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Enhancing GPS Receiver Certification by Examining Relevant Pilot-Performance Databases

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16. Abstract

The rapid introduction of Global Positioning System (GPS) receivers for airborne navigation has outpaced the capacity of international aviation authorities to resolve human factors issues that concern safe and efficient use of such devices. Current certification technical standards appear to have had little impact on promoting the design of standardized receiver architectures, interfaces and operating manuals- despite evidence from a variety of sources that lack of standardization may undermine safety. This paper explores the relationship between existing human factors data relevant to GPS-interface design and incident/accident databases, which are a rich source of information and serve to highlight the safety-critical nature of GPS-receiver interface issues. An approach to expanding the role of human factors assessments in the certification of GPS receivers is briefly summarized.

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ENHANCING GPS RECEIVER CERTIFICATION BY EXAMINING RELEVANT PILOT-PERFORMANCE DATABASES

INTRODUCTION

The accelerated development and introduction of Global Positioning System (GPS) receivers for use in airborne navigation has outpaced the capacity of international aviation authorities to fully implement regulations and guidance for the safe and efficient use of such devices (Nendick & St. George, 1996). Technical Standard Order (TSO) C129 A1 is currently used to certify standalone, Instrument Flight Rules (IFR) GPS receivers for installation in the United States and Canada and is accepted as the certification standard elsewhere, including Australia and New Zealand. However, it appears to have had little influence on standardizing receiver architectures, interfaces, and operating manuals (Heron, Krolak, & Coyle, 1997). In addition, there is no standard for the design of hand-held GPS receivers despite their prevalence among General Aviation (GA) pilots as a supplemental aid to Visual Flight Rules (VFR) navigation with an approved primary means of navigation (e.g., dead reckoning, pilotage, and/or electronic navigation). RTCA, Inc. (1993) has published guidance material for the use of such receivers, which are considered portable electronic devices under Federal Aviation Regulation Part 91.21. Furthermore, the Aircraft Owners and Pilots Association (AOPA) is currently publishing guidance material for use with GPS technology (AOPA, in press).

At least two human factors references directly support TSO C129 A1. McAnulty's (1994) review of human factors principles and guidelines for the design of controls and displays for standalone, IFR GPS and Long Range Navigation (LORAN) receivers is germane to regulatory requirements. In fact, this review is the basis for the other reference that supports TSO C129 A1: the aircraft certification human factors and operations checklist for standalone, IFR GPS receivers (Huntley, Turner, Donovan, & Madigan, 1995). The checklist includes a bench test and a flight test, both of which are designed to assist certification personnel and manufacturers in evaluating the characteristics of GPS receivers in accordance with TSO C129 A. These tests focus on GPS-receiver controls, displays, and operating characteristics.

The guidelines proposed by McAnulty (1994) and the checklist developed by Huntley et al. (1995) represent important progress in resolving some of the safety-critical interface issues associated with GPS receivers and their certification. However, many issues still remain. This paper serves a dual purpose, the first of which is to review unresolved interface issues by summarizing existing corroborative evidence from a variety of independent sources. The second is to illustrate the safety-critical nature of these issues by analyzing evidence from several incident and accident report databases.

SUMMARY OF EXISTING EVIDENCE

Analysis of GPS Receivers using System Design Principles

O'Hare and St. George's (1994) and Heron et al.'s (1997) use of system design principles to analyze existing GPS-receiver interfaces illustrates how complex receiver architectures and cumbersome receiver operations can combine to impair pilot performance. The myriad of functions supported by receiver architectures necessitates multiple modes, pages and subpages, which quickly overwhelm pilot information processing resources, especially memory. In addition, receiver operations are constrained inappropriately by unintuitive logic, control knobs and buttons that induce data-entry errors, and displays that are not optimized for legibility and intelligibility. Heron et al. also point out that the databases used by GPS receivers occasionally contain erroneous or missing data and anomalous identifiers.

Flight Tests of GPS Receivers

Specific observations made during FAA flight tests of Terminal Instrument Procedures using IFR-approved GPS receivers support the general results of Heron et al.'s analysis. Winter and Jackson (1996) and Williams (1998a) summarized these observations by giving examples of GPS-receiver design problems. These examples illustrated overly complex receiver operations, inadequate feedback, inconsistent labeling and placement of control knobs and buttons, procedural problems involving alternate airport selection and waypoint sequencing, and differences in receiver functioning attributable to methods used for installation. Winter and Jackson (1996) also cited instances where GPS receivers affected pilot performance because they did not support flight functions appropriately during critical flight phases (e.g., intermediate or final approach segment). In particular, they noted increased pilot workload and delays in communication when Air Traffic Control (ATC) requested information about the distance of the aircraft from the airport. The GPS receivers did not allow easy access to such information, and pilots were forced to calculate distance manually, or to access distance information by exiting the current function page, entering a different page, and then returning to the previous page to continue the approach segment. The latter procedure required at least four keystrokes when done correctly and as many as nine if done incorrectly (i.e., reprogramming the approach).

Flight Simulation Tests of GPS Receivers

Flight simulation research at the Federal Aviation Administration Civil Aeromedical Institute (FAA/CAMI) indicates that some features of hand-held GPS-receiver interfaces can compromise their effective use and perhaps undermine safety. Wreggit and Marsh's (1998) systematic examination of a typical hand-held receiver's interface design serves as a benchmark for usability testing of GPS receivers. Initially, they used flow diagrams of GPS menu structures to familiarize and train pilots with no GPS receiver experience. After this training phase, pilots observed a demonstration of the receiver's features and procedures, and practiced with the receiver until they passed proficiency tests. Pilots then performed 37 GPS-related tasks during an hour-long flight simulation. The tasks required waypoint setting, navigation, and data entry and retrieval. Pilot performance was affected by several menu structures that slowed data entry, editing of stored data, and activation of functions. Pilots frequently exceeded the minimum number of keystrokes necessary to accomplish a given task and spent a significant amount of time "head-down" while programming the GPS receiver. The average length of a head-down glance while working on a GPS-related task was 10 seconds, whereas the average head-down time (i.e., sum of head-down glances) necessary to complete each of 28 GPS-related tasks ranged from approximately 10-75 seconds, with a median time of nearly 24 seconds. Wreggit and Marsh (1998) concluded that several factors had the potential to negatively affect pilot performance (e.g., excess keystrokes and head-down time). Among these were the constraints imposed by the logic of receiver menu structures, pilots' understanding of receiver controls, the difficulty of recovering from erroneous inputs, lack of appropriate feedback, and inconsistent mapping of controls to functions.

Other FAA/CAMI flight simulation research has illustrated that specific GPS receiver functions can be designed to better support pilots as they perform in-flight tasks using GPS. Williams (1998b) has used empirical data to make a compelling argument against the use of existing text-only, tabular displays of nearest airport information, especially during emergencies. His work indicates that pilots using such displays are three times more likely to misjudge the relative direction of the nearest airport, and are five seconds slower, on average, than pilots who use map or enhanced-text GPS displays. Consistent with Wreggit and Marsh (1998), Williams (1998b) also found that most pilots did not cross-reference GPS receiver information with other instruments (e.g., heading indicator) that could help orient them. The failure to cross-reference information may indicate that GPS receivers trap pilots' attention, thereby disrupting their scan.

Questionnaires about GPS-Receiver Interface Design

Nendick (1994) developed a comprehensive questionnaire (viz., GPS User Survey) to gather responses from 227 New Zealand pilots in an attempt to identify GPS-receiver interface design and operational issues that eroded flight safety. The 125-item GPS User Survey elicited pilot perceptions of and experiences with GPS receivers by asking questions about controls and displays, operating logic, functions, operations, operating procedures, navigation performance, pilot attitudes, and training. Joseph, Jahns, Nendick, and St. George (1998) used an expanded version of this survey (i.e., 163 items) to collect responses from 308 American pilots, and Nendick and St. George are currently using it to compile responses from Australian and New Zealand pilots. Several recommendations that are relevant to the present discussion can be drawn from the GPS User Survey data. Nendick (1994) suggested that:

- the design of future GPS-receiver interfaces, especially controls and displays, would benefit from strict adherence to published guidelines (cf., McAnulty, 1994);
- receiver operating logic could be improved through standardization of various models;
- serious consideration should be given to the inclusion of receiver features that reduce and possibly eliminate over-reliance and complacency;
- improvements in the content, layout and indexing of GPS operating manuals were necessary; and,
- pilots should be required to undergo some type of formal GPS training.

Finally, Joseph et al.'s (1998) analysis of GPS User Survey data identified numerous GPS-interface design and operational issues that are not addressed by the TSO C129 A1 human factors checklist and could be used as a basis for revising or supplementing existing GPS receiver certification standards.

ANALYSIS OF INCIDENT AND ACCIDENT DATABASES

ASRS and FAA Incident Databases

O'Hare and St. George (1994) discussed the implications and speculated about possible unintended consequences associated with the use of GPS in aviation. These authors introduced their discussion by expressing the need for "…an awareness of the relevant human factors issues amongst pilots and controllers before a GPS incident/accident database has developed." Similarly, they concluded their discussion by hoping that the many human factors issues associated with GPS would be "…carefully considered by the regulatory authorities, and widely discussed by potential users before these latent problems manifest themselves in operational experience." The statements made by O'Hare and St. George (1994) presaged the trend shown in Figure 1, which illustrates an accelerated increase in the number of Aviation Safety Reporting System (ASRS) and FAA Incident Database reports containing the term "GPS." The information in Figure 1 is based on an analysis of ASRS and FAA incident reports from January 1989 through September 1998. A search of the databases for this period produced a sample of 468 incident reports in which the term "GPS" appeared in the report narrative. Four of these reports were from the FAA incident database. Further analysis of each report narrative revealed that the use of GPS contributed as a factor in 162 of the 468 incidents. The term "GPS" was used only to describe the type of navigation in the remaining 306 incident reports. Although Figure 1 shows a steady increase in the frequency of incident reports containing the term "GPS" and those involving GPS as a contributing factor, the ratio between the former and the latter type of incident reports has remained relatively constant from 1995 to 1997. The data for 1998 are incomplete. The ratio is represented in Figure 1 by the line with the filled circles and is expressed as a percentage on the right ordinate.

The 162 incident reports involving GPS were categorized based on the 24 non-orthogonal, GPS-interface design and operational issues identified by Joseph et al. (1998). Frequency counts are listed for categories, as are percentages, which have been rounded to the nearest whole number. Six issues accounted for 77% (n=124) of the incident reports. Thirty percent (n=49) of the 162 reports described incidents that were associated with changes in pilot workload due to the use of GPS. For example, pilot interaction with GPS receivers changed mental workload, increased head-down time, and reduced the use of charts. Fifteen percent (n=25) of the incident reports were characterized as operational errors committed by the pilot. That is, the incidents were associated with incorrectly entering data into the GPS receiver, misreading the receiver display, or being unaware of the active receiver mode.

Nine percent (n=16) of the reports described incidents in which pilots were overly dependent on GPS and became complacent or relied solely on it for operations. Eight percent (n=13) of the incidents were associated with GPS signal reception; specifically, the signal lacked integrity or was not reliable. Seven percent of incident reports (n=11) involved

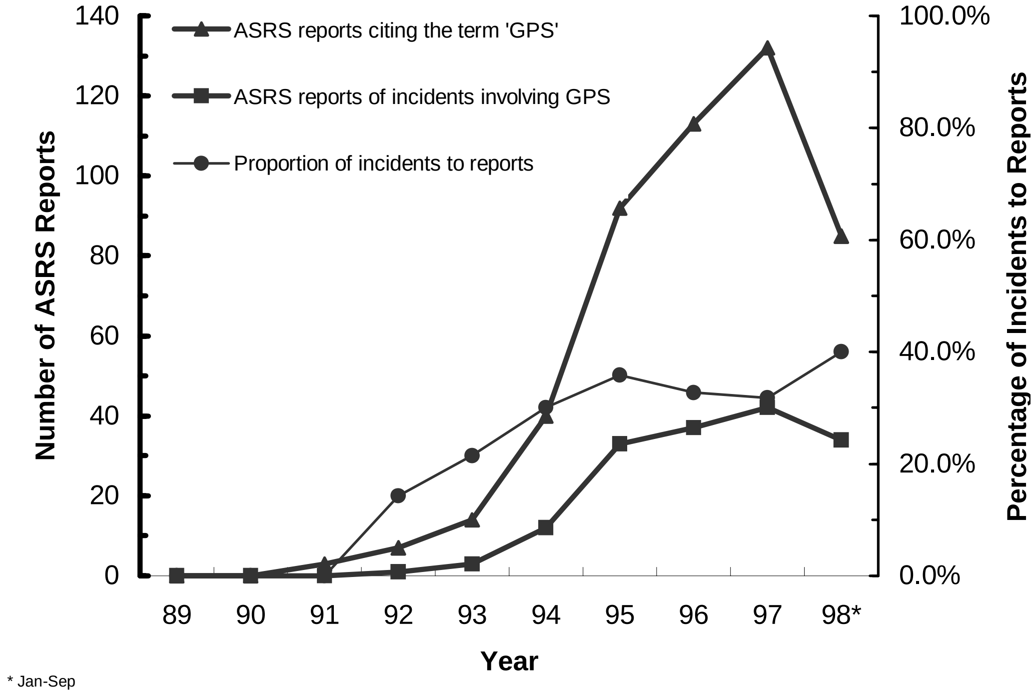

Figure 1. ASRS and FAA Incident Report Databases- Reports citing the term "GPS" and reports of incidents involving GPS.

problems with receiver accessories. For instance, pilots reported unreliable power supplies in the form of spent batteries or loosely connected cords, and poorly mounted antennas. Finally, despite Heron et al.'s (1997) call for more comprehensive, accurate and standardized GPS-receiver databases, 6% (n=10) of the incident reports involved errors, missing data, or anomalous identifiers in such databases.

Of the 162 ASRS incident reports involving GPS, 58% (n=93) resulted in deviations from assigned clearances or unauthorized entries into restricted airspace. Deviations from an assigned altitude clearance were very common, as were unauthorized entries into terminal areas and special use airspace. Ten percent (n=15) of the incident reports described instances where database or programming errors were discovered and corrected before safety was jeopardized. Fifteen percent (n=24) of incidents involving GPS were divided equally among deviations or diversions from the planned route of flight, deviations from standard approach procedures, and unintended landings at the wrong airport.

NTSB Aviation Accident/Incident Database

A search of the National Transportation Safety Board (NTSB) Aviation Accident/Incident Database from 1989-1998 revealed nine accident reports involving GPS receivers. Although only one of these reports explicitly stated that the use of a GPS receiver was a probable cause for the accident, each of the remaining reports listed at least one probable cause (e.g., diverted attention) that was associated with GPS receiver use. Accidents were not categorized because there were too few. Six accidents were characterized as either an in-flight collision with terrain or loss of control on ground/collision, one accident was a mid-air collision, one was a gear-up landing, and another was a forced landing/collision with trees. The accidents resulted in one minor injury and one fatality.

GPS User Survey

GA pilots' written responses to four open-ended questions from the GPS User Survey administered by Joseph et al. (1998) provide another source of data on the operational experiences and design preferences of pilots using GPS receivers. Responses to the four questions were categorized based on the 24 non-orthogonal, GPS-interface design and operational issues identified by Joseph et al. The questions and results of the categorization are discussed in turn.

Question 1. This question asked pilots what they found difficult about using GPS. Of the 308 pilots who returned a completed survey, 185 provided at least one response to this question. Several pilots gave more than one response to this question; hence, 192 responses were counted. Twenty-eight percent (n=53) indicated that GPS receiver operations were inordinately complex, that they quickly consumed available pilot memory resources, and required significant amounts of practice to achieve and maintain proficiency. Another 24% (n=46) noted that receiver programming demands were burdensome. Many of these pilots suggested that programming and reviewing a route, and selecting or entering waypoints should be simplified. They also favored a standard set of functions for all GPS receiver interfaces. Several other issues accounted for the remaining pilot responses. Those listed most frequently by pilots included difficulty reading information on receiver displays (9%, n=17), lack of knowledge and experience with receiver operations (6%, n=12), trouble with receiver accessories and installation (6%, n=11), and difficulty entering and modifying data (6%, n=11).

Question 2. This question asked pilots what problems they have had using GPS. At least one response was provided by each of 199 pilots. As with Question 1, several pilots gave more than one response to this question; hence, 208 responses were counted. Thirty-one percent (n=65) of pilots stated that they had problems with signal reception or the integrity of receiver information. Sixteen percent (n=33) remarked about problems created by overly complex receiver operations. A majority of the remaining responses to this question focused on four issues: problems with accessories and installation (9%, n=19); problems with errors, missing data and anomalous identifiers in the receiver database (8%, n=16); burdensome receiver programming demands (7%, n=14); and problems reading information on receiver displays (7%, n=14).

Question 3. This question asked pilots if they had examples of “hazards” or “traps” that may catch GPS users off guard. At least one response was provided by each of 129 pilots. As with Question 1, several pilots gave more than one response to this question; hence, 134 responses were counted. Pilots most frequently (17%, n=23) gave examples of how their sole dependence on GPS receivers for navigation gave way to complacency and lapses in awareness during flights. Sixteen percent (n=22) cited instances where unreliable signals or lack of signal integrity prevented them from using GPS. Consistent with the results of Wreggit and Marsh (1998) and Williams (1998b), 12% (n=16) of pilots noted that the use of GPS consumed valuable information processing resources, thereby reducing the amount of time spent on other flight tasks such as “see-and-avoid” lookout and scanning of instruments. Finally, 8% (n=11) of pilots cited examples of how errors, missing data, and anomalous identifiers in the receiver database could cause unintended consequences.

Question 4. This question asked pilots if they had views on how GPS should be developed further. At least one response was provided by each of 149 pilots. As with Question 1, several pilots gave more than one response to this question; hence, 171 responses were counted. Nineteen percent (n=33) of pilots stated that GPS should be developed further by easing programming demands and standardizing receiver interfaces. An almost equal number (19%, n=32) wanted GPS infrastructure improvements to the National Airspace System (NAS). Such improvements included additional GPS approaches, the elimination of intentional signal error, and availability of integrated terrain and weather information for use with GPS receivers. Many of the remaining responses were nearly equally divided among four issues. These were improvements in availability and reliability of GPS signals (12%, n=21), improvements in GPS-receiver accessories (e.g., antenna) and installations (12%, n=21), enhancements in receiver display legibility (12%, n=20), and corrections to GPS-receiver databases (12%, n=20).

EXPANDING THE ROLE OF HUMAN FACTORS IN GPS RECEIVER CERTIFICATION

One of the many challenges for the FAA and aviation community as they progress towards sole reliance on augmented, satellite-based navigation is to enhance TSO C129 A1 and future technical standard orders with human factors specifications for GPS-receiver interfaces. Such specifications should ensure usability by providing a standard set of receiver functions without prohibiting GPS-receiver manufacturers from adding new features to their GPS devices. The evidence in favor of expanding the role of human factors in GPS receiver certification is compelling and reliable. The previous sections of this paper showed that research and analyses of GPS-receiver interfaces and operations in several different environments consistently yield similar results. For example, GA pilots, who compose the largest and most diverse user group in the NAS, prefer GPS-receiver interfaces that include a standard set of functions, are easier to program, are more reliable, and have more legible displays. These preferences are consistent with the views of the AOPA Air Safety Foundation, whose executive director suggested in a personal communication that the design of basic IFR-approved, GPS receivers should include simple programming that allows navigation to and from a waypoint on a selected bearing; holding, using a waypoint as a reference; execution of an approach; and a missed approach (B. Landsberg, personal communication, April 9, 1999). According to GA avionics equipment estimates 42% of the 187, 312 active GA aircraft were equipped with some type of GPS receiver (AOPA, 1998). Hence, expanding the role of human factors in the GPS receiver certification process would benefit tens of thousands of pilots.

One possible approach for expanding the role of human factors in the GPS receiver certification process begins with a collaborative review of the existing TSO C129 A1 human factors supplement by a team of FAA certification personnel, manufacturers, and human factors specialists. The addition of new functions has made GPS receivers more complex, and the 1995 supplement may not adequately support present-day, certification tasks. Joseph et al.'s (1998) analysis of GPS User Survey data identified numerous GPS-interface design and operational issues that do not appear to be adequately addressed by the TSO C129 A1 human factors supplement and could be used to enhance it. After reviewing the current standards, the team would develop a list of functions common to all GPS receivers. The team also would develop a list of bench and flight usability tests for each function. The usability testing procedure might resemble the bench and flight-simulation tests used by Wreggit and Marsh (1998). All GPS receivers then would be tested on the selected set of functions and the test results would be used to establish standards for receiver-interface design. Performance-based standards for the selected set of functions could be defined by using cutoff scores, which would be based on point estimates from score distributions for each function. For example, if the waypoint function of a receiver is to be certified, *x* percent of a representative sample of pilots must be able to select or program a waypoint in *y* seconds or less. These standards would be applied to new receiver models only, and they could be reviewed and revised periodically to reflect incremental improvements in receiver interfaces. Finally, manufacturers could use the results of such performance-based comparisons to demonstrate the capability of their receivers.

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