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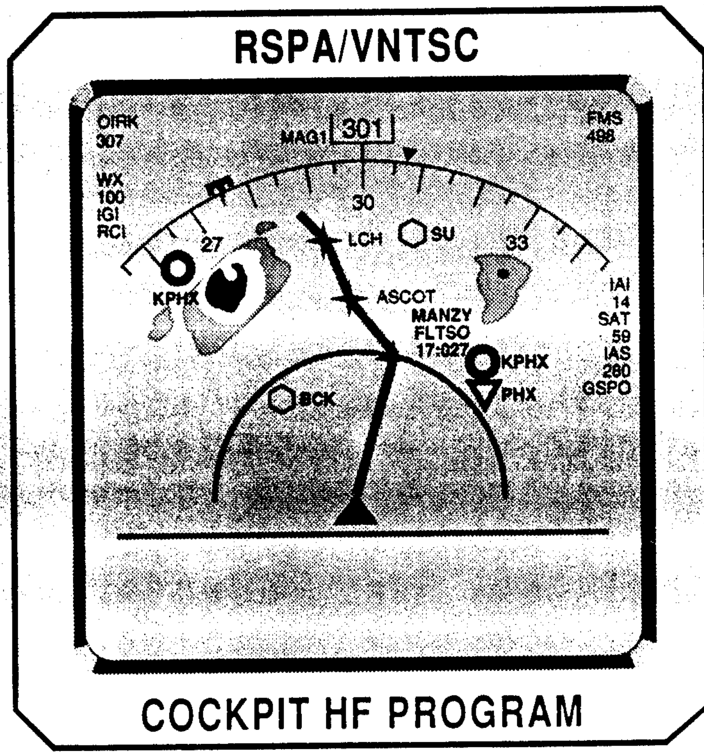
Guidelines for the Design of GPS and LORAN Receiver Controls and Displays



M. Stephen Huntley, Jr.
U.S. Department of Transportation
Research and Special Programs Administration
John A. Volpe
National Transportation Systems Center
Cambridge, MA 02142

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D. Michael McAnulty

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Anacapa Sciences, Inc.*
Military Programs
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13. ABSTRACT (Maximum 200 words)

Long range navigation (Loran) and global positioning system (GPS) receivers are widely used in aviation. The Loran and GPS receivers are similar in size and function but derive their navigation signals from different sources. The design of the controls, displays, and computer logic is usually similar for the two types of receivers from a single manufacturer, but differs substantially among manufacturers. Some or all of the designs may provide a suboptimal human-computer interface, which may result in simple time delays or in serious safety risks if the pilot cannot use the system effectively and efficiently. The design variations also make it difficult to certify receivers for different applications. As a result, the Volpe National Transportation Systems Center has sponsored a program of research to address issues in Loran and GPS receiver design. This report first reviews the literature on user experiences with Loran and GPS receivers and other types of similar, automated equipment. Second, the report reviews the major human factors references, texts, and individual journal articles that are relevant to the regulatory requirements for the receivers. Finally, specific human factors principles and guidelines are proposed for the design and certification of GPS and Loran receiver controls, displays, and control-display integration.

14. SUBJECT TERMS
Global Positioning System (GPS), Long Range Navigation (LORAN) System, Human Factors Design Guidelines, Equipment Controls, Equipment Displays, Control-Display Integration, Human-Computer Interface, Automation Effects

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PREFACE

Long range navigation (Loran) systems and global positioning system (GPS) receivers are widely used in general, commercial, and military aviation. The Loran and GPS receivers are similar in size and function, but they derive their signals from different sources. The control and display designs and computer interfaces used for the two types of receivers are virtually identical for similar products (e.g., hand held versus panel mounted) by a single manufacturer, but there are wide variations among different manufacturers' designs. Some or all of the designs may provide a less than optimal human-computer interface (HCI). The differences may also create transfer problems for users of more than one system and may make it difficult to certify receivers for different applications. The effects of suboptimal design and system variations can range from minor time delays to potentially serious safety risks if the pilot cannot use the system effectively and efficiently.

This report documents a survey of human factors guidelines and standards relevant to the design of displays and controls intended for use with avionics receivers. It provides a basis for the development of guidelines for evaluating such interface media and was prepared as a reference document supporting the *FAA Aircraft Certification Human Factors and Operations Checklist for Standalone GPS Receivers (TSO-C129 Class A).*

This work was sponsored by the FAA's Human Factors program under the Office of Chief Scientific and Technical Advisor for Human Factors.

Dr. M. Stephen Huntley (Volpe Center) and Mr. Donald Eldredge (Battelle) both contributed to the conceptual development of this effort and supplied guidance and relevant literature for the review. Dr. Kenneth Cross (Anacapa Sciences) provided guidance in organizing the literature search, review, and presentation, including a critical review. Ms. Ernestine Pridgen and Ms. Annette Swan (Anacapa Sciences) assisted in collecting the literature. Ms. Pridgen also performed all the word processing and proofread the initial and final drafts of the report.

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (k)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (he) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg)	=	1.1 short tons

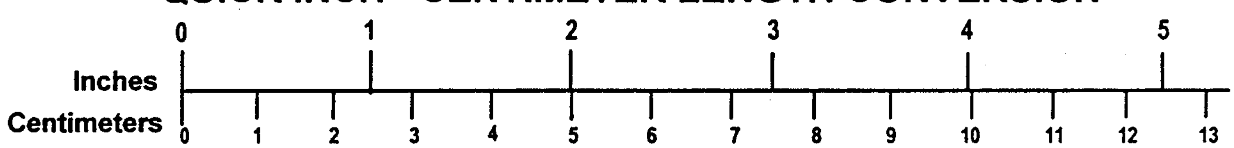
VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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ACRONYMS AND ABBREVIATIONS

AC - advisory circular

AIR - Aerospace Information Reports

ANSI - American National Standards Institute

ARP - Aerospace Recommended Practice

AS - Aerospace Standards

ATC - air traffic control

CDI - course deviation indicator

CRT - cathode ray tube

FAA - Federal Aviation Administration

GPS - global positioning system

HCI - human-computer interface

HFS - Human Factors Society

IFR - instrument flight rules

LCD - liquid crystal display

LED - light emitting diode

Loran - long-range navigation

MIL STD - Military Standard

MTFA - Modulation Transfer Function Area

RAIM - Receiver Autonomous Integrity Monitoring

RTCA - Radio Technical Commission for Aeronautics

SA - selective availability

TSO - technical standard order

VFR - visual flight rules

VOR - very high frequency omnidirectional range

1. INTRODUCTION

1.1 LORAN AND GPS NAVIGATION SYSTEMS

The long-range navigation (Loran) system was developed in the U.S. during the 1940s and was upgraded to the Loran-C system in the 1970s. The system operates multiple chains of transmitters that emit time-synchronized pulses. The Loran receiver measures the difference in arrival times of the pulses from a master and secondary transmitters to determine the two-dimensional horizontal location of an aircraft. The Loran system provides absolute horizontal location accuracy of better than 200 meters and can provide repeatable horizontal position locations of better than 20 m. Areas of useable Loran coverage include almost all of the US but do not extend more than about 325 kilometers beyond land. Loran signals are negatively affected by atmospheric conditions.

Most Loran receivers are currently approved only for navigation under visual flight rules (VFR), although a few are certified for navigation under instrument flight rules (IFR) in the en route and terminal area phases of flight (Huntley, 1990). The first Loran nonprecision approach was flown in 1985 (Boyer, 1991), and 10 Loran approaches were published for public use in 1990 (Haines, 1991). Recently, however, the Federal Aviation Administration (FAA) has committed to instituting nonprecision approaches using the Loran system at 500 airports (Twombly, 1993).

The U.S. Department of Defense subsequently developed and implemented a global positioning system (GPS) in 1994 that operates on the basic principle of measuring arrival times of signals from different locations. In contrast to the ground-based Loran transmitters, however, the GPS uses 21 NAVSTAR satellites (plus 3 orbiting spares) to provide more accurate, three-dimensional location information. Each satellite transmits its exact position and precise time codes, which the receiver computer uses to determine aircraft location. The design accuracy of GPS is within 7.6 m horizontal and 11.7 m vertical (Golbey, 1991). However, the signals available to civil and commercial users are intentionally degraded by the Department of Defense under a Selective Availability (SA) process. Under SA, horizontal positions are accurate to 100 m or better 95% of the time and 300 m 99.6% of the time.

1.2 RECEIVER DESCRIPTION

Numerous manufacturers have developed and marketed Loran receivers, GPS receivers, and combined GPS/Loran units. For each manufacturer, the design of the controls and displays is essentially identical for the three types of receivers. The only apparent difference in most receivers marketed by a single manufacturer in a given category (e.g., hand held versus panel mounted models) is whether they are labeled on the front panel as Loran or GPS. Furthermore, the information provided by each type of receiver is basically the same (Loran does not provide altitude), even though the signals used to determine aircraft position are derived from different sources (i.e., ground versus satellite transmitters) and employ different hardware components and software logic. Therefore, they will hereinafter be referred to collectively as GPS receivers in reviewing the applicable design literature. Loran receivers will continue to be used for several years but eventually the Loran transmitters will be removed from service and only satellite signals will be available to the aircrew.

1.2.1 System Information

The primary purpose of the GPS systems is to provide aircraft location and navigation information to the pilot. The location information includes present horizontal position in degrees, minutes, and seconds of latitude and longitude; and vertical position information about geometric altitude (i.e., not referenced to mean sea level) and rate of altitude change. The navigation information includes bearing and distance to or from a selected waypoint or airport, course deviation, air or ground speed, estimated time en route, and estimated time of arrival. When the GPS system is integrated with other onboard systems and databases, it can provide information to the pilot about barometric altitude, fuel consumption, winds aloft, nearest airports and waypoints, and airport and waypoint data (e.g., location, runway information, and communication frequencies). Although there are variations in the capabilities of some models, most allow the development and preflight entry of flight plans, which can be edited in flight as necessitated by weather or situational conditions and by air traffic control (ATC) instructions. Some systems also present a moving map display showing the legs of the flight plan.

Despite the commonalities in information provided by the GPS systems, there are wide variations among manufacturers in the controls and displays used on the receivers. For example, Driskell and Hughes (1992) reviewed the controls and displays used on six systems, which included at least one of each type of receiver (GPS, Loran, and GPS/Loran). The primary differences among the receivers are summarized in the following two subsections.

1.2.2 System Control Variations

Four of the systems used a push/pull button to turn the receiver on and off. One system used a rotary knob and one used a rocker switch to turn the receiver on and off. One of the on/off push buttons was not labeled to indicate its function. Two of the on/off controls could also be used to adjust the brightness of the display. Three systems automatically adjusted the display brightness using a photosensor and one system did not have a brightness control. All of the receivers used from 6 to 20 push buttons to perform some command and function inputs, with most using from 6 to 10 buttons.

The 20-button system was the only one that used an alphanumeric keypad for data entry. The other five systems used some combination of rotary knobs for data entry or search, one of which could also be pushed to select an item. Two of the receivers had a single set of two concentric, or ganged, knobs for data entry or search. The remaining two receivers each used two sets of two concentric knobs. The double sets of knobs were associated with either a split display screen or primary and secondary display information. However, both sets were used to perform some common functions. In general, systems with more knobs include fewer buttons.

In addition to variations in the type and number of control devices, there were also large variations in the arrangement of common controls. For example, some of the power switches were on the left of the panel, some were on the right of the panel, and one was in the center of the panel. Similarly, some of the on/off controls were in the lower portion of the panel and some in the upper portion of the panel.

1.2.3 System Display Variations

Driskell and Hughes (1992) also described wide variations in the displays used in the six receivers. One used a cathode ray tube (CRT) display screen, one used a liquid crystal display (LCD) screen, and two used a light emitting diode (LED) display screen; the other two display screen types were not reported. Two of the display screens were divided either into separate pages of equivalent levels of information or into primary and secondary display information. All the displays contained multiple pages for at least one information mode. For example, the number of rows of information ranged from one to five. The number of characters per row on two of the systems was 16 and 22; the number of characters per row was not reported for the other systems. The format of the data displayed on the six receivers was not described in detail by Driskell and Hughes.

There were also variations in the number of indicator, annunciator, and alert or warning lights in the displays. The receiver that has a keypad entry has only one indicator light, which flashes when a message is available. The receiver also generates an audible tone to alert the pilot that a message is waiting. A tone also sounds each time the pilot presses a key and a tone indicates that inappropriate data have been entered in a field. However, the tones can be turned off by the pilot. The other five receivers have between four and eight indicator lights, most of which indicate the current mode of operation. One receiver has four dedicated lights to alert the pilot about special use airspace, waypoints, extended range operation, and system problems. The remaining systems alert the pilot to a waiting message, which provides similar alert information.

1.3 USER EXPERIENCE

Two types of user experience literature are relevant to GPS system design: the general effects of automation on pilot performance and specific reports on GPS use. Automation is a broadly defined term (Wiener, 1988, calls it ill defined) that includes the automated flight control systems; continuously available navigation aids; and the acquisition, computation, and presentation of critical flight information.[1] Billings (1991) divides the concept into control automation, information automation, and management automation. However defined, the principal objectives of automation are to reduce aircrew workload, reduce flight errors, and improve the safety and efficiency of flight. As such, the Loran and GPS technologies represent forms of navigation automation. Depending on its integration with other onboard systems, the GPS may also affect the flight control and information computation functions. Therefore, the experience of pilots with other forms of aircraft automation are relevant to GPS design issues.

1.3.1 Automation Effects

Different forms of automation have been developed since World War I (Pallett, 1983) and routinely used in military and civil air transport since World War II (Billings, 1991). Norman and Orlady (1988; pp. 167-173) have traced the development of aviation automation from early gyroscopic stabilizers through autopilots, radio and inertial navigation systems, and flight directors to the current "glass cockpit." Technological developments (e.g., small computers and CRT displays), more demanding flight environments (e.g., all weather, high speed, congested airspace), and economic efficiency (e.g., shorter flight times and smaller aircrews) have driven the development of automation. GPS and Loran navigation systems are part of that technological continuum.

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[1] The automation of the ATC system is also a factor in flight automation but is not treated as a separate topic here.

Automation has met many of its objectives. Although there are numerous factors that can affect accident data, aircraft with increasing levels of automation appear to have a reduced rate of crew-caused accidents per million departures (Norman & Orlady, 1988, p. 11). The crew size of many commercial aircraft has been reduced by at least one and sometimes two crewmembers. Automation has also relieved the crew from many routine responsibilities and increased flight precision under many circumstances (Wiener & Curry, 1980).

However, automation has produced some negative effects. Norman and Orlady (1988) noted that automation introduces new types of errors and breakdowns, especially when the crew is not adequately trained and coordinated in its use of the automated systems. Automation also changes the roles, tasks, and needed skills for the crewmembers without changing their responsibilities. They also found that automation is best suited to normal operations and that navigation automation is more troublesome than aircraft subsystem automation (e.g., autofuel).

Wise, Guide, Abbott, and Ryan (1992) surveyed 421 corporate pilots flying aircraft with different levels of automation. The pilots generally had a positive attitude about automation, but they identified several problems with the current systems. They found the programming procedures to be complex, difficult to learn, and prone to error. A related problem was the generally poor training they received on using the automation. They also reported that the automation increased the need for crew coordination. Perhaps most importantly, they reported the "paradox of automation": reducing workload when it is already low (e.g., en route straight and level flight, producing boredom, complacency, and loss of situational awareness) and increasing workload when it is already high (e.g., having to reprogram the automation in response to ATC instructions while in the terminal area).

Both the advantages and disadvantages associated with automation in general probably apply to automated navigation systems such as the GPS. Compared to manual navigation or to point-to-point, ground-based systems such as very high frequency omnidirectional range (VOR) transmitters, GPS navigation systems produce reduced workload (for most phases of a flight), greater route precision, and more efficient operations (i.e., the pilot can fly directly to the destination without following Federal airways). The problems of operational complexity, adequacy of training, and crew coordination are also likely to affect the use of GPS receivers. Finally, the workload paradox is of particular concern. During low workload periods, the crewmembers may not maintain a sufficient level of navigation awareness to resume manual navigation if the system fails. During high workload periods, they may be required to reprogram the flight plan (e.g., changes to the ATC approach clearance) under adverse weather conditions and high time pressure when the traffic density dictates that they give maximum attention to the external environment.

1.3.2 GPS User Experience

Although the U.S. military has been using the GPS for some time, there is very little published research literature about its utility. Most of the reports or articles address its potential accuracy (e.g., Golbey, 1991) rather than the results of operational experience. An exception is an FAA test of GPS instrument approaches. The participating pilots reported they were favorably impressed with both the ease of operation and the accuracy of the navigation information (Horne, 1993). The only serious problem encountered during the intentionally difficult approach was with premature switching of waypoints (i.e., the display indicated waypoint passage prior to reaching the actual fix location).

More user experiences have been reported for the Loran system. Huntley (1990) conducted both laboratory and flight tests of Loran-C receivers. He found that the Loran was a functionally more powerful navigation system than the VOR system. However, he also found that it was more difficult to use, more prone to pilot error, and less error tolerant. Some of the major design problems he identified include error-inducing control locations, time-consuming data entry procedures, system logic that makes it difficult to detect and correct data entry errors, and a lack of in-flight guidance on system operation. He also found that the sensitivity of the course deviation indicator (CDI) was not optimal for some applications, that the display capability was inadequate for extreme viewing conditions, and that the data entry logic was inconsistent with ATC standard communication procedures. He recommended that the user interface be redesigned and to a limited degree standardized, and that the user be better educated about Loran system operation and limitations.

Adams. Adams. Eldredge. & Huntley (1993) conducted a survey using a written questionnaire and structured interviews with 77 pilots about their experience using Loran and GPS systems (only 4 had used the GPS). The sample included fixed and rotary wing aviators. air carrier and corporate pilots, civil and U.S. Coast Guard search and rescue pilots, and general aviation pilots who fly for both business and pleasure. The pilots reported the systems provided sufficiently reliable and accurate navigation information for VFR, en route, and point-to-point flight, but only the best trained (Part 135 offshore operators and Coast Guard pilots) indicated the information was sufficient for IFR or approach purposes. Many of the pilots expressed concerns about becoming so reliant on the system during routine flight phases that they failed to notice system problems and that they were unprepared to revert quickly to other navigation methods when required (e.g., system failure, IFR conditions, emergencies).

The pilots also identified several problems related to control and display design, system logic, and support materials that resulted in significant underutilization of the system and the increased potential for system-induced pilot errors. Because of the complexity of system operation, many pilots reported they only used some of the more simple and necessary functional capabilities of the system; they also tended to revert to less complex navigational systems (e.g., VOR) when the workload became high. The potential consequences of these problems ranged from minor inconveniences and time delays to serious safety risks.

Some of the problems are directly a function of the design of the system controls and displays; others are more a function of the system logic and support materials, but they have design implications for the controls and displays. The primary design problems are described in the following paragraphs.

- The controls are difficult to learn to use and the procedures are difficult to remember unless used frequently. Partly, this problem is caused by software and function organization that is not intuitive or operations oriented. It is also caused by control input design, arrangement, and labeling. The problem is especially severe for multifunction and concentric controls. For example, not all of the multifunction knobs are labeled, and the labels associated with concentric controls do not necessarily apply to both knobs.

- The control designs lead to pilot errors, such as inadvertent control inputs or data erasure. In some systems, for example, pressing the clear button once backspaces over the last character entered; pressing it twice in succession erases the entire field or the entire data page. This problem is most serious under high workload conditions and in turbulence, times when the pilots can least attend to their inputs and are least likely to notice the errors or have the time to correct them.

- The displays are not visible under extreme lighting conditions and critical information is not adequately annunciated. Indications of system failure or degraded operation can go unnoticed for extended periods while the pilot continues to navigate using the displayed information. This problem is compounded by the usual location of the system display, which is normally on the periphery of or outside the pilot's primary field of view.

- The lack of control and display standardization creates problems for pilots who fly aircraft equipped with different systems. This problem not only increases the effort required to learn each system, but also creates confusion in remembering how to operate each system, thus increasing the potential for underutilization and operational errors.

- All of the problems are exacerbated by the reported inadequacies in user's manuals and by the lack of handbooks, checklists, training tutorials, and instructor pilot knowledge.

Adams, Adams, Eldredge, & Huntley (1993) concluded with three primary recommendations for addressing the major problems they identified. First, they recommended that a comprehensive study be conducted to determine the principles and guidelines, possibly including standardization requirements, for designing controls and displays. Second, they recommended an analysis and redesign of the system software logic and functional organization. Third, they recommended improvements in the training and operating materials used by pilots. Implementing the first recommendation is the objective of the current research.

1.4 PROJECT OBJECTIVES AND UTILIZATION

Design trade-offs, such as selecting between two control input methods, are made for various reasons, including cost, availability of hardware, and functionality. The weight given to each of these factors in the equipment design process may result in various design outcomes. The variety of control and display designs that result from these considerations are indicative of two potentially serious problems. First, at least some and possibly all of the designs may result in a less than optimal human-computer interface (HCI). That is, the controls may be designed in ways that make user inputs unnecessarily complicated or inefficient. Equally important, the displays may be designed in ways that make it difficult for the user to obtain, perceive, and process the information the system provides. The design problems may result only in delays in using the information or they may result in critical errors in piloting and navigating the aircraft. Second, differences in design may create confusion for operators who use more than one system. In addition, design differences make it difficult for the FAA to evaluate and certify the systems for purposes such as en route navigation, terminal operations, and instrument approaches.

Therefore, this research is intended to identify ergonomic information that is relevant to the design of controls and displays on GPS receivers. The ergonomic information will provide practical guidance to system designers so the controls and displays will optimize system utilization rather than detract from it. The information will also provide a basis for greater consistency across the receiver designs so that pilots will be better able to use more than one system without negative transfer of procedures.

The results of this research are also intended to support certification evaluations of GPS receivers by identifying and discussing relevant certification criteria and standards to be used in conjunction with the *Human Factors Checklist for Standalone GPS Receivers*. The checklist is to be used by FAA certification specialists when they evaluate GPS receiver conformance to the requirements in Technical Standard Order (TSO) C-129, RTCA/DO-208, and other regulatory and advisory documents. Some of the items in the checklist are self-explanatory and can be objectively evaluated (e.g., "Are labels printed in all capital letters without punctuation?" or, "Can a single control action activate the Direct-To function?"). However, many others require the specialist to make subjective judgments about the receiver design (e.g., "Is the spacing between label words adequate?" or, "If knob diameter is used as a coding parameter, are the differences between knobs noticeable?"). The information in this report is designed to be a resource for the certification specialist to understand the human factors issues involved in receiver design and to provide specific principles and, in some cases, objective criteria that can be applied if the appropriateness of a given design is not apparent through inspection and operation. For example, the report discusses the guidelines for labels and exceptions to them, and specifies the minimum size of control knobs and the minimum spacing between label words if there is doubt about these design attributes.

When using specific standards for a single control, display, label, etc., however, the certification specialist should consider the total receiver attributes and allow for compensatory characteristics. For example, a single control may be slightly smaller than the standard, but its small size can be compensated for by additional spacing between controls. Unless the size was so small that the control could not be operated effectively, the receiver could still be certified. If both size and spacing for the control were below the standards, or if all the controls were of inadequate size, then the receiver should not be certified. The information in this report should be used as a resource for understanding design issues and for implementing the more global design objectives of the regulatory documents, but not as an absolute criterion for certification. In many cases, there are small differences in the design guidance cited from different references and much of the supporting research for the guidance is not based on GPS receiver or aviation equipment applications. Nonetheless, it is the best available guidance, and recommendations for GPS receivers were selected to be conservative.

1.5 REPORT ORGANIZATION

The remainder of this report is organized into three major sections. The Method section describes the constraints that were used to select the relevant literature, identifies the literature that was included in the review, and establishes the order of precedence for employing the literature to develop design guidelines. The Results section is divided into four major subsections. The first subsection describes the regulatory and advisory requirements that apply to GPS receivers. The second and third subsections present the literature and recommended guidelines for the design of GPS controls and displays, respectively. The fourth subsection describes design guidance for control-display integration. The final section of the report summarizes the findings of the literature review, itemizes general principles for control and display design, and summarizes the limitations in using this research document.

2. METHOD

2.1 CONSTRAINTS AND ASSUMPTIONS

Five constraints were applied in selecting literature and developing design recommendations. The first two constraints are dictated by the operational environment. First, the GPS system is limited in the space it can occupy in the cockpit; Huntley (1990) reported that the controls, alerts, and alphanumeric displays of most receivers are confined to a front panel area of no more than 12 to 18 square inches (77.4 to 116.1 cm^2). As a result, the number and size of controls and display characters or symbols that a receiver can accommodate are also limited. The literature reviewed was therefore restricted to information that is appropriate to small avionics devices. Second, there is a regulatory requirement that controls must be operated with one hand. Therefore, only controls that are appropriate by virtue of their size, shape, location, or force required to activate are evaluated in the review.

The third constraint is based on current usage and the limited potential for future usage of color in the GPS display. None of the systems reviewed by Driskell and Hughes (1992) was reported to use color for coding display information; the manufacturers' literature reviewed in this effort showed only one system that used colored lights as annunciators. Color coding can be beneficial in complex displays (e.g., Jubis, 1991; Stokes & Wickens, 1988) and may be considered for use in future GPS systems. However, color interacts with other visual factors and may not improve performance (e.g., Calhoun & Herron, 1981) or may even degrade it (e.g., Boff & Lincoln, 1986; Carter, 1979).

For example, the perception of color is affected by ambient lighting conditions (e.g., Military Standard [MIL STD] 1472D, 1989), which may vary in the cockpit from red light at night to extremely bright sunshine during the day. CRT displays are unable to reproduce saturated colors, which makes them even more difficult to perceive under adverse ambient light conditions (Helander, 1987). Color discrimination is not as good in small areas of a CRT as in large areas (American National Standards Institute Standard ANSI/HFS 100-1988, 1988). Color also changes the contrast between a character or symbol and its background (Woodson, Tillman, & Tillman, 1992). Color can only be perceived within 30° of the center of the fovea. Finally, individuals who suffer from various color vision deficiencies may have difficulty discriminating color displays (e.g., Mangold, Eldredge, & Lauber, 1992). Cardosi (in preparation) reported that 3% of private pilots, 2% of commercial pilots, and 1% of airline transport pilots have color vision deficiency, and that the ability to distinguish different colors decreases with age. Boff and Lincoln (1988) found that subjects who were 35 years old or older made more errors in reading colored LED displays than younger subjects.

For the reasons indicated, the (voluminous) literature related to color coding of display information was not reviewed in detail. Instead, only basic guidelines about the use of color for coding controls and displays are summarized. Additional principles and guidelines for the use of color in electronic displays are available in sources such as MIL STD 1472D, ANSI/HFS 100-1088 (1988), Aerospace Recommended Practice (ARP) 1782, and ARP 4032.

The last two constraints are contractual. The fourth constraint is that the review is directed only toward stand-alone receivers. Many GPS receivers can be integrated with other onboard systems or instruments to obtain input data (e.g., barometric altitude), to annunciate system status and messages closer to the pilot's primary line of sight, to display navigation information (e.g., on an external CDI or horizontal situation indicator), or to provide flight control guidance (e.g., input to the autopilot). The current review does not include the controls and displays used on or required for integration with the other onboard systems or instruments. The final constraint is that this review is directed only at the design of the controls and display characteristics, not at the software logic or the information requirements in the display.

In addition to the constraints and assumptions that were used to select the literature and to organize the report, a caveat is added here about the interpretation and use of the principles and guidelines identified in the review. Although some of the principles and guidelines identified were based on aviation-specific research, many were based on research and experience in designing other types of systems and extrapolated to the aviation (and small avionics device) environment. Additional research may be required to verify the principles and guidelines or to develop new ones where appropriate information is not available.

2.2 LITERATURE REVIEWED

Literature related to the design of GPS controls and displays was collected from multiple sources for review. First, current regulatory and advisory information was collected from the Department of Transportation (e.g., Technical Standard Orders [TSOs] and Advisory Circulars [ACs]), the Radio Technical Commission for Aeronautics (e.g., RTCA Document Number DO-208), and the Society of Automotive Engineers (e.g., ARPs, Aerospace Standards [ASs], and Aerospace Information Reports [AIRs]). Second, the major design reference works were collected, such as MIL STD 1472D and other military standards, the *Engineering Data Compendium* (Boff & Lincoln, 1988), the *Handbook of Human Factors* (Salvendy, 1987), the *Human Factors Design Handbook* (Woodson, Tillman, & Tillman, 1992), and the *Human Engineering Guide to Equipment Design* (Van Cott & Kinkade, 1972). ANSI/HFS 100-1988 was also included as a reference work, although it is currently being revised (Malone, 1993).

Third, relevant human factors texts were collected for review, including Hawkins (1987), Jensen (1989), Kantowitz and Sorkin (1983), McCormick (1976), Roscoe (1980), Wiener and Nagel (1988), and Wickens (1984). Four of the texts are directed specifically toward aviation applications. Fourth, a computer search and a manual abstract search were conducted to identify relevant professional journal articles, published conference proceedings, and technical reports. The computer search was based on the keyword string "Design of controls and displays for avionics equipment." The identified articles, proceedings, and reports were collected for review.

Finally, recent issues of user oriented publications, such as *AOPA Pilot* and *GPS World*, were searched for relevant articles. Manufacturers' information that was advertised in the publications and the operator's manuals for two GPS systems were also ordered for review.

2.3 ORDER OF PRECEDENCE

In general, there is reasonable consistency across the various sources of information about control and display design, although no one source contains exhaustive information and there are differences in level of detail in the sources. Therefore, an order of precedence was developed for identifying source materials that were used to develop the design recommendations. Regulatory and advisory material was accorded the first priority because of its mandatory requirements and specificity to the project objectives. However, much of the information is general in nature (e.g., avoid inadvertent system turn off); other sources were then searched for design guidance that would implement the general directive.

Second priority was accorded to the major reference works because of the extent of their coverage and because they are generally based on the experimental evidence reported in professional journals, proceedings, and technical reports. Within that group, the reference works with the broadest scope, most relevant material, and most recent information were used as primary citations. Unless contradictory information was identified in the other references, MIL STD 1472D was used as the primary source. If sufficient information was not available in MIL STD 1472D, other military standards, specifications, and handbooks, and the major reference handbooks (Boff & Lincoln, 1988; Salvendy, 1987; Woodson, Tillman, & Tillman, 1992; Van Cott & Kinkade, 1972) were used as primary sources.

As a third priority, human factors texts and individual research articles and reports were used to interpret and support (or reject) the information identified from the other sources. This literature generally is relatively narrow in scope but provides more detail about specific issues and about the research that was performed to evaluate the effects of design alternatives. This literature also contains the most recent findings that are not included in the regulatory publications or reference works. The relevance, recency, generalizability, and quality of the research reported in these articles were considered in deciding whether to include them in the design recommendations.

3. RESULTS

3.1 REGULATORY AND ADVISORY REQUIREMENTS

The two primary regulations for GPS receiver design and operational use are RTCA DO-208 (1991), entitled *Minimum Operational Performance Standards for Airborne Supplemental Navigation Equipment Using the Global Positioning System (GPS)*, and TSO C129 (1992), entitled *Airborne Supplemental Navigation Equipment Using the Global Positioning System (GPS)*. Many of the operational requirements stipulated in these documents address the types of information the system must provide, the conditions under which it must be displayed, the amount of error that is acceptable, and the resolution of the information displayed (e.g., a pilot selectable numeric display of cross-track deviation to at least ± 20 nmi with a minimum resolution of 0.1 nmi up to 9.9 nmi and 1.0 nmi beyond). The functional information and resolution requirements are straightforward and can be directly evaluated by a certification specialist. The requirements that are explicit in DO-208 and TSO C129 are not addressed further in this report.

RTCA DO-208 contains nine minimum operational requirements that directly affect the design of the system controls and displays. Three of the requirements are supplemented or modified by requirements in TSO C129. These requirements are open to interpretation or need additional information for the design and evaluation process. The nine regulatory requirements (and their paragraph numbers) are quoted below; the supplemental requirements are added in parentheses at the end of the quotation. The requirements are grouped according to their control, control/display, and display application rather than their order of presentation in the source documents.

3.1.1 Control Characteristics

The following four requirements apply to control characteristics. They specify general requirements for safety protection, the availability of controls, and operational effectiveness criteria.

- (3.1.4) There shall be minimal risk of inadvertent turnoff.

- (4.1.3) Each cockpit control required for proper operation of the equipment shall be available for use.

- (2.1.4) Controls intended for use during flight shall be designed to minimize errors and, when operated in all possible combinations and sequences, shall result in a condition whose presence or continuation would not be detrimental to the continued performance of the equipment. (Controls shall be designed to maximize operational suitability and minimize pilot workload. Reliance on pilot memory for operational procedures shall be minimized.)

- (2.1.5) Controls that are not normally adjusted in flight shall not be readily accessible to the operator. (Controls that are normally adjusted in flight shall be readily accessible to the operator and properly labeled as to their function).

3.1.2 <u>Control/Display Capability</u>

The following two requirements apply to control/display capabilities. They specify general requirements for operational suitability and visual perception.

- (2.1.7) A suitable interface shall be provided to allow data input, data output and control of equipment operation. It shall be possible for the operator to manually select waypoint(s). The control/display shall be operable with the use of only one hand.

- (2.1.8) The equipment shall be designed so that all displays and controls shall be readable under normal cockpit conditions and arranged to facilitate equipment usage. (The equipment shall be designed so that all displays and controls shall be readable under all normal cockpit conditions and ambient light conditions [total darkness to bright reflected sunlight]).

3.1.3 Display Characteristics

The following three requirements apply to display characteristics. They specify general requirements for displayed information and the visibility of the displays. The first and last requirements overlap with the excluded requirements for specific information, but were included in this listing because they provide an umbrella regulation for identifying specific principles and guidelines for displaying navigation and alert or warning information.

- (2.2.1.13.2) The GPS equipment must give a clear and timely annunciation of alarm for each phase of flight.

- (3.1.2) The appropriate flight crew member(s) shall have an unobstructed view of displayed data when in the seated position. Displays used for maneuver anticipation and for failure annunciation shall be located within the pilot's primary field of view. The brilliance of any display shall be adjustable to levels suitable for data interpretation under all cockpit ambient light conditions ranging from total darkness to reflected sunlight.

- (4.1.2) Each of the required displays for determining position and relationship of the airplane to the desired course shall be available for use.

3.1.4 Summary

The regulatory requirements listed in this section are, in many ways, system objectives rather than guidelines that an engineer could readily use to design a GPS receiver or that a certification specialist could use to evaluate a receiver. They specify that all the controls, displays, and annunciations needed by the pilot to navigate the aircraft should be readily available (and unnecessary ones not available or protected), and that they should be usable and effective under all expected conditions without placing excessive demands on the pilot's workload, sensory, or memory capabilities. The following two subsections provide more specific principles and guidelines that can be used to meet the design objectives.

3.2 PRINCIPLES AND GUIDELINES FOR CONTROLS

The principles and guidelines for controls are presented in four parts. The first part describes the control types that are appropriate for use on the GPS receiver. The selection of appropriate controls is based on the functions each is designed to perform and the suitability of the control for the avionics panel. The second part describes the desirable characteristics of the selected controls. The characteristics include the size, shape, spacing, coding, feedback, and movement of each control. The third and fourth parts describe principles and guidelines for arranging the controls on the receiver (and the receiver in the cockpit) and for labeling the controls.

3.2.1 Control Types

The controls on the GPS receiver are used for two basic purposes: to input system commands and to perform system functions. The command controls are used to turn the system on and off, move the display cursor, shift operating modes (e.g., navigation, flight planning, and auxiliary modes), retrieve navigation information (e.g., to initiate navigation directly to or from a waypoint), activate or delete data entries (e.g., change to a new waypoint), and respond to system messages, alerts, and warnings (e.g., system malfunction or entry into restricted airspace). Most commands involve discrete activation of a limited number of alternatives.

The function controls are used to select modes,[1] scroll through pages within a mode, scroll through information in a database, and enter data into the receiver computer (e.g., waypoint identifiers, latitude and longitude, flight plans, and barometric altitude). Most functions involve the search for or entry of one of a relatively large number of discrete alternatives (e.g., the digits 0 - 9 or the 26 characters of the alphabet). Although some functions may

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[2] Exactly what constitutes a mode varies between receivers as does their terminology as to whether mode selection is a command or a function. Mode selection is included in both categories but is distinguished by whether there are only a few modes available (command) or numerous modes available (function).

have very few alternatives (e.g.. the sensitivity of the CDI). most function controls must be capable of rapidly traversing the entire range of alternatives. There appear to be no requirements for continuous control manipulations.

Although there are useful design distinctions between command and function controls, they are seldom utilized in isolation. That is, a command control may be used to select a mode, a function control may be used to modify the data displayed for the mode, and then a command control may be used to implement the modification. The primary distinction between them in selecting the appropriate controls, and the desirable characteristics of the selected controls, is in the number of alternative positions, values, or actions the control is used to manipulate.

There is no universal set of guidelines and principles that can be used to select controls, nor is there a well established theoretical basis for selecting between linear and rotary controls (Kantowitz & Sorkin, 1983). However, ARP 4102 expresses a preference for key and rotary controls over thumb wheels and slew controls. ARP 4102 also stipulates that the number of different types of controls should be minimized for an application and that their actuation and related effect should be standardized as much as possible.

Foot-operated controls and large, hand-operated controls, such as cranks, levers, and handwheels, are obviously inappropriate for use on GPS receivers because of their size, their control-display relationships, and the force needed to operate them. ARP 4102 and MIL STD 1472D both describe the permissible uses of the various types of controls that are applicable to GPS receivers, such as push buttons, push-pull buttons, toggle switches, rocker switches, slide switches, rotary knobs, concentric knobs, and keyboards, but neither makes a direct comparison between the different types. However, several of the reference works (e.g., Boff & Lincoln, 1986; Bullinger, Kern, & Muntzinger, 1987; McCormick, 1976; Chapanis & Kinkade, 1972,; Woodson et al., 1992) contain tables that compare the desirability of the control types for performing different functions. These tables were used to identify the appropriate control types for meeting the GPS command and function requirements.

3.2.1.1 Command Control Types - For discrete activation or for discrete cycling through a limited number of alternatives, the push button is an acceptable control in all the tables and the most preferred control in the tables that designate levels of preference. MIL STD 1472D states that push buttons should be used when a control is needed for momentary contact or for activating a locking circuit. The push button is also recommended when an array of controls is required, which is appropriate for the multiple command requirements of the GPS receiver. The standard also states the push button is particularly appropriate for controls that are used frequently. Many of the commands on the receiver (e.g., mode shift, enter, and clear) are frequently used. Chapanis and Kinkade (1972) indicate that push buttons require minimal time to make control settings, have minimal requirements for space, and are effective for operating with similar controls in an array.

Discrete push-pull buttons may also be used for command applications, but they should be used sparingly and in applications where they are typically expected, such as turning a system on and off. MIL STD 1472D also indicates that, when panel space is limited, a miniaturized knob may be used to serve two related but distinct purposes, such as on-off and adjusting audio or video levels.

Toggle switches and rocker switches are acceptable alternatives to the push button, but they are generally restricted to two-alternative applications. Toggle switches should be used instead of push buttons only when space limitations are severe. They should not be used as three-position controls unless other alternatives are infeasible or when the switch is a spring-loaded type with the center position representing the off condition. Rocker switches are an acceptable alternative when the protrusion of the toggle switch may result in inadvertent activation. However, three-position rocker switches should only be used if the control is spring-loaded to the center off position.

The ergonomic considerations for selecting command controls are summarized in Table 3-1.

3.2.1.2 Function Control Types - The tables also consistently indicate that rotary switches and knobs are optimal for continuous adjustments and for selecting discrete or quantitative

Table 3-1. Ergonomic Considerations in Selecting Command Control Types

Control Type	Ergonomic Considerations
Push Button	Preferred for discrete activation or momentary contact Use to cycle through a limited number of alternatives Use when an array of controls is required Requires minimal space and time to operate Provides minimal feedback about activation Difficult to determine setting unless back lighted
Push-pull Button	Use sparingly and in applications where expected With limited space, a miniature knob can be used for two related purposes (e.g., on-off and video adjust) Requires minimal space and time to operate Provides moderate feedback about activation Moderately easy to determine setting
Toggle Switch	Use when space limitation is severe Restrict to two positions unless spring loaded to center off position Provides good feedback about activation Easy to determine setting Guard against highly possible inadvertent activation
Rocker Switch	Use when space limitation is severe Restrict to two positions unless spring loaded to center off position Provides moderate feedback about activation Moderately easy to determine setting Do not intermix toggle and rocker switches Guard against possible inadvertent activation

Note. Compiled from Boff and Lincoln (1988); Bullinger, Kern, and Muntzenger (1987); Chapanis and Kinkade (1972); Military Standard 1472D (1989); and Woodson, Tillman, and Tillman (1992).

settings with numerous positions (e.g., McCormick, 1976). The recommended number of position alternatives is from 3 to 24 (Chapanis & Kinkade, 1972). MIL STD 1472D states they should be used for selecting 3 or more detented positions when low forces or precise adjustments are required. They are rated as medium to quick in time to make the control setting and have medium space requirements, but are poor in effectiveness for operating similar controls in an array. However, ganged knobs may be used in limited applications when panel space is severely limited, but there is a major risk associated with their use.

They are susceptible to inadvertent activation of one knob while the other knob is being manipulated.

None of the major reference works or human factors texts considers keyboards in their comparisons of control types, yet they are widely used for one of the major functional requirements of GPS receivers; data entry. Hawkins (1987) reports that the use of keyboards on the flight deck has been increasing steadily, probably reflecting the increased use of computer systems in the cockpit. MIL STD 1472D states that keyboards (defined as an arrangement of push buttons) should be used when alphabetic, numeric, or special function information is to be entered into a system.

The ergonomic considerations for selecting function controls are summarized in Table 3-2.

3.2.2 Command Control Type Characteristics

The reviewed literature provides numerous, but generally consistent, recommendations for designing the controls that were identified as being appropriate for command and function controls. The major characteristics these sources indicate that are desirable for each identified control are enumerated in the following paragraphs. Any differences in the recommendations from the various sources are noted and potential resolutions to the differences are discussed.

As previously mentioned, these characteristics include the size, shape, spacing, coding, feedback, and movement of each control. The recommendations presented assume that the

Table 3-2. Ergonomic Considerations in Selecting Function Control Types.

Control Type	Ergonomic Considerations
Rotary Knob	Use for continuous adjustments Use to select discrete settings with numerous positions Requires low force and has high precision Control movement unlimited if no stops Moderately fast to make control setting Requires moderate space Poor operation as part of an array Guard against possible inadvertent manipulation
Concentric Knobs	Use sparingly and only when space is severely limited Requires low force and has high precision Control movement unlimited if no stops Guard against probable inadvertent manipulation
Keyboard	Use to enter alphabetic, numeric, or special function information As an array of push buttons, the same ergonomic considerations apply (see Table 3-1)

Note. Compiled from Boff and Lincoln (1988); Bullinger, Kern, and Muntzenger (1987); Chapanis and Kinkade (1972); Military Standard 1472D (1989); and Woodson, Tillman, and Tillman (1992).

controls will be mounted on the receiver panel face and operated in the vertical plane with respect to the pilot. That is, recommendations for controls operated in the horizontal plane are not presented. The recommendations also assume that the pilot will manipulate the controls with one finger (e.g., push buttons and keypads) or with the forefinger and thumb encircled (e.g., push-pull buttons or rotary knobs). Finally, the recommendations presented assume that the pilot will not be wearing gloves when operating the controls.

3.2.2.1 Push Buttons - Push buttons are universally used in the currently available GPS and Loran receivers, and are the preferred control for making command inputs. Because they are usually limited to two positions (although they may be used to cycle through a larger number of alternatives), the primary ergonomic considerations in the design of push buttons are their size and spacing. These considerations are intended to insure that the buttons can be accessed easily to activate the command while minimizing the risk of inadvertent activation. A variety of sizes is acceptable under the conditions that exist in the cockpit (Woodson et al., 1992), so the following recommendations present the minimum sizes. The maximum sizes will be dictated by the availability of space on the receiver panel. Spacing considerations are presented for both normal operation and operation under severe turbulence.

The major reference works do not agree precisely on the minimum diameter for push buttons, but they are similar. MIL STD 1472D recommends a minimum diameter of .375 in. (9.5 mm), which is an intermediate value. The recommendations from the other sources range from a minimum diameter of .25 in. (6.4 mm) to .6 in. (15 mm). Because of the potential for operation in turbulence, the minimum diameter should be .375 in. The larger diameter also provides an area that can be designed with a concave or friction surface to prevent slippage.

A second aspect of size is their length. Only Woodson et al. (1992) recommend a minimum length for push buttons (.125 in. or 6.4 mm). They also note that the button should extend far enough from the panel that it is still exposed when depressed. The other sources simply recommend a minimum displacement, which is the distance the button must be depressed to activate the command. MIL STD 1472D recommends a displacement of between .078 in. (2 mm) and .25 in. (6 mm). Chapanis and Kinkade (1972) recommend a displacement between .125 in. (3 mm) and 1.5 in. (38 mm). Because of space requirements and concerns about accidental activation, the displacement of push buttons on the GPS receiver should be within the range specified by MIL STD 1472D (i.e., .078 in. to .25 in.). Push buttons with larger displacements should probably be protected against inadvertent activation by being recessed below the panel surface.

The minimum recommended spacing (edge-to-edge) for push buttons ranges from .5 in. (13 mm) to .78 in. (20 mm). Several references state a preference for an even larger interbutton spacing of 2 in. (50 mm). However, the spacing of collocated push buttons is somewhat dependent upon their sizes: larger push buttons require less space between them to avoid inadvertent activation. Woodson et al. (1992) recommends a center-to-center push button spacing of .75 in. (19 mm) for horizontal separation and .625 in. (16 mm) for vertical separation. This reference also recommends a minimum separation of 3 in. (76 mm) when the buttons must be manipulated under severe vibration. The center-to-center spacing recommendations are reasonably consistent with the edge-to-edge recommendations and take the button size into consideration. Therefore, they are recommended as GPS push button guidelines. If the minimum spacing recommendations cannot be implemented, mechanical interlocks or barriers should be included to prevent accidental activation.

The literature provides little guidance about other desirable design characteristics for push buttons. The shape of the push button makes no biomechanical difference (Woodson et al., 1992), although different shapes provide different amounts of space for labeling their use. Shape can also be used as a nonvisual cue for determining the purpose of a given push button in an array. Although push buttons can be divided into three subtypes (latching, momentary contact, and alternate action), there is no difference in their direction of movement (in to activate). The literature does consistently recommend a minimum resistance for push buttons of 10 oz (2.8 N) with a maximum resistance of 40 oz (11 N) for single finger operation. Finally, all the references recommend that the operator receive feedback on the activation of a push button, such as an audible click (if environmental conditions make it perceptible) or an integral light. An alternative source of feedback is a change in the receiver display.

3.2.2.2 Push-Pull Buttons - For most applications, MIL STD 1472D recommends .75 in. (19 mm) as the minimum diameter and length for push-pull buttons. The larger diameter, compared to push buttons, is required to grasp the control to pull it out. The minimum recommended displacement is 1 in. (25 mm) with a minimum of .5 in. (13 mm) between the push and pull positions. The minimum recommended spacing between push-pull buttons is 1.5 in. (38 mm). Resistance should not exceed 64 oz (18 N). For miniature electrical panels, which may apply to the GPS receiver. MIL STD 1472D presents a different set of recommendations: minimum diameter of .25 in. (6 mm), minimum displacement of .5 in. (13 mm), and minimum space between buttons of 1 in. (25 mm). The general recommendations should be considered desirable design parameters with the electrical panel recommendations considered the minimum acceptable. If the push-pull button is used frequently or for critical purposes, the larger standards should be applied.

There is disagreement in the literature about the direction of movement to activate a command with a push-pull button. MIL STD 1472D indicates the button should be pulled out for the on condition and pushed in for the off condition. ARP 4102 stipulates the opposite direction of movement for control activation. ARP 4102 is more aviation specific and should therefore be followed for GPS receivers. Pushing the button in to activate a command (e.g., to turn the receiver on) is both consistent with most other controls in the cockpit (e.g., the throttle) and it reduces the possibility of inadvertent deactivation. That is, the pilot is more likely to accidentally push a button in than to accidentally pull a button out. Because of the time required to acquire signals and return to active navigation after turning the receiver on, protection against inadvertent system turn off must be a major ergonomic design consideration.

However, special consideration must be given to the length or displacement of the control if it can also be rotated (e.g., to adjust the brightness of the display). The button must be long enough that it can be grasped and rotated while in the in position. If the button is too short, the pilot may inadvertently pull it to the out position while attempting to rotate the button.

3.2.2.3 Toggle Switches - The literature is consistent about the design parameters for toggle switches. The arm length should be between .5 in. (13 mm) and 2 in. (51 mm) and the diameter of the tip should be between .125 in. (3 mm) and 1 in. (25 mm). The displacement between the two positions should be between 30 and 80 degrees. For a three-position switch, the displacement between any two positions should be between 17 and 40 degrees. The separation between switches that are operated sequentially should be between .5 in. (13 mm) and 1 in. (25 mm). If the switches are operated randomly, the separation should be increased to between .75 in. (19 mm) and 2 in. (51 mm). The resistance of the switch should be between 10 oz (2.8 N) and 40 oz (11 N). Because the switch arm is exposed, the possibility of inadvertent activation is relatively high. Using higher force levels reduce the possibility, but the only sure method of protection is to provide a cover or guard over the toggle switch. However, the guard interferes with access to frequently used toggle switch controls. Toggle switches should be vertically oriented with on (or activate) in the up position and off in the down position.

3.2.2.4 Rocker Switches - Less information is available in the literature about design guidelines for rocker switches, but the available recommendations are consistent. The switch should have a minimum width of .25 in. (6 mm) and a minimum length of .5 in. (13 mm). The displacement of the switch should have a minimum height of .125 in. (3 mm) and a minimum angle of 30 degrees. The center-to-center separation of the switches should be .75 in. (19 mm). Switch resistance should be between 10 oz (2.8 N) and 40 oz (11 N). Rocker switches are also easy to activate accidentally. If avoiding unintentional command activation is critical, higher resistance or protective guards should be used. As with the toggle switches, however, both methods of protection impede the use of the control. Where practicable, rocker switches should be vertically oriented; activation of the upper wing should activate the command.

The recommendations for command controls are summarized in Table 3-3.

3.2.3 Function Control Type Characteristics

3.2.3.1 Rotary Knobs - The literature is less consistent in design recommendations for rotary knobs. Woodson et al. (1992) provides recommendations for the smallest useful knob, a preferred minimum size, and a common application. The common application recommendations are generally consistent with the recommendations for other sources. Because of the limited space available on the receiver panel, all three sets of recommendations are presented. All the recommendations assume the knob will be operated with the finger and thumb encircled rather than by a single finger.

Table 3-3. Recommendations for Command Controls

Consideration	Push Button	Push-pull Button	Toggle Switch	Rocker Switch
	Control Type			
Min Diameter	9.5 mm	6 mm	3 mm	6 mm
Min Length	6.4 mm	19 mm	13 mm	13 mm
Min Displacement	2 mm	13 mm	17 deg	30 deg
Min C-C Spacing	19 mm[a]	25 mm	13 mm	19 mm
Max Resistance	11 N	18 N	11 N	11 N
Desirable Features	Provide feedback	Push to activate	Vertical orientation	Vertical orientation
	Concave or friction surface	Increase length if dual use	Arm guard Up for on	Upper wing for on

Note. Compiled from Boff and Lincoln (1988); Bullinger, Kern, and Muntzenger (1987); Cardosi (in preparation); Chapanis and Kinkade (1972); Military Standard 1472D (1989); and Woodson, Tillman, and Tillman (1992). Min = minimum; mm = millimeters; deg = degrees; C-C = center-to-center; Max = maximum; N = Newtons.

[a]If spacing is less than recommended, mechanical interlocks or barriers should be used.

The smallest useful knob should be a minimum of .25 in. (6 mm) in diameter and .75 in. (19 mm) in length with a knurled or serrated edge to facilitate gripping. The preferred minimum size should be .5 in. (13 mm) in width and length and should also be knurled or serrated. In both cases, resistance should be between 2 oz and 4 oz (.55 N to 1.1 N). For most common applications, the minimum recommended width of a rotary knob is 1 in. (25 mm). The recommended length varies between .5 in. (13 mm) and .75 in. (19 mm). Although it is not as critical with knobs of this size, some method of maintaining grip friction is desirable. MIL STD 1472D recommends a minimum width of .375 in. (10 mm) and a length of .5 in.

(13 mm). Because this is an intermediate value that avoids the interaction between the dimensions, it is recommended for GPS rotary knobs.

In both references, a minimum separation of 1 in. (25 mm) is recommended between rotary knobs, although 2 in. (51 mm) is preferred. However, Boff and Lincoln (1988) report only minor decreases in error rates beyond 25 mm. The recommended movement resistance for the common application size rotary knob is between 4 oz (1.1 N) and 12 oz (3.3 N). Higher force requirements reduce the likelihood of inadvertent activation or slippage under turbulence or vibration. The only other reasonable forms of protection against inadvertent activation are to place the control in a location where it is unlikely to be hit or to lock the control.

The direction of movement for rotary knobs should be consistent with the related movement of an associated display or with stereotypic population expectations. For rotary knobs that are used to select sequential settings, clockwise movement should result in increasing values and counterclockwise movement should result in decreasing values. For example, if the rotary knob were used to select numeric digits, turning the knob clockwise should rotate through the digits in ascending order. There should be no less than 15 degrees separation between adjacent settings. Feedback about the selection of the desired setting should be provided through a setting detent, an audible click, or a change in the associated display.

For continuous adjustments, the control/display ratio (the amount of control movement that is required to adjust the display by a given amount) is dependent upon the number of settings and the relative requirements for speed of movement (coarse adjustment) and precision (fine adjustment). Although accuracy is critical for almost all GPS control functions, the time required with a low control/display ratio to cycle through the letters of the alphabet to enter a new waypoint can be detrimental to pilot performance. As a compromise, Bullinger et al. (1987) recommend a control/display ratio of between 0.1 and 0.4.

3.2.3.2 Concentric Knobs - The literature provides recommendations for the design of three concentric knobs but advises against their use unless it is absolutely mandatory because of space requirements. Because of this caution and because none of the current receivers employ a three-knob control, all of the recommendations presented are for two-knob controls (see Boff & Lincoln, 1988, pp. 2488 - 89, for design guidance on three-knob controls, if needed). The two knobs must be of different sizes, with the largest knob located closest to the panel surface. If the knobs are associated with different displays, the large knob should be associated with the left-most or upper-most display. Both knobs should have serrated edges.

The smaller, outer knob should be at least .5 in. (13 mm) in diameter and .625 in. (13 mm) in height. The larger, inner knob should be at least .875 in. (22 mm) in diameter and .5 in. (13 mm) in height. The differences in diameter between the outer and inner knobs should be at least maintained if the diameter of either knob is increased above the minimum. If the knob diameters are made substantially larger or the difference in diameter between them is increased, the knob height may be reduced slightly (Bradley, 1969). Because of the panel space restrictions on increasing the knob sizes, the listed heights should probably be considered an absolute minimum. The minimum separation between sets of concentric knobs should be 1 in. (25 mm), with a preferred separation of 2 in. (51 mm). For both knobs, the resistance should be between 4.5 oz (1.2 N) and 6 oz (1.7 N).

Considerations about direction of movement, feedback about the selected setting, and control/display ratios are the same as for single rotary knobs.

3.2.3.3 Keyboards - A primary source for recommendations about the design of alphanumeric keyboards is ANSI/HFS 100-1988, which incorporates the critical design literature. However, it primarily addresses full size keyboards used with computers. Other sources provide recommendations that are more appropriate to GPS receiver keyboards. The ergonomic considerations addressed include key size, shape, spacing, displacement, force, and feedback. The final considerations are directed toward keyboard layout. Because the keyboard will be panel mounted with a vertical orientation, considerations of keyboard height and slope are not presented.

ANSI/HFS 100-1988 states that the keys may be of any shape (e.g., square, round, rectangular) as long as the minimum width of the strike surface is .47 in. (12 mm). However, Greenstein and Arnaut (1987) recommend a square key with a slightly concave surface. MIL STD 1472D indicates the minimum width may be as small as .385 in. (10 mm), but a width of .5 in (13 mm) is preferred. Alden, Daniels, and Kanarick (1972) found that increasing key size within this range reduced keying time only slightly, but that it reduced input errors by a factor of four. Because of the small panel area on GPS receivers, the size suggested in MIL STD 1472D is recommended as the minimum for GPS receivers.

MIL STD 1472D recommends a minimum spacing between keys of .25 in. (6.4 mm); the minimum recommended spacing is also the preferred spacing. ANSI/HFS 100-1988 recommends slightly larger spacing, which is based on center line distances, and different spacing between horizontal and vertical keys. For horizontal keys, the spacing should be between .71 and .75 in. (18 and 19 mm); for vertical keys, the spacing should be between .71 and .82 in. (18 and 21 mm). Greenstein and Arnaut (1987) recommend a spacing of .75 in. (19 mm) between all keys. When the minimum key width is considered, all the recommendations are very similar. Because of the potential for error and the likelihood of operation in turbulence, the larger minimum spacing (.75 in. or 19 mm) is recommended for all keys.

ANSI/HFS 100-1988 recommends a displacement of between .06 in. (1.5 mm) and .24 in. (6 mm), although a displacement between .08 in. (2 mm) and .16 in. (4 mm) is preferred because they produce the greatest data entry rates with minimum errors. MIL STD 1472D recommends a displacement between .05 in. (1.3 mm) and .25 in. (6.3 mm) for alphanumeric keyboards. Again, the displacement range cited in MIL STD 1472D is recommended for GPS receivers. The sources agree on the key resistance parameters, or force required to press each key. The force should be within a range of .9 oz (.25 N) to 5.3 oz (1.5N), but a force between 1.8 oz (.5 N) and 2.2 oz (.6 N) is preferred.

All the sources (except Boff and Lincoln, 1988) recommend that the operator should receive either auditory or tactile feedback about key actuation. Monty, Snyder, and Birdwell (1983) found that tactile feedback is preferred if only one type of feedback could be provided. ARP 4102 also stipulates that tactile feedback should be optimized, especially for operation during turbulence. In the cockpit, the noise levels are usually high enough that auditory feedback is not feasible for routine actions such as key presses. The recommended tactile feedback is for the key force to increase during the first 40% of the displacement, followed by a substantial decrease in force during the next 20% of the displacement. Once feedback is received from the break in force, the force should increase again to cushion the key press. Failure to provide the cushioning effect may result in slower keying and higher error rates (e.g., Klemmer, 1971). Visual feedback is important during training and for error correction, but does not affect data entry speed or accuracy (Greenstein & Arnaut, 1987).

Because of space limitations on the GPS panel, only recommendations for a 10-button keyboard layout were reviewed, although numerous guidelines are available for larger, typewriter-style keyboards (e.g., MIL STD 1280). There are two basic layouts in widespread use for a 10-digit keyboard, although both employ a 3 X 3 matrix with the zero key centered below the matrix. The telephone layout has the numbers 1, 2, and 3 in left to right order on the top row with 4, 5, and 6 on the middle row and 7, 8, and 9 on the bottom row. The calculator layout reverses the numbers on the top and bottom rows (i.e., 1, 2, and 3 are on the bottom row). ANSI/HFS 100-1988 does not recommend one or the other layout, stating the choice of layout depends on the application. However, ARP 4102 stipulates that the numeric keys should be arranged in the telephone layout. This stipulation is widely supported in the literature. For example, Lutz and Chapanis (1955) found that a majority of the population expected the numbers 1, 2, and 3 to be on the top row. Conrad and Hull (1968) found greater accuracy with the telephone layout, although there was no difference in data entry speed.

ARP 4102 recommends that combined numeric and alphabetic keyboards should not be used unless absolutely necessary. When required, the alphabetic characters should be arranged in ascending order from left to right and top to bottom. This arrangement also conforms to the typical telephone layout that is most familiar to the general population.

Therefore, the telephone layout should be considered the standard for GPS receiver keyboards. However, a caution should be applied regarding the consistency of the GPS layout with other keyboard entry devices in the cockpit, which may use the calculator or some specialized layout for other systems. Andre and Wickens (1992) found that consistency across devices may be more important for accuracy than compatibility (e.g., with the population stereotype). This concern should not alter the design of the GPS keyboard, but an appropriate caution should be included in the operator's manual about possible confusion or negative transfer if other devices are used in the cockpit that employ a different keyboard layout design.

The recommendations for function controls are summarized in Table 3-4.

3.2.4 Control Arrangement

There are two aspects to the arrangement of controls: location of the receiver with respect to the pilot and location of individual controls on the panel. Obviously, the receiver must be located so that the pilot can reach and operate the controls with one hand without interfering with other flight responsibilities. In most cases, the pilot must also be able to see the control to determine its use or setting. Woodson et al. (1992) and ARP 571C (1985) state the general principle that the operator should not be required to shift from the normal operating position to reach a control. Boff and Lincoln (1988) indicate the functional reach from the seated position is 28.8 in. (73.1 cm) for 5th percentile male aviators and 25.5 in. (64.0 cm) for female aviators. Similarly, the operator should not be required to shift attention from other visual tasks to look for the control. MIL STD 203G (1991) states that navigation controls should be located on the right side of the cockpit where they can be easily operated by the pilot's right hand. Within the general requirement that the controls on the panel must be accessible, however, discussion of the receiver placement with respect to the pilot is deferred to the more critical considerations of its placement for viewing the display.

The only specific panel arrangement guidelines address the spacing between controls and the orientation of nonsymmetrical controls, which have already been discussed in the desirable

Table 3-4. Recommendations for Function Controls

Consideration	Control Type: Rotary Knob	Concentric Inner Knob	Concentric Outer Knob	Keyboard
Min Diameter	10 mm	22 mm	13 mm	10 mm
Min Height	13 mm	13 mm	16 mm	NA
Min Displacement	NA	NA	NA	1.3 mm
Min C-C Spacing	25 mm	25 mm	25 mm	19 mm
Setting Separation	15 deg	15 deg	15 deg	NA
Max Resistance	3.3 N	1.7 N	1.7 N	1.5 N
Movement	Clockwise to increase	Clockwise to increase	Clockwise to increase	NA
Desirable Features	Provide feedback	≥1.5 times outer size	Right/lower display	Telephone layout
	Serrated or knurled edge	Serrated edge	Serrated edge	Tactile feedback[a]

Note. Compiled from Boff and Lincoln (1988); Bullinger, Kern, and Muntzenger (1987); Chapanis and Kinkade (1972); Military Standard 1472D (1989); and Woodson, Tillman, and Tillman (1992). Min = minimum; mm = millimeters; NA = not applicable; deg = degrees; C-C = center-to-center; Max = maximum; N = Newtons.

[a]Boff and Lincoln (1988) report studies showing either no effect on speed and accuracy for keyboard feedback and one showing an increase in errors with kinesthetic feedback. However, all other references recommend feedback.

characteristics of the selected control types. However, there are five general principles in the literature that can be applied to the arrangement of controls on the GPS receiver. First, all of the references recommend that the controls should be arranged into functional groups. For example, command controls should be grouped together and spatially separated from function controls, unless they are used in combination. Boff and Lincoln (1988) recommend a horizontal rather than a vertical arrangement of groups of controls. Certainly, controls that are associated with a separate display should be grouped together. In addition, controls should be collocated with their associated displays to the extent possible (ARP 571C). A second, and related, principle is that the controls should be arranged systematically according to their sequence of use. The most common systematic arrangements are left to right and top to bottom. The third principle states that, if more than one set of controls is used to perform similar functions, their arrangement should be consistent across sets.

The fourth principle is to place the most important or the most frequently used controls in the most accessible locations. This arrangement principle facilitates operational performance and minimizes operator workload. Certainly, emergency controls that require rapid and accurate operation should be located so that the pilot can operate them efficiently. The principle also helps to avoid the inadvertent activation or deactivation of a rarely used control, such as the on-off switch. Finally, the controls should be arranged so that any one control does not obscure another control or an associated display from the pilot's view. This consideration applies most often to concentric knobs, and to a lesser degree, rotary knobs, which have the largest diameter and extend further out from the panel surface than the other control types.

The five principles for control arrangement, which are summarized in Table 3-5, are individually reasonable ergonomic considerations, but they are subject to interpretation (e.g., what is a functional group and which controls are more important) and they may be collectively contradictory (e.g., placement in a functional group or sequence may remove an important or frequently used control from a primary use location). No data are available to establish an absolute priority for one principle over another; their application is dependent upon individual circumstances that are in many ways determined by other design decisions, such as the number of controls that are employed. In addition, the principles are neither as specific nor as easily incorporated or measured as many of the guidelines presented for the characteristics of individual control types. However, the control arrangement principles should be considered by both system designers and system certification evaluators.

Table 3-5. Principles for Control Arrangement on the GPS Receiver Panel

- Meet or exceed the control spacing requirements (Tables 3-3 and 3-4)
- Collocate the controls with associated displays to the extent possible
- Partition the controls into functional groups
- Arrange groups of controls horizontally rather than vertically
- Place the most important controls in the most accessible location
- Place the most frequently used controls in the most accessible location
- Arrange the controls according to the sequence of use
- Arrange the controls so they do not obscure other controls or displays
- Arrange sets of controls that perform similar functions consistently

Note. Compiled from Aerospace Recommended Practice 571C (1985); Boff and Lincoln (1988); Chapanis and Kinkade (1972); Military Standard 203G (1991); Military Standard 1472D (1989); and Woodson, Tillman, and Tillman (1992).

3.2.5 Control Coding and Labeling

Obviously, an operator must be able to identify the function of a control and to determine its setting. ARP 4102 and MIL STD 1472D both state that appropriate methods should be used to facilitate control identification. MIL STD 1472D further states that the method used is dependent on the particular application and the relative advantages and disadvantages of each method (see Table 3-6). Two basic methods for identifying the function of a control are coding and labeling. The primary coding methods are to vary the size, shape, or color of the control. Control location can also be used to identify its function, sequence, or color of the control. Control location can also be used to identify its function, sequence, or frequency of use, but this ergonomic consideration is discussed further under control arrangement.

3.2.5.1 Size and Shape Coding - Size and shape coding are most appropriate when the controls are to be operated, at least occasionally, by feel alone (i.e., without visual feedback). If the variations in size and shape are sufficient for touch discrimination, they will also be

Table 3-6. Advantages and Disadvantages of Labeling and Coding Types

	Labeling and Coding Types				
Advantages	Label	Location	Shape	Size	Color
Improves visual identification	X	X	X	X	X
Improves nonvisual identification		X	X	X	
Helps standardization	X	X	X	X	X
Aids identification under low levels of illumination and colored lighting	[a]	X	X	X	[a]
Aids identification of control setting	X		X		
Minimal training or forgetting	X				
Disadvantages					
May require more space	X	X	X	X	
Affects ease of control manipulation		X	X	X	
Limited number of usable values	X	X	X	X	
Possible inadvertent activation during discrimination		X	X		
Control must be seen to discriminate (control in visual field and have adequate illumination)	X				X
Discrimination affected by color and level of illumination	X				X

Note. Adapted from Boff and Lincoln (1988); Military Standard 1472D (1989); and Woodson, Tillman, and Tillman (1992).

[a]Advantage only when transilluminated.

useful for improving visual discrimination. Shape coding can also facilitate the determination of the control setting. Both types of coding are routinely used in most cockpits (e.g., to distinguish between the throttle and fuel mixture controls). When using size coding, the sizes between similar controls should differ by at least 20% (Chapanis & Kinkade, 1972). MIL STD 1472D stipulates that the difference in control diameter for coding purposes must be at least .5 in. (13 mm). When using shape coding, the shapes employed must be easily distinguishable both tactually and visually, they should be easily associated with their function (if possible), and sharp edges should be avoided (Chapanis & Kinkade). The same size and shape should be used for controls that perform the same or similar functions.

However, there are several disadvantages to using size and shape coding. The major disadvantages are that they may require more space, which is severely limited on the GPS receiver panel, and they may alter the manipulation of the control (MIL STD 1472D). There are also only a limited number of size and shape coding categories that can be used, especially when the selection of different types of controls selected for command and function controls already result in size and shape variations. Finally, size and shape coding places an additional burden on the pilot's memory for recalling which size or shape is associated with each control. Therefore, size and shape coding should be restricted to a limited number of critical controls. No more than three sizes should be used for coding controls on an absolute basis (MIL STD 1472D) nor more than five sizes on a relative basis (Boff & Lincoln, 1988). The maximum number of shape codes is between 8 and 10 (Boff & Lincoln).

3.2.5.2 Color Coding - Color coding is a widely used and effective method for identifying control functions and settings, especially when the color used has inherent meaning for most users (e.g., red for emergency controls). However, there are three serious problems with using color coding of controls. First, individuals can discriminate only a few colors accurately for coding purposes. Boff and Lincoln (1988) set a maximum number of color codes at between 8 and 10. Most of the reference sources indicate a maximum of 5 colors should be used for control coding. Second, color discrimination is dependent upon ambient lighting conditions. As discussed in the methodological constraints section, the ambient light in the cockpit varies from red light at night to bright sunshine. The variation in light conditions severely restricts the utility of color coding the controls. Third, color is effective only when viewed within 30 degrees of the center of the fovea (Boff & Lincoln), which requires relatively direct viewing of the control or setting, thus minimizing the effectiveness of the coding technique. Certainly, color should not be the sole or even the primary method of coding the controls. MIL STD 1472D states that controls shall be black or gray, unless color coding is absolutely required. If color coding is necessary, only red, green, orange-yellow, white, and blue colors should be used for control coding.

3.2.5.3 Labeling - Because of the disadvantages associated with control coding, the primary method of identifying control functions and settings on GPS receivers should be labeling, which also has the most advantages (see Table 3-6). MIL STD 1472D stipulates that labels, legends, etc. shall be used to identify, interpret, or follow procedures, except where it is obvious to the operator what the control is and how it is to be used. In addition to the requirement that the label be accurate and functional (i.e., identifies the critical features of the control), there are three sets of guidelines that should be applied to label design: orientation, location, and standardization.

The preferred orientation of labels is horizontal, so the label can be read from left to right. When the labels are not critical for safety or performance and space requirements dictate the use of vertical labels, they should read from top to bottom. The labels should be located on or adjacent to linear controls they identify to avoid confusion between nearby controls; labels should not be on rotating controls because the orientation will change as it is manipulated. The location of labels (on, to the side, above, or below the control) should be consistent for the entire system. If the location of the receiver in the cockpit can be determined, labels should be placed above controls that are below normal eye level; controls that are above normal eye level should be labeled below the control. Labels should not obscure other needed information on the panel surface. The design should also ensure that the label is not obscured by the associated control.

The guidelines for label standardization are more extensive and precise than the recommendations for orientation and location. For the purposes of this discussion, the ergonomic considerations for standardization are subdivided into issues about the physical characteristics of labels and about their terminology. Consideration of physical characteristics is based primarily on recommendations in MIL STD 1472D and is further subdivided into character color, style, and size under different levels of illumination and viewing distance. Consideration of label terminology is based primarily on MIL STD 783D.

Where the ambient illumination is sufficient, labels should be constructed of black characters on a light background. If dark adaptation is required, the characters should be white on a dark background. Labels should be printed in all capital letters without punctuation, unless confusion or misinterpretation would occur because of its omission. At luminance levels of 3.5 cd/m^2 (1 fL) or greater and at an expected viewing distance of 19.7 in. (50 cm) to 39.4 in. (1 m), the label characters should have a minimum height of .18 in. (4.7 mm). If the expected viewing distance is less than 19.7 in., the minimum height can be reduced to .09 in. (2.3 mm); if the expected viewing distance is greater than 39.4 in., the minimum height should be .37 in. (9.4 mm). The minimum height of critical markings should be increased by approximately 60% when the luminance level falls below 3.5 cd/m^2.

For black characters on a light background, the stroke width of the characters should be between 14% and 17% of the height. For white characters on a dark background, the stroke width should be between 12% and 14% of the height. The width of most letters and numerals should be 60% of the height. The width of the letters M and W should be 80% of the height. The width of the letter I and the number 1 should be one stroke width; the number 4 should be one stroke width wider than 60% of the height. If characters are labeled on a curved surface or if the label is oriented vertically, the width of the characters can be the same size as the height. There should be at least one stroke width between characters, one normal character width between words, and 50% of character height between label lines. A font should be used that does not have extraneous details (e.g., sans serif), but letters and numbers that could be easily confused (e.g., l and 1, 0 and O) should be readily distinguishable (AS 8034, 1982; Boff & Lincoln, 1988.

In general, label terminology should be as concise as possible with minimal redundancy. Words should be used that are familiar to the operator. Common symbols may be used as necessary but abstract symbols should be avoided unless they have an accepted meaning to all intended users. The complete word should be spelled out if possible. Words of four letters or less should not be abbreviated unless common usage has rendered the word and its abbreviation completely synonymous. The same word should be used for all variations of number, case, or tense. Where space limitations require it, words may be abbreviated by removing letters in a manner that minimizes the effect on the phonetic sound of the word. If the word cannot be abbreviated, an acronym may be formed by using the first few letters of the word; acronyms for word combinations or phrases may be formed from the first or first few letters of each word.

Obviously, abbreviations and acronyms used to label an identical control or setting on the GPS receiver should be identical. Equally as obvious, the same abbreviation or acronym should not be used for more than one word or phrase. It is desirable that abbreviations and acronyms be standardized across all the systems in the cockpit to avoid confusion or misinterpretation, but that standardization is beyond the scope of this effort. However, standardized abbreviations and acronyms are recommended for all GPS receivers, to avoid confusion for pilots who fly with more than one system.

Driskell and Hughes (1992) provide a glossary of abbreviations used on the six receivers they reviewed. The glossary indicates substantial agreement across systems, but there are some minor differences that could be easily resolved. For example, one system used the acronym FLP for the flight planning mode command; all the other systems used FPL. This particular disparity is unlikely to cause a serious problem (unless the pilot mistakes FLP to mean 'flip' a display page), but the advantages of standardization could be achieved at minimal cost without infringing upon important prerogatives of any manufacturer. MIL STD 783D contains tables listing standardized abbreviations and acronyms for use in aircrew stations and on airborne equipment that are subject to international standardization agreements. The tables could serve as a basis for standardizing abbreviations and acronyms on GPS systems, but agreement is required for needed terms that are not included in the tables (like flight plan). Table 3-7 summarizes the guidelines for control labels.

Table 3-7. Guidelines for Control Labeling

- Label controls to identify their function, operation, or setting
- Orient the label horizontally so it can be read from left to right
- Place the label on (except rotary controls) or adjacent to the control
- Place the labels consistently across the panel
  - above the control if below eye level
  - below the control if above eye level
  - to the side if the label is not obscured by the control

- Use concise terminology that is familiar to the operator
- Spell out words if possible or use standard abbreviations or acronyms
- Use the same word for all variations of number, case, or tense
- Use terminology consistently across the receiver controls and displays
- Character construction guidelines
  - use black characters on a light background
  - use all capital letters without punctuation
  - the minimum character height should be .18 in. (4.7 mm)
  - the stroke width should be between 14% and 17% of the height
  - the width of most letters should be 60% of the height
  - the letters M and W should be 80% of the height
  - the letter I and number 1 should be one stroke width
  - the number 4 should be one stroke width wider than 60% of height
  - use a font without extraneous details but ensure confusable characters are distinguishable

- Minimum spacing guidelines
  - use one stroke width between characters
  - use one normal letter width between words
  - use 50% of character height between label lines

Note. Compiled from Chapanis and Kinkade (1972); Military Standard 783D (1984); Military Standard 1472D (1989); and Woodson, Tillman, and Tillman (1992).

3.3 PRINCIPLES AND GUIDELINES FOR DISPLAYS

Practically, GPS output information (other than control input feedback) could be presented to two of the operator's sensory modalities: visual and auditory. However, this review addresses only the visual modality except for auditory alert and warning signals. There are two reasons for limiting the display guidelines primarily to visual information. First, nonspeech auditory signals are considered to be poor indicators of either quantitative or qualitative information. Cardosi (in preparation) states they should be used only when absolutely necessary. Smith and Mosier (1986) state that auditory displays are inappropriate for spatial information, which is a major product of GPS receivers. The primary problems with auditory signals are that the operator can recognize very few (five to six) tones, cannot interpolate accurately between signals, and has difficulty judging the approximate value and direction of deviations from a null setting unless the signals are presented in a close temporal sequence. The best usage of auditory signals is for status indications, such as alerts and warnings (Woodson et al, 1992). Natural or synthetic speech generation is capable of conveying more information, but its use with GPS receivers should also be limited to alerts and warnings because there is no known means of conveying complex spatial information (e.g., aircraft position or track) in the auditory modality (Smith & Mosier, 1986; Stokes et al., 1990). In addition, speech warnings and alerts may not be recognized as quickly if speech is used for other messages (Stokes et al.).

The second reason for generally excluding auditory signals on the GPS receiver is the cockpit environment, which is likely to have a high ambient noise level that would make it difficult to detect and interpret the signals. The noise level can be both continuous (e.g., engine noise) or random (e.g., communicating with other crewmembers, passengers, aircraft, or air traffic control). In addition, other onboard systems may employ auditory signals that could be confused with the GPS signals. For example, the Canadair Flight Crew Operating Manual (CSP A-013 (1992) describes 10 types of aural warnings that are in general use in the air transport industry. The manual also describes 51 voice messages. Stokes, Wickens, and Kite (1990) concluded that the practical effectiveness of an auditory signal depends on the cognitive demands of the task and the acoustic environment in which it occurs. Therefore, auditory signals should be restricted to providing critical status information: even then. auditory signals should not be the sole method of alerting the pilot to the presence of critical information (MIL STD 1472D).

Some types of information displays are specifically required by RTCA DO-208 and TSO C129, such as cross-track deviation, waypoint distance, TO-FROM indication, flight path, and annunciations of approach mode activation and equipment failures. The information has to be continuously available but not necessarily continuously displayed. In some cases, the format (e.g., digital or analog) of the data display is specified. The documents also specify a global requirement that each of the required displays be available to determine the position of the airplane and its relationship to the desired course. The FAA Type Inspection Authorization for project STO346WI-A (1994) required the minimal GPS displays to include depiction of the TO waypoint, intercept and track to or from a designated waypoint, distance to the waypoint, estimated time of arrival or estimated time en route, ground speed, turn anticipation, flight plan and waypoint sequencing, and annunciation of failure modes.

Except for the CDI, this section does not include further discussion of the specific types of data or information to be displayed, because it is available in the regulatory documents. Instead, this section describes ergonomic guidelines and principles for displaying data and information, regardless of its specific content. The principles and guidelines for visual displays are presented in four parts. The first part presents general principles of display design. The second part describes the types of technology that are appropriate to generate displays for GPS receivers. The third part describes guidelines for the desirable characteristics of the general display. The characteristics include the viewing distance and angle, character size and spacing, lighting requirements, contrast, resolution, and terminology. The fourth part describes principles and guidelines for specialized display characteristics, such as analog and map displays and alert and warning signals.

3.3.1 General Principles

Contradictory experimental results abound in the literature that underscore the difficulty of developing a theory of display design (Sanderson, Haskell, & Flach, 1992). However, the literature presents several general principles (sometimes presented as criteria for evaluation) that should be applied to the design of visual displays. The following five principles, drawn primarily from Woodson et al. (1992), summarize the guidance in the literature. The principles are global in scope and subject to interpretation, and therefore may be perceived as being of limited utility to a system designer or certification evaluator. Nonetheless, they provide overall guidance that is applicable to the total display, which can vary widely and still be acceptable. More specific guidelines, such as those available for display characters or fields, cannot be developed or applied without infringing on the prerogatives of the manufacturer. Such guidelines could also have the effect of imposing suboptimum design requirements and of limiting design innovations. More specific guidelines for the total display would also require the specification of the information content, which is beyond the scope of this report.

The first principle, and probably the most important one, is to use the simplest display concept that provides the pilot with the required system information. The first principle for data display recommended by Smith and Mosier (1986) is to ensure that all the data a user needs for any transaction are available. Their second principle is to provide only necessary and immediately usable data for any transaction and to not overload displays with extraneous data. AC 25-11 (1987) suggests that pilot selection of additional information or the automatic deselection of unneeded information may be desirable for navigation displays. Complex displays require more training and practice to use, take more time to read and interpret, and are more apt to induce errors. Reports of the effects of automation on pilot performance have frequently mentioned the problems associated with the complexity of system controls and displays (e.g., Billings, 1991; Norman & Orlady, 1988; Wise, Guide, Abbot, & Ryan, 1992; Wiener et al., 1991). Hoh, Bergeron, and Hinton (1983) found that the excellent pilot interface characteristics associated with the simplest display actually outweighed the improved format of the more sophisticated displays they tested.

There are, of course, limits on how simple a display can be and still present the required information. Mann and Schnetzler (1986) found that higher information density (30% of the display area or more) in the display generally produced slower reaction times and more performance errors. However, they also found that the effects of information density interacted with the format of the display. The placement of labels was more important than the placement of data in the display. They found that performance improved when display labels were clearly marked, when the number of labels associated with each data point was minimized, and when main and subordinate label relationships were clearly indicated. Table 3-8 summarizes display labeling guidance in Smith and Mosier (1986).

Table 3-8. Guidelines for Display Labeling

- Each data field should be identified with a label
- The label should describe the data content of the field
- Label wording should be used consistently if the same field appears in multiple displays
- Labels for different fields must be distinct from each other
- The label should be placed consistently either above or to the left of its associated data field
- The label should be near its associated data field but separated from it by at least one character space
- Labels should be distinctive in format or positioning to distinguish them from other display features

The unit of measurement should be included either as part of the label or part of the data item (i.e., following the data field)

Note. Adapted from Smith and Mosier, 1986.

In addition to the density of information and use of labels, the use of an excessive number or variety of symbols, colors, or small spatial relationships produces a cluttered display that increases processing time for display interpretation (AC 25-11). Although symbols must be distinctive and color can be used to enhance detectability, their use should be restricted to critical information. Excessive use of symbols and color can result in increased errors in interpretation and a reduction in the attention-getting capability of the display.

The principle of display simplicity, while widely espoused and logically reasonable, is not universally accepted. Tullis (1983) concluded that overall density, local density, and grouping in displays do affect operator performance, but that the relationships probably resemble an inverted U function. That is, a moderate level of density and grouping produces the best performance. He also noted that there is little empirical evidence about the effects of layout complexity on human performance, although numerous guidelines suggest that it is detrimental. Despite the lack of experimental evidence, the anecdotal reports and majority of experience represented in the design literature support the principle of display simplicity.

A corollary to the principle of display simplicity is that all the required information for a task should be presented in a single display. However, there frequently is more information required than can be presented on a single page without creating an unacceptable level of information density and clutter. When this occurs, the information must be displayed on multiple pages. In keeping with the simplicity principle, only as many pages should be used as are absolutely necessary to present the required information while maintaining an acceptable level of information density. When multiple pages are used, each page should clearly indicate that additional information is located on other display pages.

The second principle is closely related to the first: Use the least precise display format that will convey the information required by the operator. To some degree, this principle is incorporated into the regulatory requirements for GPS displays (RTCA DO-208; TSO C129). For example, the mandatory sensitivity of the CDI varies depending on the phase of flight (e.g., en route, terminal area, approach). Roscoe (1990) calls this the principle of optimum scaling, which requires tradeoffs between control precision and control stability. Comparable considerations could be incorporated into the design of many other display fields, such as airspeed and distance to a waypoint. Ultimately, the needs of the pilot for safe and efficient flight management should determine the precision of the information displayed on the GPS, not the capabilities of the receiver software.

The third principle is to use the most natural or expected display format for the type of information presented. Because pilots are accustomed to various types of information presented in a standardized format, the population expectations should be employed as much as possible in designing the display. In some cases, the information format is specified in RTCA DO-208 and TSO C129, at least in terms of whether it is presented in analog or digital form, or both. When it is not specified, display formats should be developed that are consistent with user conventions, with data entry requirements, and with similar types of displays (Smith & Mosier, 1986). In addition to a natural format, the use of familiar terms and symbols results in faster and more accurate detection and identification (e.g., Remington & Williams, 1986). Finally, the display format should avoid requiring the pilot to transpose, calculate, interpolate, or translate into other units before using the information (MIL STD 1472D, 1989; Smith & Mosier, 1986).

The fourth principle is to use the most effective display technique for each type of information, which presumably will be consistent with the expected format. Woodson et al. (1992) provide a table showing the most appropriate type of display for different information requirements. The most relevant types of requirements for GPS information and their associated display technique include the following:

- status indication should use lights, flags, or meaningful symbols;
- instructional information (e.g., menu directions) should use labels and printed words, arrows, and pictorial symbols;
- exact quantity information should be presented using digital readouts;
- approximate quantity information or positional relationships should be presented using a moving pointer with a fixed scale or a fixed pointer with a moving scale; and
- geographic position should be presented using a plan position reference analog, such as a map or electronic map and grid display.

The use of multiple techniques in a small display area appears to conflict with principles recommending design simplicity, minimal precision, and format consistency. For dynamic process monitoring and control, however, Coury and Pietras (1989) found that using multiple display techniques produced optimal performance. In general, graphic-only displays produced the worst performance with digital-only displays producing intermediate performance. There is also evidence that there are minimal performance differences between graphic, numeric, and narrative displays, which does not support the exclusive use of one format. Tullis (1981) found that response times were faster, initially, for graphic displays than for narrative displays, but there was no difference in accuracy between any of the formats. With practice, the differences in response time were also eliminated. Boles and Wickens (1987) recommended a mixed format of analog, digital, and verbal information unless display components must be integrated (e.g., two numbers must be added) or unless speed of performance is critical and the requirements for precision are low. In the latter case, they recommended using an analog display.

Another method that has been used to improve the effectiveness of displays is to color code the information. In environments such as aviation, Stokes et al. (1990) report that the judicious use of color to represent and organize data has the potential to speed up the location and processing of displayed information, especially if visual clutter and high workload are present. Boff and Lincoln (1988) agree, stating that color coding may improve operator performance when data are unformatted, symbol density is high, legibility is degraded, the operator must search for information, or color codes are logically related to the task. They caution, however, that the task-irrelevant use of color or using more than six colors can cause performance decrements. They also point out a number of other problems with the use of color, such as the interaction between luminance, ambient illumination, and hue; effect of location in the visual field; and individual differences in color vision deficiency. Because of these problems, and the potential loss of color-generating capability, color should be used only as a secondary coding method. The display must still be interpretable if the color coding cannot be perceived or is lost.

If color coding is used, AC 25-11 specifies that the number of colors should be limited to as few as practical, that the color contrasts should be adequate to discriminate between them, and that the coding should follow a logical scheme. Once a color has been assigned a specific meaning, no other color should be used for the same purpose. Although they do not restrict electronic displays to a specified set of colors, AC 25-11 and ARP 4102 recommend two color sets for navigation-related displays (see Table 3-9), which have been shown to work well together. Cardosi (in preparation) reports that blue should be avoided for characters or symbols, but can be used as a background color.

Table 3-9. Recommended Display Color Sets

Associated Information	Color Set 1	Color Set 2
Warning or danger	Red	Red
Caution or abnormality	Amber/Yellow	Amber/Yellow
Fixed reference symbols	White	Yellow
Current data or values	White	Green
Armed modes	White	Cyan
Selected data or values	Green	Cyan
Selected heading	Magenta	Cyan
Active route/flight plan	Magenta	White

Note. Adapted from Aerospace Recommended Practice 4102 (1988) and Advisory Circular 25-11 (1987).

The fifth general principle is a global requirement to meet the more specific guidelines for the individual characters and fields in the display. This principle states that the design should optimize the following display features:

- visibility (e.g., viewing distance and angle, adequate illumination, and minimal glare),
- consciousness (i.e., the ability of critical display information to attract attention among background distraction),
- legibility (e.g., size, shape, brightness contrast, and pattern discrimination), and
- interpretability (e.g., providing the intended meaning and allowing for extrapolation).

The general principles of display design are summarized in Table 3-10.

3.3.2 Display Technologies

CRT technology has dominated the electronic display market (Helander, 1987; Mangold et al., 1992), and is the only technology for which specific display design standards are published in ANSI/HFS 100-1988. However, there are numerous alternative technologies available, including electroluminescence, gas plasma, LED, and LCD displays. Hitt (1994) conducted

Table 3-10. General Display Principles

- Use the simplest display concept that provides the needed information
  - avoid clutter from unnecessary information or symbols
  - keep information density to 30% or less
  - use clearly marked display labels
  - clearly indicate if additional information is located on other display pages

- Use the least precise display format to convey required information
  - provide exact quantity information only when needed
  - enable pilot control of scale sensitivity when possible

- Use the most natural or expected display format
  - use familiar terms, symbols, and units of measurement
  - present information in a directly usable format

- Use an appropriate type of display for the type of information
  - meet regulatory specifications for the type of information
  - use lights, flags, or symbols for status indications
  - use labels, words, arrows, or symbols for instructions
  - use digital readouts for exact quantity information
  - use scales or analog displays for approximate quantity information
  - use analog, map, or grid displays for geographic position

- Meet character and field guidelines to optimize visibility, conspicuousness, legibility, and interpretability

Note. Compiled from Bullinger, Kern, and Muntzenger (1987); Military Standard 1472D (1989); and Woodson, Tillman, and Tillman (1992).

laboratory assessments and B-52 flight tests of LCD, gas plasma, and electroluminescent displays in comparison to existing CRT displays. The flight tests were performed in five crew positions, so each technology was viewed at different angles, distances, and ambient illumination conditions. Hitt found that no one technology was consistently considered to be superior to the others. Each had its strengths and weaknesses, and was preferred by some crewmembers at some crew stations. For example, the LCD display imagery was rated as better than the CRT, but the display suffered from limitations in the vertical field of view and nonuniformity of the backlight across the complete screen. The evaluators indicated that all the technologies needed a larger dynamic range for control of brightness and contrast.

Driskell and Hughes (1992) reported that CRT, LED, and LCD technologies are all currently in use in GPS and Loran receivers. According to a flow chart developed by Snyder (1980), each of these technologies is appropriate for presenting GPS displays, at least in terms of the physical size, pixel size, resolution, and illumination requirements. The following two paragraphs further address these three technologies.

Numerous experiments have been conducted to evaluate the readability of CRT displays, frequently in comparison to print information (e.g., Gould et al., 1987; Gould, Alfaro, Finn, Haupt, & Minuto, 1987). Journa and Snyder (1991) found that reading speed was equivalent for CRT and hard copy as long as the physical and perceived image quality was similar for both displays. Krantz, Silverstein, and Yeh (1992) noted that CRT displays have been used successfully in avionics applications, but they found that LCD displays maintained superior contrast under bright sunlight conditions. They attributed the difference to the relatively low reflectance by LCDs of incident ambient illumination, compared to the highly reflective phosphor surface of CRTs. They also found that, under the worst ambient light conditions, discrimination performance reached asymptotic levels at a display luminance of approximately 180 cd/m^2. Gunderson, Gruetzmacher, and Swanson (1991) found that errors and response times reached minimum levels with small LED displays as long as the minimum visual angle subtended (VAS) was approximately 7 minutes of arc.

Although all three technologies may be used, Hawkins (1987) reports that each has its own human factors problems that require evaluation for use in an aviation context. Similar to Hitt (1994), Hawkins indicates that brightness and contrast are potential problems with all three technologies; color capability is also a concern for all three types, if used. Flicker and raster display resolution are concerns for the CRT; lighting and viewing angle are potential problems with the LCD technology. Until further research determines whether one or more display technologies are inappropriate, the only guidelines that can be recommended for their use in GPS receivers is that their luminance and luminance contrast adjustment must be sufficient to accommodate the anticipated range of ambient light conditions likely to occur in the cockpit. Rogers, Spiker, and Cincinelli (1986) found that under low to moderate ambient illumination, character-background contrast ratios beyond 1.4:1 provide little improvement in legibility. Under the high ambient illumination in the cockpit on a sunny day, however, increases in the contrast ratio up to 30:1 may improve legibility.

> Any display technology (CRT, LCD, LED, etc.) is acceptable for GPS receivers as long as the luminance and luminance contrast adjustment are sufficient to accommodate all expected ambient illumination conditions (night cockpit lighting to bright sunlight).

3.3.3 General Display Characteristics

The literature contains numerous recommendations for the design of electronic displays. There are more extensive standards for CRT displays, which have been in use longer and are used more extensively, but the same design principles apply to the other display technologies (MIL STD 1472D). The following recommendations for display characteristics are integrated from ANSI/HFS 100-1988; ARP 1874; ARP 1048; AIR 1093; Boff and Lincoln (1988); Cardosi (in preparation); Helander (1987); MIL STD 1472D; Smith and Mosier (1986); and Woodson et al. (1992).

3.3.3.1 Viewing Distance and Angle - Viewing distance and angle are extremely important considerations because they determine the legibility of display characters of a fixed size under constant light conditions; however, they cannot be specified precisely because of different cockpit sizes and instrumentation arrangements. The literature contains recommendations for the minimum and maximum distance and angle for a display from the pilot's design eye point. The literature also describes an approximate nominal viewing distance that will be used as a reference in defining size recommendations for display characters; display characters will also be defined in terms of the minimum VAS (in minutes of arc subtended) so that maximum mounting distances can be calculated.

AIR 1093 lists the minimum viewing distance as 10 in. (254 mm) and the maximum viewing distance as 40 in. (1,016 mm), with a nominal distance of 29 in. (737 mm). ANSI/HFS 100-1988 specifies a minimum viewing distance of 12 in. (300 mm) but does not recommend a maximum viewing distance. MIL STD 1472D recommends a smaller range of viewing distances. The minimum distance should be at least 13 in. (330 mm), but with a preferred minimum of not less than 20 in. (510 mm). The maximum viewing distance should be 30 in. (760 mm).

Because of the regulatory requirements to place critical instruments in the pilot's central field of view (see AC 25-11 and ARP 4102), the GPS display is unlikely to be located near the minimum viewing distances. It is more likely to be located beyond the preferred minimum in MIL STD 1472D and near the nominal distance in AIR 1093. Therefore, the nominal distance of 29 in. (737 mm) is used for character size recommendations. This distance is also the midpoint of the viewing distances (19.7 - 39.4 in. or 500 - 1000 mm) used to determine control label character sizes (see Section 3.3.3.2).

There are three aspects to the viewing angle: orientation of the display surface and horizontal and vertical angle of regard from the design eye point. MIL STD 1472D recommends that the display surface should be perpendicular to the operator's normal line of sight whenever feasible, but the angle of incidence should never be less than 45 degrees from the line of sight. Because most GPS receivers will be mounted in the instrument panel, their orientation should be nearly perpendicular to the pilot's line of sight.

The optimum horizontal angle of regard should be within 15 degrees of the forward line of sight (MIL STD 1472D). However, more critical flight control instruments are likely to be placed in this central field of view. With eye rotation only, the maximum angle is 35 degrees; with head rotation, the maximum angle is 60 degrees. Therefore, the preferred maximum horizontal angle should be 35 degrees or less with an absolute maximum of 60 degrees. The optimum vertical angle of regard should also be within 15 degrees of the normal line of sight. With eye rotation only, the maximum angles are 20 degrees below and 40 degrees above the line of sight. With head rotation, the maximum angles are 36 degrees below and 66 degrees above the line of sight. Therefore, the preferred vertical angles should be at or below the maximum for eye rotation alone with absolute maximums at the head rotation angles.

As indicated previously, these recommendations apply to the installation of the GPS receiver rather than to its design. However, the allowable and likely viewing distance and angles must be considered in designing other aspects of the receiver display, such as the character size and spacing. The recommendations also imply that the more critical types of information (e.g., alerts and warnings) should be presented near the left end of the display so that they will be closer to the pilot's line of sight.

Table 3-11 summarizes the expected viewing distance and angle considerations when the GPS receiver is mounted in the cockpit. When conducting certification flight tests, mounting the receiver outside the expected values may affect the evaluation of other display characteristics.

3.3.3.2 Character Size - MIL STD 1472D stipulates that alphabetic display characters should all be in uppercase (i.e., capital letters). Recent research (Bednall, 1992) found there was no difference in search times for all uppercase characters when compared to mixed upper and lowercase display characters. Although using mixed case characters may not detrimentally affect performance under optimum conditions, upper and lowercase characters are necessarily of different sizes and subtend different visual angles, which may affect readability at the extreme ranges of viewing distance, angle, and light conditions. Therefore, using lowercase characters is not recommended unless there is an overwhelming reason to

Table 3-11. Viewing Distance and Angle Considerations in Mounting the GPS Receiver

- The nominal viewing distance should be approximately 29 in. (737 mm) from the pilot's design eye point
- The minimum viewing distance should be 13 in. (330 mm)
- The maximum viewing distance should be 40 in. (1,016 mm)
- The angle of incidence of the display surface should be between 45 and 90 degrees relative to the pilot's normal line of sight
- The maximum horizontal angle of regard relative to the pilot's forward line of sight should be 60 degrees (35 degrees preferred)
- The maximum vertical angle of regard should be 36 degrees (20 degrees preferred) below or 66 degrees (40 degrees preferred) above the pilot's forward line of sight

Note. Compiled from Aerospace Information Report 1093 (1969); American National Standards Institute ANSI/HFS 100-1988; and Military Standard 1472D (1989).

use them (e.g., Smith & Mosier, 1986, recommend mixed upper and lowercase for running text messages, such as system error messages or airspace alerts that are presented in a conventional sentence format).

Recommendations in this report for character size are based on the assumption that all alphabetic characters are upper case. Numeric characters should have a minimum of 7 segments and alphabetic characters should have 14 to 16 segments. The most legible fonts do not have extraneous details, such as serifs (Boff & Lincoln, 1988). AS 8034 specifies that characters should not have tails, skews, etc. However, highly similar character (e.g., I and 1 or 0 and zero) that could be confused should be distinguishably different.

Character size for electronic displays can be defined in terms of the dot matrix size. ANSI/HFS 100-1988 stipulates a minimum character matrix of 5 X 7 (width by height) for numeric and upper case only presentations. When individual alphabetic character legibility is important, the minimum matrix size should be 7 X 9. MIL STD 1472D concurs with this recommendation, stating the minimum size should be 5 X 7 with 7 X 9 preferred for CRT, LED, and LCD displays of alphanumeric and symbolic characters. Boff and Lincoln (1988) found that a 7 X 9 matrix produced significantly better identification than a 5 X 7 matrix. ANSI/HFS 100-1988 permits a 4 X 5 matrix for superscripts and fractions.

AIR 1093 stipulates the character size in inches and millimeters. The minimum character height is .15 in. (3.8 mm) for fixed symbols and .20 in. (5.1 mm) for moving symbols. The minimum character height is .19 in. (4.8 mm) for fixed alphanumeric characters and .25 in. (6.4 mm) for moving characters.

Both ANSI/HFS 100-1988 and MIL STD 1472D stipulate a minimum VAS of 16 minutes of arc, and AC 25-11 stipulates a minimum of 15 minutes of arc. Boff and Lincoln (1988) report that character recognition improves as the size increases from 10 to 20 minutes of arc and that accuracy is best with characters subtending 16 to 22 minutes of arc. ANSI/HFS 100-1988 recommends a preferred size of 20 to 22 minutes of arc, with a maximum height of 45 minutes of arc. MIL STD 1472D stipulates a minimum VAS of 24 minutes of arc for flight display characters that must be read under aircraft environmental conditions. Therefore, the larger sizes recommended in the preceding paragraph should be used whenever possible with the smaller acceptable sizes used only when absolutely necessary or for noncritical information. The approximate character height (H) in inches can be determined for a given distance (D) in inches and a given VAS in arc minutes (A) by the formula $H = AD/3484$ (Helander, 1987). Thus, for a VAS of 24 minutes at the nominal viewing distance of 29 in., the character height should be .20 in. (5.1 mm). An alternative method for estimating minimum VAS is that the character height should be at least 1/200th of the viewing distance, which would result in a VAS of 17 minutes of arc (Cardosi, in preparation).

The literature is relatively consistent about the other aspects of character size, which are similar to the guidelines for control labels. The height-to-width ratio should be between 1:0.7 and 1:0.9 for most characters. The alternative width-to-height ratio should be approximately

3/5 for most characters. The requirements for narrow and wide letters and numbers (e.g.. I. 1. M, W, and 4) are the same as for control labels (see Section 3.2.5.3). The minimum stroke width should be at least one pixel and 1/12th the character height. However, Boff and Lincoln (1988) report that stroke widths of 20% to 30% of character height result in more rapid character recognition.

3.3.3.3 Spacing - AIR 1093 stipulates that the minimum spacing should be one stroke width between characters or scale graduations and one character width between words. ANSI/HFS 100-1988 approximates these guidelines but states the character spacing standard as a minimum of 10% of character height. Boff and Lincoln (1988) recommend horizontal spacing of 25% of character height for CRTs. ANSI/HFS 100-1988 also stipulates a minimum of two stroke widths or 15% of character height between lines in a display. ANSI/HFS 100-1988 spacing recommendations should be considered the minimum for GPS displays. ANSI/HFS 100-1088 suggests that increased space between characters increases readability. Bednall (1992) found that inserting a blank line between categories of information facilitated the location of desired information.

Table 3-12 summarizes the recommendations for display character design.

3.3.3.4 Light Considerations - An extensive discussion of light variables and photometric measurement is beyond the scope of this document. However, a general definition of a few basic terms is required to discuss the lighting (and contrast) guidelines for GPS receivers. First, luminance is the luminous power emitted or reflected from a surface. It is measured in candelas per square meter (cd/m^2) in the international system and in footlamberts (fL) in the English system. Second, illuminance (also called illumination) is the luminous power striking a unit surface area. It is measured in lux in the international system and in footcandles (fc) in the English system. Finally, the reflectance of a surface is the ratio (expressed as a percentage) of the luminance reflected to the illuminance incident to the surface.

Table 3-12. Alphanumeric Display Character Design Recommendations

- The font should not have extraneous details but confusable characters should be distinguishable
- Display characters should be all capital letters except for text messages
- Numeric characters should have a minimum of 7 segments
- Alphabetic characters should have a minimum of 14 segments
- The minimum character matrix sizes are the following:
  - 4 X 5 for superscripts and fractions
  - 5 X 7 for normal characters
  - 7 X 9 for critical alphabetic characters
- The minimum character heights are the following:
  - .19 in. (4.8 mm) for fixed alphanumeric characters
  - .25 in. (6.4 mm) for moving alphanumeric characters
  - .15 in. (3.8 mm) for fixed symbols
  - .20 in. (5.1 mm) for moving symbols
- The minimum visual angle subtended should be 16 minutes of arc
- The minimum width for most characters is 60% of their height
- The minimum width of narrow (1, I) and wide (M, W, 4) characters is the same as for control labels (see Table 3-7)
- The minimum stroke width should be one pixel and 1/12 of character height
- The minimum spacing requirements are the following:
  - the greater of one stroke width or 10% of height for characters
  - one normal character width between words
  - the greater of two stroke widths or 15% of character height between lines

Note. Compiled from Aerospace Information Report 1093 (1969); Aerospace Standard 8034 (1982); American National Standards Institute ANSI/HFS 100-1988; Bednall (1992); Boff and Lincoln (1988); Helander (1987); Military Standard 1472D (1989); and Smith and Mosier (1986).

RTCA DO-208, TSO C129, and AC 25-11 require that brightness be adjustable because the display must be visible under different levels of ambient illumination. For emissive displays, such as a CRT, ANSI/HFS 100-1988 specifies that either the character or its background, whichever is of higher luminance, must be able to achieve a luminance of at least 35 cd/m^2 (10 fL) or more. For reflection displays, such as the LCD, the incident illumination on the display surface must be at least 110/R lux or 10.2/R fc, where R is the reflectance of the display surface. AIR 1093 specifies a minimum character brightness of 1 cd/m^2 (0.3 fL). MIL STD 1472D specifies a minimum luminance of .07 - .35 cd/m^2 (.02 - .10 fL) when dark adaptation is required. MIL STD 1472D also specifies that the display must be adjustable from 10% of the minimum ambient illumination up to the full luminance of the display.

The minimum high brightness setting must, of course, conform to the regulatory requirements. The difference between the recommended low brightness settings is barely discernible to the naked eye. Because it is aviation specific, the AIR 1093 minimum brightness setting is recommended for the GPS display.

The display luminance should also be uniform across all parts of the display. ANSI/HFS 100-1088 states that the luminance at the edge of the active area of the display should not vary more than 50% of the center luminance. AS 8034 stipulates that the luminance should not vary more than 20% within the central 80% of the useful display area. Both recommendations should be accommodated in the GPS display design. In addition to the design characteristics of the display, operators should use any available means (e.g., reducing illumination from other sources and installing glare shields) to improve the brightness of the display relative to the ambient illumination.

3.3.3.5 Contrast - To be readable, there must be a difference in the luminance of the characters and their background, which is called contrast. Contrast can be measured in several ways, but the most straightforward is the ratio of the higher luminance to the lower luminance. ANSI/HFS 100-1988 specifies a contrast ratio of 3:1 or higher. The other reference sources make more general recommendations that the contrast should be sufficient to permit reading under all expected environmental conditions. Rogers et al. (1986) found that a contrast ratio of 1.4:1 was sufficient under low and moderate ambient light conditions. but that a ratio as high as 30:1 may be needed for legibility under bright sunlight conditions. If the contrast is adjustable for the GPS display, the range recommended by Rogers et al. should be used. If it is not adjustable, the ratio of 3:1 should be considered the minimum contrast.

3.3.3.6 Resolution - Visual display resolution is a measure of the quality or sharpness of the smallest displayed character. There are several methods of measuring resolution. ANSI/HFS 100-1988 uses the Modulation Transfer Function Area (MFTA) as the standard for display resolution, but its explanation and computation are quite complex and beyond the scope of this report. Assuming a standard scan line width, Helander (1987) defines resolution simply in terms of minimum dot matrix size, which has already been presented under the topic of character size. He recommends a minimum of 5 horizontal scan lines per character, which would be a character height of .13 in. Woodson et al. (1992) recommend 10 scan lines per character and Boff and Lincoln (1988) report a preference for 10 to 12 lines. Given the previously recommended minimum height of .20 in. at the nominal viewing distance to maintain a VAS of 24 minutes of arc, the minimum resolution should be approximately 7 to 8 lines per character.

There are several other factors that can affect the legibility of electronic display characters. Two important temporal considerations are flicker and jitter. Flicker results from the variation in luminance caused by the constant reactivation of the phosphors in a CRT or reapplication of voltage to the pixels of an LCD. Flicker occurs at different spatial frequencies (called the critical flicker frequency) for different individuals. ANSI/HFS states that the display should be flicker free for at least 90% of the population, but this standard provides little help to the display designer or evaluator. Woodson et al. (1992) recommends that the phosphor driver combination should not generate pulses in the range of 30 to 55 Hz. Boff and Lincoln (1988) report that CRT refresh rates of less than 20 Hz are annoying but that flicker is eliminated above 35 Hz. Mangold et al. (1992) recommend a refresh rate of 50 to 60 Hz for CRT displays and a frame rate of 30 Hz for LCDs. The technology-specific rates suggested by Mangold et al. are recommended for GPS displays (see Table 3-13).

Table 3-13. Technical Considerations for Displays

Display Characteristic	Guideline
Minimum character brightness	1 cd/m^2 (0.3 fL)
Minimum high brightness (emissive display)	35 cd/m^2 (10 fL)
Minimum high brightness (reflection display)	110/R lux (10.2/R fc)
Luminance variability at edge	≤50% of center
Luminance variability in central 80% of display	≤20%
Minimum contrast ratio (adjustable brightness)	1.4:1
Minimum contrast ratio (not adjustable)	3:1
Minimum resolution (lines per character)	7
Minimum refresh rate	50 Hz
Minimum frame rate	30 Hz
Maximum variability per in. (mm) of viewing distance	.0002

Note. Compiled from Aerospace Information Report 1093 (1969); Aerospace Recommended Practice 1874 (1988); Aerospace Standard 8034 (1982); American National Standards Institute ANSI/HFS 100-1988; Boff and Lincoln (1988); Helander (1987); Military Standard 1472D (1989); and Woodson, Tillman, and Tillman (1992).

The second temporal consideration is jitter, which is the geometric instability of a display element as the screen is refreshed. Jitter occurs primarily with CRT displays. ANSI/HFS 100-1988 specifies that variations in the geometric location of a display element must be equal to or less than .0002 in. per in. of viewing distance or .0002 mm per mm of viewing distance. AS 8034 and ARP 1874 prescribe standards for jitter in terms of viewing angle, but they disagree: the former specifies 0.6 milliradians and the latter 0.3 milliradians. If jitter can be perceived, the ANSI standard should be used to determine if it is excessive, because of the disagreement in the other sources.

Other display characteristics include symbol alignment, linearity, drift, convergence, focus, line width, and chrominance uniformity, but they are less obvious to an observer and more complicated to measure (see ARP 1874; AS 8034; and Cardosi (in preparation). However, AC 25-11 states that the manufacturer should identify any of these characteristics (including flicker and jitter) that do not comply with the specifications in ARP 1874 and AS 8034. In the event of noncompliance, AC 25-11 states that the FAA test team is to determine whether the display, as installed in the airplane, is satisfactory.

3.3.3.7 Terminology - Words may be used in the display either as data output (e.g., identifying the nearest airport), messages (e.g., system status), operator instructions (prompts), or field identifiers (labels). The terminology used in the GPS display should conform to the same principles enumerated for control labels (see Table 3-7). The most important principle is that words should be used consistently to communicate the same intended meaning. That is, the words used in the display should be standardized to avoid confusion. The choice of words should conform to the general principle of presenting information in a form that is familiar to the user. Display wording should also be as concise as possible while still transmitting the required information. Finally, whole words should be used if space permits. Abbreviations and acronyms may be used if their meanings are clear and their usage is standardized. MIL STD 783D contains lists of word and phrase abbreviations and acronyms that are appropriate to the aviation community.

3.3.4 Specialized Display Characteristics

Additional guidelines were identified for three specialized display characteristics, which are presented in this section. The first two characteristics address the display of nonalphanumeric information: analog displays and map displays. The third characteristic addresses special considerations for alerts and warnings, which provide critical information to the pilot.

3.3.4.1 Analog Displays - Analog displays should be used instead of or in addition to alphabetic or numeric displays when high precision is not required and speed of interpretation and response is important (Boles & Wickens, 1987). There are regulatory requirements in

RTCA DO-208, TSO C129, and AC 25-11 for presenting some types of navigation information in nonalphanumeric displays. The primary nonalphanumeric display is the CDI, which has a fixed horizontal scale of equal increments about a center null point. The sensitivity of the scale can be adjusted for different flight phases to present the maximum information about the total situation as possible within the size limits of the display (i.e., Roscoe's [1990] principle of optimum scaling). A moving pointer is used to indicate the direction and magnitude of aircraft deviations from the desired course.

The regulatory documents provide detailed requirements about the deflection, readability, minimum discernible movement, resolution, accuracy of the centered display, and linearity of the display output for en route/terminal, approach transition, and non-precision approach flight phases, but they do not address ergonomic considerations in the design of the analog CDI or other displays, such as a vertical situation indicator. The following recommendations for analog scale design are drawn primarily from Boff and Lincoln (1988), Grether and Baker (1972), McCormick (1976), MIL STD 1472D, and Woodson et al. (1992).

The guidelines for selecting an analog scale are very general. Essentially, the scale range should encompass the minimum and maximum values and the scale should present the least precision that still fulfills the needs of the operator. In addition, the scale should indicate values in an immediately usable form that do not require mental conversion. For example, if the critical CDI information is nautical miles off course, the scale should not be presented in angular degrees off course. Boff and Lincoln (1988) recommend that numeric scales begin with zero and increase in value in a clockwise direction. This guideline may be appropriate for some analog scales, but not a CDI, which shows both magnitude and direction. Scale axes should be labeled. Unnecessary ornamentation or graphic patterns and alignment flaws should be avoided.

The guidelines for scale intervals and marker dimensions are much more specific. The scale intervals should be graduated in values of 1, 2, or 5, or decimal multiples of those values. Graduation values of 1 are most preferred and values of 2 are least preferred. There should be no more than nine minor or intermediate graduation marks between numbered intervals.

Scales numbered by intervals of 1, 10, 100, etc. and subdivided into 10 graduation intervals are normally superior to other acceptable scales.

The following scale dimensions assume adequate illumination, a nominal reading distance, and high contrast. Under these conditions, the minimum width of a graduation mark should be .0125 in. (.3 mm). The minimum height of major, intermediate, and minor graduation marks should be .22 in. (5.6 mm), .16 in. (4.1 mm), and .09 in. (2.3 mm), respectively. The graduation marks should be spaced at least .035 in. (.9 mm) apart, edge-to-edge, or .05 in. (1.3 mm) apart, center-to-center. However, the distance should be not less than one stroke width for black marks on a light background or less than two stroke widths for white marks on a dark background. The distance between major graduation marks should be at least .5 in. (13 mm) apart for maximum accuracy. Wider graduation distances have little effect on reading the scale value (Boff & Lincoln, 1988).

Under low illumination conditions that may occur in the cockpit at night, the marker width and spacing dimensions should be increased to the following values: major graduation marks should be at least .035 in. (.9 mm) wide, intermediate marks should be .03 in. (.8 mm) wide, and minor marks should be .025 in. (.6 mm) wide. The graduation marks should be spaced at least .07 in. (1.8 mm) apart, center-to-center.

The recommended scale dimensions only address minimum size and spacing. The maximum size is controlled by the space available in the display and the range of scale values required. However, Woodson et al. (1992) recommend that 'thick' marks be avoided and that scale marks not be joined by a 'heavy' base line. Unfortunately, they do not define thick or heavy except by figural example. They do make two additional recommendations that should be applied to the GPS analog scale design. First, the scale pointer tip should be the same width as the scale mark. Second, numbers associated with the scale values should be located so the pointer does not obscure them. Finally, Boff & Lincoln (1988) found that horizontal scales are read more rapidly than vertical scales. Tables 3-14 and 3-15 summarize the design guidance for analog displays.

Table 3-14. Analog Display Design Guidance

- Use to present data requiring low precision but rapid interpretation
- The scale range should encompass the minimum and maximum value required for the task
- Scale values should be directly usable (no conversion required)
- Scale values should be clearly indicated unless they are obvious
- Unnecessary ornamentation or graphic patterns should be avoided
- Graduate scale intervals in multiples of 1, 2, or 5
- No more than nine graduation marks between numbered intervals
- Scales numbered by intervals of 1, 10, etc. and subdivided into 10 graduation intervals are preferred
- Use the same width for scale marks and the pointer tip
- The pointer should not obscure scale values
- Horizontal scales are preferred to vertical scales

Note. Compiled from Boff and Lincoln (1988); Grether and Baker (1972); McCormick (1976); Military Standard 1472D (1989); and Woodson, Tillman, and Tillman (1992).

Table 3-15. Minimum Analog Display Scale Dimensions

Scale Characteristic	Minimum Dimension
• Graduation mark width	.0125 in. (0.3 mm)
• Major graduation mark height	.22 in. (5.6 mm)
• Intermediate graduation mark height	.16 in. (4.1 mm)
• Minor graduation mark height	.09 in. (2.3 mm)
• Graduation mark edge-to-edge spacing	.035 in. (0.9 mm)
• Graduation mark center-to-center spacing	.05 in. (1.3 mm)
• Distance between major graduation marks	.5 in. (13 mm)

Note. Compiled from Boff and Lincoln (1988); Grether and Baker (1972); McCormick (1976); Military Standard 1472D (1989); and Woodson, Tillman, and Tillman (1992).

3.3.4.2 Map Displays - Another type of nonalphanumeric display used with GPS data is a map display of geographic position. Roscoe (1990) suggests that map displays are beneficial because they lend themselves to the application of pictorial realism. That is, their graphically encoded information content can be readily identified with what they represent. Design considerations for map displays are complex. However, Table 3-16 summarizes general recommendations for map display from ARP 4102/7 and Smith and Mosier (1986).

One other major design issue is discussed in this section: whether the map should be oriented with north up or the aircraft track up. A track-up alignment eliminates the need for mental rotation to maintain navigational awareness and simplifies flight control because all turns are made to the left or right of the current heading shown on the display. With these advantages, it is the logical choice for map orientation (Aretz, 1991). However, research has failed to demonstrate performance advantages for either design (see Wickens, 1984, for a review). For example, Marshak, Kuperman, Ramsey, and Wilson (1987) found that fewer errors were committed in spatial awareness tasks with track-up maps, but Harwood (1989) found that the search and identification of specific landmarks was aided by using a north-up map.

Aretz (1991) recommends that the design of the map display should depend on its primary use. Navigation tasks that require an egocentric frame of reference (forward view of the world; directions indicated by reference to clock positions) should use the track-up map. Navigation tasks that require world-centered frame of reference (top-down view of the world; directions indicated by compass headings) should use the north-up map. Because both types of tasks are frequently performed by most pilots, the GPS should be capable of both types of displays. However, there is a danger that the pilot may mistake the type of map currently displayed (Aretz). Therefore, the map orientation should be clearly indicated on the display.

3.3.4.3 Alarms - By regulation, the GPS display must be capable of indicating critical system states. A navigation warning flag is required when there is a loss of navigation function caused by the absence of power or a probable equipment malfunction or failure. In the approach mode, the flag must also be displayed when there is either inadequate or invalid navigation data or when there is a loss of the Receiver Autonomous Integrity Monitoring

Table 3-16. Design Guidance for Map Displays

- Maps should cover the areas and display all the essential details needed to perform the navigation tasks; the map scale should be clearly indicated
- Waypoints should be identified by conventional terminology and abbreviations
- Symbols should follow accepted navigation chart usage
- Label significant features on the map when it can be done without producing clutter
- Position map labels consistently in relation to the features they designate
- Alphanumeric legends and labels should remain upright with map rotation, except for compass numerals on the heading scale
- Alphanumeric data and legends should not interfere with or degrade moving symbols or tracks
- Courses and desired track lines should remain in view even when their origin or termination is not visible
- Actual courses or projected track lines should be clearly distinguishable from coincident planned courses or track angles
- Movement of symbols and lines should be smooth during map rotation or parameter selection

Note. Compiled from Aerospace Recommended Practice 4102/7 (1988) and Smith and Mosier (1986).

(RAIM) function. In addition, the GPS equipment is required to annunciate certain system states (e.g., RAIM indicates that the horizontal radial position error is outside the alarm limit for the phase of flight or there is an absence of a positive integrity check of the navigation solution) or flight mode conditions (e.g., the approach mode is enabled or the system is in the approach mode).

3.3.4.3.1 Visual Alarms - For visual alert and warning signals, MIL STD 1472D only states that the display should provide the operator with a greater probability of detecting the condition than normal observation would provide in the absence of the display. To get the operator's attention, the signal should be of large size, high brightness in comparison to the rest of the display, or employ motion. However, the signal should not disrupt the operator's attention to other duties. They should also indicate what is wrong or what action to take (Grether & Baker, 1972). Normally, alerts and warnings indicate only two information values (e.g., safe or unsafe, on or off), but some contain three levels of information (e.g., stop, caution, or go).

Flags have low attention value unless the operator is viewing the display (Grether & Baker, 1972). That is, some time may pass before the pilot is aware of the flag. Therefore, flag motion is a desirable attribute, because it is an excellent attention-getting device (AC 25-11). An alternative method of attracting the operator's attention is to use a secondary alert, such as an audio signal. Whether additional attention-getting methods are employed, the flag should be large enough to obscure the affected information in the display to ensure the pilot does not continue to use the data while failing to notice the flag. As an example, the pilot could interpret a centered CDI as proficient navigation rather than a system failure if the CDI is not obscured by the flag.

Light signals or transilluminated word signals are much more effective in attracting the pilot's attention. Light signals can annunciate alerts and warnings by their location or color. However, light signals indicating urgent warnings should be within 30 degrees of the operator's normal line of sight to ensure timely detection. Boff and Lincoln (1988) recommend that high priority warnings be within 15 degrees of the normal line of sight, but this is probably not realistic for the placement of the GPS receiver in the cockpit. Because of the limited space in the GPS panel, only a few of the most critical warnings should be annunciated by light signals to ensure they can be easily distinguished by their location. They must also be bright enough to be detected from the display luminance or over the ambient illumination, but not bright enough to cause a loss of dark adaptation during night flight. The contrast ratios for display information (see Table 3-13) should also be used for light signals. When lighted words are used as an alert or warning signal, a letter height of .2 to .3 in (5.1 to 7.6 mm) should be used. Grether and Baker (1972) recommend using dark letters on a light background for word alerts and warnings.

If color can be used for the light signal, ARP 4102/4 and AC 25-11 stipulate that red should be used to warn the pilot of emergency conditions such as serious system failures and yellow or amber should be used to alert the pilot of abnormal conditions such as system failures that have no immediate effect on flight safety. Colors other than red or yellow/amber can be used at the designer's discretion for advisory messages such as a loss of system redundancy. However, the use of more than six colors in the entire display can lead to errors in color discrimination (Boff & Lincoln, 1988; Cardosi, in preparation). In addition, alphanumeric characters and symbols that are colored need to be larger than the dimensions for black or white characters or symbols. If the light signal is bright and has high contrast with the background, the color of the signal has little effect in attracting attention. With low brightness contrast, red is the easiest to detect and so should be used for the most urgent warnings (McCormick, 1976).

A flashing light or word signal is more likely to attract attention than a steady state signal, but it can also be more distracting of attention needed for equally important tasks. In addition, the advantage of more rapid detection is lost if more than one light is flashing (Boff & Lincoln, 1988). Therefore, flashing or intermittent signals should be used only for the most urgent warnings (Grether & Baker, 1972). The flash rate should be well below the critical flicker fusion frequency, which for most individuals is approximately 30 Hz. McCormick (1976) recommends flash rates of between 3 and 10 per second with a duration of at least .05 seconds. The recommendations for visual alerts are presented in Table 3-17.

3.3.4.3.2 Auditory Alarms - When a secondary means of warning or alerting the pilot is required because of the criticality of the situation or because visual signals are unlikely to attract attention, audio signals should be used. MIL STD 1472D recommends that audio signals should consist of two elements, an alerting signal and an identifying or action signal. When reaction time is critical, however, a single element signal is permissible. In either case, the purpose of the audio signal should be to alert the pilot to the appropriate visual annunciation or display; audio signals should never be the only warning or alerting signal. Periodic tones should be used for limited information, such as on and off. Complex sounds can be generated for specific meanings. The number of distinct audio signals used should be

Table 3-17. Ergonomic Considerations for Visual Alerts and Warnings

- Critical system states must be indicated on the GPS display (e.g., excessive horizontal radial position error or absence of a positive integrity check
- A navigation warning flag must be displayed whenever there is a loss of navigation function (e.g., power loss or system malfunction) or inadequate navigation data in the approach mode
- The use of motion increases the probability the flag will be detected
- Light signals are a better method of attracting the pilot's attention but the number of signals used should be limited to critical warnings
  - light signals should be within 30 degrees of the normal line of sight
  - light signals should be bright enough to be detected against the display luminance or ambient illumination but should not cause a loss of dark adaptation at night
  - The contrast ratio should be at least 3:1
- The minimum letter height of lighted words should be .2 in. (5.1 mm)
- Color is effective for attracting attention if six or fewer colors are used in the display
  - red should be used for warning of emergency conditions
  - yellow or amber should be used for alerting of abnormal conditions
- Flashing or intermittent signals increase the probability of detection if only one light is flashing
  - the flash rate should be less than 30 Hz (3 to 10 preferred)
  - the flash duration should be at least .05 seconds
- Audio signals can attract the pilot's attention to the visual warning

Note. Compiled from Advisory Circular 25-11, 1987; Boff and Lincoln, 1988; Cardosi, in preparation; Grether and Baker, 1972; McCormick, 1976; Military Standard 1472D (1989); RTCA Document No. DO-208, 1991; and Technical Standard Order C129, 1992.

limited to five or six sounds (Sorkin, 1987). Cardosi (in preparation) recommends limiting the number of audio signals to three or four when workload and time pressure are high.

MIL STD 1472D recommends an audio frequency range between 200 Hz and 5000 Hz. with a preferred range of 500 Hz to 3000 Hz. It also recommends that the audio signal be at least 20 dB greater than the ambient noise level, but not so loud that it causes discomfort or aftereffects. Sorkin (1987) defines signals that are 30 dB above the masked threshold (ambient noise level) as being annoying and disruptive. He also suggests that audio signals that are 15 to 16 dB above the masked threshold are sufficiently intense for warning signals. Woodson et al. (1992) recommend that continuous and intermittent tonal signals should be confined between 400 and 1500 Hz and that the signal should exceed the background noise by at least 15 dB. The signal should also be set at least 60 dB above the absolute threshold but not be greater than 135 dB. For warble or undulating tones, Woodson et al. recommend a signal frequency between 500 and 1000 Hz with a rise and fall rate of 1 to 3 Hz. The same intensity levels should be used for the undulating tones. Boff and Lincoln (1988) recommend using multiple frequencies in the range of 250 to 4000 Hz with an amplitude of at least 15 dB above the marked threshold. Cardosi (in preparation) recommends that audio signals should be in the frequency range of 500 to 3000 Hz and should have a minimum duration of .5 seconds.

The recommendations for audio signals are reasonably consistent. For GPS alerts and warnings, the parameters suggested in MIL STD 1472D are the least restrictive in terms of frequency range but set a higher minimum intensity, which is probably appropriate to the aircraft cockpit. The upper limit on intensity should conform to the recommendations by Woodson et al. (1992). The recommendations for GPS audio signals are presented in Table 3-18.

3.3.4.3.3 Speech Alarms - None of the current GPS receivers use speech generation to convey alerts, warnings, or advisory messages to the pilot, but it is possible they will in the future. Speech displays may be advantageous when a rapid means of communicating complex information is needed, the information can be communicated in a short message, the meaning is intrinsic in the signal, and the message will not be needed later (Cardosi, in preparation). In addition to the limitations discussed in Section 3.3 for auditory signals in general, there are additional limitations to the use of speech messages. First, comprehending

Table 3-18. Ergonomic Considerations for Audio Alarms

- Audio alarms can be used to attract the pilot's attention to the visual alert or warning, but should not be the only signal
- Each audio alarm should be distinct so that it can be easily recognized
- The number of audio signals should be limited to six (four preferred)
- The audio signal should consist of two elements unless reaction time is critical
  - the first element should be an alerting signal
  - the second element should be an identifying or action signal
- Periodic tones can be used for limited information (e.g., on or off) and complex sounds should be used for specific meanings
- The audio frequency range should be between 200 and 5000 Hz (500 to 3000 Hz is preferred)
- The audio signal should be at least 60 dB and at least 20 dB above the masked threshold, but should not exceed 135 dB
- Undulating tones should rise and fall at a rate of between 1 and 3 Hz
- The minimum duration should be .5 seconds

Note. Compiled from Boff and Lincoln, 1988; Cardosi, in preparation; Military Standard 1472D (1989); Sorkin, 1987; and Woodson, Tillman, and Tillman, 1992.

speech messages may be slower than reading a visual display. Second, the speech message cannot be scanned for critical information nor recalled for later review. Third, the pilot can hold only a limited number of sequentially presented speech messages in working memory (Smith & Mosier, 1986).

Finally, there are many design alternatives for speech messages (e.g., speech rate, synthetic versus natural speech, audio frequency and amplitude, and the sex and accent of the speaker) and only limited rules of thumb to guide the designer or evaluator (Kantowitz & Sorkin, 1983; Stokes et al., 1990). In some cases, the guidance is conflicting. For example, Boff and Lincoln (1988) recommend that the speech message should be preceded by an alerting signal, but Stokes et al. (1990) report empirical research that indicates that an alerting signal may increase the response time. Another conflict is the sex of the spoken voice. Early speech generation systems usually used a female voice, presumably because female voices were less likely to be part of the ambient environment. That presumption is no longer valid for many applications. In addition, the intelligibility of the female voice may be less than the male voice, especially in the cockpit environment (see Stokes et al., 1990).

Although the available guidance for speech alerts and warnings is limited, the information that is relatively consistent across references and applicable to GPS receivers is summarized in Table 3-19.

Table 3-19. Ergonomic Considerations for Speech Alerts and Warnings

- Limit the number of speech messages
- Make each message distinctive in terms of pitch, accent, loudness, etc.
- Keep each message as simple as possible while providing appropriate syntax and context
- Use words that are familiar to the pilot, but avoid jargon
- Avoid words that rhyme with other words that could be used in the same context and could be confused with the intended word
- The speech rate should be approximately 156 words per minute (wpm), but not more than 178 wpm nor less than 123 wpm
- Use an "average" American accent without a regional dialect
- Pilots prefer direct male synthesized speech but the sex of the voice or whether it is natural or synthesized has less effect on intelligibility than the speech rate, accent, and vocabulary
- Use the same frequency ranges as for nonspeech audio signals
- The speech message should be at least 5 dB above the ambient noise level

Note. Compiled from Boff and Lincoln, 1988; Cardosi, in preparation; Smith and Mosier, 1986; Stokes, Wickens, and Kite, 1990; and Woodson, Tillman, and Tillman, 1992.

3.3.4.3.4 General Alarm Considerations - In addition to the specific recommendations for visual, audio and speech, alerting and warning signals, there are several design issues that apply to all types of alarms. It is explicit in the specific recommendations that each alarm should be readily distinguishable from the others. Furthermore, the alarms should be distinguishable by category. That is, alarms that are critical to the flight and require immediate responses should be easily distinguished from noncritical alarms. The distinction between alarm types also leads to a need for a prioritization of the alarms. That is, the most critical alarm signal should be presented until the problem is resolved (or at least the pilot acknowledges the alarm) before a less critical alarm is presented.

Boff and Lincoln (1988) make three additional recommendations that are applicable to GPS receivers. First, the alerting and warning signal(s) should be presented until the pilot responds. Second, distracting stimuli and workload should be minimized while alerting or warning signals are being presented. Third, there should be a method for the operator to cancel the alarm(s). Smith and Mosier (1986) further recommend that there be a simple means for the operator to cancel an auditory alarm without erasing the associated visual message. However, critical alarms shall be repeated until the condition causing the alarm is corrected or overridden by the operator.

3.4 CONTROL-DISPLAY INTEGRATION

Many ergonomic considerations about control-display relationships were addressed in the subsections describing the separate guidelines for controls and displays. For example, guidelines were presented about placing controls in close proximity to their associated displays, using labels to identify the controls and displays, using terminology consistently, providing feedback to the pilot about control inputs through changes in the associated displays, and maintaining consistency in the direction of movement of controls and displays. There is an extensive literature about the human-computer interface (e.g., Mayhew, 1992; Schneiderman, 1987; Smith & Mosier, 1986), but the guidelines in these sources generally apply to highly complex computer systems and multiple applications, which are only partially applicable to GPS receivers. The following two subsections describe basic guidelines that are relevant to GPS receiver design and are not redundant with previously presented guidance. The first subsection presents guidance about data entry and display; the second subsection presents guidance about error management. The guidelines in both subsections were compiled primarily from Cardosi (in preparation), and Smith and Mosier (1986).

3.4.1 Data Entry

Smith and Mosier (1986) list the following five primary objectives for design guidance related to data entry:

- consistency of data entry transactions,
- minimal entry actions,
- minimal memory load on the user,
- compatibility of data entry and display, and
- flexibility for user control of data entry.

Because data entry in GPS receivers is highly formatted, guidelines related to flexibility are not presented. Guidelines addressing the other objectives are summarized in Table 3-20.

3.4.2 Error Management

Errors will inevitably occur in data entry, and the GPS receiver must permit the pilot to recognize and correct the errors. Whenever possible, the system should also recognize errors (e.g., unacceptable data formats or out-of-tolerance values) and advise the pilot of the errors. Design guidelines for error management are summarized in Table 3-21.

Table 3-20. Design Guidelines for Data Entry

- Design the display to indicate which data entry or command options are available in the current mode or configuration
- Provide a clearly defined field for data entry
- Provide prompting for acceptable data formats and values
- Provide a movable cursor with distinctive visual features to designate the data entry position
- When a mode is initiated, normally position the cursor in the first data field
- Design the cursor control to permit rapid movement and accurate placement from one position to another
- Provide a method for entering data that requires the minimum number of actions by the user; where possible, allow the user to select from a menu
- Provide a method for entering data that imposes the least requirements on user memory by making the interactive sequences intuitive and consistent
- Allow the user to control the pace of data entry
- Rapidly acknowledge (e.g., character by character) data entry actions on the user's primary display
- Enable the user to review entered data
- Enable the user to edit entered data using the same method as the original entry; where possible, the user should be able to edit all or a part of a data field
- Require minimal, simple user actions to execute commands
- Require an explicit ENTER of the user to initiate the processing of entered data; clearly label the ENTER key
- Require an explicit CANCEL or DELETE action of the user to remove entered data or to terminate a command; clearly label the CANCEL or DELETE key
- Provide feedback to the user about the status of an operation

Note. Compiled from Cardosi, in preparation; and Smith and Mosier, 1986.

Table 3-21. Design Guidelines for Error Management

- Design the system software to provide an appropriate response to all possible control entries, both correct and incorrect
- Design the system to recognize errors and to immediately prompt the user to correct them
- Use error messages that describe the problem and, if possible, recommend a solution
- Design the error messages to present factual information and to avoid value judgments
- Enable the user to correct data entry errors directly and immediately
- Enable the user to stop a process at any point to make corrections
- Require the user to take an explicit ENTER action to enter corrected data or to initiate a revised operation
- Require the user to confirm a control entry that will result in extensive changes in stored data, procedures, or operations

Note. Compiled from Cardosi, in preparation; and Smith and Mosier, 1986.

4. SUMMARY AND RECOMMENDATIONS

The literature reviewed contained relatively comprehensive recommendations for design principles and guidelines that are applicable to critical aspects of GPS receiver controls and displays. Many of the recommendations were specific to the aviation context and were based on research and experience with similar aviation systems. The remaining sources of information and recommendations were based on research and experience with other types of systems, but appear to be applicable to aviation navigation systems.

Many of the aviation regulations that apply to the navigation receivers are presented at the level of design objectives rather than as specific principles and guidelines that can be used directly by system designers and evaluators. Design principles that were identified in the literature are generally at a global level of detail, but they provide guidance that can be used in selecting or evaluating design alternatives. The guidelines that were identified in the literature provide highly detailed information that can be used to define acceptable minimum and maximum control and display component parameters.

The Results section presented and discussed variations in the principles and guidelines suggested by the different reference sources. Overall, the recommendations in the literature were reasonably consistent; the variations are generally attributable to differences in the level of detail, the research and experience context that was used to develop the recommendations, and the scope of the intended application of the recommendations. When there were substantial variations for a design topic, the discussion concluded with a suggested resolution to the disparities.

The following three subsections enumerate the recommended principles and guidelines for controls, displays, and control-display integration, respectively, in concise statements that are uninterrupted by the presentation or discussion of variations in recommendations. The final subsection summarizes the restrictions and qualifications on using this document.

4.1 CONTROL DESIGN PRINCIPLES AND GUIDELINES

Although there is overlap between their uses, appropriate controls were selected separately for command and function purposes. The primary distinction between them is the number of alternative positions, values, or actions the control is used to manipulate. Command controls are used to select among relatively few alternatives (e.g., to turn the system on or off or to activate a data entry). Function controls must be capable of traversing a larger range of alternatives, such as scrolling through a database or entering data into the receiver computer.

4.1.1 Control Types and Characteristics

The literature indicates that seven types of controls are appropriate for interacting with GPS receivers. Push buttons, push-pull buttons, toggle switches, and rocker switches are appropriate for command controls (see Table 3-1). Rotary knobs, concentric knobs, and keyboards are appropriate for function controls (see Table 3-2). The literature contained guidelines for the design of each type of control.

4.1.1.1 Push Buttons - Push buttons are the preferred command control. Their shape is relatively unimportant, except that some shapes (e.g., squares or rectangles) provide more space for labeling. The operator should receive feedback (e.g., an audible click, an integral light, or a change in an associated display) that the push button has been activated. No maximum sizes were identified for push buttons, but unnecessarily long push buttons are more likely to be accidentally activated. The following list describes the size, spacing, and force guidelines for push buttons.

- The diameter should be .375 in (9.5 mm) or larger.
- The length should be .125 in. (6.4 mm) or longer.
- The displacement should be .078 in. (2 mm) to .25 in. (6 mm).
- The minimum center-to-center spacing should be .75 in. (19 mm) for horizontal separation and .625 in. (16 mm) for vertical separation. If severe vibration is expected, the minimum separation should be 3 in. (76 mm). If the minimum spacing cannot be implemented, mechanical interlocks or barriers should be used to prevent accidental activation.

- Push button resistance should be between 10 oz (2.8 N) and 40 oz (11 N) for single finger operation.

4.1.1.2 Push-Pull Buttons - Push-pull buttons should only be used sparingly and in applications where they are typically expected, such as turning the system on and off. When panel space is limited, a miniaturized rotary knob may be used in conjunction with the button to perform two related but distinct purposes. The following list describes the size, spacing, and force guidelines for push-pull buttons.

- The diameter should be .25 in. (6 mm) or larger.
- The length should be 1 in. (25 mm) or longer.
- The displacement between the push and pull positions should be at least .5 in (13 mm).
- The spacing between buttons should be 1 in. (25 mm) or more.
- The resistance should not exceed 64 oz (18 N).

The push-pull button should be pushed in to activate a command and pulled out to deactivate it. If the button can also be rotated (e.g., to adjust the brightness of the display), then the button should be long enough to be grasped when in the activate position.

4.1.1.3 Toggle Switches - Toggle switches are an acceptable alternative to push buttons for command purposes, but only where space is extremely limited. They are generally limited to two-alternative applications, unless the switch has a spring-loaded center off position. Toggle switches should be vertically oriented with on (activate) in the up position and off in the down position. The following list describes the size, spacing, and force guidelines for toggle switches.

- The arm length should be .5 in. (13 mm) to 2 in. (51 mm).
- The tip diameter should be .125 in. (3 mm) to 1 in. (25 mm).
- The two-position displacement should be between 30 and 80 degrees For a three-position switch, the displacement between any two positions should be between 17 and 40 degrees.

- The separation between switches that are operated sequentially should be .5 in. (13 mm) to 1 in. (25 mm). If the switches are operated randomly, the separation should be .75 in. (19 mm) to 2 in. (51 mm).
- The resistance of the switch should be 10 oz (2.8 N) to 40 oz (11 N).

4.1.1.4 Rocker Switches - Rocker switches are an acceptable alternative to toggle switches when the protrusion of the toggle switch may result in inadvertent activation. Unless the switch has a spring-loaded center off position, it should be limited to two positions. The rocker switch should be vertically oriented; pressing the upper wing should activate the command. The following list describes the size, spacing, and force guidelines for rocker switches.

- The width should be .25 in. (6 mm) or wider.
- The length should be .5 in. (13 mm) or longer.
- The displacement should be at least .125 in. (3 mm) and a minimum angle of 30 degrees.
- The center-to-center separation should be .75 in. (19 mm) or more.
- The resistance should be 10 oz (2.8 N) to 40 oz (11 N).

4.1.1.5 Rotary Knobs - Rotary knobs are optimal for continuous adjustments and for selecting discrete or quantitative settings with numerous positions. All the recommendations assume the knob will be operated with the finger and thumb encircled rather than by a single finger. Some method (e.g., serrated or knurled knob edges) should be used to maintain grip friction. For rotary knobs that are used to select sequential settings, clockwise movement should result in increasing values and counterclockwise movement should result in decreasing values. There should be no less than 15 degrees separation between adjacent settings. The control/display ratio should be between 0.1 and 0.4. Feedback about the selection of the desired setting should be provided through a setting detent, an audible click, or change in the associated display.

The following list describes the minimum and preferred size, spacing, and force guidelines for rotary knobs.

- The minimum diameter and length should be at least .25 in. (6 mm) and .75 in. (19 mm), respectively.
- The preferred diameter and length should both be .5 in. (13 mm).
- The minimum spacing between rotary knobs should be 1 in. (25 mm); 2 in. (51 mm) is preferred.
- The resistance should be between 2 oz. (.55 N) and 4 oz (1.1 N), but it can be as high as 12 oz (3.3 N) if severe turbulence or vibration could cause inadvertent slippage.

4.1.1.6 Concentric Knobs - Double concentric rotary knobs may be used instead of single rotary knobs when panel space is limited. Three knob configurations are highly discouraged. The two knobs must be of different sizes, with the largest knob located closest to the panel surface. If the knobs are associated with different displays, the large knob should be associated with the left-most or upper-most display. If the knobs are used for different levels of adjustment, the small knob should be used for coarse adjustment and the large knob should be used for fine adjustment. Both knobs should have serrated edges. Considerations about direction of movement, feedback about the selected setting, and control/display ratios are the same as for single knobs. The following list describes the size, spacing, and force guidelines for concentric knobs.

- The smaller, outer knob should be at least .5 in. (13 mm) in diameter and .5 in. (13 mm) in height.
- The larger, inner knob should be at least .875 in. (22 mm) in diameter and .625 in. (16 mm) in height.
- The minimum separation between sets of concentric knobs should be 1 in. (25 mm), with a preferred separation of 2 in. (51 mm).
- For both knobs, the resistance should be between 4.5 oz (1.2 N) and 6 oz (1.7 N).

4.1.1.7 Keyboards - Keyboards are also an acceptable method of performing GPS functions, especially for data entry. Because of space limitations on the GPS panel, only recommendations for a 10-button keyboard layout were reviewed. The basic layout should be a 3 X 3 matrix with the zero key centered below the matrix. The telephone layout with the numbers 1, 2, and 3 in left to right order on the top row with 4, 5, and 6 on the middle row and 7, 8, and 9 on the bottom row should be used for GPS receiver keyboards. When alphabetic characters are included in the keyboard, they should be arranged in ascending order from left to right and top to bottom.

The keys may be of any shape that meets the minimum width requirements, but a square key with a slightly concave surface is recommended. The operator should receive either auditory or tactile feedback about key activation. The recommended tactile feedback is for the key force to increase during the first 40% of the displacement followed by a substantial decrease in force during the next 20% of the displacement. Once feedback is received from the break in force, the force should increase again to cushion the key press.

The following list describes the size, spacing, and force guidelines for keyboards.

- The minimum key width should be .47 in. (12 mm).
- The key displacement should be .06 in. (1.5 mm) to .24 in. (6 mm).
- The center-to-center spacing between keys should be at least .75 in. (19 mm).
- The resistance should be .9 oz (.25 N) to 5.3 oz (1.5N), with a force between 1.8 oz (.5 N) and 2.2 oz (.6 N) preferred.

4.1.2 Control Arrangement

The location of the receiver in the cockpit is more a function of the display requirements than the control requirements, except that the pilot should be able to reach and operate the controls with one hand without shifting position. Specific guidelines about control spacing on the receiver panel have already been presented for each control type. The following five general principles should be applied to the arrangement of controls on the GPS receiver.

- The controls should be arranged in functional groups.
- The controls should be arranged systematically according to their sequence of use.
- If more than one set of controls is used to perform similar functions, their arrangement should be consistent across sets.
- The most important or the most frequently used controls should be placed in the most accessible locations.

- Collocate controls with associated displays, if possible.
- The controls should be arranged such that one control does not obscure another control or an associated display from the pilot's view.

4.1.3 Control Coding and Labeling

The controls must be coded or labeled to identify their function and to determine their settings. Codes, labels, legends, etc. should be used to identify, interpret, or follow procedures, except where it is obvious to the operator what the control is and how it is to be used. The following two subsections describe the principles and guidelines for coding and labeling.

4.1.3.1 Coding - Coding can be accomplished through location (discussed earlier under control arrangement), size, shape, and color variations in the controls. Although widely used, there are several disadvantages with size, shape, and color coding that limit their utility (see Table 3-6). When they are used for GPS receiver controls, they should meet the following guidelines.

- When using size coding, the sizes between similar controls should differ by at least 20% and the difference in control diameter must be at least .5 in. (13 mm).
- When using shape coding, the shapes employed must be easily distinguishable both tactually and visually, they should be easily associated with their function (if possible), and sharp edges should be avoided.
- The same size and shape should be used for controls that perform the same or similar functions.
- The controls should be black or gray, unless color coding is absolutely required. If required, only red, green, orange-yellow, white, and blue colors should be used for control coding.

4.1.3.2 Labeling - Because of the disadvantages associated with coding, the primary method of identifying control functions and settings on GPS receivers should be labeling. In addition to the requirement that labels be accurate and functional, there are three sets of guidelines that should be applied to label design. The following list summarizes the guidelines for label orientation and location.

- Labels should be oriented horizontally so they can be read from left to right. If space requires vertical labels, they should be read from top to bottom.
- Labels should be located on or adjacent to the linear controls they identify.
- Labels should be adjacent to rotary controls. The placement of labels should be consistent across all the controls and placed where they can be easily read.

The following list summarizes the guidelines for label character construction.

- Labels should be printed in all capital letters without punctuation, unless confusion or misinterpretation would occur because of its omission.
- At luminance levels of 3.5 cd/m^2 (1 fL) or greater and at an expected viewing distance of 19.7 in. (50 cm) to 39.4 in. (1 m), the label characters should have a minimum height of .18 in. (4.7 mm).
- If the expected viewing distance is less than 19.7 in., the minimum height should be .09 in. (2.3 mm); if the expected viewing distance is greater than 39.4 in., the minimum height should be .37 in. (9.4 mm).
- The minimum height of critical markings should be increased by approximately 60% when the luminance level falls below 3.5 cd/m^2.
- If the ambient illumination is high, the labels should be black characters on a light background. If dark adaptation is required, the labels should be white characters on a dark background.
- The stroke width of black characters should be between 14% and 17% of the height. The stroke width of white characters should be between 12% and 14% of the height.
- The width of most letters and numerals should be 60% of the height. The width of the letters M and W should be 80% of the height. The width of the letter I and the number 1 should be one stroke width; the number 4 should be one stroke width wider than 60% of the height. If characters are labeled on a curved surface or if the label is oriented vertically, the width of the characters can be the same size as the height.
- There should be at least one stroke width between characters, one normal character width between words, and 50% of character height between label lines.
- A font should be used that does not have extraneous details (e.g., sans serif), but easily confused characters (e.g., 1 and I) should be readily distinguishable.

The following list summarizes the guidelines for label terminology.

- The wording on labels should be as concise as possible with minimal redundancy. Words should be used that are familiar to the operator. Common symbols may be used as necessary but abstract symbols should be avoided unless they have an accepted meaning to all intended users.
- Complete words should be spelled out if possible. Words of four letters or less should not be abbreviated unless the word and its abbreviation are considered to be synonymous.
- The same word should be used for all variations of number, case, or tense.
- Words may be abbreviated by removing letters in a manner that minimizes the effect on the phonetic sound of the word.
- If the word cannot be abbreviated, an acronym may be formed by using the first few letters of the word; acronyms for word combinations or phrases may be formed from the first or first few letters of each word.
- Standardized abbreviations and acronyms are recommended for all GPS receivers to avoid confusion for pilots who fly with more than one system.

4.2 DISPLAY DESIGN PRINCIPLES AND GUIDELINES

GPS information can be displayed in either the visual or auditory modalities. Because of the high ambient noise levels in the cockpit, however, the primary display modality is visual. Auditory signals are reserved for limited purposes to attract the pilot's attention to alerts and warnings. The principles and guidelines are presented in four sections: general display principles, display technology, desirable characteristics for the general display, and principles and guidelines for specialized display characteristics.

4.2.1 General Principles

Contradictory research results have made it difficult to develop a theory of display design. The following five principles summarize the global guidance found in the literature that can be applied to GPS displays.

- Use the simplest display concept that provides the pilot with the required system information.
  - keep information density to 30% or less
  - label display fields to describe their content
  - use coding techniques judiciously
  - present all the information on one page if possible or clearly indicate the availability of additional information
- Use the least precise display format that will convey the information required by the operator.
- Use the most natural or expected display format for the type of information presented.
  - use formats that are consistent with user conventions and data entry requirements
  - use familiar terms and symbols
  - use formats that are directly usable by the pilot
- Use the most effective display technique for each type of information, (status, instructions, quantitative data, etc.) which presumably will be consistent with the expected format. Section 3.3.1 describes the optimum technique for displaying the different types of GPS information and for color coding the display.
- Optimize the following display features: visibility, conspicuousness, legibility, and interpretability.

4.2.2 Display Technologies

CRT technology has dominated the electronic display market; LCD, LED, and other flat panel technologies may also be appropriate for generating GPS displays. However, each technology has its own ergonomic problems that require evaluation for use in an aviation context. Brightness and contrast are potential problems with all the technologies. Flicker and raster display resolution are concerns for the CRT; lighting and viewing angle are potential problems with the LCD technology.

The only guidelines currently recommended for using each technology in GPS receivers is that their luminance and luminance contrast adjustment must be sufficient to accommodate the anticipated range of ambient light conditions. Under low to moderate ambient illumination, character-background contrast ratios beyond 1.4:1 provide little improvement in legibility.

Under the high ambient illumination in the cockpit on a sunny day, increases in the contrast ratio up to 30:1 may improve legibility.

4.2.3 General Display Characteristics

There are more extensive standards for CRT displays, which have been in use longer and are used more extensively, but the following design principles apply equally to the other display technologies.

4.2.3.1 Viewing Distance and Angle - Viewing distance and angle cannot be specified precisely because of different cockpit sizes and instrumentation arrangements. However, the literature makes the following recommendations for minimum, maximum, and nominal distances for a display from the pilot's design eye point.

- The minimum distance should be at least 13 in. (330 mm), but with a preferred minimum of not less than 20 in. (510 mm).
- The maximum distance should be 40 in. (1,016 mm).
- The nominal distance of 29 in. (737 mm) will be used for character size recommendations.

The following three viewing angle guidelines address orientation of the display surface and horizontal and vertical angle of regard from the design eye point.

- The display surface should be perpendicular to the operator's normal line of sight, but the angle of incidence should never be less than 45 degrees from the line of sight. Because most GPS receivers will be mounted in the instrument panel, their orientation should be nearly perpendicular to the pilot's line of sight.
- The optimum horizontal angle of regard should be within 15 degrees of the forward line of sight. The preferred maximum horizontal angle should be 35 degrees or less with an absolute maximum of 60 degrees.
- The optimum vertical angle of regard should also be within 15 degrees of the normal line of sight. The preferred maximum vertical angle should be 20 degrees below and 40 degrees above the line of sight. The absolute maximum angles are 36 degrees below and 66 degrees above the line of sight.

4.2.3.2 Character Size - Recommendations for character size are based on the assumption that all alphabetic characters are upper case. Numeric characters should have a minimum of 7 segments and alphabetic characters should have 14 to 16 segments. The following guidelines for the size of characters are specified according to dot matrix size, height and width, and VAS.

- The minimum matrix size should be 5 X 7 for alphanumeric and symbolic characters. When individual alphabetic character legibility is important, the minimum matrix size should be 7 X 9. A 4 X 5 matrix can be used for superscripts and fractions.
- The minimum character height is .15 in. (3.8 mm) for fixed symbols and .20 in. (5.1 mm) for moving symbols. The minimum character height is .19 in. (4.8 mm) for fixed alphanumeric characters and .25 in. (6.4 mm) for moving characters.
- The height-to-width ratio should be between 1:0.7 and 1:0.9 for most characters. The alternative width-to-height ratio should be approximately 3/5 for most characters. The requirements for narrow and wide letters and numbers (e.g., I, 1, M, W, and 4) are the same as for control labels. The minimum stroke width should be at least one pixel and 1/12th the character height.
- The absolute minimum character VAS should be 16 minutes of arc. A minimum VAS of 24 minutes of arc is preferred for flight display characters that must be read under aircraft environmental conditions. The maximum height is 45 minutes of arc.
- The font should not have extraneous details but confusable characters (e.g., 1 and I) should be readily distinguishable.

4.2.3.3 Spacing - The minimum spacing for GPS displays should be one stroke width between characters or scale graduations or a minimum of 10% of character height, whichever is greater. The minimum spacing between words should be one character width. The minimum spacing between lines in a display should be two stroke widths or 15% of character height, whichever is greater.

4.2.3.4 Light Considerations - The brightness of the GPS display must be adjustable because it must be visible under different levels of ambient illumination. The following guidelines are recommended for display luminance.

- The minimum character brightness should be 1 cd/m^2 (0.3 fL).
- The minimum high brightness for emissive displays should be 35 cd/m^2 (10 fL).
- The minimum high brightness for reflection displays should be 110/R lux (10.2/R fc), where R is the reflectance of the display surface.
- The luminance should be uniform across all parts of the display. The luminance at the edge of the active area of the display should not vary more than 50% of the center luminance. The luminance should not vary more than 20% within the central 80% of the useful display area.

4.2.3.5 Contrast - If the contrast is adjustable for the GPS display, a contrast ratio of 1.4:1 is sufficient under low and moderate ambient light conditions. A ratio as high as 30:1 may be needed for legibility under bright sunlight conditions. If it is not adjustable, a ratio of 3:1 should be considered the minimum contrast.

4.2.3.6 Resolution - Given the previously recommended minimum height of .20 in. at the nominal viewing distance to maintain a VAS of 24 minutes of arc, the minimum resolution should be approximately 7 to 8 lines per character. To avoid unacceptable flicker, the refresh rate should be 50 - 60 Hz for CRT displays and the frame rate should be 30 Hz for LCDs. To avoid jitter in CRT displays, variations in the geometric location of a display element must be equal to or less than .0002 in. per in. of viewing distance or .0002 mm per mm of viewing distance. Other display characteristics (e.g., alignment, linearity, drift) must meet the specifications in ARP 1874 and AS 8034. Noncompliance must be identified by the manufacturers and operationally evaluated in the cockpit.

4.2.3.7 Terminology - Words may be used in the display either as data output, messages, operator instructions, or field identifiers. The terminology used in the GPS display should conform to the same principles enumerated for control labels. The following guidelines summarize the major considerations.

- Use words that are familiar to the user.
- Use words consistently to communicate the same intended meaning.
- Use wording that is as concise as possible while still transmitting the required information.

- Use whole words if space permits. Abbreviations and acronyms may be used if their meaning is clear and their usage is standardized.

4.2.4 Specialized Display Characteristics

Additional guidelines were identified for three specialized display characteristics: analog displays, map displays, and alarms.

4.2.4.1 Analog Displays - Analog displays should be used instead of or in addition to alphabetic or numeric displays when high precision is not required and speed of interpretation and response is important. The scale range should encompass the minimum and maximum values required and the scale should present the least precision that still fulfills the needs of the operator. The scale should also indicate values in an immediately usable form that do not require mental conversion. The values of the scale intervals should be clearly indicated on the display, unless their values are obvious. Unnecessary ornamentation or graphic patterns should be avoided. The following guidelines address the basic design of the scale.

- The scale intervals should be graduated in values of 1, 2, or 5, or decimal multiples of those values. Graduation values of 1 are most preferred and values of 2 are least preferred.
- There should be no more than 9 minor or intermediate graduation marks between numbered intervals.
- Scales numbered by intervals of 1, 10, 100, etc. and subdivided into 10 graduation intervals are normally superior to other acceptable scales.

The following recommended scale dimensions assume adequate illumination, a nominal reading distance, and high contrast.

- The minimum width of a graduation mark should be .0125 in. (.3 mm).
- The minimum height of major, intermediate, and minor graduation marks should be .22 in. (5.6 mm), .16 in. (4.1 mm), and .09 in. (2.3 mm), respectively.
- The graduation marks should be spaced at least .035 in. (.9 mm) apart, edge to edge, or .05 in. (1.3 mm) apart, center to center. However, the distance should not be less than one stroke width for black marks on a light background or less than two stroke widths for white marks on a dark background.

- The distance between major graduation marks should be at least .5 in. (13 mm).

Under low illumination conditions that may occur in the cockpit at night, the scale marker width and spacing dimensions should be increased to the following values.

- Major graduation marks should be at least .035 in. (.9 mm) wide, intermediate marks should be .03 in. (.8 mm) wide, and minor marks should be .025 in. (.6 mm) wide.
- The graduation marks should be spaced at least .07 in. (1.8 mm) apart, center-to-center.

The maximum size is controlled by the space available in the display and the range of scale values required. Two additional recommendations that should be applied to the GPS analog scale design are: (a) the scale pointer tip should be the same width as the scale mark, and (b) numbers associated with the scale values should be located so the pointer does not obscure them.

4.2.4.2 Map Displays - The following guidelines address the design considerations for map displays.

- Maps should cover the areas and display all the essential details needed to perform the navigation tasks.
- Waypoints should be identified by conventional terminology and abbreviations. Symbols should follow accepted navigation chart usage.
- Label significant features on the map when it can be done without producing clutter. Position map labels consistently in relation to the features they designate.
- Alphanumeric legends and labels should remain upright with map rotation, except for compass numerals on the heading scale. Alphanumeric data and legends should not interfere with or degrade moving symbols or tracks.
- Courses and desired track lines should remain in view even when their origin or termination is not visible. Actual courses or projected track lines should be clearly distinguishable from coincident planned courses or track angles.
- Movement of symbols and lines should be smooth during map rotation or parameter selection.
- Navigation tasks that require an egocentric frame of reference (forward view of the world; directions indicated by reference to clock positions) should use the track-up map.

- Navigation tasks that require a world-centered frame of reference (top-down view of the world: directions indicated by compass headings) should use the north-up map.
- Because both types of tasks are frequently performed by most pilots, the GPS should be capable of both types of displays. However, the map orientation and scale should be clearly indicated on the display.

4.2.4.3 Alarms - By regulation, the GPS display must be capable of indicating critical system states, either by a navigation warning flag or a visual or auditory annunciation. Alert and warning signals should provide the operator with a greater probability of detecting the condition than normal observation would provide in the absence of the display.

4.2.4.3.1 Visual Alarms - Navigation flags do not readily attract the pilot's attention. Therefore, flag motion is a desirable attribute; an alternative method of attracting the operator's attention is to use a secondary alert, such as an audio signal. Whether additional attention-getting methods are employed or not, the flag should be large enough to obscure the affected information in the display to ensure the pilot does not continue to use the data while failing to notice the flag.

Light signals are superior to flags for attracting the pilot's attention. Only a few of the most critical warnings should be annunciated by light signals to ensure they can be easily distinguished by their location. The following guidelines should be applied to the design of light signals.

- Light signals indicating urgent warnings should be within 30 degrees of the operator's normal line of sight.
- Light signals must be bright enough to be detected against the display luminance or over the ambient illumination, but not bright enough to cause a loss of dark adaptation during night flight.
- The contrast ratio should be at least 3:1.
- When lighted words are used as an alert or warning signal, the letter height should be .2 to .3 in (5.1 to 7.6 mm).
- If color is used, red should warn the pilot of emergency conditions and amber should alert the pilot of abnormal conditions. Colors other than red or amber can be used for advisory messages. Do not use more than six colors.

- Flashing or intermittent signals should be used only for the most urgent warnings. The flash rate should be well below the critical flicker fusion frequency, which for most individuals is approximately 30 Hz. The flash duration should be at least .05 seconds.

4.2.4.3.2 Auditory Alarms - Auditory tones can be used as alert and warning signals, but their purpose should be to alert the pilot to the appropriate visual annunciation or display element. The following guidelines should be applied to the design of audio signals.

- Each audio alarm should be distinctive so that it can be easily recognized. Do not use more than six audio alarms.
- The tone should consist of two elements, an alerting signal and an identifying or action signal. When reaction time is critical, a single element signal is permissible.
- Periodic tones should be used for limited information, such as on and off. Complex sounds can be generated for specific meanings.
- The audio frequency should range between 200 Hz and 5000 Hz, with a preferred range of 500 Hz to 3000 Hz.
- The audio signal should be at least 20 dB greater than the ambient noise level and at least 60 dB above the threshold, but not more than 135 dB.
- Undulating tones should rise and fall at a rate between 1 and 3 Hz. The minimum duration should be .5 seconds.

4.2.4.3.3 Speech Displays - Speech displays may be advantageous when a rapid means of communicating complex information is needed, the information can be communicated in a short message, the meaning is intrinsic in the signal, and the message will not be needed later. Because of the limitations discussed in Section 3.3, the number of speech messages employed should be limited. If speech is used, the following guidelines should be employed.

- Make each message distinctive in terms of pitch, loudness, etc.
- Keep messages simple but provide appropriate syntax and context.
- Use familiar words, but avoid jargon and rhyming words that may be confusing.
- Use speech rates between 123 and 178 wpm.
- Use an "average" American accent without a regional dialect.
- Use the same frequency ranges as for nonspeech audio signals.
- Use an amplitude at least 5 dB above the ambient noise level.

4.2.4.3.4 General Alarm Recommendations - There are several design issues that apply to both visual, auditory, and speech alarms. In addition to the requirement that each alarm should be readily distinguishable from the others, all flight critical alarms should be distinguishable as a category from noncritical alarms. Furthermore, alarms should be prioritized on the basis of their importance, severity, and time urgency. To the extent possible, distracting stimuli and workload should be minimized when alarms are presented. The alarm should be presented until the pilot responds, but there should be a method for canceling it. However, critical alarms should be repeated until the condition causing the alarm is corrected or overridden by the operator.

4.3 CONTROL-DISPLAY INTEGRATION

Many ergonomic considerations about control-display relationships are addressed in the separate guidelines for controls and displays (e.g., placing controls near their associated displays, using terminology consistently, and providing feedback about control inputs through changes in the associated displays). The following two subsections provide additional guidelines to facilitate consistent and compatible data entry, display, and editing while minimizing user actions and memory requirements.

4.3.1 Data Entry and Display

- Design the display to indicate which data entry or command options are available in the current mode or configuration.
- Provide a clearly defined field for data entry and use prompts to indicate acceptable data formats and values.
- Provide a movable cursor with distinctive visual features to designate the data entry position. When a mode is initiated, the cursor should normally be positioned in the first data field. Design the cursor control to permit rapid movement and accurate placement from one position to another.
- Provide a method for entering data that requires the minimum number of actions by the user (e.g., allow the user to select from a menu) and that imposes the least requirements on user memory by making the interactive sequences intuitive and consistent.

- Allow the user to control the pace of data entry. Rapidly acknowledge (e.g., character by character) data entry actions on the user's primary display.
- Enable the user to edit entered data using the same method as the original entry; if possible, enable the user to edit all or a part of a data field.
- Require minimal, simple user actions to execute commands, but require an explicit ENTER action to initiate data processing; clearly label the ENTER key.
- Require an explicit CANCEL or DELETE action of the user to remove entered data or to terminate a command; clearly label the CANCEL or DELETE key.
- Provide feedback to the user about the status of an operation.

4.3.2 Error Management

- Design the system software to provide an appropriate response to all possible control entries, both correct and incorrect.
- Design the system to recognize errors and to immediately prompt the user to correct them. Use error messages that describe the problem in factual terms and, if possible, recommend a solution.
- Enable the user to correct data entry errors directly and immediately and to stop a process at any point.
- Require the user to make an explicit ENTER action to enter corrected data or to initiate a revised operation.
- Require the user to confirm a control entry that will result in extensive changes in stored data, procedures, or operations.

4.4 QUALIFICATIONS ON USING THIS DOCUMENT

Numerous guidelines and principles that apply to the design of controls and displays have been identified in the literature and are presented in this document. Although many of the guidelines and principles were developed for equipment other than small avionics equipment, they represent the best available guidance for the design and certification of GPS receiver controls and displays to meet the regulatory requirements. In general, there is reasonable consistency among the references, but there are small discrepancies that probably reflect differences in the experimental conditions under which they were derived.

The recommendations in this document were selected to represent the most conservative guidance available, taking into consideration the cockpit environment in which the GPS receivers will be used. However, GPS receiver designers and certification specialists should exercise situation-specific judgment in applying the recommendations presented. In addition, the guidance in this document primarily addresses the design of the receiver controls and displays. The guidance includes operational issues about HCI design but does not cover technical details about software logic or HCI dialog. The regulatory documents must be employed to address issues related to the information requirements for pilots during various phases of flight or during specific maneuvers.

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