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An investigation into cockpit display developments in the general aviation aircraft fleet

Brent Kevin George

To the Graduate Council:

I am submitting herewith a thesis written by Brent Kevin George entitled "An investigation into cockpit display developments in the general aviation aircraft fleet." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

Ralph D. Kimberlin, Major Professor

We have read this thesis and recommend its acceptance:

Charles Paludan, Robert Richards

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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AN INVESTIGATION INTO COCKPIT DISPLAY DEVELOPMENTS IN THE GENERAL AVIATION AIRCRAFT FLEET

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

Brent Kevin George
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DISCLAIMER

A portion of the information contained within this thesis was obtained from product literature and magazine articles on the design features of the avionics systems from Sierra Flight Systems, Garmin International, Sandel Avionics, and Vision Microsystems Inc. The research, discussion, and conclusions presented are the opinion of the author and should not be construed as an official position or an endorsement of these products by the University of Tennessee, Space Institute, Tullahoma, Tennessee.

DEDICATION

This thesis is dedicated to my wife

and *Tu Blave*,

Kelly Ann George,

for her patience, understanding, and encouragement
during the long trek that it took to complete this journey.

To my sons

Emmett Robert,
Kiernan Brent,
and
Brennan Kelly,

who appeared along the path from time to time
to detour me from my course,
but filled those side journeys with joy
and happiness

Also to my parents

Robert and Shelva George

for nurturing in me the skills necessary
to begin the voyage in the first place.

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ABSTRACT

As we have progressed into the 21st Century, the general aviation (GA) cockpit has been slow to evolve to keep pace with the advances in technology and research that have been applied to the avionics displays for military and civil commercial aviation applications. GA cockpits are just now beginning to reflect the benefits of these advances The increased use of human factors research in the design of GA avionics displays has led to the awareness of the importance of improved information presentation and data cueing As a result, instrument panels are integrating a variety of highly configurable electronic, full-color, hierarchical in design, multifunction displays (MFD) These MFDs are being utilized for inserting a significant increase of coded and processed information into the often display-cluttered aircraft cockpit for use by the GA pilot. MFDs, coded and formatted properly, can aid the GA pilot in an overall increase in situational awareness (SA) of both the aircraft's performance and the surrounding flight environment. In addition, many of these new MFDs have the capability to combine and integrate multiple data inputs onto a single display sometimes referred to as "Data Fusion." In a similar vein, as "data fused" MFDs proliferate, the number of single functionality avionics system displays and control boxes can be reduced and replaced by MFD systems with multiple roles and capabilities. This will increase the available instrument panel space for additional or redundant components This thesis will investigate applicable human factors research and see how advanced GA avionics technologies are evolving as a result. This thesis will also discuss systems that should be incorporated in GA aircraft to improve SA for pilots in the GA aircraft sector.

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LIST OF ABBREVIATIONS

2-D	Two-Dimensional
3-D	Three-Dimensional
ADF	Automatic Direction Finding
ADI	Attitude Display Indicator
ADS-B	Automatic Dependent Surveillance-Broadcast
AGATE	Advanced General Aviation Transport Experiments
AMLCD	Active Matrix Liquid Crystal Display
AMS	Aircraft Monitoring System
AOA	Angle-of-Attack
ATC	Air Traffic Control
AWIN	Aviation Weather Information
BDHI	Bearing Distance Heading Indicator
CDI	Course Deviation Indicator
CDTI	Cockpit Display of Traffic Information
COSIMA	Cockpit and Simulator for General Aviation
CRT	Cathode-Ray Tube
CY	Calendar Year
DG	Directional Gyroscope
DME	Distance Measuring Equipment
EFIS	Electronic Flight Instrumentation System
EHSI	Electronic Horizontal Situation Indicator
EICAS	Engine Instrumentation and Caution Advisory System
FAA	Federal Aviation Administration
FBO	Fixed Base Operator
FMS	Flight Management System
FPNS	Flight Planning and Navigation System
FOV	Field Of View
GA	General Aviation
GPS	Global Positioning System
GS	Glide Slope
HITS	Highway-in-the-Sky
HSI	Horizontal Situation Indicator
HUD	Head-Up Display

IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
LOC	Localizer
LORAN	Long-Range Aid for Navigation
LOS	Line-of-Sight
MFD	Multifunction Display
NASA	National Aeronautics and Space Administration
NAVAID	Navigational Aid
NDB	Non-Directional Beacon
PFD	Primary Flight Display
RAF	Royal Air Force
RMI	Radio Magnetic Indicator
RPM	Revolutions Per Minute
SA	Situational Awareness
SUA	Special Use Airspace
TCAS	Traffic Alert and Collision Avoidance System
U.S.	United States
USGS	United States Geological Survey
UTSI	University of Tennessee Space Institute
VFR	Visual Flight Rules
VHF	Very High Frequency
VNE	Velocity Never Exceed
VOR	Very High Frequency Omni-Directional Receiver
VSI	Vertical Speed Indicator
WW	World War

CHAPTER I

INTRODUCTION

Cockpit Development

A review of the historical development of aircraft cockpits shows that the evolution of cockpit design has followed the expansion of aircraft capabilities. In the earliest days of aviation when flight times were expressed in seconds and then minutes, the cockpit was merely the location of the pilot and flight controls and minimal if any instrumentation was present (AGARD, 1996). When Orville and Wilbur Wright made their epic flight in 1903, their aircraft instrumentation consisted of nothing more than a piece of string used as a slip indicator (Hawkins,1987). Subsequent instrumentation prior to World War (WW) II was limited to simple displays such as a single engine revolutions per minute (RPM) indicator to determine engine performance or a fuel quantity gauge to determine fuel remaining (Ardey, 1999). As aircraft performance increased, more sophisticated controls and more complex displays were introduced to permit satisfactory aircraft operation (Hawkins, 1987). The advent of increased aircraft performance allowed the possibility of cross-country flight. In turn, cross-country flight necessitated the addition of navigation instruments, engine instruments, and rudimentary flight instruments to the cockpit panels. As the complexity of aircraft systems increased, the gauges, switches, and status panels for the variety of systems expanded and became a part of the cockpit. As the density of air traffic became a factor in aircraft operations, radios, transponders, and precision navigation systems were introduced into the cockpit. This proliferation of cockpit instrumentation (in the form of mechanical, pneumatic or electrical dials and gauges, and displays) expanded to fill all of the available area in the cockpit. Each of these additions has been made to address the various essential tasks that the pilot and aircrew must attend to during a flight. Primarily: fly the aircraft; navigate the aircraft, monitor the systems of the aircraft, operate the aircraft in conjunction with those around it, and perform mission related tasks. (AGARD, 1996). In most instances, the usual integration of new cockpit systems were as additions, not substitutions or replacements for current systems. This has resulted in the further complexity of aircraft systems (Ardey, 1999).

The following figures are representative of the evolution of cockpit complexity. Figure A-1 (Appendix, Figure 1) shows the progression in the increase in complexity of military aircraft cockpits from the 1910's time frame until the 1970's. Figure A-2 shows the further development of military aircraft cockpits from the 1970's until the 1990's. Figure A-3 shows the cockpit complexity of a representative general aviation (GA) aircraft cockpit from 1948. Figures A-4 and A-5 show the development in complexity of two representative cockpits from GA aircraft of the 1990's.

Complexity Drivers

Competition drove much of the increase in complexity and capabilities of both the military and civil commercial sides of aviation development. (Ardey, 1999) The military was primarily interested in developing more efficient and capable aircraft to ensure successful operations against less capable adversaries while ensuring pilot and air crew mission success and survival. The civil commercial side became more complex as a result of two factors – economics and safety (Hawkins, 1987).

Economics

The number of passengers increased when the general populace discovered the advantages of commercial air transportation, therefore forcing an increase in fleet and aircraft sizes. Multiple airlines were subsequently founded and competition erupted to move more passengers along similar routes in less time. Aircraft performance increased to facilitate the movement of passengers, thus requiring more information input to the pilot, more sophisticated controls, and more complex displays to permit satisfactory and cost driven operations (Hawkins, 1987).

Safety

As the number of civil commercial aircraft increased to facilitate the movement of more passengers, aircraft speeds increased, routes became established, and subsequently aircraft safety became a consideration An air traffic control (ATC) system was established to facilitate the safety of civil commercial operation. This necessitated the advent of a navigation and locating system for aircraft reporting which added further complexity to aircraft cockpits. Once reliable position fixing capabilities were added to aircraft, the aircraft now had to convey reports of their positions over reliable communication systems to ATC ground stations along the route of flight (Ardey, 1999). When aircraft accidents occurred, especially with civil commercial aircraft, there was greater exposure because of the number of victims involved per accident. In initial cases, aircraft design was cited as responsible, whether it was faulty or failed instruments or placement of operating controls. The GA industry's solution was to add more redundancy and complexity to the cockpit in an attempt to provide more information to the pilot (Hawkins, 1987). Many modern day aircraft accidents and incidents cite crew error as a causal factor (Schutte, 1997).

Human Error

It is widely accepted that human error is a major contributing factor in aircraft accidents (Schutte & Willshire, 1997). In addition to the evolutionary process of simply adding more controls and displays to existing cockpit systems, crew systems designs and flight station layouts have frequently ignored the limitations and capabilities of the human operator (Sexton, 1988). Through human factors research, it has been determined that workload is an important determinant in causing human error. The human is most reliable under moderate levels of workload that do not change suddenly or unpredictably. Extremes of workload increase the likelihood of human error. When workload is excessive, errors arise from the inability of the human to cope with high information rates imposed by the environment (Kantowitz & Casper, 1988).

In today's modern civil commercial aircraft, pilots repeatedly report that they are 'behind the aircraft', i.e., they do not know what the automated aircraft is doing or how the aircraft is doing it until after the fact (Schutte, 1997). In aviation, the human interface with the cockpit and its environment is an important aspect of aircraft safety and flight operations. The pilot performs a large number of tasks, many of which involve cognitive performance capabilities. Cognitive performance in cockpit-related systems interfaces with flight operations and safety, and is known to have contributory relationships with the incidence of aviation accidents due to human error (Chambers & Cihangirli, 1990) This loss of cognitive performance and many cited human errors in aircraft cockpits have also been attributed to information overload.

Information Overload

Aircraft displays are the pilot's primary means of determining how and what the aircraft is doing The pilot's senses have become overloaded with information as aircraft have grown in complexity and technology has provided the capability of offering increased levels of information. (Stokes & Wickens, 1988). A display is any means of presenting information directly and it usually makes use of the visual, aural, or tactual senses A stall warning using a stick-shaker is using the tactual sense as well as aural (the sound of the stick shaker) and visual (a warning light). The purpose of a display in an aircraft is to transfer information about some aspect of the flight accurately and rapidly from its source to the brain of the crew member, where processing can take place. The human sensory capacity is enormous, but the human information transmitting rate is very limited, as is man's short-term memory capacity (Hawkins, 1987). The short-term (also referred to as working memory) is the gateway to long-term memory. Information conveyed from the visual, aural, and tactual senses must pass through the short-term memory first before it enters long-term memory. To encode and transfer information from the senses to short-term memory and to hold information in short-term memory requires that the human direct attention to the process. Information in short-term memory is transferred to long-term memory by semantically coding it, that is, by supplying meaning to the information and relating it to information already stored in long-term memory. To recall more information, it must be analyzed, compared, and related to past knowledge (Sanders & McCormick, 1993). This imbalance in the short-term memory results in a bottleneck arising when the information, which is being fed to the brain, is being filtered, stored, and processed. This bottleneck is of fundamental importance in the design of flight deck displays. The display must not only present information, but also present it in such a way as to help the brain in its processing task. Furthermore, the display is of little use in the overall flight deck system unless it is designed so that the crew member will be able to utilize it. Not only under normal circumstances, but also when the pilot's performance is affected by stress or fatigue (Hawkins, 1987). The limits of a pilot's attention may be rapidly exceeded by the proliferation of warning indicators, status displays, flight path displays, air traffic control data links, meteorological information, navigational information, and communications data (Stokes & Wickens, 1988)

Human Factors Inputs

The military and civil commercial aircraft industries turned to human factors techniques to aid in cockpit design to reduce overall cockpit complexity, improve pilot and air crew performance, and to improve information recognition. This helped to better understand information flow and overload in the aviation cockpit and to reduce human errors. Human factors is not easily defined, but Sanders & McCormick (1993) give the following definitions:

> *Human Factors focuses on human beings and their interactions with products, equipment, facilities, procedures, and environments used in work and everyday living The emphasis is on human beings and how the design of things influences people Human factors, then, seeks to change*

the things people use and the environments in which they use these things to better match the capabilities, limitations, and needs of people Human factors has two major objectives The first is to enhance the effectiveness and efficiency with which work and other activities are carried out Included here would be such things as increased convenience of use, reduced errors, and increased productivity The second objective is to enhance certain desirable human values, including improved safety, reduced fatigue and stress, increased comfort, greater user acceptance, increased job satisfaction, and improved quality of life The approach of human factors is the systematic application of relevant information about human capabilities, limitations, characteristics, behavior, and motivation to the design of things and procedures people use and the environments in which they use them This involves scientific investigations to discover relevant information about humans and their responses to things, environments, etc This information serves as the basis for making design recommendations and for predicting the probable effects of various design alternatives The human factors approach also involves the evaluation of the things we design to ensure that they satisfy their intended objectives

Human-Centered Design

Designers have turned away from technology-centered design and have focused more on human-centered flight deck design to emphasize human factors in cockpit design In technology-centered design, technology was the primary consideration and humans were secondary. In many instances, humans dealt with this technology domination and poor cockpit designs by relying on their unique traits of flexibility and adaptability. With human-centered design, the emphasis has now been on human behavior and capabilities. The human has been the center of the flight deck and the goal has been to produce task-oriented displays that present identifiable, relevant information. Rather than provide individual pieces of information, which the pilot had to combine (a task not very well suited for humans as we've seen from the discussion on information overload), the display presented the information after it was combined. Information traditionally provided on multiple displays was integrated or synthesized into one display, thus reducing the pilot's effort by having to refer to only one display versus multiple displays. This synthesized quantitative information was presented in a form that was processed qualitatively by the pilot; a level of processing sufficient for the task The key to human-centered display design has been to understand the tasks the flight crew must perform (Schutte & Willshire, 1997).

Allocation of Functions

Kantowitz and Casper (1988) term the systematic decisions about which tasks should be assigned to humans and which to automation, allocation of functions (also termed functional allocation). The selection or allocation of functions is changed dynamically as environmental demands change. In other words, the pilot can enable or disable flight deck automation and displays by changing the format or selecting different functionality.

Multifunction Displays

Multifunction displays (MFD) were introduced out of the desire to cope with the enormous amount of data presented onboard and to provide a means for allocation of functions The advantage of an MFD is information can be removed from the instrument panel which is not relevant for a specific phase of a flight. In other words, the MFD can be configured according to the present needs of the user (AGARD, 1996) However herein lies another problem with information overload. An MFD imposes additional workload on the pilot The pilot has to have a mental model of the information system so that he is aware of what information is available and how to access it. In many hierarchical MFD systems, if the menu structure is deep or broad the operator may 'get lost' in the systems especially when he is unable to retrieve his mental model from the long-term memory because of a stressful situation. Organizing the menus and display pages based on the concept of allocation of functions instead of subsystems is one avenue to combat the overload and memory recall problems Selecting a function at a high level should cause the disappearance of irrelevant segments of the menu thus reducing the choice. In addition, required controls and information to accomplish specific tasks should be grouped together on the MFD in close proximity and easily accessible (AGARD, 1996).

"Glass Cockpits"

The military and civil commercial cockpit designers of today have made extensive use of these human factors concepts and principles in current evolutions of what can be termed "glass cockpits." They have utilized multiple highly configurable MFDs and in some cases head-up displays (HUD) to minimize extraneous cockpit instrumentation. In many cases, the only instrumentation other than multiple MFDs and HUDs are backup airspeed, altitude, and heading instruments. Utilizing MFDs in the modern military and civil commercial cockpit, it is now possible to select from hierarchical menu driven systems and select a view of primary flight displays (PFD), electronic flight instrumentation systems (EFIS), navigation moving map displays, flight management systems (FMS), and engine instrumentation and caution advisory systems (EICAS) Any combination of these displays are selectable dependent on the number of MFDs in the cockpit and the requirements of the phase of flight. On the military side and in some limited civil commercial cases, HUDs are being used as PFDs and the MFDs are utilized only for display of secondary system and status information. Figure A-2 shows the evolution of the military "glass cockpit" from the F-18A which was leading edge technology in 1975 to the now in development F-22 of the 1990's. Figure A-6 shows the "state-of-the-art" "glass cockpit" of the modern McDonnell Douglas MD-11. Much of the cockpit real estate is devoted to MFD technology in the later military aircraft cockpit display examples depicted in Figure A-2 and the MD-11 cockpit display depicted in Figure A-6.

The "Pilot" Subsystem

In the process of human factors engineering of aviation cockpits the pilot must be considered as a subsystem within the aircraft which has a performance envelope just like the other on-board subsystems or the aircraft itself. The pilot's performance envelope can be defined by the human's capabilities and limits. The performance envelope of an individual is not constant Many environmental and personal influences shape behavior and performance over time. For the cockpit designer, it is important to become sensitive to the dependencies and to have a sound knowledge of the sensory, cognitive, and motor capabilities and limitations of the subsystem "pilot" (AGARD, 1996). For purposes of looking at the "pilot" subsystem, the visual, color, and auditory capabilities for human information processing will be explored

Visual Capabilities

Humans depend primarily on vision to gather information about the state of the world outside their own bodies. Humans use normal vision to perceive objects and recognize familiar patterns. They use peripheral vision extensively for perceiving motion. Humans have two eyes set in a binocular fashion therefore they perceive the world in three dimensions. A look at the composition and capabilities of the eye is essential to understanding of how humans perceive visual information Light enters the front of the eye through the lens and strikes the back portion of the eye at the retina as shown in Figure 1. The retina at the back of the eye is composed of cones and rods. The cones function at high levels of illumınatıon, such as daylight, and provide superior detail, color determination, and motion perception. The rods function at lower levels of illumination, such as nighttime, and only differentiate between shades of black and whıte. The cones are concentrated ın the center of the retinal area called the fovea. The fovea area is the area of the eye with greatest visual acuity. For an object to be seen clearly, there must be sufficient lıght to activate the cones and the eye must be directed so that the image is focused on the fovea (Sanders & McCormick, 1993)

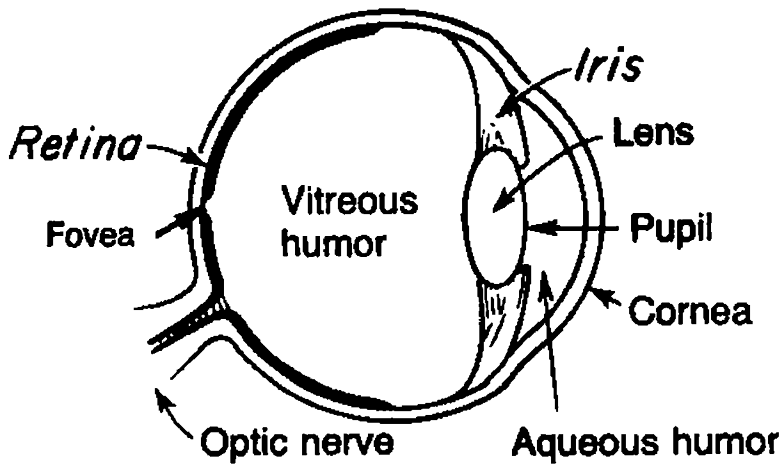


Figure 1. Principal Features of the Human Eye in Cross Section.

Source: Sanders M. S. and McCormıck, E. J (1993). *Human Factors ın Engıneerıng and Desıgn,* Seventh Edition. New York, NY: McGraw-Hill, Inc. pp. 92.

Foveal Vision

Since most objects are normally seen under illumination levels high enough to activate the cones, humans have developed a strong tendency to position their eyes to ensure foveal vison by looking directly at objects (Leibowitz, 1988). The foveal region of the eye is generally taken to be one to two degrees of vision (AGARD, 1996). Since the rods are activated at low levels of illumination and are concentrated around the periphery of the retina, the eye can see a dim object more effectively if it is positioned slightly to one side of the object rather than directly at it. However, the rods provide a much poorer quality of vision than the cones, because they are completely insensitive to color and are less sensitive to fine detail and movement (Sanders & McCormick, 1993).

Color Capabilities

The aesthetic appeal of color is strong. In addition, color can contribute to image realism. Color can enhance the presentation of information and gain user acceptance for display systems. Humans can recognize about nine distinct surface colors, varying primarily in hue (Sanders & McCormick, 1993). Humans can discriminate between 24 colors when hue, luminosity, and saturation are varied (Stokes & Wickens, 1988) An advantage of the use of color is that the human's cognition of color occurs fast and relatively automatically. Color can be used to group symbols into categories, reduce visual clutter, add additional information to a symbol or an alphanumeric, grab attention, and separate elements, not separable in space Evidence shows color leads to performance improvements in complex displays or pictorial formats, especially for search tasks, whereas no advantage was observed in well formatted or simple displays. A reduced response time and error rate was also observed when using shape and redundant color coding instead of shape coding only (AGARD, 1996).

Color Coding

Color proved effective to reduce confusion resulting from visual clutter when a great deal of information must be presented in a dense format. Color groups data into larger categories of information more efficiently processed in short-term memory. Color coding may be the single most effective type of coding available, being superior to size, shape, or brightness in identification tasks and significantly reducing search times (Stokes & Wickens, 1988). The actual choice of colors to represent different display elements may be based upon the use of environmental color codes, traditional color codes, and population stereotypes color codes Environmental color codes refers to color coding that, rather than being wholly symbolic, suggests the actual appearance of features in the environment, i.e., blue represents the sky and brown the earth. Traditional color codes refers to the use of red, amber, and green code for danger, caution, and advisory or normal information, respectively Red, for example, is customarily used for the velocity never exceed (VNE) line on airspeed indicators Figure 2 is an example of a traditional color coded display. Population stereotypes color codes are more esoteric and have to be defined within the user group of each population type. An example of population stereotypes is that red can mean 'stop', 'danger', or 'hot' within a given population (Stokes & Wickens, 1988).

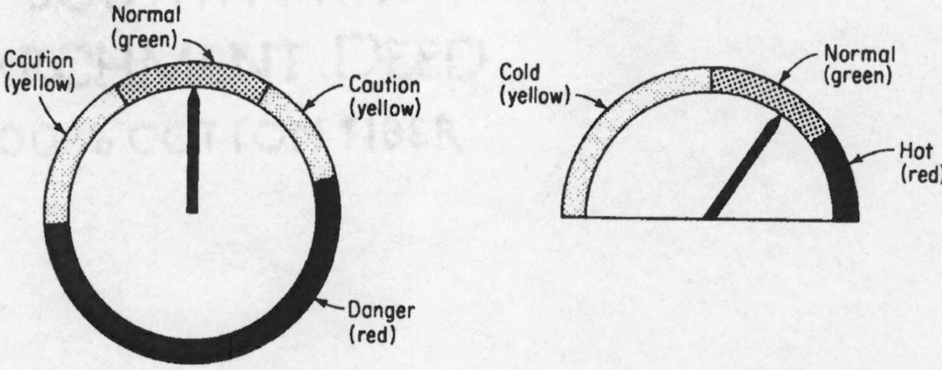


Figure 2. Illustration of Color Coding of Instrument Displays.

Source: Sanders M. S. and McCormick, E. J. (1993). *Human Factors in Engineering and Design*, Seventh Edition. New York, NY: McGraw-Hill, Inc. pp. 146.

Auditory Capabilities

The auditory display is used for verbal communication, warnings, system messages, and answers to pilot queries (AGARD, 1996). If the human visual channel is overloaded, there are obvious advantages in allocating some functional tasks to the auditory channel. Replacing traditional visual indicators with aural signals such as bells, beepers, electronic tones, and voice annunciators reduces the need for visual instrument scanning, thereby allowing the pilot to devote more attention to other visual tasks. In addition, auditory displays possess a number of characteristics which can make them preferable to visual displays even when the human visual channel is not overburdened (Stokes & Wickens, 1988). Auditory signals alert the user quickly, irrespective of head position or eye fixation, and appear to do so faster than visual displays without using panel space (AGARD, 1996). Auditory displays are less affected by high aircraft load factors, anoxia, darkness, bright sunlight, glare, or vibration that may inhibit vision when using visual displays. They therefore lend themselves well to the transmission of cautions, alerts, and warnings.

Vocal Warnings

Some studies have found that pilots' responses to audio taped warnings are faster than to similar warnings presented visually In addition, visual displays combined with a voice warning provide shorter response times than when combined with a tonal warning (Stokes & Wickens, 1988). Voice warnings are more flexible than simple sounds, because they not only alert the pilot to any existing problem, but can concurrently provide more cues as to its nature and thereby assist the user in taking immediate corrective or responsive action (AGARD, 1996).

Limitations

Auditory displays do, however, possess certain limitations that need to be considered. Overuse of auditory displays can lead to auditory clutter. Auditory displays are, by their nature, intrusive and distracting and may therefore disrupt concentration. Pilots sometimes consider speech displays to be noisy, strident, and intrusive. Speech displays may also be masked in ambient noise to a greater extent than a warning tone or bell (Stokes & Wickens, 1988). The other consideration is the number of acceptable warning sounds Sanders & McCormick (1993) state the maximum number of sounds that can be discriminated on a relative basis is 12. Whereas, Wagner (1996) states that for absolute signal identification the maximum allowable number of tones is four

Synthesized Speech

Advances in synthesized speech technology have given auditory displays considerably greater flexibility than was previously possible. They have, for example, made it possible to expand caution and warning applications beyond simple alerts to include more complex diagnostic information and instructions for corrective action (Stokes & Wickens, 1988) The use of speech is also likely to be more effective in conditions of high workload and stress, when the meaning of coded signals, i.e., tones and bells could be forgotten However, as with the limitations of other warning tones, a program of priorities must be established, so that only one message, the one of highest priority, is presented at a time (Hawkins, 1987)

There are a large number of variables that influence the intelligibility of synthesized speech. These include the method of speech generation, i.e., taped speech, digitized speech, or synthesized speech and the similarity to human speech, i.e , speech rate, voice pitch, and volume Contextual factors such as ambient noise level and frequency, are important as well as linguistic factors, such as the size and choice of the vocabulary set. Early taped auditory displays used a female voice, but studies have found that female speech may be less intelligible than male speech in the cockpit environment. In addition, studies showed the sex of the speaker did not contribute significantly either to intelligibility or user confidence ratings. Synthesized speech did not need to sound natural at all and that by its unnaturalness it would be perceived as distinct from human speech and therefore draw more attention to itself (Stokes & Wickens, 1988).

Stereophony

Stereophony is the ability to localize the direction from which sound waves are emanating. Differences in both intensity and phase of the sounds are the primary cues used by people to determine the direction of a sound source An application of sound localization is being explored for use in the military cockpit called *head-coupled auditory displays*. Specifically, threats, targets, radio communications, etc. are heard as if they originated from their specific locations in three-dimensional (3-D) space by manipulating the signal's intensity and phase to each ear. A computer senses and compensates for the pilot's head position so that the sounds are directionally accurate and stabilized in space regardless of the position of the pilot's head. Stereophony should increase the pilot's situational awareness (SA) Enhanced audio communication by giving each source a different apparent direction should provide a natural method of cueing where to look (Sanders & McCormick, 1993). However, when implementing a spatial auditory system, the spatial location of a sound may require additional attention capacity of the pilot. It is human nature to turn the head to the direction from which a sudden sound comes, thereby distracting the pilot (AGARD, 1996)

Display Basics

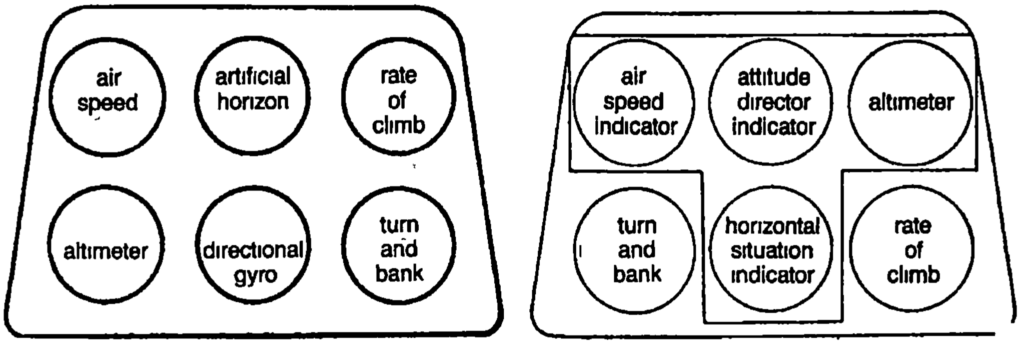
In order to discuss cockpit layout and display incorporation, it is essential to have an understanding of the history and evolution of the current instrument panel T configuration of the primary flight instruments. This is the basis for most of the modern day flight instrument panels,whether the panels use conventional gauges and displays or advanced MFD technology. Also, it is necessary to study the nature of the visual display types available for presentation of data and display positioning.

Flight Instrument Evolution

Historically the flight instrument panel gets the most attention.. As previously mentioned, instrumentation was added to instrument panels in a haphazard fashion as needed to complete specific tasks or provide additional information for aircraft operations. The breakthrough in instrumentation came with the development of a usable gyroscope, which could be applied to aviation in the form of an artificial horizon. The gyroscope led to the development of "blind-flying" or flying without visual references defined as instrument flight rules (IFR) flying today. In 1937, the Royal Air Force (RAF) published details of a standard "blind-flying" panel that was installed in WW II RAF aircraft (Figure 3 a)). Extensive studies of visual scanning patterns later resulted in a small change to this panel to convert it into the basic T layout as shown in Figure 3 b). The basic T layout is configured to allow fast and accurate scanning of four basic parameters: airspeed, attitude, altitude, and heading. The priority in the scan is attitude (Hawkins, 1987).

Visual Display Types

It is essential to the understanding of visual display types to consider how information should be displayed and formatted to offer the pilot the most automatic and compatible representation of the current and future state of the aircraft and its environment (Stokes & Wickens, 1988).



a) "Standard Blind-Flying Panel" b) "Basic T Panel"

Figure 3. The Pre-War RAF "Standard Blind-Flying Panel" and "Basic T Panel."

Source: Hawkins, F. H. (1987). *Human Factors in Flight.* Aldershot, Hants, England: Gower Technical Press Ltd. pp. 261.

Static or Dynamic

Visual displays can be generally categorized into two types: static or dynamic. Static displays are those that present data that is unchanging or that remain in place for a reasonable time, such as placards, signs, and graphs. Dynamic displays are those that present data that changes through time, such as altimeters and attitude indicators (Sanders & McCormick, 1993).

Quantitative or Qualitative

Visual displays can also be described by the type of information they present. They can be quantitative such as providing a discrete value for altitude or heading. In many cases, digital is the best type quantitative data display, but increasingly a combination of digital and analog information is being used. Digital provides greater accuracy, but in most instances demands more time to be read and processed. The displays can be qualitative such as reading an approximate value, discerning a trend, rate of change or change in direction. An example of a qualitative display would be the vertical speed indicator (VSI). In most cases, analog displays are being used which utilize fixed scales with moving pointers A further subset of a qualitative visual display is those used for "check readings." A "check readings" display determines if parameters are within some "normal" bounds or that several parameters are equal In many cases, color coding will have been applied to make the display more readable. An airspeed indicator is such an example with color coding for normal (green), caution (yellow), and red (danger) indications (Hawkins, 1987; Kantowitz & Casper, 1988). A further use of the "check readings" display is with functional groupings of similar display types such as an engine instrument cluster When the instruments are used together in panels, their configuration should be such that any deviant reading stands out from the others Most research points to the normal position on the displays being aligned with the nine o'clock positions (with the twelve o'clock positions being secondary). The advantage of such a systematic alignment is based on "gestalt." "Gestalt" is the human tendency to perceive complex configurations as complete entities, with the result that any feature that is "at odds" with the configuration is readily apparent. Additional research has shown that the addition of extended lines between the dials can add to the "gestalt," helping to make any deviant readings stand out more clearly (Sanders & McCormick, 1993). An example of the check readings "gestalt" configuration is shown in Figure 4

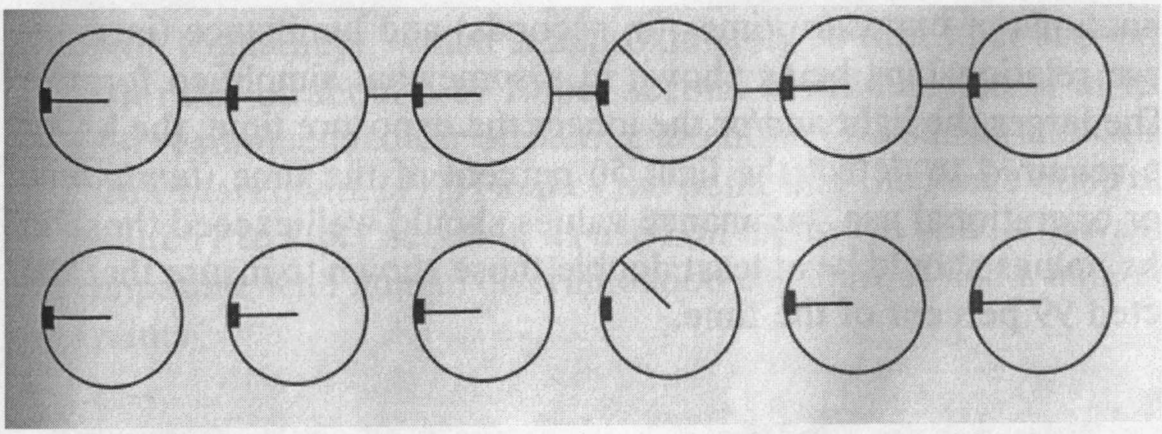


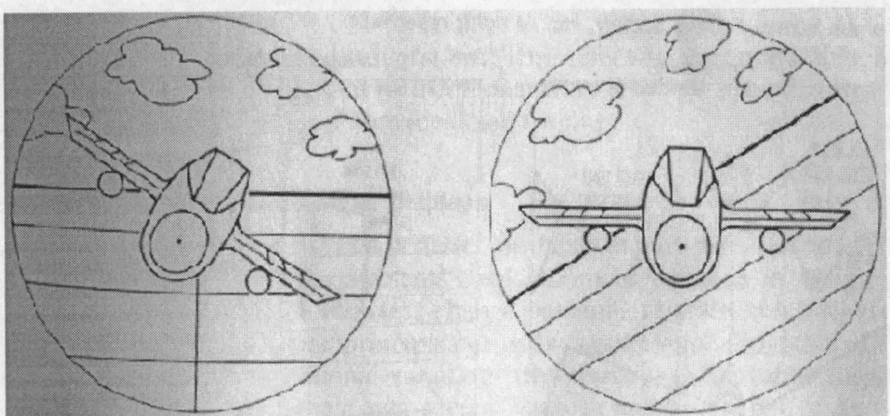
Figure 4. A Panel of Dials Used for Check Readings Utilizing "Gestalt" Principles.

Source: Sanders M. S. and McCormick, E. J. (1993). *Human Factors in Engineering and Design*, Seventh Edition. New York, NY: McGraw-Hill, Inc. pp. 147.

Flight Displays

Flight displays, which are necessarily dynamic, may be described in terms of command displays, predictive displays, or situation displays (also called status displays). The command display tells the pilot how to control the aircraft, as in a flight director. The predictive display provides information concerning how to respond, without sacrificing the presentation of accurate information about the current state of the aircraft. The predictive display usually offers the pilot one or more symbols depicting the future state of the aircraft, inferred from assumptions concerning the pilot's future control activity. Predictive displays lack spatial economy and despite their benefit to performance, may add display clutter and increase visual workload. A situation display provides information on the status of the aircraft. Examples include the horizontal situation indicator (HSI) and the traditional instrument panel that provides status information about the rate of climb, altitude, and attitude. The attitude display indicator

(ADI) was the earliest form of the situation indicator and raised the issue of whether such displays should be "inside-out" or "outside-in." An "inside-out" display representation reflects what the situation would look like from inside the aircraft with a fixed aircraft symbol and a moving background. An "outside-in" display representation reflects the situation from outside the aircraft with a moving aircraft symbol and a fixed background. The "outside-in" type of situation display is shown in Figure 5 a). The "inside-out" type of situation display is shown in Figure 5 b). One drawback to the situation display is that extra cognitive computations are often required to translate a knowledge of the current state of the aircraft into a decision as to what the appropriate control action should be to change that state according to the desired flight path (Hawkins, 1987; Stokes & Wickens, 1988).



a) Moving Aircraft (Fixed Horizon) "Outside-In"

b) Moving Horizon (Fixed Horizon) "Inside-Out"

Figure 5. Situation Display Types.

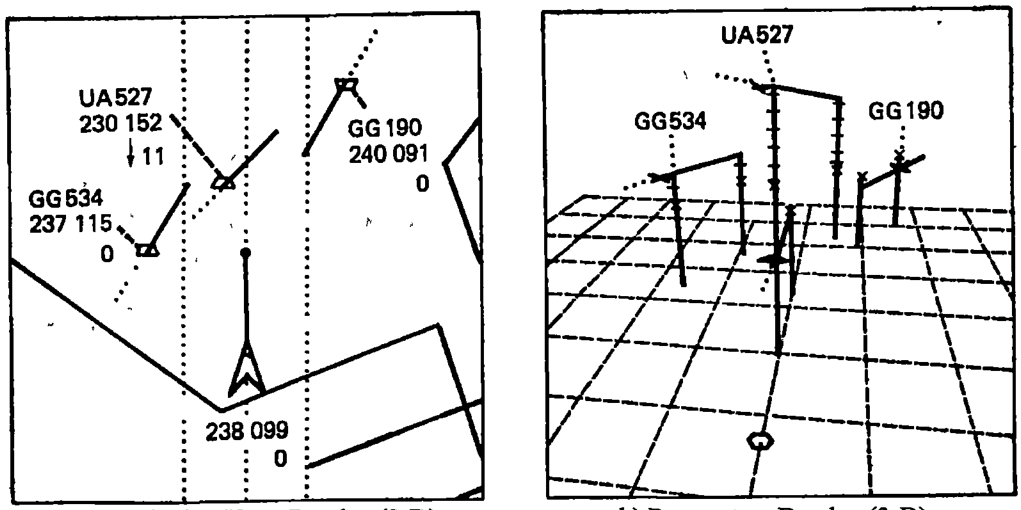
Source: Sanders M. S. and McCormick, E. J. (1993). *Human Factors in Engineering and Design*, Seventh Edition. New York, NY: McGraw-Hill, Inc. pp. 153.

Navigation Displays

Navigation displays present aircraft position information upon a map of the terrain beneath and around the aircraft. In most cases navigation displays integrate information from other instrumentation in the cockpit, such as HSI information, cockpit display of traffic information (CDTI) (a new technology which is currently being tested to present traffic around an aircraft), or possibly even weather information. The navigation displays are termed moving map displays, since the aircraft symbol is fixed in the center of the display and the map moves and rotates as the aircraft maneuvers (an "inside-out" display format). The traditional type of moving map display is in a plan-view or a two-dimensional (2-D) display format. Perspective format displays are currently being developed that will utilize artistic techniques to give depth cues. The depth cues will include linear perspective, interposition of objects, object size, texture gradients, shadow patterns, and in some cases, color. With the perspective format displays, traffic around the aircraft will appear in 3-D space (Sanders & McCormick, 1993, Stokes & Wickens, 1988). There is also research into presenting terrain data on navigation and status displays in a perspective format. Figure 6 presents both the plan-view (2-D) display in part a) and a perspective (3-D) display in part b) showing the positions of three aircraft relative to the pilot's own aircraft.

Pictorial Displays

Pictorial or synoptic displays mount the displays and controls for aircraft subsystems in a schematic form with the displays and controls appropriately



a) Plan-View Display (2-D)　　b) Perspective Display (3-D)

Figure 6. Plan-View and Perspective Display Formats.

Source: Sanders M. S and McCormick, E. J. (1993). *Human Factors in Engineering and Design*, Seventh Edition. New York, NY· McGraw-Hill, Inc. pp. 154.

placed in the system. A pictorial display may be used for representations of the fuel, electrical, hydraulic, or pneumatic systems. To be more effective, pictorial displays often use a redundant combination of color coding and text to improve recognition (Hawkins, 1987).

Head-Up Displays

A visual workload problem is imposed by the multi-dial cockpit, in which numerous displays, each of which requires foveal vision for precise reading, are arrayed across a wide panel. Information from one dial cannot be extracted unless the eye fixates upon it, which precludes extracting information from other displays This forces the pilot into a serial mode of information gathering that has been found to be detrimental to performance and safety under conditions of stress and high information overload.

The answer to a multi-dial cockpit has been to restructure the spatial layout of the panel displays in two separate ways. The first approach involves moving nonessential and non-critical information to peripheral displays, removing it from the foveal vision and lowering the information overload. The second approach has been to bring all essential information into the foveal field of view (FOV) The second approach is the design premise behind the HUD.

The HUD is used as an extension of the conventional ADI or artificial horizon The ADI information is projected onto a transparent screen located on top of the instrument panel between the pilot and the windscreen or onto the windscreen itself in the pilot's line-of-sight (LOS) In most cases, it is accompanied by the projection of related flight instrument information in the basic T flight instrument layout or an inverted T variation that places the heading information at the top of the display. The intended purpose of such a projection is to allow the pilot to take in information from the instruments projected onto the HUD without taking his eyes off the outside scene (Stokes & Wickens, 1988).

Cockpit Display Design

As we have already discussed, much of the information a human digests is received through the visual system Extensive studies have been undertaken to determine how humans process visual information and to determine what factors aid in the perception and comprehension of the displayed information. No less important is the positioning of displays within the cockpit and on the instrument panel. The Federal Aviation Administration (FAA) has evaluated the available research and has taken great strides in the area of human factors to compile and outline essential design parameters when deciding on a cockpit layout The following are excerpts from the FAA's *Human Factors Design Guide* (Wagner, *et al*, 1996) applicable to display positioning

Display Grouping

When functional grouping is used, the location should be based on order of use from left-to-right or top-to-bottom or both as necessary. The display groups most frequently used and most important should be in the areas of easiest access. In addition, if there is more than one functional grouping of displays, each display group should be delineated by marking the group as with a line marked on the panel or by color coding the display group.

Display Coding

Visual coding shall be used to facilitate the following. discrimination among individual displays, identification of functionally related displays; indication of relationships among displays; and identification of critical information within a display. Displays can use a combination of color, size, location, shape, or flash coding as applicable As has been discussed earlier, information can be coded in analog or digital formats dependent on its application. If an immediate emergency condition arises within a display then flashing red shall be used to denote the condition. This can either be the information flashing on the display or a master warning or caution light located near the top of the instrument panel in direct view of the pilot

Display Location

Displays should be placed so a pilot can read them to the degree of accuracy required without having to assume an uncomfortable, awkward, or unsafe position. A display position should be located so it can be read without resorting to special equipment, i.e., a flashlight, to see the display A display should be constructed, arranged, and mounted to prevent interference from reflections of illumination sources, windows, and other displays. A filter should be incorporated if necessary to ensure adequate system performance. A display face should be perpendicular to the pilot's LOS and no more than 45 degrees from the LOS of the pilot as shown in Figure 7. In addition, parallax should be kept to a minimum. As mentioned previously, displays shall be arranged in relation to one another according to the sequence of use of the functional

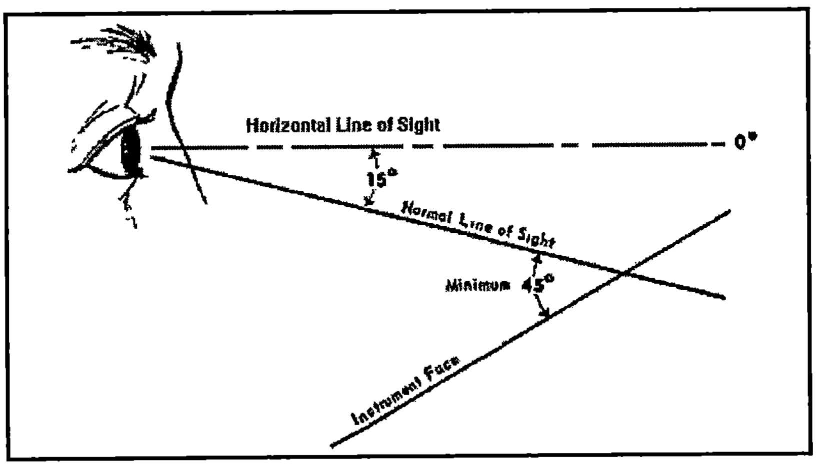


Figure 7. Lines of Sight.

Source: Wagner, D., Birt, J A., Snyder, M., & Duncanson, J. P. (January 15, 1996). *Human Factors Design Guide For Acquisition of Commercial-Off-The-Shelf Subsystems, Non-Developmental Items, and Developmental Systems.* DOT/FAA/CT-96/1. Atlantic City International Airport, NJ: FAA Technical Center. pp. 7-11.

relationships of the components the displays represent, so that they provide the essential left-to-right or top-to-bottom information flow within the group. Most important though is that the displays most frequently used should be grouped together and situated in the optimum visual field as shown in Figure A-7. Within the optimal visual field, the most important or critical displays should occupy a privileged position in that field or they should be highlighted in some manner.

Viewing Distances

The maximum viewing distance to a display situated with a control should be no more than 25 inches from the eye reference point (also called the design eye point). With the exception of a cathode-ray tube (CRT) display and a collimated display, i.e , HUD, the absolute minimum viewing distance to a display should no less than 13 inches from the eye reference point and the preferred minimum viewing distance should be at least 20 inches. The minimum view distance to a CRT from the eye reference point should be at least 10 inches.

Conclusion

As has been discussed there has been much research and effort into the human factors of cockpit design. The military and civil commercial sectors in aviation have reaped the benefits of the last century of cockpit evolution. Unfortunately the GA sector has not been so fortunate. This thesis will investigate the current state of GA cockpit design and avionics displays integration. Current and future avionics display technologies will be examined to see how human factors concepts and techniques have been used to aid in alleviating cockpit information overload and to improve the GA pilot's SA.

CHAPTER 2

GENERAL AVIATION

Introduction

Historically GA cockpit design has been the forgotten branch of the aviation industry. Looking at cockpit development in the military and civil commercial sectors, there has been an apparent revolution in display design that has transformed these cockpits into marvels of modern technology GA cockpit design appeared to progress along with the military and civil commercial sectors until about the 1940's and 1950's, then most design efforts seemed to taper off. Figure A-3 shows the instrument panel of a 1948 Cessna 170 Figure A-4 shows the instrument panel of a 1990's Cessna 172. Comparing the two figures, the number of displays and instrumentation doubles over the time span, but reflects none of the revolution in automation, computers, or electronic displays that has occurred in the military or civil commercial aviation sectors These figures can be compared to Figures A-1 and A-2 showing the progression in development of the military aviation cockpit displays from 1910 through 1990 and Figure A-6 showing the modern civil commercial aviation "glass cockpit" of the McDonnell Douglas MD-11. Unfortunately, the stagnation in GA cockpit design has proven detrimental when looking at the statistics of accident rates as compared to the civil commercial sector. Ritchie (1988) uses the following quote he excerpted from in 1981 to highlight this point:

> *The emerging role for general aviation in air transportation is accompanied, unfortunately, by an accident rate considerably higher than that found in commercial operations During instrument approaches,*

general aviation was found to have, over a two-year period, an accident rate 17 times as high as that of the carriers. A closer review of these accidents shows that almost 90 percent are attributed wholly or in part to pilot error. Of these pilot error accidents, the preponderance occur during single-pilot IFR flight.

This chapter will briefly look at how GA is defined and some of the statistics that make up the GA sector. The economic side of GA will then be explored to understand the halt in cockpit development. In addition, the tasks necessary to pilot a GA aircraft will be discussed in terms of visual flight rules (VFR) and IFR flying and the workload, information overload, and human error that can result. Also, SA will be discussed to provide a suitable definition and to determine how the design of a cockpit can contribute or detract from overall success in maintaining SA.

General Aviation Defined

GA is usually defined as all of aviation except the military, air freight operators, and the civil commercial airlines (Zyskowski, 1995). The term "General Aviation" was created in the sixties, when there was significant developments and increases in the numbers of light civilian aircraft. Even today, GA has a great significance when compared to other branches in aviation. About 90% of world wide registered civil aircraft belong to the GA sector (Ardey, 1999).

Aircraft Statistics

Some statistics help emphasize the importance of GA in the aviation community. There are currently 212,000 GA aircraft in domestic service. They account for 62% of all flight hours flown, 37% of all miles flown, 78% of airport departures, and 17% of all passengers flown in the United States (U. S.) (Ethell, 1994). GA is therefore a large market with many different missions and types of aircraft In a 1991 calendar year (CY) survey of the GA community, the FAA (1991) found that the average annual flight time per aircraft was 149 hours. Additionally, the survey stated that 69% of all operations were local flights and 31% were cross-country flights. Approximately 87% of GA flying took place during the day. Twenty-five percent of GA hours flown were under VFR flight plans, 23% of the hours flown were flown under IFR flight plans, and the other 52% were flown under no flight plan at all or what could also be considered VFR. Almost 62% of the GA fleet operations flew in VFR conditions

Avionics Statistics

It is also important to consider how GA aircraft are configured. The FAA's 1991 CY survey (1991) stated that 83% of GA aircraft had two-way very high frequency (VHF) communication equipment and 70 % had transponder equipment. Fifty-five percent of the GA fleet had at least one component of an instrument landing system (ILS), such as a localizer, marker beacon, or glide slope and 78% of the GA aircraft had some form of navigation equipment, such as VHF omni-directional range (VOR) equipment or long-range aid for navigation (LORAN) equipment.

GA Composition

Unfortunately, the majority of the GA fleet currently in service is more than 20 years old and reflects airframe and powerplant technologies that were "state-of-the-art" in the 1950s (Phillips, 1998) Of these GA aircraft, more than 80% are powered by a single piston engine, include up to four seats, and have a maximum take-off weight up to 12,500 pounds (Ardey, 1999).

General Aviation Economics of Decline

U. S. factories produced almost 18,000 GA aircraft in 1978. By 1993, the number of GA aircraft produced had declined 95% to 954 (Ethell, 1994). Much of the drop in aircraft production can be attributed to several key economic considerations. First, as the GA aircraft population increased, so did the accident rate. Even with FAA imposed safety rules and regulations on aircraft manufacturers, many victims of aircraft accidents sued the aircraft manufacturers with liability claims. This in turn raised the manufacturers' insurance costs that were passed on to the GA aircraft purchasers thus inflating the total aircraft cost by 30%. Second, increased aircraft costs were then passed on to fixed base operator (FBO) flight instruction schools who in turn raised flight instruction rates and operational rates for renting aircraft Essentially, the GA aircraft became more expensive forcing the recreational aviation user right out of the market (Zyskowski, 1995) Although product liability played a major role in the decline in the numbers of GA aircraft, it was not the only factor. The steady increase in the price of aviation fuel from a low of 50 cents a gallon in the 50's and 60's to a high of two dollars a gallon in the late 70's and early 80's also contributed to the increasing and costly expenses attributable to GA and aided its decline.

General Aviation Cockpit Stagnation

Cost has been the primary factor in the slow growth of the GA cockpit. Generally, many GA pilots and owners are quite limited in the amount of money they have available for aviation (Ritchie, 1988). With the cost of avionics being up to 10% of the cost of a GA aircraft, it is understandable why manufacturers would wish to keep costs down by using proven, albeit antiquated, avionics. The use of older avionics will not pass on the costs of new avionics development combined with the increased insurance cost to the GA consumer (Ardey, 1999). The FAA is reluctant to impose display upgrade requirements which are costly and is additionally careful to restrict their requirements to those which are required for safe GA aircraft operations (Ritchie, 1988).

The CRT is the primary technology upon which the military and civil commercial aviation sectors have based new cockpit display designs. It is a mature and relatively economical technology for their purposes and when first introduced thirty years ago allowed the integration of displays, more effective use of panel space, and greater flexibility Even though CRTs have advanced in terms of brightness and resolution, they are still heavy, large in terms of dimension and bulk, and have very high power requirements (Hawkins, 1987). In 1994, the used GA aircraft market size was 40,000 sales per year with an average cost of $70,000 per aircraft (Ethell, 1994). Unfortunately for GA aircraft purposes, one has to spend as much for a CRT and the peripheral equipment used for a display in the Airbus A340 as for a used Cessna 172 In light of the costs of aviation grade CRTs and the fact that they are too large and heavy to be installed in most GA aircraft, it is understandable why displays in GA aircraft have been slow to evolve (Ardey, 1999).

General Aviation Tasks

The majority of GA pilots are not full-time professional pilots. Flying is a secondary activity used primarily for recreational purposes. With only 149 average flight hours per aircraft in 1991, it is understandable why achieving and maintaining adequate flying skills and adequately functioning equipment are continual problems for a large number of GA pilots and owners (Ritchie, 1988) The tasks all GA pilots have to learn can be broken down into several distinct categories: piloting the aircraft or aviating, managing the aircraft and its equipment, navigating the aircraft, preflight planning for a flight, and conducting the flight in accordance with current ATC requirements and guidelines. Communicating with outside agencies during the flight can be seen as a subset of flight conduct. Flying can be broken down into two basic categories, each of which is ruled by its own set of guidelines: VFR and IFR.

Visual Flight Rules

As was discussed previously, in 1991, approximately 87% of GA flying took place during the day, 25% of the hours flown were under VFR flight plans and 52% of the hours flown were under no flight plan at all or what could also be considered VFR. In addition, 62% of the GA aircraft operations were flown in VFR conditions. VFR flying involves the most basic of primary flight tasks: get an aircraft into the air, climb to an altitude, turn to any direction, maintain a direction, descend, and make a safe landing (Ritchie, 1988). These tasks are all conducted while looking out the windscreen to maintain proper aircraft orientation and scanning for other aircraft traffic and obstacles. Minimal time should be spent looking into the cockpit at displays and interpreting the information presented. Unfortunately the great number of cockpit displays, in many cases haphazard positioning, poor readability, and complexity have forced the pilot into long periods of head-down flying, interpreting the information that is being presented. For VFR flight, these conditions become detrimental to aircraft and pilot safety (Ardey,

1999) The workload in VFR flight is not always high, but as information overload increases, so will overall stress levels and the workload will be adversely impacted.

Instrument Flight Rules

The basic tasks for IFR flight remain the same as for VFR flight. However, now the aircraft is operated without visual reference to the ground and in many cases single-pilot. In most instances, IFR is conducted in foul weather or at night and entirely head-down in the cockpit except during the takeoff and landing phases. Much greater precision in aircraft control is expected to comply with the strict rules the ATC requires on an IFR flight. With the instruments currently available, and current navigation and ATC procedures, it takes considerable time to learn to fly by these instruments and the skills may be subject to decay when not practiced (Ritchie, 1988). These higher expectations additionally increases the workload and stress levels imposed on the GA pilot A quote from Ritchie (1988) sums up IFR flight best:

> *Single-pilot instrument flight, particularly without an autopilot, is about as difficult as any kind of flying that exists The pilot must fly the airplane, handle all communications, including numerous frequency changes, navigate with precision, using the many necessary charts, comply with all ATC procedures, and periodically monitor the performance of fuel and electrical systems In an aircraft which might cruise at 170 and approach at 120 knots, much can happen while the pilot is dealing with one of his many tasks*

General Aviation Situational Awareness

The pilot has an array of information displayed through the windscreen and windows, through visual displays of the instrument panel, the sounds of the aircraft, a headset or speaker system, the aircraft's motion, and the feel of the controls. Information from all these sources is organized by information stored in the pilot's long-term memory, which represents his flying skill. This stored information provides the rules which of the many information sources is to be noticed and the significance of their use at each moment The complexity of the flying information presented should be addressed and the solution should lie in the adequate structuring of the information to be processed and for similarly structuring its display for optimum use. There is much more information on the display side of the pilot's tasks than on the control side Once a pilot has determined what the situation is at a particular moment, there is a limited set of things that can be done about it. However, there may be a large number of alternatives involved while determining just what the situation is (Ritchie, 1988). The pilot and the aircraft can be regarded as a unit. The unit is expected to fulfill its flight mission effectively and to ensure that the specific mission flight tasks are completed safely with an acceptable level of performance. Thus, a sufficient level of SA is a prerequisite for the pilot to operate effectively (AGARD, 1996) The impetus then is to design displays to maximize the SA of the GA pilot as to the performance and operation of his aircraft.

Situational Awareness Defined

There are many definitions for SA AGARD (1996) provides the following two definitions:

> *The perception of the elements in the enviroment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future* or *Knowing what's going on so that you can figure out what to do*

SA can be further defined as looking at the specific tasks that need to be accomplished to achieve the total or global SA picture of how the aircraft is operating

Situational Awareness Tasks

The GA pilot needs to first and foremost have the awareness of how the aircraft is operating and determine whether all subsystems on board the aircraft are functioning normally. In addition, the pilot should be able to monitor basic flight parameters, i e., straight and level, climbing or descending, or in a turn. Both of these tasks come under the term ownship SA The next type is positional SA. Knowing the aircraft's position at any given time as it relates to navigational aids (NAVAID), special use airspace (SUA), airports, and route of flight Also, positional SA implies knowing the aircraft's position in relation to weather across the flight path, traffic information in relation to the aircraft's position at each given moment, and terrain and obstacle clearance information (Avidyne, 1999). Communication awareness is knowing who to communicate with and doing it following proper procedures, the process of knowing the frequencies of radio and navigation aid equipment for the area the aircraft is using, and keeping the systems updated along the route of flight. During any given flight, the GA pilot finds that many of these tasks are usually interrelated. When the entire mental picture of how the aircraft is operating and how the flight profile is progressing is known, then the GA pilot has achieved complete SA

Conclusion

As was discussed, the large numbers of GA pilots and aircraft are a considerable portion of the aviation population in the U. S. With the amount of GA aircraft hours flown annually and the numbers of GA aircraft flown, it is easy to understand why GA has such a major economic impact on the aviation community With the passing of the

General Aviation Revitalization Act of 1994, limiting aircraft manufacturer liability to 18 years after the sale of an aircraft, the aviation industry has been able to allocate sufficient funds to begin the process of reform in GA aircraft and cockpit design (Zyskowski, 1995). Two other factors have spurred the growth of new systems and display designs for the GA cockpit. First, the increasing performance capabilities of microprocessor technologies, with a continuing decreasing price tag, have solved the processing needs required for most integrated display designs. In addition with the development of new display technologies, such as active matrix liquid crystal displays (AMLCD) and gas plasma discharge displays, the MFD is now a possibility in the GA cockpit. These factors together have made the "glass cockpit" possible for the GA aircraft.

CHAPTER 3

THE "GLASS COCKPIT" IN GENERAL AVIATION

Introduction

In the last few years, there has been a revolution in GA aircraft cockpit design possibilities An abundance of economical, low cost, highly powerful microprocessors has resolved most of the graphics processing impediments for efficient display functionality. AMLCD panels have become more economical and their color, brightness, and resolution levels are advanced enough to be used in direct sunlight. They are lightweight, have low power consumption levels, and have reduced panel depth requirements (in most cases on the order of two to three inches from front to back of the display) GA manufacturers are now designing a variety of highly configurable MFDs that have the potential to augment the GA pilot's SA of his aircraft and his flight environment These MFDs incorporate many of the cueing techniques that were discovered through human factors research and were described in the previous chapters of this thesis. The "glass cockpit" is now a reality for GA aircraft. In addition, many of these manufacturers are designing systems to integrate multiple functions into one control source, i.e , the MFD and its controller. This fusion of data into one source or "data fusion" has the advantages of reducing cockpit clutter and allowing for redundancy to be designed into cockpit panels. These advances in technology have removed the obstacles that hindered bringing the capabilities of the military and civil commercial aircraft cockpits into the GA sector

This chapter will look at the advances in GA display design and how human factors techniques have improved their usability for SA in the cockpit. Representative MFD systems for replacing the standard dial and gauge primary flight instruments, navigation and communication displays, and engine instrument displays in GA aircraft will be discussed and examined for their suitability to relieve cockpit clutter and improve information presentation to the GA pilot.

Primary Flight Instrument Displays

As was discussed, the most efficient instrument layout for the fast and accurate scan of the primary flight instruments of aircraft airspeed, attitude, altitude, and heading is the basic T layout shown in Figure 3 b). A variation that is used is the inverted T layout that places the heading indicator strip at the top of the layout or display. The GA aircraft cockpit adapted to the basic T layout when it was introduced, but until now has not had the capability to integrate the instruments into one display, appropriately named the PFD.

Primary Flight Display

The PFD has been used in the military and civil commercial sector for many years with great success Figure A-8 shows the EFIS-1000 PFD from Sierra Flight Systems. The EFIS-1000 PFD is projected on a microprocessor-controlled, full-color configurable AMLCD MFD (the MFD is configurable in that either a PFD, moving map or engine instrument cluster format may be displayed). As Figure A-8 shows, the EFIS-1000 PFD utilizes the inverted T primary flight instrument layout for flight instrument scanning. The PFD format utilizes environmental color coding of blue for sky and a brown-orange color for terrain depiction. The PFD utilizes quantitative digital readings for precision in airspeed and altitude control and moving pointers along the airspeed, altitude, VSI, and angle-of-attack (AOA) vertical scales to depict rates of change for qualitative assessments. The PFD also utilizes traditional color coding along the vertical airspeed strip to present a quick qualitative assessment of whether the aircraft is too slow or too fast based on the aircraft orientation and configuration The altitude is presented with a traditional color coded vertical scale that provides a qualitative prediction as to whether terrain clearance will occur based on the U. S. Geological Survey (USGS) database of terrain elevation data stored within the microprocessor's memory The USGS database allows the microprocessor to depict real-time 3-D modeling of the terrain for pilot SA as the aircraft maneuvers The EFIS-1000 PFD is a predictive display Based on the current aircraft flight parameters, the PFD will display a predicted flight path marker showing the aircraft's position projected sometime into the future, if none of the aircraft's parameters are changed. In addition, the EFIS-1000 PFD incorporates color coded AOA and VSI vertical tapes for qualitative readings. If the PFD becomes too crowded for a particular phase of flight, the display may be selectively decluttered to remove unwanted information The PFD used in this discussion has been designed making extensive use of human factors techniques.

Navigation Displays

Navigation displays have seen the greatest advances in display technologies of all displays in the aircraft. These advances in the navigation displays have the potential to provide the GA pilot with increased levels of SA. A look at navigation displays first requires a review of the background of their development. This will be followed by an analysis of a representative system available to the GA pilot.

Navigation Display Background

The first navigation displays were a handheld chart the pilot referenced as he flew while reading heading off of a magnetic compass. The development of the stabilized compass card of the directional gyro (DG) alleviated problems with precession and instability that affected the magnetic compass. More NAVAIDs soon followed.

Automatic Direction Finding Equipment

In order to gain more SA and allow the pilot to have greater positional awareness, automatic direction finding (ADF) equipment was developed that allowed the pilot to tune the ADF to radio station frequencies and non-directional beacons (NDB). The network of NDBs was created to layout preferred flight routes throughout the U. S. for airline travel. When the pilot tuned in one of these potential navigation sources, a needle on a radio magnetic indicator (RMI) display would swing toward the relative bearing and point to the heading of the station. With the RMI as a display, the ADF provided navigational headings accurate to approximately ±30 degrees

Very High Frequency Omni-Directional Range and Distance Measuring Equipment

Navigation display evolution continued with the introduction of the VOR. After tuning to the frequency of a VOR ground station, the pilot could read a more accurate heading off of an additional RMI in the cockpit, without the needle swings as was evident with the reception of ADF signals. The introduction of distance measuring equipment

(DME) displays then gave the pilot a cockpit readout of distance in nautical miles to a DME ground station. In most cases, the DME ground stations were collocated with VOR ground stations, giving the pilot the direction and distance to navigation aids as a route was flown. Initially, the RMI readout from a tuned VOR and the DME readout were on separate displays. The introduction of the bearing distance heading indicator (BDHI) allowed simultaneous readouts of bearing and distance to tuned VOR and DME stations. This was the first indication of navigation equipment "data fusion" beginning in the cockpit.

Horizontal Situation Indicator

The HSI was the next step in integrating information and "data fusion" for the pilot. The HSI was the evolution of a BDHI combining the compass card of a DG with an RMI needle and a DME readout. The pilot now had a combined scan of aircraft heading and distance and bearing to a NAVAID ground station in one glance at the HSI.

Instrument Landing System Capabilities

Shortly after the introduction of the VOR, localizers (LOC) were created to provide more precise heading indications as pilots made approaches to airports The LOC provided a broadcast beam that provided a horizontal corridor for the pilot to fly down during an approach. The corridor became narrower the closer the pilot flew to the airport. A course deviation indicator (CDI) provided a vertical needle that showed deviation indications to the pilot if the aircraft was left or right of course line The next integration effort was to add glide slope (GS) information in the form of a horizontal needle that provided altitude deviations up or down from a broadcast beam The GS provided a vertical corridor for the pilot to fly in decreasing altitude during an approach. Again, the vertical corridor became narrower the closer the pilot flew to the airport. Hearing the words "on course and glide slope" meant the pilot was in the center of the horizontal and vertical corridors and was flying a precise approach that would allow the aircraft to land at the landing threshold of the runway.

The integration of the LOC and GS broadcast equipment created the ILS and its approach corridor. As an added aid to give the pilot further SA during an ILS or LOC approach, a system of marker beacon transmitters was set up along the approach corridor As the aircraft proceeded down the corridor and the aircraft flew over the marker beacon stations, a receiver would illuminate lights on the instrument panel ("O" for outer marker, "M" for middle marker, and "I" for inner marker) to give the pilot an indication of position within and along the approach corridor Further integration to the HSI "data fusion" added the CDI, LOC, and GS needles and the O, M, and I marker beacon lights for ILS approaches.

Long Range Aid to Navigation

The LORAN chain of broadcast stations was created out of the necessity to know precise position while navigating at sea LORAN was initially created by the U. S. Coast Guard for precise nautical navigation, but it was adapted for aviation use once the utility of the system was discovered and the development of high speed miniature computers allowed the LORAN receivers to shrink in size and weight. The LORAN receiver in the aircraft would receive broadcasts from three ground stations and provide a calculation of triangulated position in horizontal 2-D space The LORAN display would then give a readout of latitude or longitude for correlation to a chart. Later, LORAN models allowed the pilot to enter waypoint (latitude and longitude of known objects or positions) information and the system could provide range and bearing information to the entered waypoints from the current aircraft position.

Global Positioning System

The U S military drove the most recent development in navigational systems. The military, in its need for precise 3-D positioning information for world wide aircraft and ship operations, designed and launched a constellation of orbiting satellites. Global positioning system (GPS) allows any user with an appropriate receiver and the signals from four satellites to know their precise position in latitude, longitude, and altitude

Display Improvements

Initial displays of LORAN and GPS systems provided a simple digital readout of aircraft position in latitude and longitude (LORAN and GPS) and altitude (GPS) Once the capabilities of microprocessors and AMCLDs increased and their prices dropped, avionics manufacturers added additional capabilities to the LORAN and GPS systems. One of the first capabilities was the addition of a waypoint database containing airports, NAVAIDs, air route intersections, and approach fixes A further addition added the capability to store pilot defined waypoints and to create flight plans by combining sequences of data items from the database. Utilizing these points in the database, a 2-D depiction of the aircraft's position and flight plan in relation to these points was soon added to system displays creating the first moving maps. Generally, most avionics manufacturers used an "inside-out" format When the coordinates of FAA airspace and

SUA were added to the database, rudimentary line drawings were able to be depicted showing airspace boundaries. Further additions to the databases gave the capability to depict airfield diagrams and approach diagrams similar to those drawn on handheld approach plates along with the appropriate communication and NAVAID frequencies. The inclusion of terrain databases containing 2-D depictions of cultural features such as cities, highways, railroads, rivers, lakes, and coastlines and in some cases state boundaries was soon added to many systems. The latest database improvement included USGS terrain elevation data depicted in 3-D perspective display types.

Display sizes were initially small, typically two to three inches across, monochrome in color, and cluttered with information. The advent of color displays allowed the color coding for the categorization and highlighting of relevant information whether it was airspace delineation, cultural features, flight plan routing, or airfield and NAVAID locations. The most recent of these full-color navigation displays are five inches or more in size and provide a fundamental increase in SA for the GA pilot.

The Modern Day General Aviation Navigation System

The modern day GA navigation system will be an integrated system with a combination of a moving map display and a versatile HSI type display or will integrate these features into one device. First, a "state-of-the-art" moving map system will be discussed. Second, an electronic HSI (EHSI) system incorporating moving map display features will be explored.

"State-of-the-Art" Moving Map

Figure A-9 shows the Garmin GNS 530 moving map navigation and communication display system. In the author's opinion, this system is the epitome of an integrated navigation system designed for GA use. The GNS 530 incorporates a five-inch full-color AMLCD display and a microprocessor-controlled waypoint database with each of the database improvements mentioned earlier, except 3-D terrain modeling. It integrates GPS, VOR, LOC, GS, and marker beacon receivers into one unit and additionally adds a communication receiver Each integrated system, which originally had separate displays on the cockpit instrument panel, are now combined into this one unit. The GNS 530 provides an "inside-out" moving map type display for displaying GPS navigation data, but still requires an interface with an HSI or EFIS to display VOR, LOC, GS, and marker beacon information. The moving map can display a centrally or bottom centered aircraft symbol and a flight plan line drawing in relation to airports, NAVAIDs, airspace, SUA, electrical discharge symbology, weather depictions, and traffic CDTI or traffic alert and collision avoidance system (TCAS) information The GNS 530 uses a hierarchical system for selecting receiver system modes and display functionality. In addition, the resident software gives the pilot the capability to configure the system to display only the desired portions of information for each phase of flight. The software also incorporates multiple declutter modes to remove information as the pilot becomes task and information saturated. This type of system integration lends itself to the redesign of a cockpit instrument panel removing display and instrumentation clutter.

Electronic Flight Instrumentation System

Figure A-10 shows six operating modes of the Sandel SN3308 EFIS. The SN3308 is a three-inch full-color EFIS that accepts inputs from GPS, VOR, LOC, GS, LORAN, ADF, DME, and marker beacon receivers. The EFIS utilizes the input from a GPS receiver as the primary navigation source with bearing and distance readout to the next selected waypoint. It incorporates two RMI needles, each of which can display a qualitative bearing to a distinct navigation receiver. Additionally, a quantitative reading of bearing and distance (if a DME receiver is selected) to each of the selected navigation receivers can be displayed For ILS approaches, the SN3308 has selectable LOC and GS needles as shown in Figure A-10 a) The "inside-out" moving map display utilizes an internally stored waypoint database or a waypoint database supplied via input from an external source (possibly a Garmin GNS 530). The internal waypoint database includes all the database features discussed previously except the 2-D and 3-D terrain databases. The moving map superimposes a flight plan and aircraft symbology in relation to airports and airport diagrams, NAVAIDs, airspace, SUA, and electrical discharge symbology. The moving map will utilize a 360 degree compass rose, shown in Figure A-10 c) with flight route, airspace, and airports depicted and Figure A-10 e) with an airport diagram depicted Also, a 90 degree arc compass rose, shown in Figure A-10 b) with flight route, airspace, NAVAIDs, and airports depicted, Figure A-10 d) with flight route and electrical discharge symbology depicted, and Figure A-10 f) with instrument approach course lines depicted, may be selected. Both RMI bearing needles may be selected to individual navigation receivers in either compass rose mode. The SN3308 software incorporates pilot definable declutter modes for removing unwanted information for specific phases of flight preventing pilot saturation. In addition, the system provides visual alerts to the pilot if navigation receiver inputs become unusable or unreliable.

Engine Instrument Displays

One of the first human factors improvements to engine instrument displays was the use of traditional color coding for an "all needles are in the green," check readings assessment of engine parameters, shown in Figure 2, rather than interpreting each needle reading. At the same time, engine instrument displays were clustered in functional groupings allowing the pilot to make a quick scan of the group to ensure that all needles were in concurrence or pointed in the same direction as shown in the "gestalt" cluster of Figure 4. This clustering of engine instrument displays prevented the pilot spending an inordinate amount of time scanning all over the instrument panel to find each of the isolated engine instrument displays. Engine instrument displays then incorporated combination gauges that allowed a qualitative assessment of engine instrument readings (check readings or "in the green") and a quantitative digital reading for precise setting of RPM, manifold pressure, or fuel flow, etc., depending on the desired flight profile, i.e., 75% cruise, best range, or best endurance. Most of the new engine instrument displays incorporate many, if not all, of these features. Some newer designs incorporate human factors research in unique ways. One engine instrument display color codes the outer ring and the inner background of each dial according to operating ranges of normal, caution, or danger. For example, if the RPM is within normal parameters, then the entire inside of the RPM arc is green, if the RPM gets too high, then the inside of the arc turns amber, and if an overspeed of RPM occurs, then the inside of the arc is red. One engine instrument display system will now be discussed.

Engine Instrumentation and Caution Advisory System

Figure A-11 show the Vision Micro Systems VM1000 and EC100 EICAS. The VM1000 Engine Management Instrumentation System portion of the EICAS, shown in Figure A-11 b), is a microprocessor-controlled AMLCD that integrates all engine instruments into a cluster on one display panel Each of the engine instruments is traditionally color coded for a quick check readings assessment of engine operation. Each engine instrument provides both a graphical qualitative view and a digital quantitative readout of engine parameters The system incorporates a tracking system that when initiated will monitor all engine parameters and determine if any readings deviate from the initial readings when the mode was set The VM1000 system will visually alert the pilot if any engine readings deviate when in the tracking mode or for low or high readings. In conjunction with the EC100 Electronic Checklist and Cautionary Systems' alphanumeric display, shown in Figure A-11 a), any engine readings that deviate from set parameters will be visually displayed in alphanumeric form stating the parameter and its deviant reading. An aural warning tone will also sound in the headset to cue the pilot to scan the engine instrument display. The EC100 can operate as a backup display in the event the VM1000 fails. All engine instrument parameters can be selected on the EC100 for a line by line review.

Future Display Capabilities

As was discussed, the improvements in microprocessor and AMLCD technologies spurred the development of displays that enhance information presentation to the GA pilot. The GA pilot currently has a choice of display system technologies that can enhance the pilot's ability to monitor the aircraft's performance and the flight progression. This section will identify and discuss additional extant and developmental technologies that will further aid the GA pilot in overall SA of the aircraft and its flight environment.

Head-Up Display

A HUD provides the pilot, while looking outside through the display, with all the essential flight information necessary to fly the aircraft, even in instrument meteorological conditions (IMC). Consequently, the pilot can focus on flying the aircraft while simultaneously searching for other traffic, scanning for airfields in poor weather, or transitioning from instrument to visual flight for an approach and landing (Trang, 1997)

The HUD projects flight information on a nearly transparent screen, called a combiner, positioned between the pilot and the aircraft windscreen as shown in Figure 8. The combiner reflects the projected flight information for viewing by the pilot while collimating the data at optical infinity. The displayed information conformally overlays the real world from the pilot's vantage point and appears from the same distance as the real world, optical infinity. Focusing the displayed image at infinity or collimating the CRT image has three distinct advantages

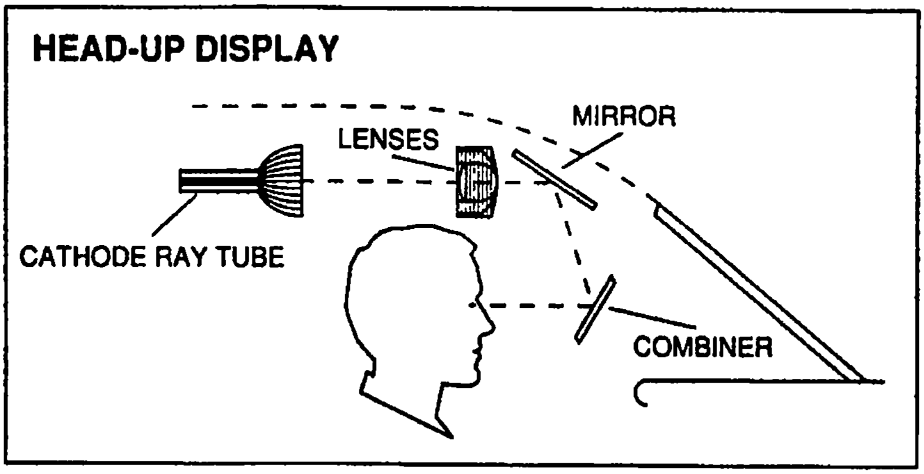


Figure 8. Head-Up Display Components.

Source: Design News (March 25, 1991). "Head-Up Display Enters Realm of General Aviation." *Design News – Engineering News Section* Vol 47, No. 6. Newton, MA: Cahners Publishing Co. pp. 26.

First, a display collimated at infinity eliminates the need for the pilot to change his eye focus when viewing either the real world or the HUD symbology as shown in Figure 9. Second, the position of the HUD symbology relative to the real world does not change with head or eye movement Hence, any parallax between real world object, e g., the horizon, and the projected HUD symbology is eliminated. Third, no eye adaptation is necessary because of ambient light level variations between the real world and head down displays, thereby improving reaction times (Kyle, 1985). If implemented correctly, the HUD allows the pilot to maintain SA on the aircraft's flight parameters as well as maintain a visual scan for other aircraft traffic. This is essential during the landing and takeoff phases of flight in the busy environment of the airport traffic area. Several HUD systems are currently in development for GA aircraft.

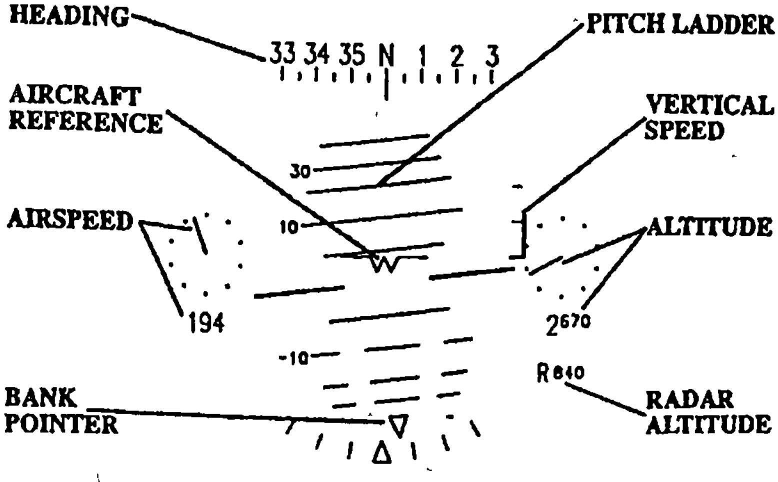


Figure 9. Head-Up Display Symbology.

Source: Anderson, M. W. (1996, May-June). "Flight Test Certification of Multipurpose Head-Up Display for General Aviation Aircraft." *Journal of Aircraft* Vol. 33, No. 3. New York, NY: AIAA, Inc. pp. 535.

Cockpit Display of Traffic Information

The CDTI system allows GA pilots to see the positions of other aircraft and to broadcast their position to those other aircraft. Utilizing GPS position data, a GA aircraft can broadcast its position through a mode S transponder in an automatic dependent surveillance-broadcast (ADS-B) mode and receive equivalent GPS position information from other aircraft through the use of a 1090-MHz receiver. The mode S transponder and ADS-B modes are used in the civil commercial aircraft sector for the TCAS system Once received, the position information of other aircraft is presented to the pilot on a navigation system MFD (similar to Garmin's GNS 530). Like TCAS, the CDTI MFD shows the pilot's aircraft in the center of the display and traffic aircraft as white diamonds or yellow circles arrayed in true position around the pilot's aircraft. A positive or negative two-digit number will be shown next to the traffic aircraft that indicates the traffic's altitude relative to the pilot's aircraft in hundreds of feet. The systems have configurable range scales for shorter or longer range detections of other aircraft (McKenna, 1996). CDTI gives the GA pilot a quick assessment of traffic around his aircraft affording him improved SA during a flight whether it is while flying on a congested airway or in the airport environment.

Aviation Weather Inside the Cockpit

In the past, most GA pilots have until now had very limited possibilities for weather detection or weather updates in flight. Weather radar was one possibility for GA aircraft, but notoriously radar systems were prohibitively expensive and heavy for most of the recreational GA aircraft fleet.

Most current radar systems give the pilot a choice of selectable range scales and use color CRT technology or color AMLCDs (AMLCD usage is now making radar systems more affordable). However, radar systems only depict areas of precipitation color coded for intensity level and are subject to attenuation effects that distort airborne weather radar returns (Horne, 2000). A radar display does not depict electrical discharge activity from lightning within thunderstorm cells The other weather alternative is lightning detection equipment that can portray thunderstorm electrical discharge activity in the vicinity of the pilot's aircraft. Most of these lightning detection systems utilize monochrome AMLCDs with selectable range scales They depict lightning as clusters of pluses or minuses or lightning bolt zigzag symbols. The density of the symbol clusters is dependent on the intensity of electrical discharges. However, lightning detection equipment does not depict areas of precipitation in the vicinity. The introduction of microprocessor-controlled AMLCDs to the GA aircraft cockpit in the form of MFDs now allows the fusion of these two technologies A weather depiction display in the GA cockpit shows color coded regions of precipitation intensity with an overlay of symbols depicting electrical discharge activity within the precipitation areas This system greatly increases the SA of the pilot

An even greater aid to weather SA for the pilot would be the ability to see real time weather depictions in and around the aircraft's route of flight New technologies that will allow the GA pilot to receive periodic or requested weather broadcasts from satellite or ground stations are in development Using a cockpit based receiver, the pilot will be able to upload and view weather depiction charts, satellite imagery, graphical depiction of weather warnings, and alphanumeric text based forecasts for enroute and destination airports. The system will require a chain of broadcast stations throughout the U S., aircraft based receivers, and compatible cockpit displays (Horne, 2000). Many of the newer navigation system MFDs based on AMLCD technology have these inherent capabilities. Both Garmin's GNS 530 and Sandel's SN3308 navigation displays, discussed previously, have inputs for lightning detection receiver data and the GNS 530 is capable of further graphical weather inputs. The aircraft will just require weather receivers.

The weather broadcast system is in work and the National Aeronautics and Space Administration (NASA) is leading a development effort for Aviation Weather Information (AWIN) systems. The AWIN system is an attempt to produce a low-cost weather depiction and broadcast system for GA cockpits capable of issuing automatic weather reports from the aircraft back to the ground stations for a real time assessment of flight conditions in various areas (Goyer, 1998). An example of a potential cockpit weather depiction from an AWIN system display is shown in Figure A-12. In Figure A-12, note the shaded areas of radar returns showing different intensities of precipitation overlaid on airspace boundaries (left), the weather depiction charts (lower right), and the airport forecast (upper right).

Conclusion

New display technologies have revolutionized the GA pilot's cockpit. A GA pilot and aircraft owner can remove the instrumentation clutter and display interpretation issues many GA aircraft cockpits experience. The understanding of the human sensory processing systems and the implementation of human factors techniques are prevalent in the "data fusion" and information integration now available in developing flight instrument, navigation, and engine instrument system displays In addition, the GA pilot will soon have resources available that will integrate into the cockpit and allow unprecedented levels of SA about the aircraft and its operating environment.

CHAPTER 4

THE FUTURE GENERAL AVIATION AIRCRAFT COCKPIT

Introduction

Further display enhancements and SA innovations are in development and will soon become available for the GA aircraft sector. The goal of any new avionics and display development program should be methods to decrease the information load on the GA pilot. Limiting the number of displays a pilot has to review during a flight is a start. Developing methods to pre-process information before presentation to the pilot will also help SA This will minimize the amount of interpretation and processing time necessary to understand the data presented. Additionally, development should focus on display format and design elements within the context of human perceptual limitations. This chapter will explore the capabilities that should soon exist in the GA cockpit and will present examples of research currently in progress on the future cockpits for GA aircraft.

Future Cockpit

The future GA cockpit will make extensive use of MFD technologies creating a true "glass cockpit" for the GA pilot These displays will make efficient use of multiple colors, hierarchical control architectures, and will allow the pilot to configure each display for optimum and desired presentations of data Each system will be data fused, integrating multiple sensor inputs into single blended displays of aircraft and subsystem status. In addition, the cockpit display systems will use visual, as well as aural inputs to the pilot minimizing saturation of one sensory channel Currently, there are several design projects in progress to create concept cockpit layouts and to evaluate their potential for the GA pilot.

Advanced General Aviation Transport Experiments

The Advanced General Aviation Transport Experiments (AGATE) program concept, initiated by NASA, will develop affordable, integrated displays and controls for GA aircraft cockpits The goals of the AGATE program concept are to improve pilot SA, reduce pilot workload, reduce requirements for voice communication, and reduce the time and cost of obtaining and maintaining safe "near all-weather" flying skills (Asbury, 1999) A cockpit information system would be designed using an integrated HUD, integrated microprocessor driven, AMLCD technologies for MFDs, and an electronic MFD depiction of a PFD A Highway-in-the-Sky (HITS) concept would utilize GPS data for exact position of the aircraft and a HUD built into the windscreen depicting a 3-D tunnel in the sky. To stay in planned route and flight parameters, the pilot would fly through the tunnel on the HUD from takeoff to landing (Ethell, 1994). HITS would also display a graphic, full-color 3-D perspective of terrain around the aircraft on the PFD The MFDs would depict graphically navigation, position, weather, traffic, flight plan, airspace, communication, and aircraft subsystem status information. All communication between ATC and the aircraft would be via datalink (with a voice system for two-way radio backup). Any frequency changes, flight clearance amendments, or instructions would appear in alphanumeric text form on one of the MFDs. Weather information would also be received from weather broadcast stations as previously discussed.

Information presented on all the displays would be highly processed for minimal interpretation by the GA pilot to minimize recoding of information and make less demands on short-term memory for operations and less demand on long-term memory for proficiency (Asbury, 1999) The AGATE concept strives to increase pilot SA and improve safety thereby placing the capabilities of a 1,000 hour instrument pilot in the hands of a 200 hour pilot (Ethell, 1994). Figure A-13 shows a depiction of the proposed AGATE concept cockpit layout

Cockpit and Simulator for General Aviation

The Cockpit and Simulator for General Aviation (COSIMA) program is a design initiative undertaken by the Institut für Flugfuhrung at the Technische Universitat Braunschweig in 1996 The COSIMA program guidelines a low-cost, modular cockpit display design adaptable to any GA aircraft. System components need to be separable for individual subsystem use in conventional cockpits and interchangeable for replacement and repair purposes. This system will use three AMLCD displays and two microprocessors. One of the microprocessors will process all data from onboard sensors and output the processed data to a subsystem display located in the center of the cockpit instrument panel called the Aircraft Monitoring System (AMS). The AMS will be a user configurable hierarchical display of engine and electrical subsystem parameters. If any parameters become abnormal, audible and visual warnings will alert the pilot to regard the AMS, which will automatically display the errant subsystem The second microprocessor will receive the processed data from the first microprocessor and output flight and navigation system parameters and data to two Flight Planning and Navigation

System (FPNS) displays, one in front of each pilot seat. Again, the FPNS will be a user configurable hierarchical display and will show the aircraft's flight parameters around the periphery of a centrally located moving map display. The FPNS would depict a profile view of the aircraft's current or intended flight path with relation to a graphical view of terrain and obstacles to the aircraft in flight The pilot will have added SA regarding all obstructions along the route of flight (Ardey, 1999).

Conclusion

These research efforts into display design make extensive use of current and available technologies. The current grade of AMLCD technologies and microprocessors embody the requisite resolution capabilities and computing power to perform the required tasks. However, suitable design efforts still need to be conducted on all the system components integration. In addition, the FAA should establish development and certification standards for the construction of suitable display systems. FAA standards will be a prerequisite before any display systems will be mass produced making them affordable to the average GA pilot and aircraft owner. Also, ATC will have to expand their infrastructure to accommodate the new capabilities of the GA aircraft. Once these issues have been solved, the components will exist to create a true "glass cockpit" for the GA aircraft.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Over the last century of aircraft evolution, the cockpit has become increasing cluttered with a profusion of avionics instrumentation and displays. The military and civil commercial aviation sectors encompasses many of these developments driven by operational performance needs, the economics of competition, and safety considerations. With the cluttered cockpits, more inefficient instrument panel designs and layouts contributed to an increase in pilot errors resulting from the additional workloads and tasks necessary to combat the effects of information overload. The effects of information overload have required the pilot to spend additional time and mental resources to process the items of presented cockpit data. The pilot experienced a degradation of adequate SA of the aircraft's performance and the elements within the aircraft's operating environment whether it be weather, traffic, or airspace constraints.

In the last fifty years, the military and civil commercial aviation sectors used human factors techniques as aids in redesigning the cockpit to reduce overall cockpit complexity to improve pilot operational and mental performance, and to improve information recognition. Some human factors research has focused on the application of human-centered design concepts to the cockpit, i.e., which tasks can be automated while others can be assigned to the pilot. This research resulted in task oriented displays that synthesize data for presentation to the pilot and improved information recognition. These displays made use of an allocation of functions premise that has been the driving force behind the introduction of full-color, hierarchical MFD cockpit systems or "glass cockpits" that are now prevalent in the military and civil commercial aviation sectors.

A second focus of the human factors research examined a pilot's performance envelope with respect to the human's capabilities and limits Studies indicated that humans process much of the information of their environment visually making extensive use of pattern recognition and color In addition, the human's auditory system, using both tonal and vocal inputs even when the human visual system is overloaded with information, is still capable of processing information.

A third focus of the human factors research evaluated cockpit display positioning and outlined design parameters for a cockpit layout. Guidelines for optimum usage of display groupings, coding, and location resulted from these studies. Additionally, the guidelines dictate optimum display viewing distances dependent on the display type.

This thesis shows that the GA sector's revolution in cockpit redesign lagged the military and civil commercial sectors even though the GA cockpit experienced the same cockpit clutter. GA aircraft comprise a large portion of the overall aviation community and fly a majority of the annual flight hours flown. The GA pilot's task loads, while conducting VFR and IFR flights, are considerable and not eased by current automation. Therefore, the GA populace has experienced much higher accident rates primarily attributable to pilot error. Until recently, the GA cockpit reflected very little of the revolutions in cockpit design that the other aviation sectors adopted. This lag results primarily from economic constraints, first from liability insurance costs and aviation gasoline prices, second from the limited funds of the average GA pilot and aircraft owner, and third from the usability and purchasing constraints of previously available technologies.

Advances in the performance of microprocessors and AMLCDs and their lower costs have made the redesign of the GA cockpit a reality. Many new low cost display systems available to the GA pilot and aircraft owner extensively use human factors design principles. Many of these systems integrate the functionality of multiple, single display systems into one display source for true “data fusion ” Instead of traditional dial and gauge displays, the GA cockpit now is capable to use MFD technologies in PFDs, “state-of-the-art” moving map navigation systems, EHSIs, and EICAS systems This thesis examined several current display system technologies and demonstrated the extensive use of functional groupings, color coding, visual as well as aural alerts, and “gestalt” design concepts. The new design technologies of the HUD, CDTI, and AWIN detailed their future benefits in improving pilot SA.

Last, this thesis explored the future of the GA cockpit in terms of desired display technologies, optimum methods of aircraft and environmental data parameter presentation, and use of the visual and aural sensory channels Two future cockpit concepts were examined for their feasibility in improving SA, increasing information processing, and decreasing the workload for the GA pilot. Both concepts made extensive use of “data fusion” in cockpit display integrations and “glass cockpit” designs.

Recommendations

This thesis’ focus was to make the GA pilot aware of the cockpit display and layout factors affecting his performance, the interpretation of his aircraft’s performance, and the SA of his environment. Many human factors concepts in display usage, design, location, and cockpit instrument panel layout were covered throughout this thesis. Included were examples of mature display technologies, currently in production, that utilize human factors principles. These examples indicated the application of human factors principles and offered similar considerations when looking to upgrade a display system Future concepts proposed to show alternative ideas for display systems.

When redesigning or upgrading a GA cockpit, the key is not becoming too enamored of the new display technologies and not getting lost in the complexity of the new hierarchical display systems available The GA pilot and aircraft owner should examine the finances available, the current aircraft displays needing maintenance or replacement, instrument panel space available, the desired performance capabilities of the display systems and aircraft (VFR or IFR), and then determine a specific system display or displays that meet the requirements. The following points give guidance when considering either an individual display system upgrade or when redesigning or replacing an entire instrument panel and cockpit layout:

1. Ensure flight instrument displays are in the basic T layout for the most efficient scan pattern.
2. Consider rehabilitating or replacing instrument displays using traditional color coding and check readings concepts.
3. Consider redesigning the layout of the current instrument panel by functionally grouping similar subsystem displays.
4. Orient functional groups of subsystem instrument displays using "gestalt" principles.

5. Layout primary instrument and system displays within the optimal visual fields as shown in Figure A-7. Secondary instruments and displays can be relegated to the peripheral portions of the panel. Consider panel lighting effects and readability of cockpit displays.
6. If purchasing a new aircraft, review avionics options available from the aircraft manufacturer with regard to human factors enhancements and mission needs. Consider buying the aircraft with a bare panel, then installing desired avionics from a secondary dealer to meet the desired level of functionality and performance.
7. If completely redesigning a used aircraft's panel, determine desired functionality and performance levels and then consider integrated avionics systems, i.e. multiple MFDs, to minimize the number of cockpit displays. Possibly sell replaced avionics and displays to overhaul dealers.
8. Consider upgrading display systems to incorporate full-color, visual and aural alerts, and multiple hierarchical submodes. Most current MFD systems incorporate multiple submodes, such as PFD, moving map, and EICAS, with the capability to switch between them.
9. When purchasing a moving map display system or MFD, consider a system with upgrade features using projected input capabilities like lightning detection, weather radar, CDTI and AWIN.

10. When a hierarchical MFD system is purchased, practice working through the menu architecture and system modes ensuring a suitable level of familiarity and performance ability prior to flight.
11. Plan for reliable redundancy. Have some traditional gauges and dials as backups to get the aircraft on the ground safely if all other systems fail

There are many points to consider when looking at the replacement or refurbishment of cockpit displays or the complete redesign or purchase of a cockpit instrument display system for the instrument panel in a GA aircraft. Each display system has to be judged on its individual merits and potential for enhancement of the entire GA cockpit display system. The key for any display system is improved information presentation, interpretation, and recognition for the GA pilot and for a greater level of SA during aircraft operations.

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APPENDIX

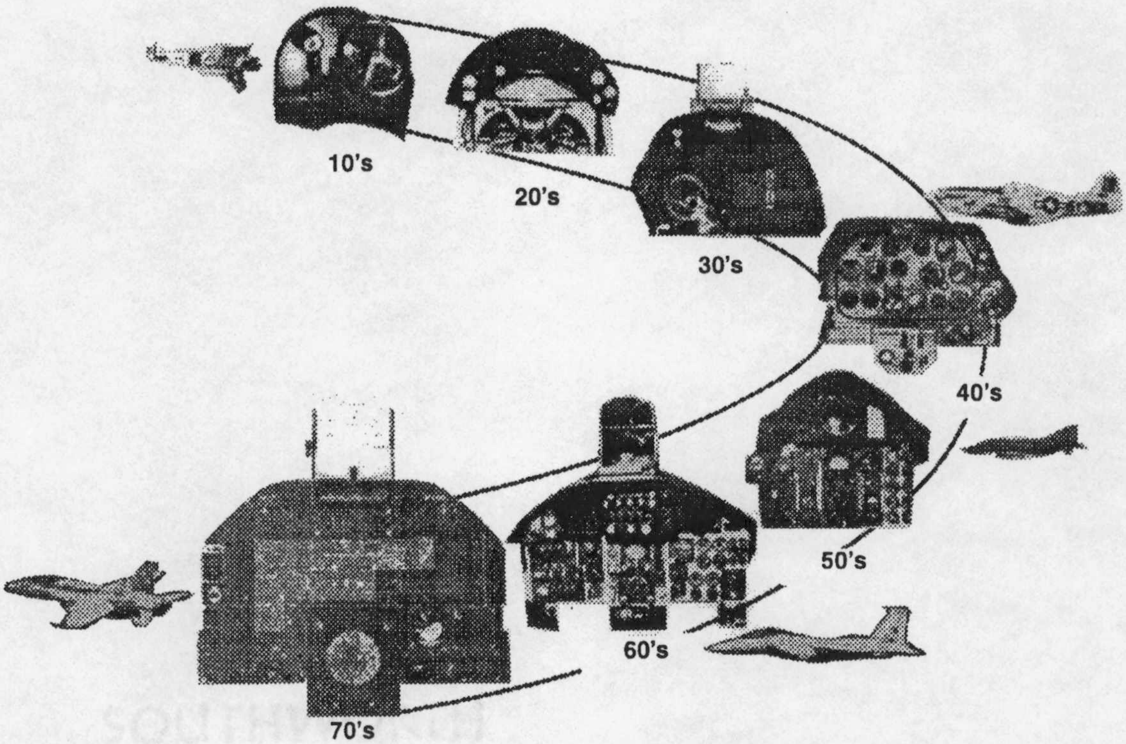


Figure A-1. Evolution of Military Cockpit Display Complexity from 1910 to 1970.

Source: Advisory Group for Aerospace Research & Development (AGARD) (1996, April). *Flight Vehicle Integration Panel Working Group 21 on Glass Cockpit Operational Effectiveness.* AGARD-AR-349. Neuilly-sur-Seine, France: AGARD, North Atlantic Treaty Organization. pp. 1.

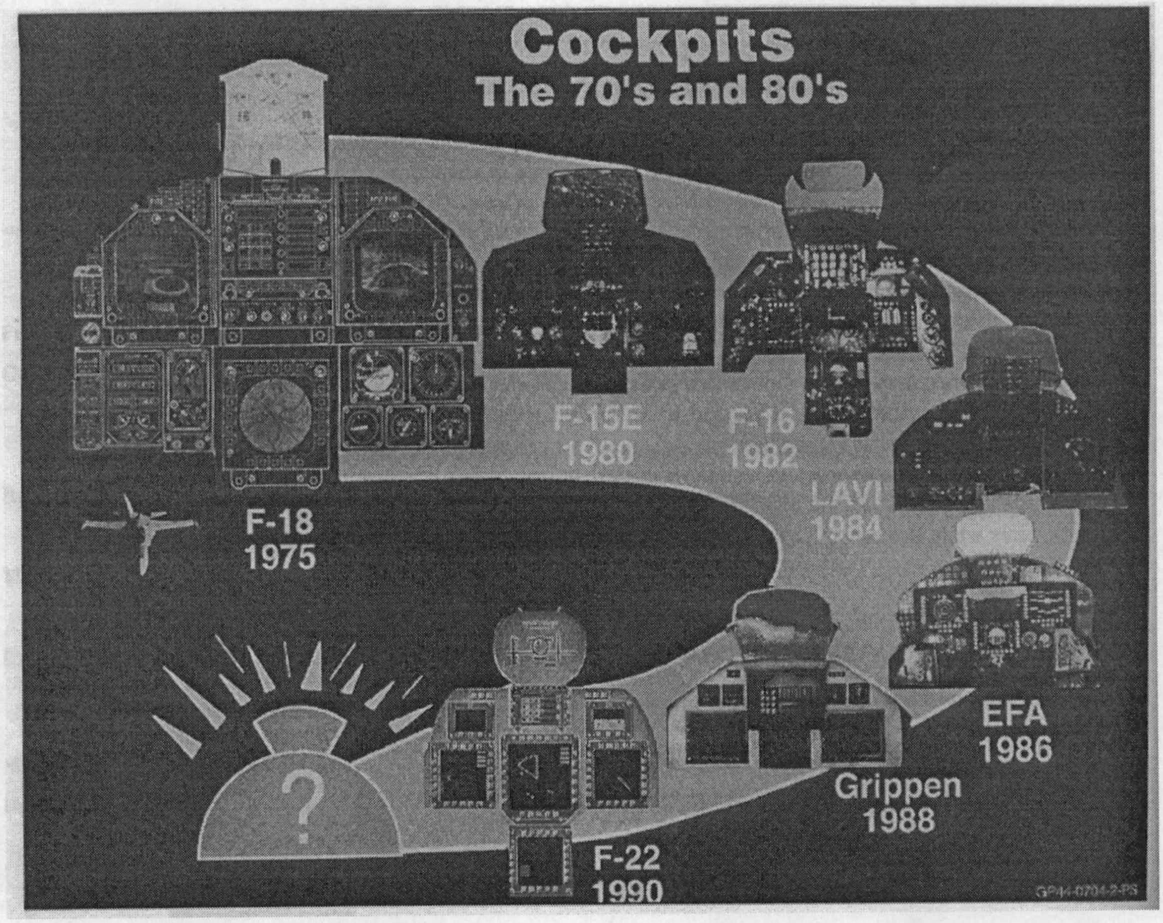


Figure A-2. Military Glass Cockpit Display Evolution from 1975 to 1990.

Source: Advisory Group for Aerospace Research & Development (AGARD) (1996, April). *Flight Vehicle Integration Panel Working Group 21 on Glass Cockpit Operational Effectiveness.* AGARD-AR-349. Neuilly-sur-Seine, France: AGARD, North Atlantic Treaty Organization. pp. 2.

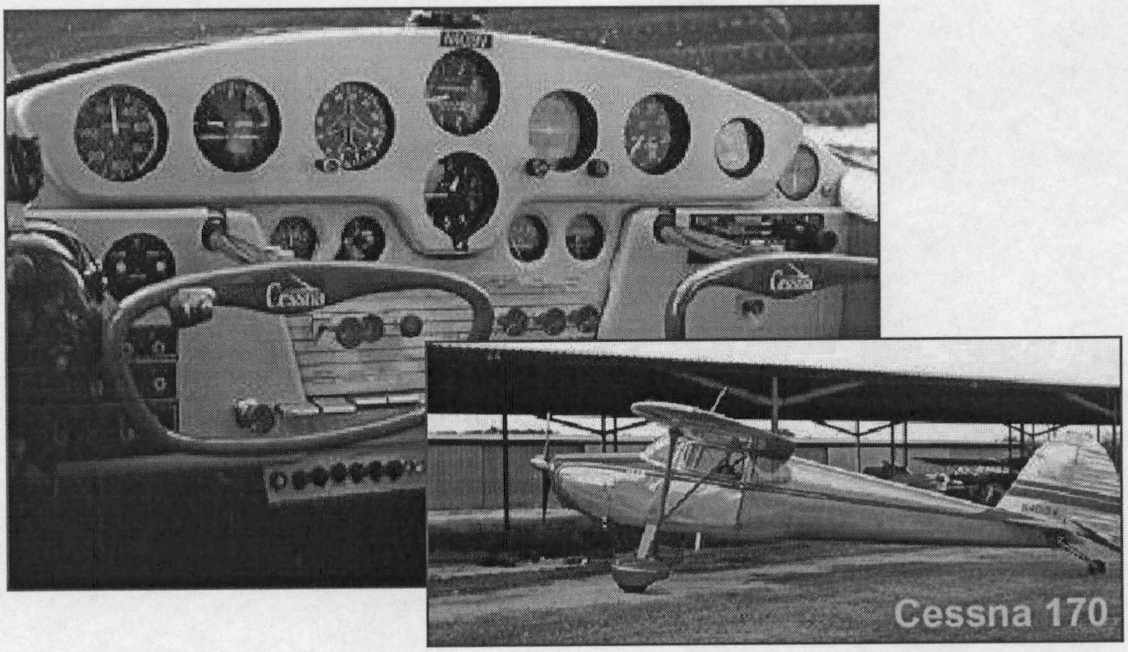


Figure A-3. 1948 Cessna 170 Cockpit Instrument Panel.

Source: Asbury, S. (June 22, 1999). "State-of-the-Art in General Aviation Avionics." *PowerPoint Presentation for SATS Planning Conference, June 22, 1999.* Hampton, VA: NASA Langley Research Center. pp. 3.

Figure A-4. 1990 Cessna 172 Cockpit Instrument Panel.

Source: Asbury, S. (June 22, 1999). “State-of-the-Art in General Aviation Avionics.” *PowerPoint Presentation for SATS Planning Conference, June 22, 1999.* Hampton, VA: NASA Langley Research Center. pp. 4.

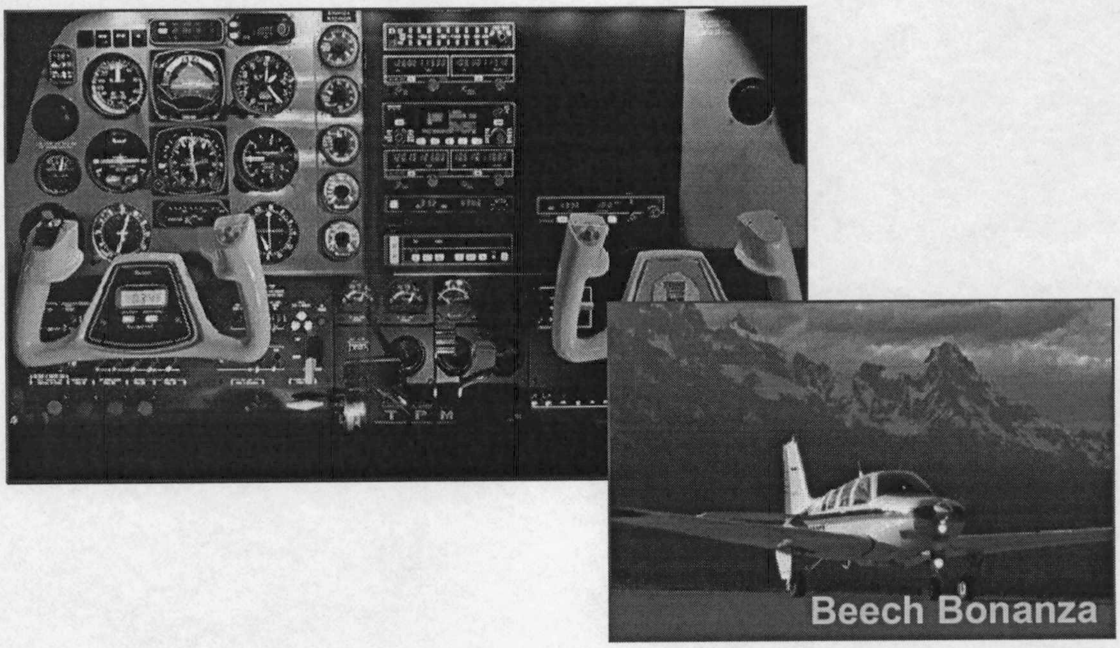


Figure A-5. 1990 Beech Bonanza Cockpit Instrument Panel.

Source: Asbury, S. (June 22, 1999). "State-of-the-Art in General Aviation Avionics." *PowerPoint Presentation for SATS Planning Conference, June 22, 1999.* Hampton, VA: NASA Langley Research Center. pp. 5.

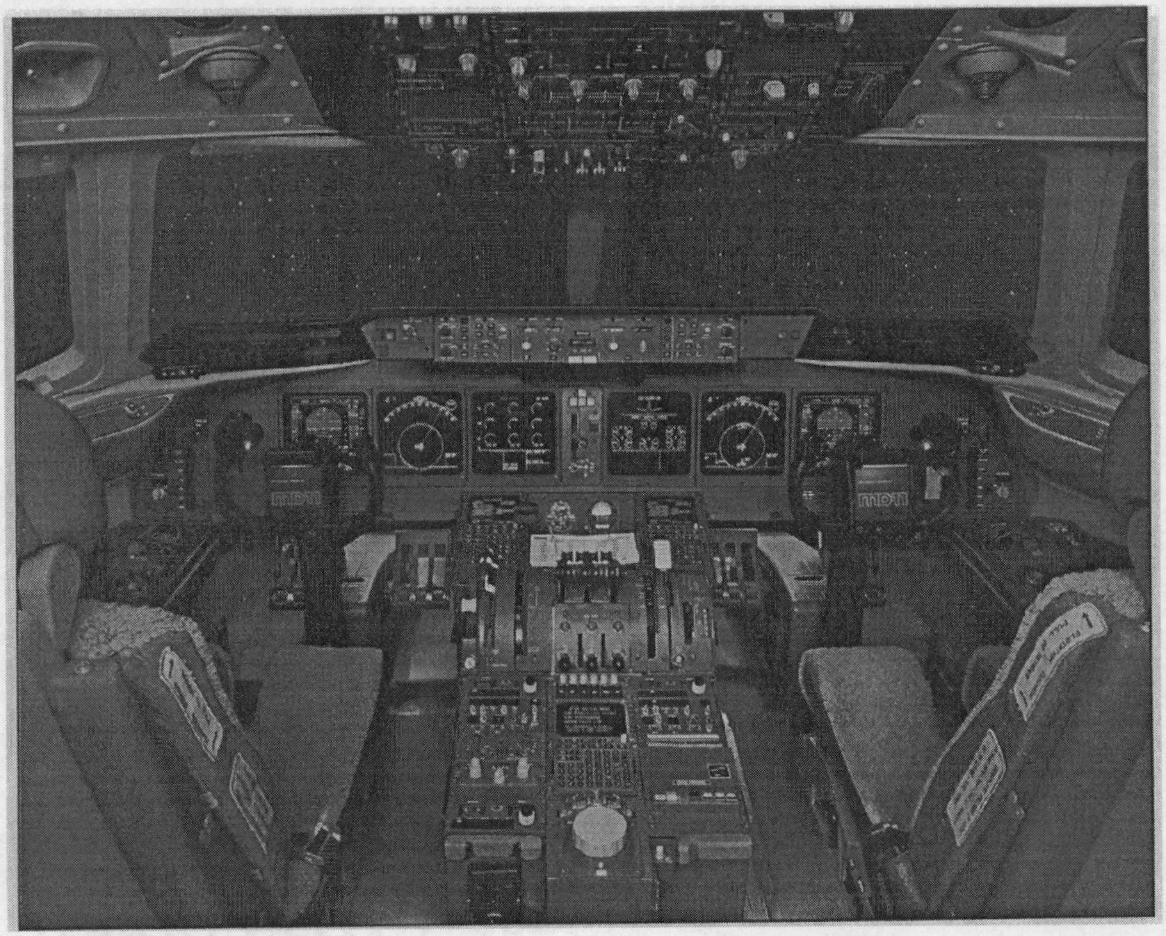


Figure A-6. McDonnell Douglas MD-11 "Glass Cockpit."

Source: Advisory Group for Aerospace Research & Development (AGARD) (1996, April). *Flight Vehicle Integration Panel Working Group 21 on Glass Cockpit Operational Effectiveness.* AGARD-AR-349. Neuilly-sur-Seine, France: AGARD, North Atlantic Treaty Organization. pp. 173

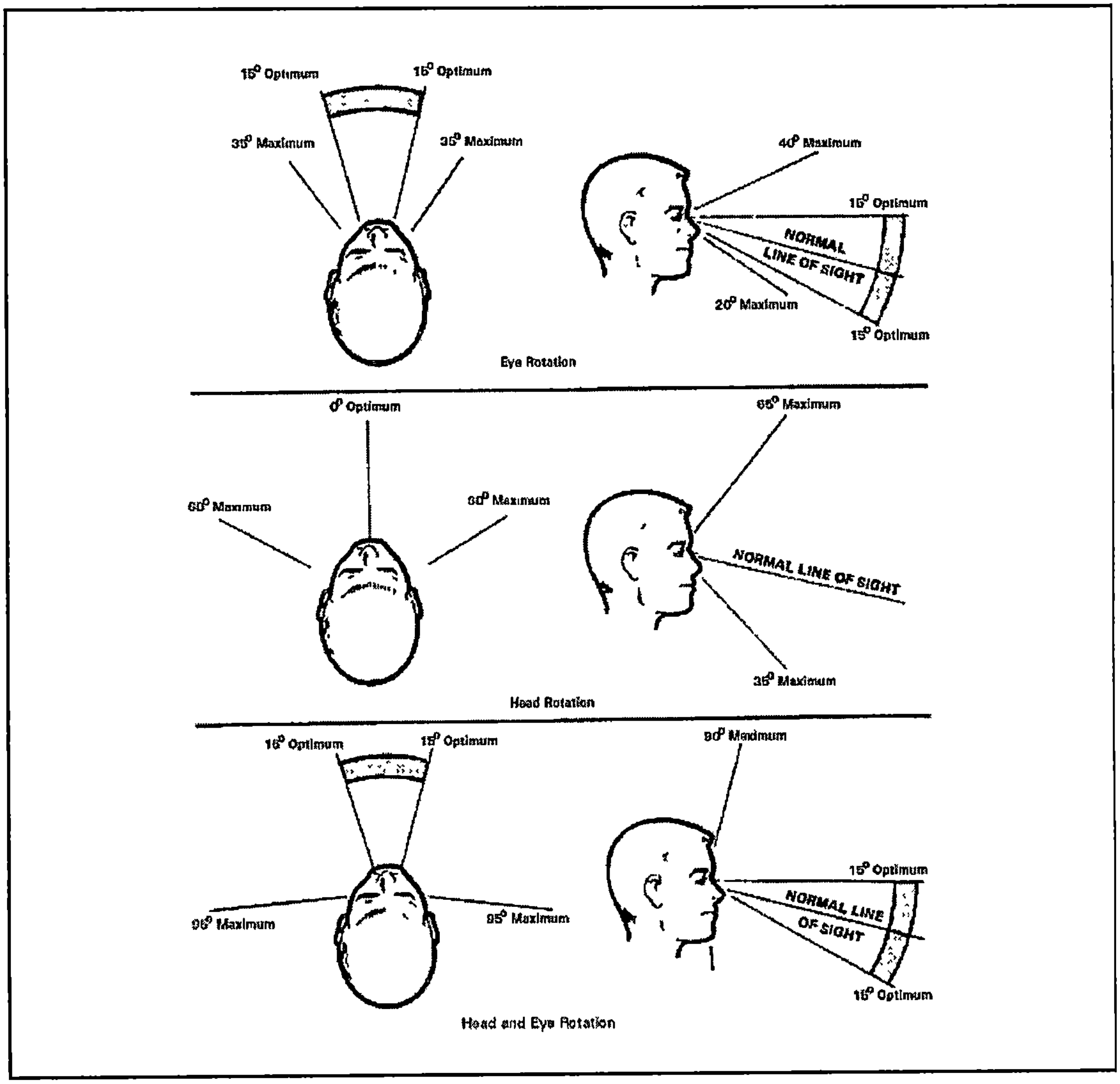


Figure A-7. Optimum Vertical and Horizontal Visual Fields.

Source: Wagner, D., Birt, J. A., Snyder, M., & Duncanson, J. P. (January 15, 1996). *Human Factors Design Guide For Acquisition of Commercial-Off-The-Shelf Subsystems, Non-Developmental Items, and Developmental Systems.* DOT/FAA/CT-96/1 Atlantic City International Airport, NJ. FAA Technical Center. pp. 7-12

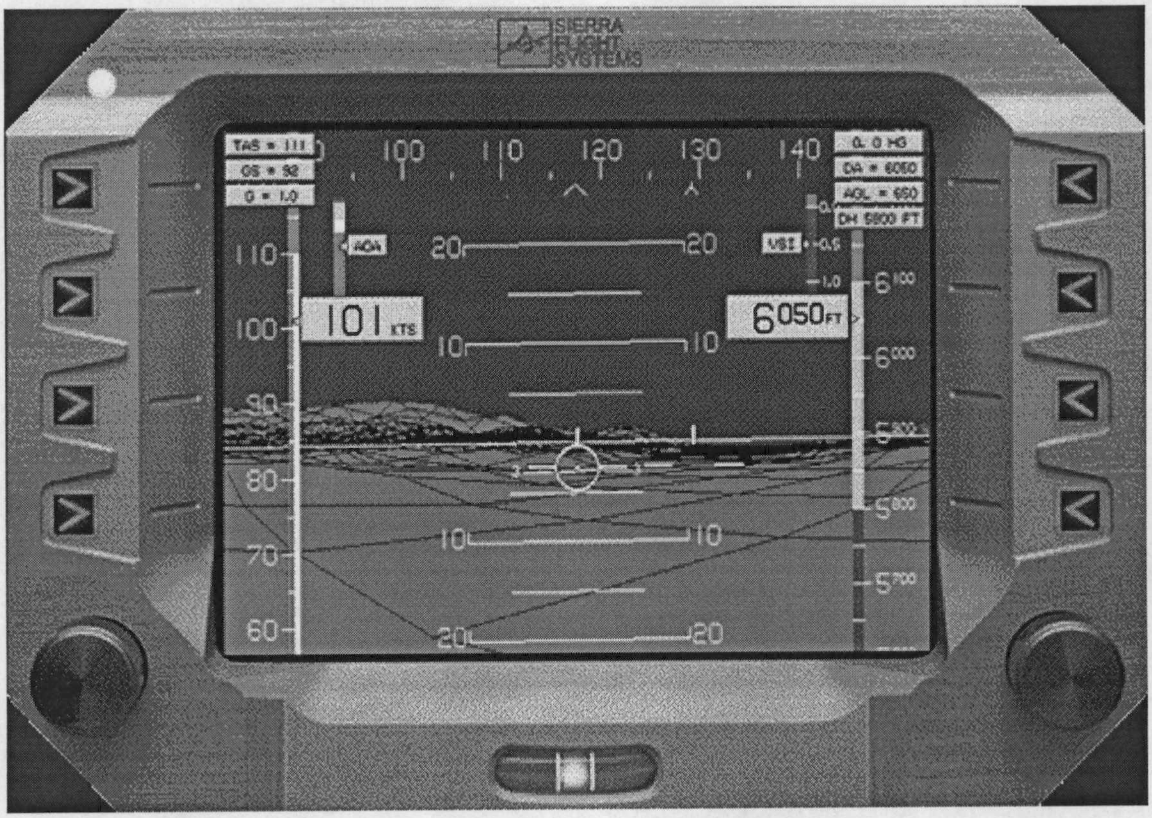
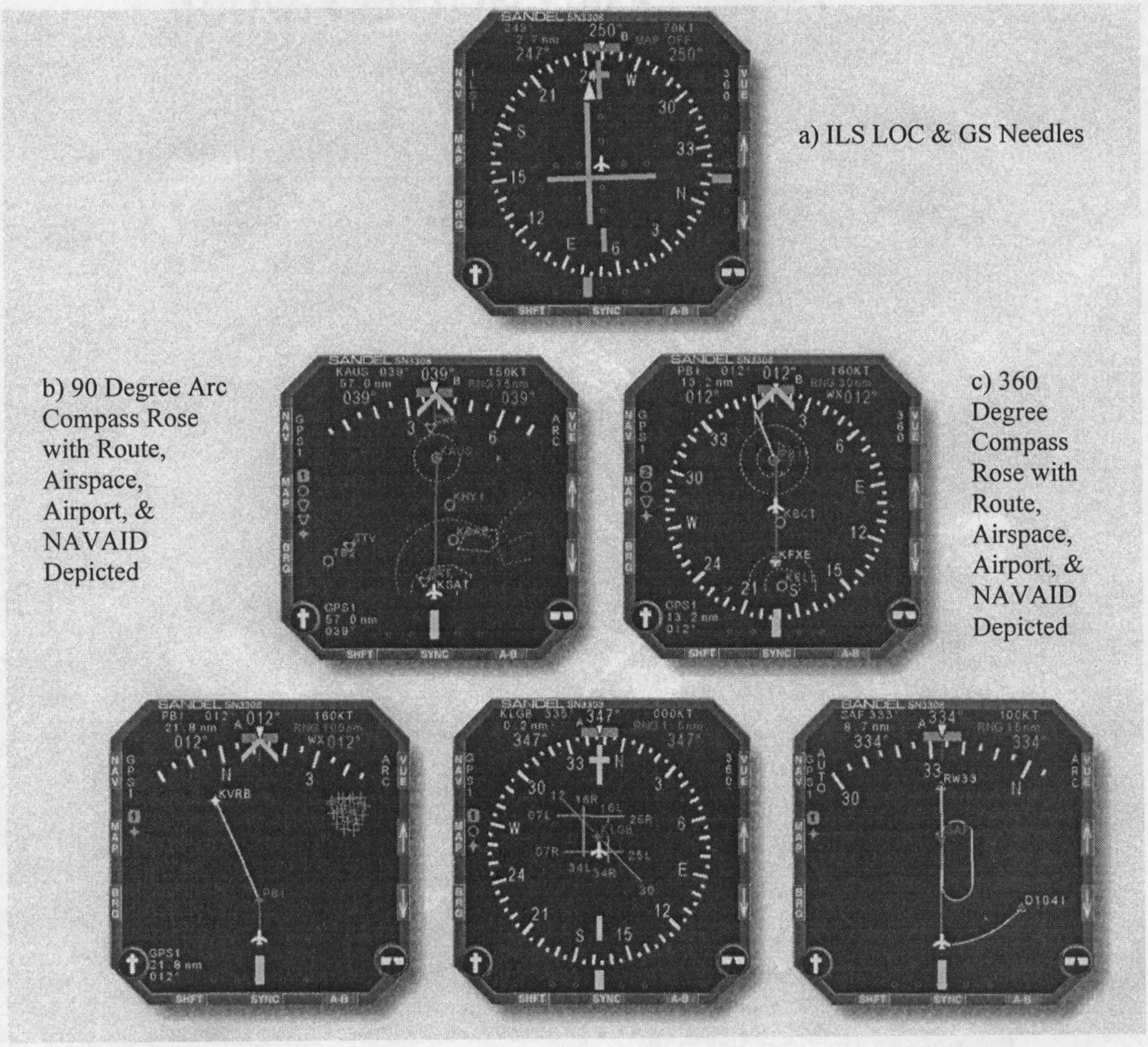


Figure A-8. Sierra Flight Systems' EFIS-1000 Primary Flight Display.

Source: Sierra Flight Systems (1999). "Sierra Flight Systems. Ultimate Situational Awareness. EFIS-1000." Web information from *http://www.sierraflightsystems.com/efis1000.html.* Boise, ID: Sierra Flight Systems. pp. 1.

Figure A-9. Garmin's GNS 530 Integrated Moving Map Display System.

Source: GARMIN (2000). "Garmin: GNS 530." Web information from *http://www.garmin.com/products/gns530/index.html.* Olathe, KS: Garmin International, Inc. pp. 1.



a) ILS LOC & GS Needles

b) 90 Degree Arc Compass Rose with Route, Airspace, Airport, & NAVAID Depicted

c) 360 Degree Compass Rose with Route, Airspace, Airport, & NAVAID Depicted

d) 90 Degree Arc Compass Rose with Route, & Electrical Discharge Symbology Depicted

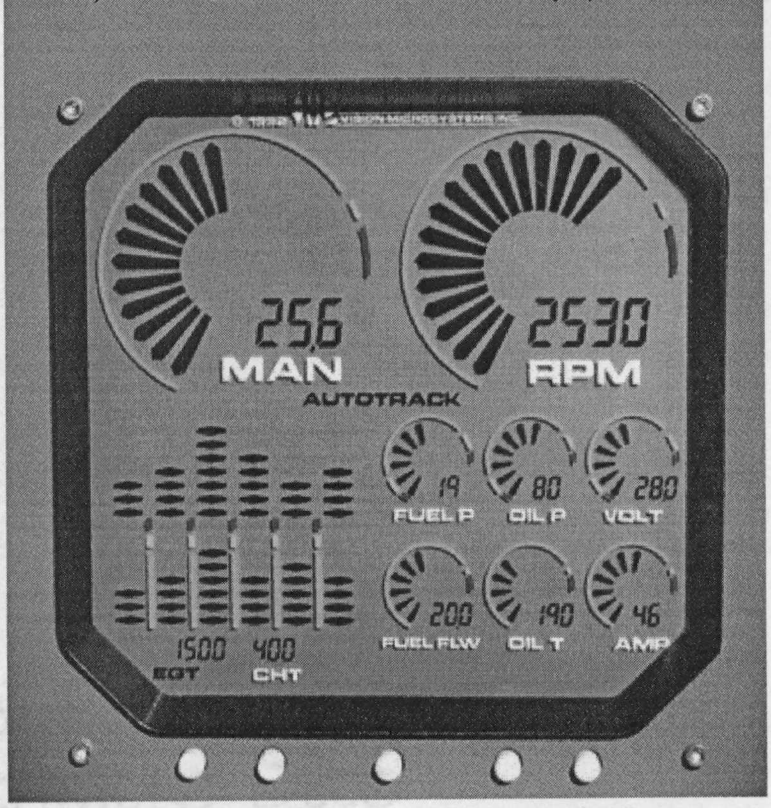
e) 360 Degree Compass Rose with Airport Diagram Depicted

f) 90 Degree Arc Compass Rose with Instrument Approach Course Lines Depicted

Figure A-10. Sandel Avionics' SN3308 Electronic Flight Instrumentation System.

Source: SANDEL (2000, May). "Sandel Avionics SN 3308 Advertisement." *AOPA Pilot.* Vol. 43, No. 5. Frederick, MD: Aircraft Owners and Pilots Association. pp. 103.

a) EC-100 Electronic Checklist & Cautionary System



b) VM1000 Engine Management Instrumentation System

Figure A-11. Vision Microsystems Inc's VM1000 & EC-100 Engine Instrumentation Caution Advisory System.

Source: Vision Micro Systems (1999). "VM1000 Engine Instrumentation Caution Advisory System and EC-100 Electronic Checklist and Cautionary System." Product Literature. Bellingham, WA: Vision Micro Systems Inc. pp. 1.

Figure A-12. Display of Aviation Weather Information.

Source: Horne, Thomas P. (2000, March). "Beaming Up the Weather. Today's Services Portend Tomorrow's Resources." *AOPA Pilot.* Vol. 43, No. 3. Frederick, MD: Aircraft Owners and Pilots Association. pp. 97.

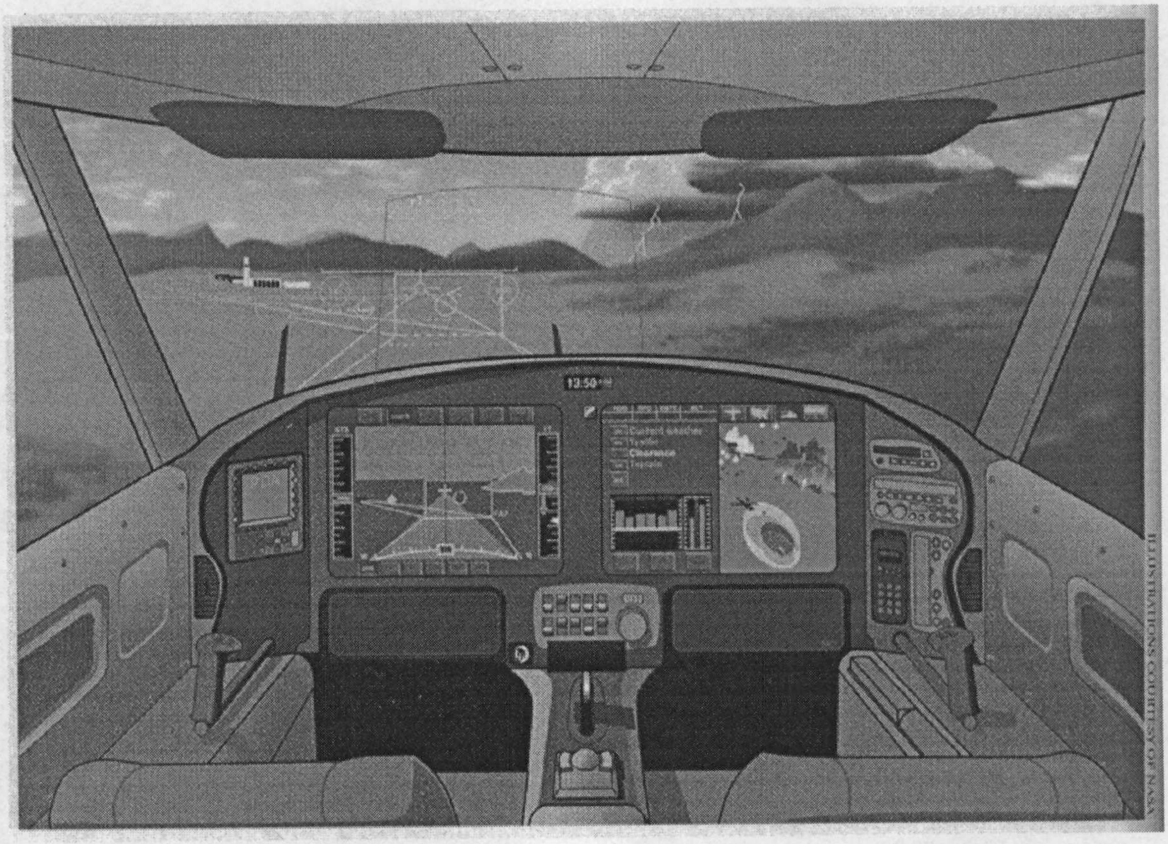


Figure A-13. Advanced General Aviation Technology Experiments' Concept Cockpit Layout.

Source: Marsh, A. K. (2000, January). "Your Future General Aviation Airplane. Where We've Been, Where We're Going." *AOPA Pilot.* Vol. 43, No. 1. Frederick, MD: Aircraft Owners and Pilots Association. pp. 86.

VITA

Brent Kevin George was born in Coldwater, Michigan on March 24, 1965. He graduated as Valedictorian from the Department of Defense Dependent School System's Nürnberg American High School, Nürnberg, Germany in 1982. In 1984, he graduated from the University of Maryland Munich Campus, Munich, Germany with an Associate of Arts degree in General Studies After graduating in 1989 from the University of Maryland University College, College Park, Maryland with a Bachelor of Science degree in Computer Science, he attended Aviation Officer Candidate School in Pensacola, Florida and was commissioned an Ensign in the United States Navy in 1990.

Following his commission, Ensign George entered Naval Flight Officer training in Pensacola, Florida and earned his Navy "Wings of Gold" in 1991 Following his assignment to the EA-6B "Prowler" Command and Control Warfare (C2W) aircraft community, Ensign George attended Electronic Warfare Officer training at Naval Technical Training Center Corry Station, Pensacola, Florida and graduated with distinction in 1991 He was transferred to the EA-6B Fleet Replacement Squadron in Whidbey Island, Washington and was designated an Electronic Countermeasures Officer (ECMO) in 1992 During a three year tour with his first operational squadron, the "Lancers" of Tactical Electronic Warfare Squadron ONE THREE ONE (VAQ-131), he made two western Pacific deployments, in 1992 and 1994, onboard the aircraft carriers USS Ranger (CV-61) and USS Constellation (CV-64).

Lieutenant George's next duty assignment was with the "Vampires" of Operational Test and Evaluation Squadron NINE (VX-9) in China Lake, California where he served as an Operational Test Director conducting operational flight tests on EA-6B "Prowler" and FA-18D "Hornet" aircraft. In 1997, he was selected to attend the U S Naval Test Pilot School (USNTPS) and graduated as an Engineering Test Flight Officer with USNTPS Class 115 in June 1999. Following his graduation from USNTPS, Lieutenant George was assigned to the "Salty Dogs" of Naval Strike Aircraft Test Squadron (NSATS), Naval Air Warfare Center Aircraft Division, Patuxent River, Maryland as Aviation Safety Officer and worked on the developmental flight testing of the EA-6B "Prowler", FA-18B/D "Hornet", and FA-18F "Super Hornet" aircraft. In June of 2000, Lieutenant Commander George transferred back to the "Testers" at USNTPS and is currently a Systems Flight Test Instructor flying in the "one-of-a-kind" NP-3D airborne systems trainer and the FA-18B "Hornet" aircraft

Lieutenant Commander George has over 1,700 hours of flight time, of which more than 1,300 flight hours are in the EA-6B "Prowler" and has flown in over 32 different types of aircraft He is married to the former Kelly Ann Whealan of Chicago, Illinois, and has three sons, Emmett, Kiernan, and Brennan.