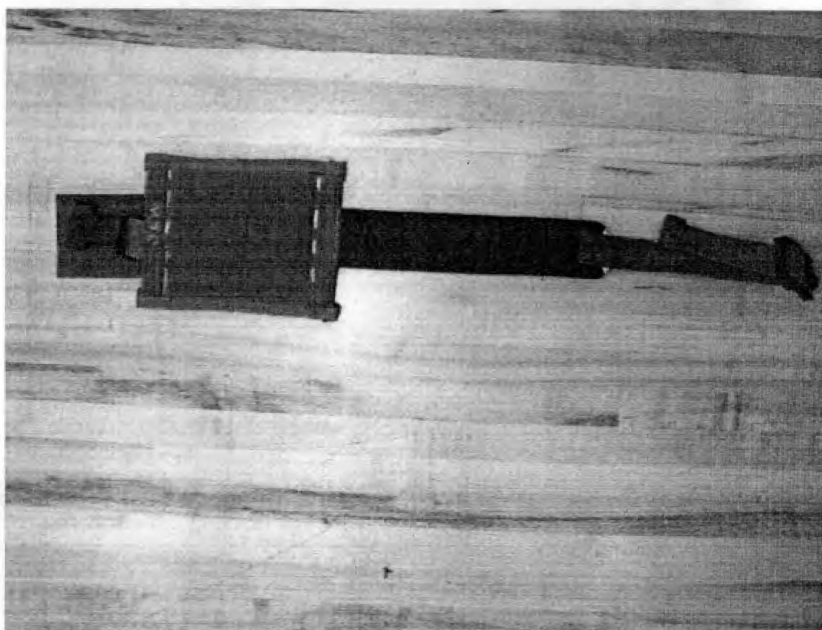
An electronic kneeboard must be properly secured. There are several electronic kneeboards currently fielded in military aircraft, and each system has a slightly different attachment method. The EA-6B Prowler uses a Panasonic CF-25 laptop computer in the aft cockpit to run electronic warfare systems as shown in figures 1 and 2. This system was originally intended to be handheld and did not include a way to secure the laptop when in use, which presented an unacceptable risk to the aircrew. This risk was mitigated by a flight restriction on the number of G's (normal acceleration) that could be pulled when the laptop was not stowed during flight operations and by the use of a Velcro strap to hold the laptop in place. Placing flight restrictions on combat aircraft may not always be a viable option depending on the mission of the aircraft and the function of the PED. An aircraft that performs air-to-ground weapons deliveries or missile defensive maneuvers must operate at the aircraft's maximum performance capabilities, and any flight restrictions may be completely unacceptable from a mission completion point of

view. The Velcro strap for the Panasonic Toughbook, shown in figure 20, also proved to be an unsuccessful option as the elastic strap quickly became stretched and no longer held the laptop securely in place. Eventually, fleet operators stopped using the Velcro strap and rested the laptop on their laps during flight.

Another method for securing a PED is to integrate it into the attachment device. As an example, the Itronix IX 300 Go Book, which is currently in developmental testing as a replacement for the Panasonic CF-25 laptop in the EA-6B, incorporates a kneeboard device that fully encloses the pentablet while providing storage for the stylus and secures the power cables to minimize cable entanglement. The prototype Go Book kneeboard is shown in figure 21. Another example is the Raytheon Air Warrior Digital Kneeboard which is mounted to a plastic and cloth kneeboard device, shown in figure 22, that has flaps that hang on both sides of the pilot's leg. These flaps can be used for holding additional items and as a storage case to protect the device from being scratched or damaged when the system is not in use. One must also look at the impact the attaching device will have on flight controls and other displays. Many COTS pentablet computers are relatively large and become even larger when attached to a protective kneeboard device. The first prototype kneeboard device evaluated during the Itronix Go Book integration into the EA-6B would not fit into the laptop stowage compartment, requiring a redesign of the kneeboard device.

The kneeboard attachment device must also account for aircrew flight and survival gear. The device must remain securely in place when the anti-g suit worn by the pilot is inflated. Likewise, the strap must not impede anti-g suit inflation, requiring some type of elastic or stretchable material to be incorporated into the kneeboard straps. The attachment strap must also be adjustable to account for the differences in aircrew thigh circumference, which can range from 20.01 inches for the 5th percentile female to 26.73 inches for the 95th percentile male.¹⁸

¹⁸ Gordon et al



Source: VX-23 EA-6B Project Office

Figure 20: Velcro Strap for Panasonic Laptop for EA-6B



Source: VX-23 EA-6B Project Office

Figure 21: Prototype Itronix Go Book Kneeboard

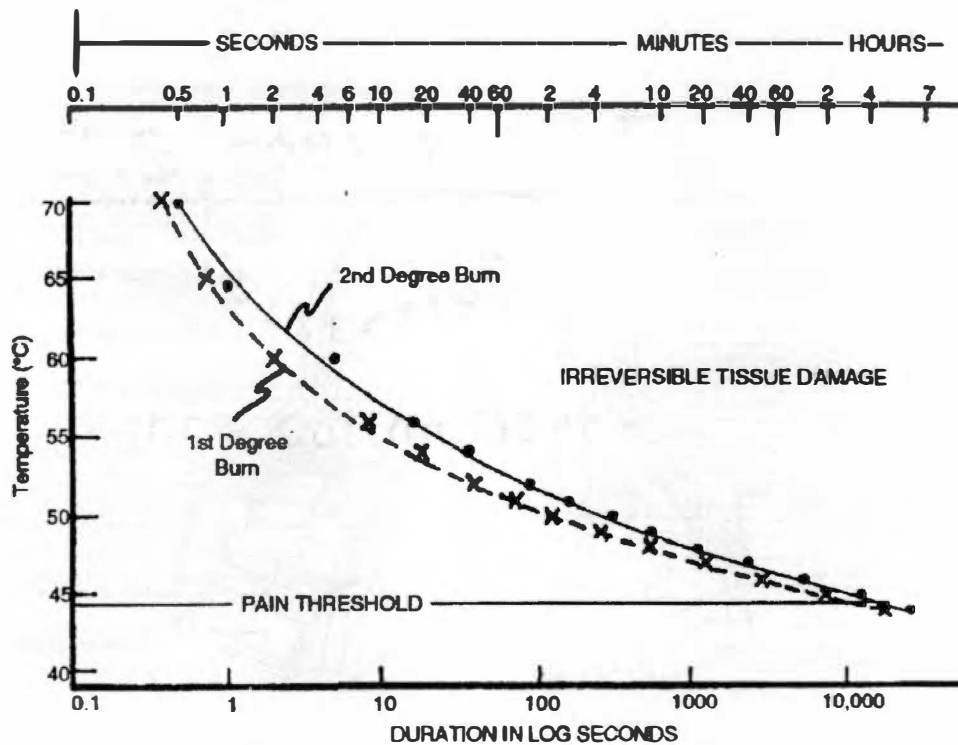


Source: Air Warrior Electronic Data Manager Brochure

Figure 22: Raytheon Air Warrior with Kneeboard Attachment

4.2.2 AIRCREW COMFORT

Securing the PED to the aircrew's leg requires the designer to account for its weight and the heat it generates. Most aircrew use kneeboards to carry a few pieces of paper and an instrument approach plate, which weigh less than one pound. However, a pentablet computer will weigh several pounds, which may be uncomfortable to wear on the leg for long missions lasting several hours. Aircrew discomfort may also be exacerbated by the additional weight placed on the leg under increased normal accelerations of maneuvering flight. Additionally, if the attachment device does not securely hold the kneeboard in place, the PED will slide up and down or rotate around the leg, which may cause rubbing and soreness. One mitigating factor for a poorly secured kneeboard is the g-suit, which tends to be tight around the aircrew's leg and does provide padding against rubbing. The PED heats up as the system is operated over time. Many pentablet computers have small fans on bottom to provide some cooling, but these fans can become blocked by flight equipment and attachment devices, potentially increasing the surface temperatures. Human factors guidelines for exposure to hot temperatures are contained in figure 23. Constant use of the PED during long combat missions may expose the aircrew to high temperatures that can reach the threshold of pain. An anti-g suit may provide some measure of protection against high temperatures.



Source: DOD Human Engineering Design Data

Figure 23: Burn Criteria For Human Skin

4.3 STOWAGE CRADLES

Another option for integrating the PED is to install a mounting bracket or cradle somewhere in the cockpit. The stowage cradle and attached PED must not impede actuation or visualization of other cockpit controls and displays, nor block aircrew external vision. The cradle should not create a snag hazard or impede normal and emergency egress. This cradle may also serve as a storage unit when the PED is not in use. The cradle must meet all cockpit loading and survivability requirements for normal and emergency operations.

The cradle must be located where sufficient cockpit space permits. Figures 24 and 25 present standard cockpit layouts for single seat strike fighter and tandem cockpit attack aircraft and illustrates the limited space available in a tactical aircraft. If the PED displays

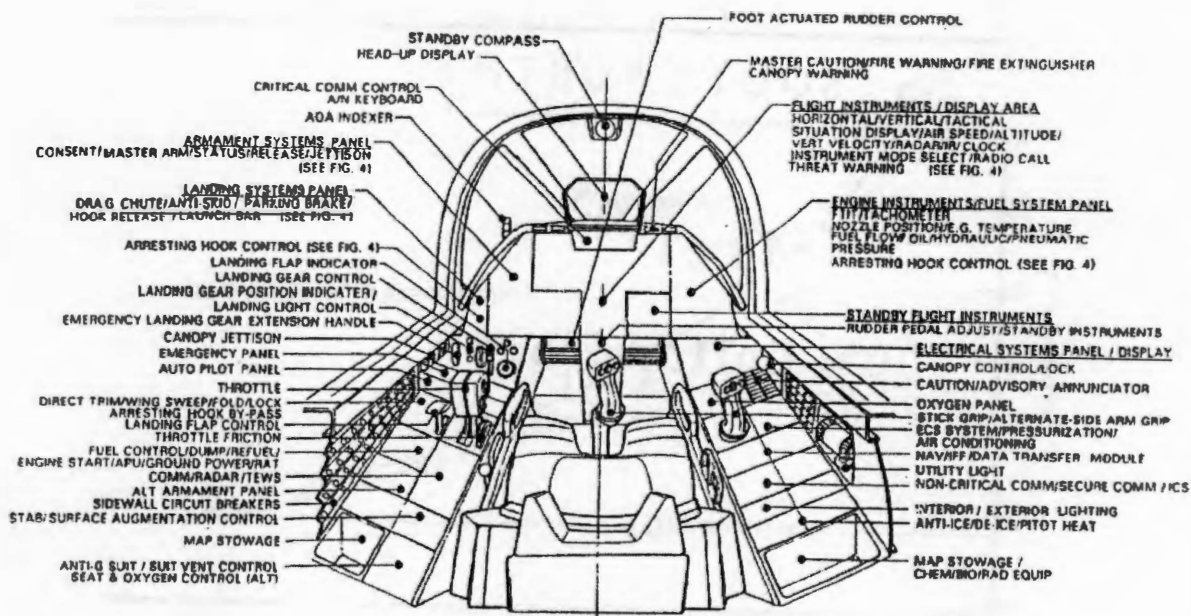


Figure 24: MIL-STD-203G Single Ejection Seat Fighter/Attack Layout

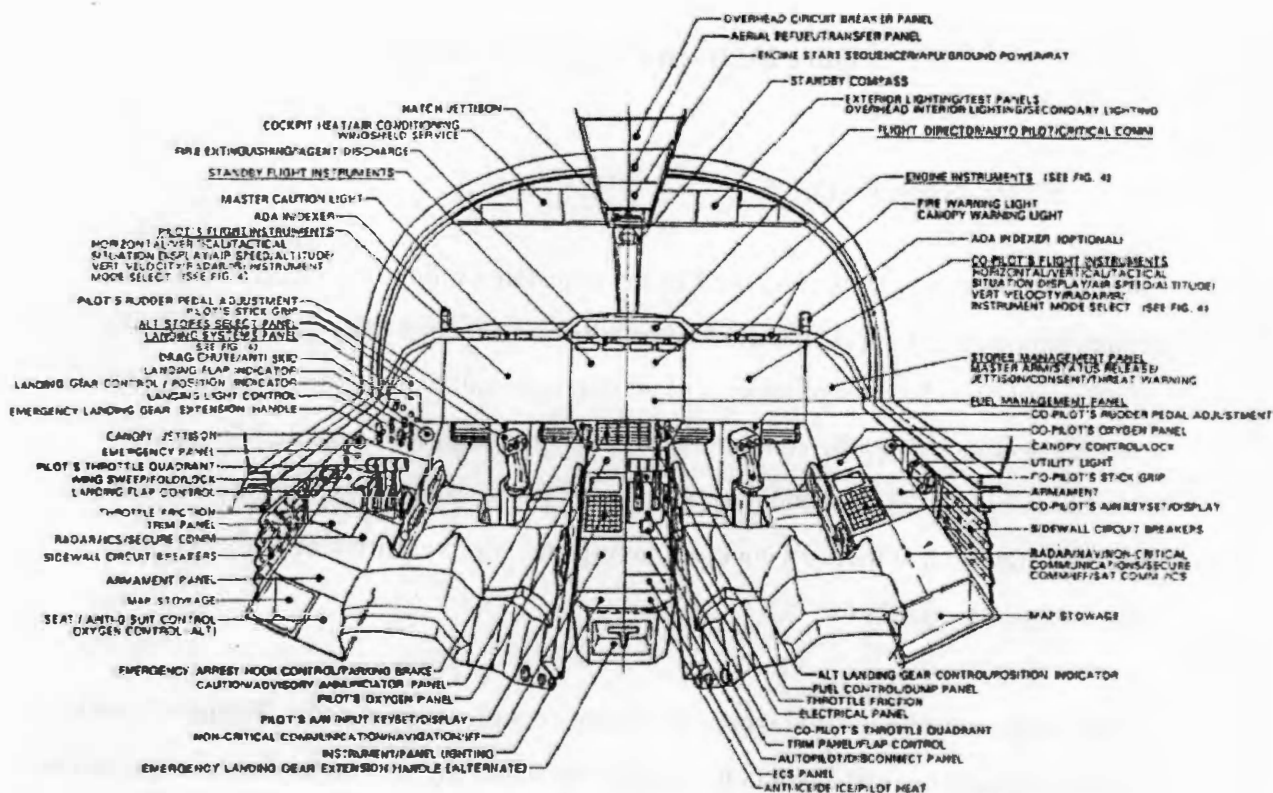


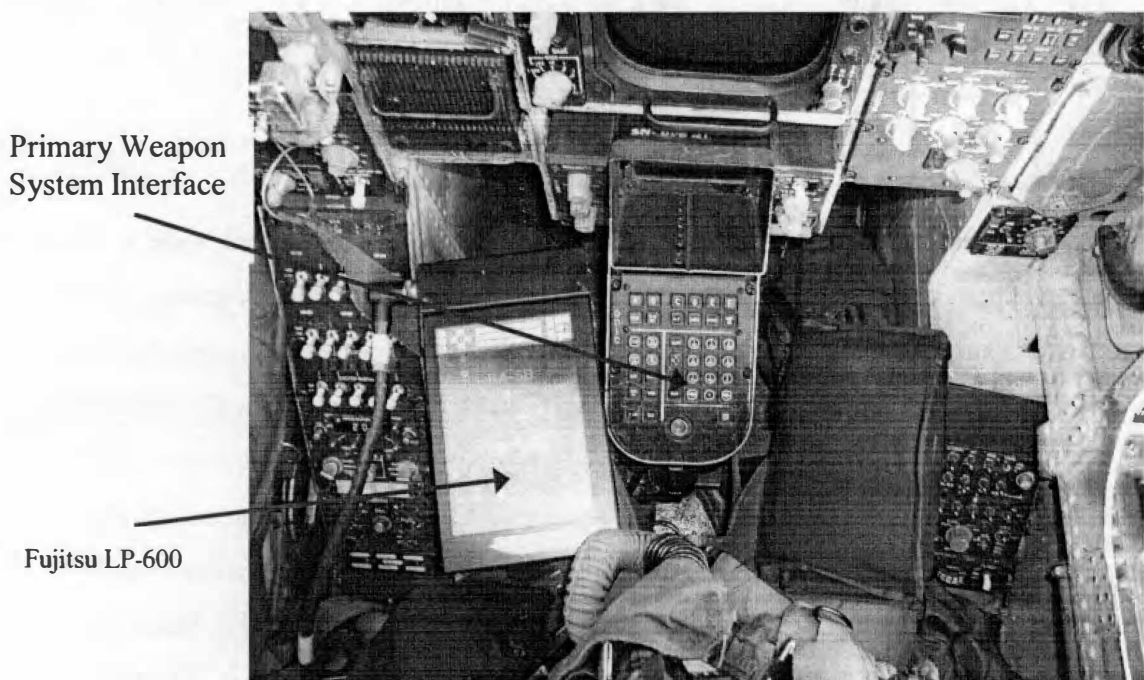
Figure 25: MIL-STD-203G Side-By-Side Ejection Seat Attack/Bomber Layout

flight critical information, the device must be mounted in the pilot's primary field of view. Most cockpit instruments panels do not have sufficient room to integrate a console mounted PED. Given this critical limitation, cockpit mounted PEDs should not be used to display safety of flight information. To minimize pilot head and body movement while reading the display, the PED should be placed within 90 degrees of the pilot's line of sight. If used for navigation information, like approach procedures, positioning the display to the side of the pilot might disorient the pilot as they look at a display that is not aligned with the flight path. Likewise, the increased heads down time may cause spatial disorientation as the pilot's head is turned from side to side. The mounting device must be adjustable to support a wide range of aircrew anthropometrical characteristics. The aircrew need to be able to position the PED in a location or orientation that allows them to view the display while minimizing reflections and glare. If the display has poor off axis readability, the display should be positioned such that the pilot is still able to read the display. For side by side cockpits where both crew members rely on the display, the PED location must be easily accessible by both aircrew.

4.4 CONTROL CLEARANCE

Regardless of whether the PED is strapped to a kneeboard or mounted to the instrument or console panel, the installation must provide the required amount of clearance between the flight controls and cockpit consoles. Control clearance requirements are outlined in the aircrew station geometry specification, MIL-STD-1333B, reference G. Sufficient clearance is required to allow for full, unhindered control deflection, reduction of inadvertent control inputs as aircrew move around, and allow aircrew to safely and expeditiously ingress and egress the aircraft. For center stick controls, a minimum of 1.5 inches is required between adjacent objects and the control stick at full deflection. The throttle also requires 1.5 inches of clearance between adjacent structures. Throttle clearance requirements may be hard to achieve if the pilot decides to wear the kneeboard device on the left leg. There is also a 1.5 inch clearance requirement between the instrument panel and the aircrew's body to provide sufficient room for the pilot to move.

The problem with control clearance is illustrated in figure 26. The Fujitsu LP-600 pentaboard computer was used during initial flight testing to find a replacement for the Panasonic CF-25 laptop in the EA-6B Prowler. (The Itronix Go Book was later selected over the Fujitsu LP-600 as the laptop replacement.) While the Fujitsu pentaboard was considerably smaller than the Panasonic laptop, it was still quite large for use in a confined cockpit. From this figure, one can see that the power chord extended over a set of switches in the center console. The power cable might potentially catch on one of the switches. The pentaboard was as wide as the opening for the aircrew's leg, which decreased aircrew mobility and increased aircrew discomfort on longer missions. Finally, the device was mounted extremely close to the primary weapon system interface for aft cockpit aircrew. The relative position of the keyboard provided opportunity for inadvertent entries on the pentaboard display.



Source: LT Chris Bahner

Figure 26: Fujitsu LP-600 in Aft Cockpit of EA-6B Prowler

4.5 SNAG HAZARD

Most PEDs use a cable to tap into the aircraft's electrical system for power and weapon system buses. This cable and any stowage cradles, if used, can create snag hazards during ingress and egress. However, if the power chord is too long or not properly secured, it may catch on adjacent cockpit controls and switches. This cable requires a quick disconnect fitting to allow the device to break free in the event of an emergency egress. The force required to inadvertently actuate a control may be less than the force required to activate the quick disconnect feature. For example, the power cable used with the EA-6B laptop and pentablet computers is designed to break when a 10 pound tensile force is applied. The power cable is unlikely to activate ejection seat and canopy jettison controls that require approximately 75 and 30 pounds respectively.¹⁹ However, for smaller controls, like the two position switches shown on the left side of figure 26, the maximum recommended force for actuation is 1 pound.²⁰

There are several ways to minimize the snag hazard risk. It is possible to put a detent or guard on the switches to prevent inadvertent actuation; however, it is not feasible to put guards over every cockpit switch that might come in contact with the power cable. Another option is to properly stow the cable and keep cable length to a minimum. The prototype kneeboard for the Itronix Go Book pentablet shown in figure 21 keeps the chord securely attached to the kneeboard. The Lil HAL system tested by the Air Force Research Laboratory modified the anti-g suit to allow the chords to be routed through channels in the anti-g-suit. If the PED is mounted in a cradle, the power and bus connections can be built into the cradle, completely eliminating the chord in the cockpit area. Other alternatives are wireless devices that depend on internal power sources and a data link to connect to the aircraft systems. The Air Force evaluated a wireless display for use in the cockpit and the results were promising from a display readability standpoint.²¹ The wireless system eliminated snag hazard risks, but the PED required a power source

¹⁹ USQ-113 Independent Safety Risk Assessment

²⁰ MIL-STD-1472F

²¹ Meyer et al

that could last through an extended combat mission. A wireless data link must also be compatible with the cockpit and meet all electromagnetic interference requirements. The data link must also be secure to prevent unintentional classified transmissions outside the cockpit that could compromise security.

SECTION 5: EMERGENCY EGRESS AND EJECTION

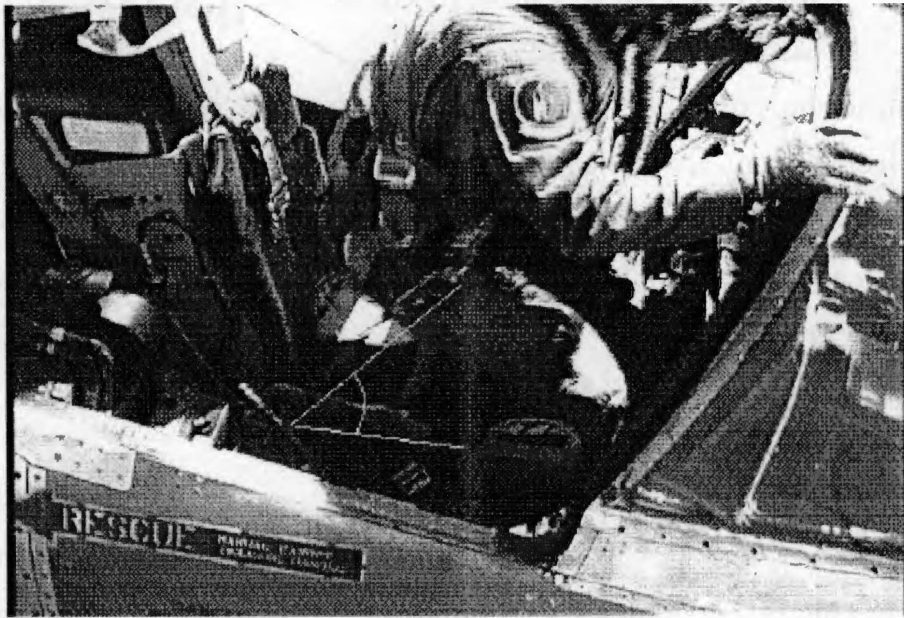
The sixth and final COI states the PED should not interfere with aircraft ingress and egress, including emergency ground egress and ejection scenarios. Several issues related to ingress and egress, such as control clearance and snag hazard, have been addressed in previous sections. This section will specifically address emergency ground egress and ejection scenarios.

5.1 GROUND EMERGENCY EGRESS

If an aircraft emergency were to occur on the ground, aircrew should be able to quickly and safely exit the aircraft. Depending on the size of the PED and how it is mounted in the cockpit, ground emergency egress could be as simple as moving the device aside and performing a normal emergency egress. If the device is small and secured well enough to be worn while exiting the aircraft, the main concern is disconnecting the power cables attached to the PED. A quick disconnect fitting should be attached to the cables to allow for quick release. The Lil HAL, which is intended to be worn during emergency egress, contains a quick disconnect fitting. The quick disconnect fitting was evaluated during ground emergency egress scenarios. The results of the tests are contained in the Lil HAL safety of flight report, reference N. Figure 27 illustrates the operation of the quick disconnect fitting. The Lil HAL system had no effect on the time required to perform an emergency egress. The aircrew stated they barely felt the quick disconnect system coming apart and the system did not impede their ability to exit the aircraft.

5.2 EJECTION

To date, very little ejection seat testing has been accomplished, and the little testing that has been done was limited to windblast testing of the kneeboard in a free stream airflow. The Itronix Go Book is scheduled to begin ejection seat testing in the summer of 2005 to



Source: Safe-for-Flight Determination for Helmet-Mounted Little High-end Airborne Laptop

Figure 27: Lil HAL Quick Disconnect System

determine the risk of ejecting with it attached. Among the questions that must be answered during these tests include the effects of increased forces on the femur as the ejection seat rocket motor propels the pilot out of the cockpit. Some ejection seats are capable of ejecting through the canopy. Testing must therefore determine the affects on the pilot while ejecting through the canopy while wearing the kneeboard. Until additional testing is completed and given the size and security of most PEDs, many systems may not receive a flight clearance to be worn during ejection scenarios. However, there will be situations where the aircrew receive little warning of the impending ejection and the risk of ejecting with the PED attached far outweighs the risk of delaying ejection to remove the kneeboard.

5.2.1 EJECTION SEAT CLEARANCE REQUIREMENTS

Minimum clearance between the cockpit and the ejection seat footprint must be maintained when PEDs are used in the cockpit. Ejection seat clearances are contained in

MIL-STD-1333B, reference G, and presented in figure 28. There are three specific clearance requirements. First, no control or other device should enter into the escape path such that it interferes with ejection initiation or the ejection process. This requirement implies that the PED must not restrict access to ejection controls. Second, the maximum lateral off center measurement should not exceed 15 inches to provide sufficient clearance with the canopy rail. Finally, the device should not enter the 30 inch clearance zone measured longitudinally from the ejection line, which provides clearance from the instrument panel. A kneeboard type device should not extend beyond the knee or be wider than the thigh. If the device extends beyond the limits of the knee or thigh, there is the potential that it may strike or catch on some object inside the cockpit, which may injure the aircrew or interfere with the ejection process. The same clearance requirements apply for devices that are mounted in the cockpit in a cradle device.

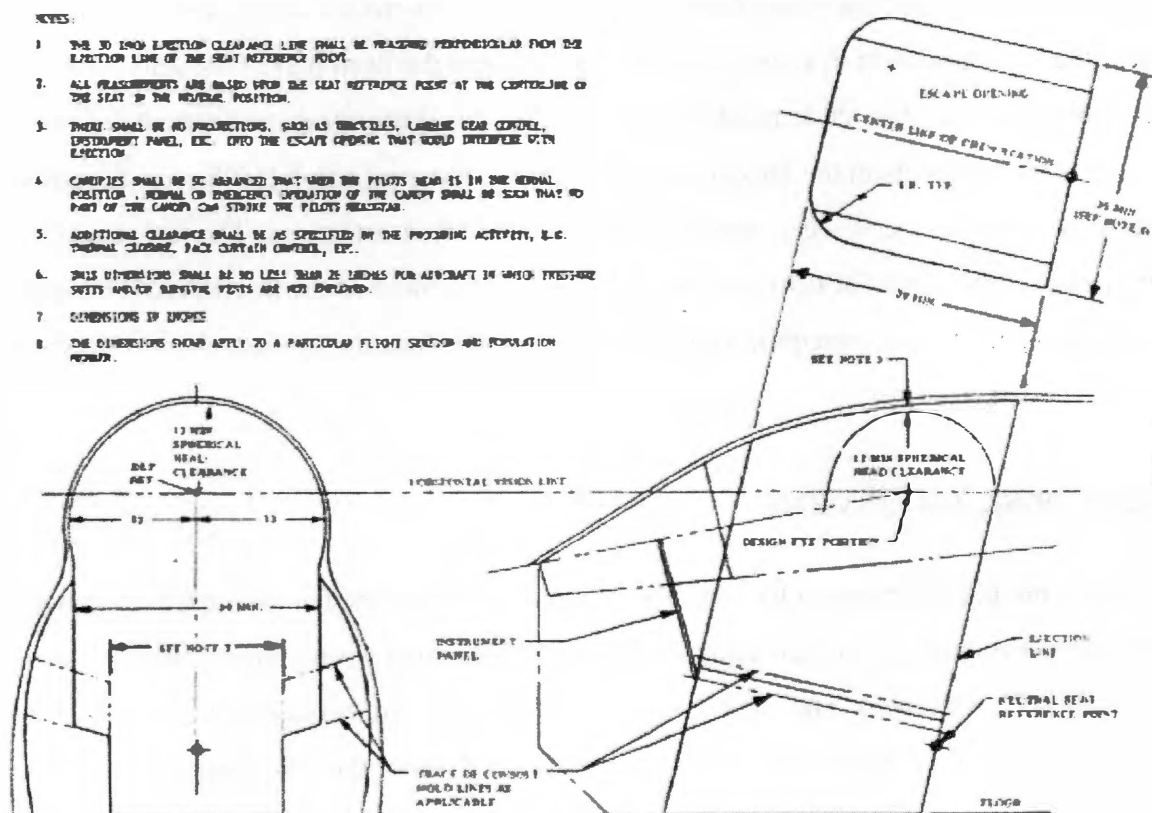


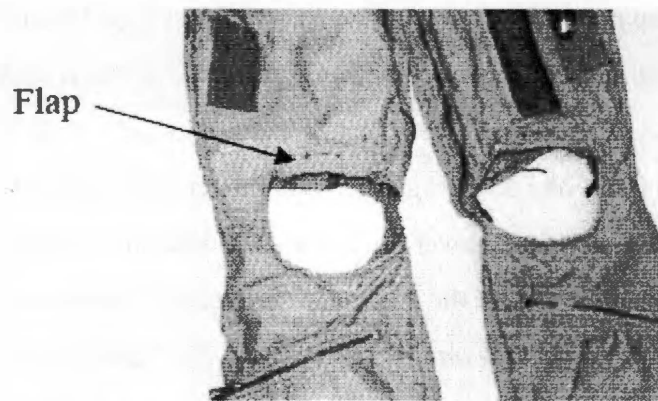
Figure 28: MIL-STD-1333B Ejection Seat Clearance Requirements

5.2.2 WINDBLAST

The Air Force Research Laboratory evaluated the Lil HAL for windblast forces during an ejection scenario. The results are reported in reference N. The Lil HAL kneeboard is considerably smaller than most COTS systems designed for aviation use. The kneeboard measures 4.75 inches wide, 6 inches long, and 0.5 inches tall and weighs less than 300 grams. During initial testing, the kneeboard was attached to the aircrew's leg using nylon straps. Two metal pins secured the strap to the kneeboard. This design configuration was evaluated during windblast tests to ensure the kneeboard remained attached during an ejection. In this configuration, the kneeboard had a tendency to lift off the mannequin's leg and move aft towards the body during initial windblast onset. As the kneeboard lifted off of the leg, the elastic strap caused the kneeboard to rotate, exposing more surface area to the windblast. Eventually, the metal pins broke and kneeboard became loose in the free stream, striking the mannequin in the right elbow. To minimize the lifting effects of the windblast, the engineers modified the pilot's anti-g suit with a flap near the knee as shown in figure 29. This flap covered the front part of the kneeboard and minimized airflow underneath it. Additionally, the elastic straps were modified and weaved through slots in the kneeboard to allow for additional windblast forces. A second series of windblast tests were conducted with the modified anti-g suit. The test results from the second series of tests, presented in figure 30, indicated the kneeboard remained securely against the mannequin's knee and did not significantly increase the forces on the aircrew's leg.

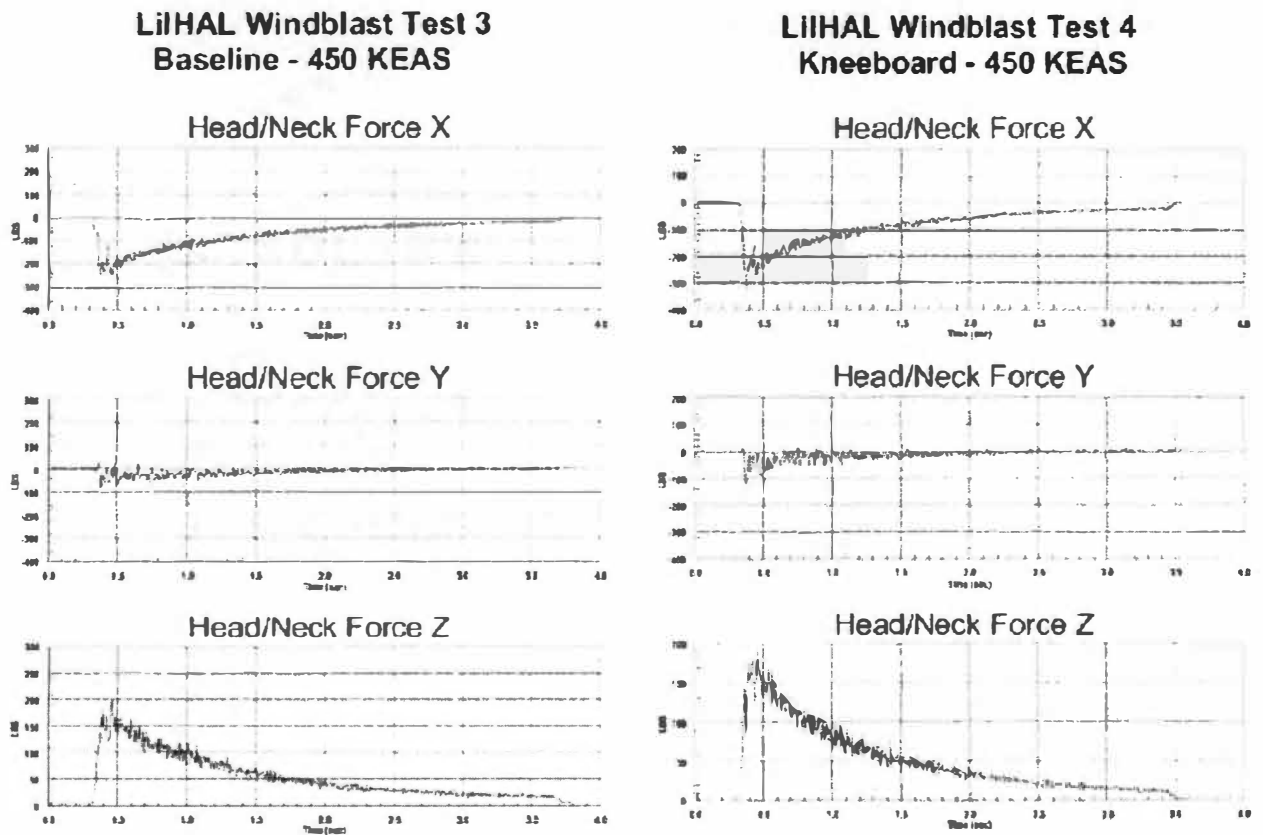
5.2.3 RISK ASSESSMENT

When the EA-6B Project Office at VX-23 was integrating the Panasonic CF-25 laptop into the aft cockpit, the project team conducted a safety analysis to determine the risks of ejecting with the laptop. The results of this safety analysis are contained in reference O. First, the unsecured laptop could potentially strike and injure the other aircrew during the ejection sequence. The laptop required a NVD filter that precluded fully closing the



Source: Safe-for-Flight Determination for Helmet-Mounted Little High-end Airborne Laptop

Figure 29: Lil HAL Modified Anti-G Suit



Source: Safe-for-Flight Determination for Helmet-Mounted Little High-end Airborne Laptop

Figure 30: Lil HAL Windblast Test Results

laptop. With the laptop open, the area exposed to windblast significantly increased, increasing the potential of losing control of the laptop and having it strike the other aircrew. The laptop obstructed the lower ejection handle, which could delay ejection initiation. While the laptop had a stowage area, the power cable did not have a storage place and was left attached to the power port. In this condition, the power cable could hit the aircrew or become entangled in the ejection seat. Based on this risk assessment, the aircrew system engineers placed several restrictions on the laptop when used in flight. Aircrew were specifically instructed to stow the laptop prior to ejecting from the aircraft and they were instructed not to hold the laptop while ejecting. Laptop use was also prohibited during take offs, landings, low level flight, and aircraft emergencies to ensure that it was properly stowed should an immediate ejection emergency occur.

CONCLUSIONS AND RECOMMENDATIONS

Six COIs were defined that are essential to successfully integrating a PED into a tactical cockpit. Human factors specifications and design considerations critical to meeting these requirements were outlined and discussed and actual PED systems were evaluated against these guidelines. When a PED failed to meet these requirements, design trade offs and mission impacts were presented. From this analysis, five conclusions were made when evaluating a PED for integration into a tactical cockpit:

- Pentablet computers are preferred over laptops and PDAs.
- PEDs should not serve as the primary indicator of safety of flight or mission critical information.
- Integrating COTS systems does not guarantee cost and schedule savings.
- Touch screens and reprogramable push buttons are the optimum control option.
- PEDs should be mounted on kneeboards vice the instrument panel.

PENTABLET COMPUTERS ARE PREFERRED OVER LAPTOPS AND PDAS

Of the three types of PEDs, a pentablet type system is best suited for the cockpit environment. Laptops are incompatible with a tactical cockpit due to their size and weight, which obstructs other cockpit controls and displays and makes them extremely hard to secure in the cockpit. PDAs can easily fit into any cockpit due their small size, however their small displays lack sufficient size and resolution to support most applications. Likewise, PDA digital keyboards and touch screen target areas are too small to be useful in the flight environment. Pentablets present the right combination of display size, weight, and control options for military applications. Pentablets do have some major deficiencies that must be overcome, such as display readability and aircrew integration, however many of these deficiencies can also be found in laptops and PDAs. When deciding which specific pentablet to use in the cockpit, systems engineers should attempt to use the smallest pentablet capable of supporting the aircraft mission. Smaller is not

always better, but given two systems that meet the six PED COI requirements, the smaller PED should be chosen over a larger one.

PEDS SHOULD NOT SERVE AS THE PRIMARY INDICATOR OF SAFETY OF FLIGHT OR MISSION CRITICAL INFORMATION

Safety of flight and mission critical information must be placed in the pilot's primary field of view, ideally located directly in front of the pilot. However, most cockpits cannot support placing additional equipment in this location. The pilot should not have to scan the cockpit to gather in essential information. One guideline to determine what information is mission critical is that which the pilot would want to see on a Heads Up Display (HUD). The HUD serves as primary flight instrument in most tactical aircraft and displays essential navigation and weapon system information. The pilot can easily scan outside the aircraft while simultaneously this information. PEDs should primarily be used to support or enhance these systems and to assist in providing better situational awareness for the pilot.

INTEGRATING COTS SYSTEMS DOES NOT GUARANTEE COST AND SCHEDULE SAVINGS

One of the principal reasons for integrating a PED into a cockpit is to avoid the time and money required to modify existing cockpit controls and displays. Many COTS systems use a PED designed primarily for home or office use and load aviation applications into the hard drive and provide a simple kneeboard strap or mounting device. While this integration option is widely accepted in commercial and general aviation, integrating office products into a tactical cockpit might not produce acceptable results. These systems are not designed for the harsh combat environment and may require extensive modification to ensure all COI requirements are met. As an example, the Itronix Go Book has display readability, NVIS compatibility, and size limitations that required system modifications and redesign that delayed developmental testing and fleet introduction by eight months. This is not to say that the Go Book is not compatible with a

military cockpit, but it highlights some of the problems one might encounter when attempting to integrate a COTS system.

TOUCH SCREENS AND REPROGRAMMABLE PUSH BUTTONS ARE THE OPTIMUM CONTROL OPTION

PEDs require a control and data input system that allows fast and accurate data entry and system optimization to present information in the correct format at the appropriate time. Several control options have been discussed in the paper, and the combination of a touch screen with reprogrammable hard or soft keys is the best option for tactical PED applications. Touch screens allow aircrew to quickly highlight an area on the display by directly touching the screen, vice having to slew a cursor using a joystick or trackball. The touch screen provides significant flexibility through software generated keypads and short hand data entry methods. Reprogrammable push buttons allow complex applications to be employed and provide additional software programming flexibility while simultaneously minimizing the number of required push buttons. However, touch screens are susceptible to accidental inputs, especially on electronic kneeboards where aircrew flight equipment will be constantly brushing against the display. Inadvertent control inputs can be controlled by software to minimize the actuation criteria. Critical functions can be assigned to hard keys where larger control actuation forces and button guards and barriers will significantly minimize unwanted inputs.

PEDS SHOULD BE MOUNTED ON KNEEBOARDS VICE THE INSTRUMENT PANEL

Very few cockpits have sufficient room to mount a PED on the instrument panel, unless the PED is located off to the side of the pilot, which increases head movement. One of the primary reasons for employing a PED is to minimize cockpit modifications, but a mounting bracket would require additional structure and electrical and bus connections to be routed to the device. Aircrew are already familiar with placing information on a kneeboard and the space is readily available and accessible. When designing the kneeboard device, one must ensure the system securely and comfortably holds the PED in

place to avoid distracting the pilot or increasing aircrew discomfort. The electronic kneeboard poses challenging ejection seat compatibility issues, and additional testing is required before this issue can be resolved.

The question still remains whether PEDs can be successfully integrated into a fixed wing tactical aircraft. The answer is yes in certain situations. Not all PEDs are compatible with the cockpit environment and not all cockpit layouts can support a PED, even an electronic kneeboard. Each PED must be evaluated with its intended cockpit and tasks and functions before one can decide if the PED can be properly integrated. If a PED can be successfully integrated, it can be an extremely useful tool to the combat aviator. Even if the sole purpose is to transition to a paperless cockpit, PEDs can reduce aircrew workload and improve data management. PEDs allow new technologies and weapon systems to be quickly installed in military aircraft, which significantly enhances war fighter capabilities. As technology improves, the potential for PED applications will be limited only by the imagination of aircraft designers. As PEDs are successfully integrated into more military aircraft and they continue to perform well in combat operations, more aircrew and acquisition program managers will look to PEDs to meet emerging aircraft and weapon systems requirements.

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VITA

LT Martin Fuerst was born and raised in Cincinnati, Ohio and is the proud son of Cliff and Sandy Fuerst. He attended the U.S. Naval Academy in Annapolis, Maryland where he majored in naval architecture. In 1996, he graduated with honors and was commissioned an Ensign in the U.S. Navy. He reported to Naval Air Station Pensacola, Florida where he began his initial training as a Naval Flight Officer. He earned his Wings of Gold in 1998 and was selected to fly the EA-6B Prowler as an Electronic Countermeasure Officer. After initial EA-6B training, he reported to VAQ-138, the Yellow Jackets, at Naval Air Station Whidbey Island, Washington. During his three year tour with VAQ-138, he completed two deployments on the USS John C. Stennis (CVN-74) and participated in Operations Allied Force (Kosovo), Southern Watch (Iraq), and Enduring Freedom (Afghanistan). In 2001, he was selected to attend the U.S. Naval Test Pilot School at Naval Air Station Patuxent River, Maryland. Upon graduation from test pilot school, he reported to the Strike Aircraft Test Squadron, VX-23, where he currently performs flight test on EA-6B and F/A-18F aircraft. Martin has logged over 1,600 flight hours in 15 different aircraft including 1,200 hours in the EA-6B Prowler and he has over 250 carrier arrested landings. He is married to the former Rebeca Anderson of Puyallup, Washington.

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