HUMAN FACTORS EVALUATION OF TSO-C129A GPS RECEIVERS

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PREFACE

This report documents an evaluation of the usability of TSO-C129a-certified Global Positioning System (GPS) receivers. Bench and flight tests were conducted on six GPS receivers. The evaluations covered 23 flight tasks. Both subjective and objective measures were recorded to assess the usability of the receivers and to identify potential human factors problems. Reports of the results of each individual evaluation were written previously and presented to the FAA and to the GPS manufacturers. This report provides an integrated summary of those six evaluations.

The evaluations took place at the Volpe National Transportation Systems Center under the direction of Dr. M. Stephen Huntley. Ms. Colleen Donovan and Mr. John Turner conducted the evaluations. Ms. Melissa Bud provided data analysis and report writing support. This final report was synthesized and rewritten by Ms. Melanie Wright of Monterey Technologies, Inc. from the previous individual reports.

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ACRONYMS

ACTV	Active
ASOS	Automated Surface Observation System
ATC	Air traffic control
AWOS	Automated Weather Observing System
CDI	Course deviation indicator
DME	Distance measuring equipment
DTK	Direct Track
ETA	Estimated time of arrival
ETE	Estimated time en route
FAA	Federal Aviation Administration
FAF	Final approach fix
FSS	Flight Service Station
GPS	Global Positioning System
HFES	Human Factors and Ergonomics Society
HSI	Horizontal Situation Indicator
IAF	Initial approach fix
ICAO	International Civil Aviation Organization
IFR	Instrument flight rules
LAT	Latitude
LONG	Longitude
MAHP	Missed approach hold point
MAP	Missed approach point
NAS	National air space
NDB	Non-directional beacon
OBS	Omni bearing selector
QRG	Quick reference guide
RAIM	Receiver autonomous integrity monitoring
SAE	Society of Automotive Engineers
SID	Standard instrument departure
STAR	Standard terminal arrival route
TAE	Track angle error
TSO	Technical Standard Order
VFR	Visual flight rules
VOR	Very high frequency omni-directional range
XTE	Cross track error

EXECUTIVE SUMMARY

This report is a compilation of findings from evaluations of all six global positioning system (GPS) receivers to be certified, as of June, 1997, according to technical standard order (TSO) C129, Class A1 for en route, terminal area, and non-precision approach navigation. These evaluations were completed over the past four years by the Volpe National Transportation Systems Center's GPS Human Factors Evaluation Team. Tests comprised a series of twenty three procedures, during which the usability of the interface was assessed. The twenty three procedures were intended to cover a range of tasks that may be performed using a GPS receiver.

The goal of these desk-top and flight test evaluations was to assess GPS receiver usability. This work was sponsored by the Federal Aviation Administration (FAA) Flight Standards Service's Flight Technical Programs Division. The objectives of this report are to summarize the results of the series of evaluations of GPS receiver interfaces and to discuss the implications of these problems for manufacturers, airlines, and the FAA.

The receivers evaluated in the test were: 1) Apollo 2001, 2) Bendix King KLN 89B, 3) Bendix King KLN 90B, 4) Garmin 155, 5) Northstar M3, and 6) Trimble 2000 Approach. The twenty-three procedures were completed by a project pilot and monitored by a human factors data collector/safety pilot. The procedures were first completed on the ground in a bench test environment (except those that required annunciators) and then completed in flight in the test aircraft, a Piper Aztec. The data collector recorded the pilot's use of GPS controls as they took place. Subjective assessments of the operability of the receiver were made by the project pilot and recorded by the data collector during and after each maneuver. The subjective assessments included both informal comments and ratings of pilot memory required, likelihood of errors, and pilot workload.

The results of the evaluation indicated that six procedures were evaluated as having medium or high workload on two or more of the receivers. These procedures included:

- Vectors to intercept final approach course
- Missed approach with a vector or heading to intercept a course to a MAHP (missed approach hold point) waypoint
- Diversion to an alternate
- DME arc approach
- Intercept a parallel offset base
- Return to departure airport.

The evaluation also indicated that tasks such as creating and editing flight plans and choosing alternate approaches or routes required a large number of control actions.

The evaluation identified the following four tasks as tasks that pilots would perform in normal operation or in emergencies and should be very easy to perform for all pilots:

- Fly direct to a waypoint
- Find and fly direct to the nearest airport
- Select and fly an approach
- Create and edit a flight plan

The evaluations pointed out several common problems across the receivers that indicate there is a need for human factors improvement in the design of GPS receivers. Areas that were problematic included button labeling, text messages, display of key information, moving map automatic scaling, and documentation format. Design recommendations are made for dealing with these and other human factors problems.

The receivers also exhibited good design characteristics. Examples of these design characteristics as well as a few unique ideas for an ideal GPS receiver are presented. One recommendation that resulted from considering an ideal GPS receiver was that GPS receivers should be "usability tested" by implementing procedures similar to those used in this evaluation. Usability testing will help identify and correct problems like those described in this report before the product is available on the market.

Finally, this report discusses the implications of these evaluations for pilot training, air traffic control, flight standards, and certification. Areas of focus for the FAA in pilot training and operations approval are discussed. A summary table of design recommendations is presented for FAA certification specialists.

1. INTRODUCTION

This report is a compilation of findings from evaluations of all six global positioning system (GPS) receivers to be certified, as of June, 1997, according to technical standard order (TSO) C129, Class A1 for en route, terminal area, and non-precision approach navigation. These evaluations were completed over the past four years by the Volpe National Transportation Systems Center's GPS Human Factors Evaluation Team. Tests comprised a series of twenty three procedures, during which the usability of the interface was assessed. Factors such as workload, pilot memory required, and control actions required to perform each procedure were recorded. Some of the problems reported here have subsequently been addressed and changed by the manufacturers in later production runs. However, there are still receivers in operation that have the same features and problems as described herein.

The goal of these desk-top and flight test evaluations was to assess GPS receiver usability. This work was sponsored by the Federal Aviation Administration (FAA) Flight Standards Service's Flight Technical Programs Division. The results of the evaluations were demonstrated to FAA representatives from Flight Standards, Aircraft Certification, Air Traffic Control, and the Satellite Navigation Program Office. The purpose of these demonstrations was to increase the FAA's familiarity with GPS technology and support the development of training requirements, guidelines for operations, and functional requirements for future systems. Reports describing the results of the evaluations were sent to AFS-400, interested certification specialists, and the manufacturer of the system tested. The objectives of this report are to summarize the results of the series of evaluations GPS receiver interfaces and to discuss the implications of these problems for manufacturers, airlines, and the FAA.

2. TECHNICAL APPROACH AND METHODOLOGY

2.1 Equipment Tested

The GPS receivers evaluated were panel-mounted, stand alone GPS receivers that were certified according to TSO C-129 Class A1 as of June, 1997. All TSO C-129 Class A1 GPS receivers have been approved by the FAA within the national air space (NAS) for the following:

- supplemental visual flight rules (VFR) and instrument flight rules (IFR) use in en route and terminal areas
- non-precision approaches.

In the test aircraft, a Piper Aztec, the receivers were connected to external panel mounted annunciators, current database cards, antennas, a Shadin digital fuel management system and air data computer, and the horizontal situation indicator (HSI) or an omni bearing selector (OBS). In addition to the receivers themselves, the external annunciators, and, to a lesser extent, the databases, also were examined. Both hardware and software aspects of these systems were evaluated. The receivers evaluated included (in alphabetical order):

1. Apollo 2001
2. Bendix King KLN 89B
3. Bendix King KLN 90B
4. Garmin 155
5. Northstar M3
6. Trimble 2000 Approach

The price of the receivers at the time of the evaluation (excluding installation) ranged from approximately $6,000 to $9,000.

Most of the GPS receivers examined had the following basic functions available:

1. Navigate direct to a waypoint in the database.
2. Nearest airport information – capability to find and navigate directly to it (with user set options to pre-screen selections, e.g., airport surface and length requirements).
3. Fly an approach (GPS overlay or stand-alone approach).
4. Program and edit flight plans/routes (most can store 20 flight plans or more and 250 or more user defined waypoints).
5. Check receiver autonomous integrity monitoring (RAIM) at destination airport.
6. A database of waypoints including VORs, NDBs, Intersections, user defined waypoints, SIDs, STARs, and approaches. Information within the database may include:
   - Airports – name, city location, location (LAT/LONG), runway length and type, ATC frequencies, fuel availability, traffic pattern
   - Similar information for other types of waypoints
7. Calculations:
   - For a flight plan – distance and bearing to your destination, distance and bearing of any leg of your flight plan, or the total distance of the flight plan
   - Winds aloft
   - Speeds – ground speed and true airspeed
   - Fuel planning functions
   - RAIM availability at destination at estimated time of arrival
8. Airspace alerts – if approaching Class B, Class C, or Special Use Airspace.
9. Primary Navigation Page – a default page displaying frequently used information such as waypoint name, bearing and distance to the waypoint, ground speed, and track angle error (TAE), e.g., 2° →.

Appendix A displays graphic figures of the front panel of each of the six receivers tested. Appendix A also displays the button labels and associated functions for the six receivers.

2.2 Evaluation Procedure

Each receiver was evaluated on a standard set of 22 maneuvers. The final three receivers were evaluated on an additional 23rd maneuver, the ability to return to the departure airport and fly an approach in an emergency (see Section 2.3). A project pilot and a safety pilot/data collector conducted the evaluations. The project pilot was a retired airline Captain with several years experience in human factors. The safety pilot/data collector was a human factors specialist with an M.S. in human factors and a private pilot's license.

The receivers were first set up on a bench for practice in simulator mode. The pilot and data collector walked through the maneuvers that could be simulated on the bench before conducting flight tests. Except for approaches and other maneuvers that require external annunciators, the sequence of operations was the same on the bench as later conducted in the air. Observations were made by the pilot and data collector during the initial walkthrough and practice.

After the pilot and data collector were familiar with the receiver, the receiver was installed in a Piper Aztec and tested in flight. The project pilot programmed the receiver and flew the aircraft through the 23 maneuvers. The data collector recorded the pilot's use of GPS controls as they took place. Subjective assessments of the operability of the receiver were made by the project pilot and recorded by the data collector during and after each maneuver. The subjective assessments included both informal comments and ratings of pilot memory required, likelihood of errors, and pilot workload. An example data sheet for evaluating one maneuver is presented in Appendix B. Section 2.4 describes each of the evaluation measures that were recorded.

Additional information was received from two other pilots who used the receiver while flying the Aztec and by FAA personnel who participated in flight demonstrations of the receiver and operated the receiver both on the bench and in the Aztec. The other pilots who used the receivers in the Aztec were both commercial pilots, one with a Ph.D. in human factors, the other an electrical engineer with extensive experience in equipment design and several other flight ratings.

2.3 Flight Test Tasks

The 23 tasks used in the flight test are summarized in Table 1. The number following each task indicates where in the sequence of the twenty-three tasks that task was performed.

Table 1. Procedures Tested in Flight Evaluation Grouped by Phase of Flight

Pre-Departure
Create a flight plan (3 waypoints) (#2)
Edit a flight plan, i.e., delete and input a waypoint (#3)
Departure
SID retrieval and selection (#14)
Return to the departure airport and shoot an approach due to an emergency during an IFR climb-out. (Predicated on the pilot in the process of flying a pre-programmed GPS flight plan when the emergency occurs.) (#23)

En route
Direct to an en route waypoint (#1)
Diversion to an alternate (#13)
Parallel offset to a route (#17)
Change the active waypoint (#19)
Multi-segmented, short-leg course reversal – TRAML (#20)
Proceed direct to the nearest airport (#21)
Find airport information (e.g., runway lengths, frequencies, etc.) when proceeding direct to the nearest airport (#22)
Terminal
STAR retrieval and selection (#15)
Select an approach (#4)
Arm approach (#5)
Approach
Full approach with a procedure turn (#6)
Direct to a FAF (#7)
Vectors to intercept a final approach course (initial/intermediate segment aligned with the final approach course) (#8)
Repeat an approach (#9)
Program to fly a different approach when one approach has already been selected (#10)
Extended downwind to intercept a parallel offset base to an extended final approach course (#18)
Missed approach with a vector or heading to intercept a course to a MAHP (missed approach hold point) waypoint (#11)
Holding pattern (#12)
DME arc approach (#16)

2.4 Evaluation Measures

For each of the 23 maneuvers, the following information was recorded:

Number of times controls used – for each pilot action in the maneuver, the data collector recorded the number of times a button was pressed or a knob was turned. The counts were summed to obtain total counts for the maneuver. For knobs, continuous rotation and reversals in rotation to scan for data were not counted as separate control use. Therefore, a single use of a knob often was more time consuming and required more pilot attention than a single use of a button. A count was also kept of the use of buttons that had a single dedicated function.

Prompts – if a message or the illumination of buttons was used as a means of indicating to the pilot what action in a series of actions should be taken next, a note was made to indicate the type of prompt and the wording of the prompt. The total number of prompts given were recorded for each maneuver.

Cursor use – if the pilot used the cursor to perform any aspect of the maneuver, a "Yes" was recorded for cursor use.

Mode switch – if the maneuver required a change in receiver mode at any time, a "Yes" was recorded for mode switch.

Mode annunciation – if the receiver annunciated a change in mode during the maneuver, a "Yes" was recorded for mode annunciation.

Multiple page use – if it was necessary for the pilot to access more than one display page to accomplish the task, a "Yes" was recorded for multiple page use.

Pilot memory required – immediately following each maneuver, the pilot rated pilot memory required as high, medium, or low.

Likelihood of errors – immediately following each maneuver, the pilot rated likelihood of errors as high, medium or low.

Pilot workload – immediately following each maneuver, the pilot rated pilot workload as high, medium or low.

The rating of pilot workload and frequency of errors was directly related to the number of control actions required to complete each maneuver and the clarity of the function of each control action within the maneuver. Additional data for each task included the most probable error, any surprises that may have occurred, any aspect of the task that made it difficult to complete, and any problems, consequences, and recommendations.

3. FINDINGS AND RECOMMENDATIONS

3.1 Findings

The findings reported here are expressed in terms of general findings from all of the evaluations. In addition, specific findings in terms of number of control actions required are provided. Because pilot workload, pilot memory required, and likelihood of error were subjective evaluations made by a very small population, findings on these areas are discussed only as they apply to different GPS procedures and not as a comparison between receivers. Specific usability problems for the receivers are discussed in section 3.1.2.

The workload ratings indicated that six of the procedures received "medium" or "high" ratings for two or more of the GPS receivers. The six procedures were:

- Vectors to intercept final approach course
- Missed approach with a vector or heading to intercept a course to a MAHP (missed approach hold point) waypoint
- Diversion to an alternate

- DME arc approach
- Intercept a parallel offset base
- Return to departure airport.

Most of the pilot workload ratings were "low" for the other 17 procedures.

Table 2 summarizes the results of the summation of control actions for the six receivers on each of the 23 procedures. The number of control actions in this table does not necessarily represent the minimum number of control actions for a given receiver. Rather, the number provided in this table is the number of control actions that were taken by the project pilot to complete the function. Receivers may have "shortcuts" that shorten the number of control actions required, but were not known to the project pilot during the evaluation. This table indicates that for all of the receivers, the following procedures required a relatively high number of control actions:

- Create a flight plan
- Edit a flight plan
- Intercept a parallel offset base
- Return to the departure airport and fly an approach

Several other procedures required a high number of control actions for certain receivers (but not for all). These include:

- Selecting an approach
- Full approach
- Programming a different approach
- Diversion to an alternate
- SID and STAR retrieval and selection
- DME arc approach
- Short leg course reversal

Table 2. Number of Control Actions Required to Perform the Twenty-three Procedures

Task	Apollo	Bendix-King KLN89B	Bendix-King KLN90B	Garmin 155	Northstar M3	Trimble
1. Direct to a waypoint	5	5	5	7	6	6
2. Create a flight plan	21	16	15	19	22	15
3. Edit a flight plan	17	17	14	14	19	15
4. Select an approach	6	19	10	4	11	7
5. Arm approach	5	0	0	6	0	4
6. Full approach	16	5	4	9	0	10
7. Direct to a FAF	5	6	5	6	8	8
8. Vectors to intercept final approach course	5	3	7	8	6	6

Task	Apollo	Bendix-King KLN89B	Bendix-King KLN90B	Garmin 155	Northstar M3	Trimble
9. Repeat approach	6	6	8	6	6	6
10. Program different approach	12	21	9	10	6	8
11. Missed approach with intercept to a waypoint	6	5	3	4 or 3 †	2	3
12. Holding pattern	5	3	3	1	4	4
13. Diversion to alternate	5	5	17	17	6	15
14. SID retrieval and selection	*	12	12	8	*	7
15. STAR retrieval and selection	*	10	10	8	*	7
16. DME arc approach	18	19	7	6	11	10
17. Parallel offset to a route	8	*	**	6	4	6
18. Intercept a parallel offset base	12	*	**	19	10	15
19. Change the active waypoint	4	6	5	4	7	7
20. Short-leg course reversal	0	19	0	8	0	5
21. Direct to nearest airport	3	5	5	3	4	3
22. Find airport information when proceeding direct	3	2	6	5	1	2
23. Return to departure airport	22	25	***	***	6	***

* The receiver doesn't have this functionality
** Evaluators were unable to determine how to do the procedure
*** Function was not tested (was added as a task after the first three systems were tested)
† Depending on whether the first waypoint was the MAHP or was an intervening waypoint.

By comparing those procedures with high workload ratings and those with a high number of control actions required, it is clear that a few specific procedures would benefit from design to reduce workload and the number of control actions required. These procedures include the following:

- Intercept a parallel offset base (Task 18)
- Return to the departure airport and fly an approach (Task 23)
- Diversion to an alternate (Task 13)
- DME arc approach (Task 16)

Discussions with several pilots during the evaluation also indicated that there are four basic GPS functions that all pilots want to know how to perform. They are (rank ordered):

- Fly direct to a waypoint (Task 1)
- Find and fly direct to the nearest airport (Task 21)
- Select and fly an approach (Tasks 4-6)
- Create and edit a flight plan (Tasks 2 & 3)

All GPS receivers should be designed so that these four functions are very easy to perform. The "direct-to a waypoint" function should be immediately usable by novice pilots. Because these are frequently used functions, GPS receiver manufacturers also may want to reduce the number of control actions for creating and editing a flight plan and selecting and flying approaches. Those functions required a high number of control actions in the evaluations.

Many of the findings in the evaluations were specific problems encountered with specific receivers. Manufacturers have received reports detailing these findings. The following section describes some of the problems that were consistent across manufacturers, gives examples of these problems, and provides recommendations for improvement.

3.2 Problems and Recommendations

3.2.1 Controls

There were a few problems related to the controls on the GPS receivers. Most of the problems were related to the labeling and logic of using the controls rather than the actual physical configuration of the control. One receiver did have a problem with the physical configuration of the controls – the buttons were positioned where accidental activation was likely when a pilot with a large hand was using the rotary knob.

Evaluators frequently found that the labeling of the buttons and knobs was difficult to interpret and did not clearly denote the button functionality. This was especially true when the button had more than one function. Generally, the buttons on the receivers were used for too many different functions – more single-function dedicated buttons were preferred by evaluators. Also, buttons and knobs that are not used consistently throughout the interface cause confusion. Examples of problems related to poorly labeled or multi-functional buttons included the following:

- In one receiver, the SEL button generally is used for editing, a more appropriate label may be EDIT.
- In one receiver, the CLR button performs several functions including deleting flight plans, cycling through fields, and selecting controlling frequencies.
- In one receiver, the functions of the DIRECT button include activating a change to the active waypoint.
- In another case, the labels of rotary knobs that have inner and outer concentric knobs were not positioned so that the user could clearly determine the different functions of the inner and outer knobs.
- The ENT button was used inconsistently on one receiver – while the ENT button normally confirms or completes an action, in one case it is used to initiate an action to activate a flight plan.
- In another receiver the function of the ENT button is inconsistent for parallel offset. Normally pressing ENT while there is a blinking "activate?" confirms that the function is to be activated. In the parallel offset situation, pressing ENT while "activate?" blinks will cancel the offset.

Recommendations:

1. Ensure that controls are positioned so that they are not accidentally activated.
2. Minimize the use of a single control for many different functions.
3. Consider front panel designs that use "soft" labels for buttons, that is, the button labels are electronic, software programmed, labels that change with the associated button function so that the label always displays the current button function.
4. Ensure that controls are used in a consistent manner throughout the interface.
5. Choose labels for controls that are descriptive of their functions and positioned so that it is easy to associate the label with the control.
6. Where buttons have multiple functions and labels cannot be completely descriptive, stress these points in training and in manuals.

3.2.2 Messages

Several of the GPS receivers provided messages that were difficult for users to understand or interpret. The most common problem of messages was that they did not provide enough information for the pilot to determine the relevance of the message to upcoming operations or for the pilot to determine what action was required. Some messages were ambiguous, vague, or used terminology that is not common in aviation. In addition, some messages were misleading or inaccurate.

Examples of these types of message problems include:

- One message stated "altitude fail" but provided no reason for the altitude failure.
- Another receiver had a similar message "no altitude input" which was intended to indicate an equipment problem (receiver is not receiving altitude inputs) but could easily be confused with an indication of pilot action or direction to the pilot.
- Another message stated "Direct-to entry may clear flight plan." In this message the vagueness of the term "may" made the consequences of any pilot action unclear.
- In one receiver, the message "Check MSG Annunciator" actually meant that there was an over-current in the MSG annunciator circuit. If the receiver has the capability to determine this level of detail, then it should be included in the message. For example "Overcurrent - MSG Ann - Check Circuit" may be a more useful message.
- A message indicated arrival at a waypoint when the waypoint was still 36 seconds away.
- In one receiver, critical messages were not displayed on the GPS receiver long enough for pilots to read and understand them. In this receiver, messages stay up for three seconds (but can be changed by the pilot to a maximum of 9 seconds), then disappear if not acknowledged. There is no way to recall the message. This was especially problematic during an approach – if the pilot misses the message to input the inbound course, the receiver will remain in autohold and will not sequence through the approach.

Recommendations:

7. Write messages using common pilot terminology or plain language. Avoid technical or manufacturer specific terms and phrases.
8. Where possible and applicable, indicate in the message what action the pilot should take following the message.
9. Provide as much information as possible as to the cause of the problem. Where multiple causes may exist, list them in the message or indicate what action the pilot may take to determine the cause.
10. For critical messages, require pilot acknowledgement before the message display is removed. If messages are removed from the display without acknowledgement, light the message annunciator and provide an easy way to recall and read the message.

3.2.3 Display Visibility/Readability

Most of the GPS receiver displays had adequate visibility and readability. In one receiver the cursor on the display was difficult to see. Another receiver display was difficult to see in reflected sunlight. Most receiver displays were adequate in all cockpit lighting conditions. There were, however, two problems noted with annunciators. In one case, white filters on the annunciator switches made the annunciator messages difficult to read. After the white filters were removed, the messages were readable. In another case, the annunciators were small and difficult to see.

Recommendations:

11. Ensure that annunciators, as well as the main GPS display are visible and readable. Consider that annunciators may be installed in different locations in different aircraft cockpits. Annunciators must be readable in the full range of cockpit lighting conditions.
12. Locate annunciators near the pilot’s primary field of view.

3.2.4 Information Display

Often the receiver displays lacked a key piece of information needed by the pilot. Many times the needed information pertained to cues or feedback to label information or to indicate that more information was available. The following list provides examples of the information that was not available and was desired on at least one of the GPS receivers:

- Desired track information was not available on the active navigation display and could not be viewed concurrent with the active navigation display.
- Navigation information was not displayed while programming in flight.
- Final approach fix was not displayed during a full approach until inbound in the procedure turn.
- The current database section (e.g., VOR, intersection, airport) in use was not indicated.
- Information labeling on the DME arc approach was inconsistent and the text was very small.
- There was no indication when more information was available by scrolling. When

selecting an approach, there was no indication when more approaches for that airport were available.

- For a desired track (DTK), only numbers were displayed, there was no desired track label.
- Some mode changes (for example, a change to OBS mode) were not annunciated.

Some receivers displayed information that was misleading or did not conform to normal aviation usage. Examples of these types of display problems include the following:

- On one receiver the approach-active light (ACTV) remained lit even when the message "abort approach, RAIM not available" was displayed.
- On one receiver, the page type labels were positioned such that they looked like button labels.
- One receiver provided two different VOR indications (a "to" bearing on the left side of the display and a "from" bearing on the right side of the display). Because the indications of "to" and "from" on either side of the display were small, it is possible that the pilot may only see "bearing," assume the wrong direction, and head in the wrong direction. This problem is compounded by the fact that the standard for VORs are in terms of radials (bearings "from" the station), while most GPS receivers use "to" for all types of waypoints.

Recommendations:

13. Whenever there is more information available related to the current display screen, indicate this, for example, with an iconic symbol such as an arrow or a "more" label.
14. Ensure that essential labels and indications (such as the current database section in use or the "to" or "from" indication of a bearing) are clearly shown on the display.
15. Ensure that the presentation of information (for example the position and appearance of labels and the timing and form of mode annunciations) is consistent throughout the user interface.
16. The primary navigation page should display the following:
    - active waypoint
    - distance and ETE to the active waypoint
    - active waypoint name
    - bearing to the active waypoint
    - TO/FROM indicator
    - desired track (DTK) or track angle error (TAE)
    - cross track error (XTE)

    Any other information displayed should be pilot selectable and readily de-cluttered (easy to remove from the display).

3.2.5 Logic/Sequence of Steps

There were a few problems with some of the GPS receivers related to confusion about the steps that were required to complete various tasks. The most consistent complaint was that some of the tasks required too many steps to complete or that there were unnecessary steps required. Specifically, the evaluators were concerned with the number of steps required for 1) an emergency IFR return to the departure airport to fly the active approach, 2) a missed approach, and 3) the steps required to change an initial approach fix (IAF) and initiate an action after an approach was already selected. For example, one receiver required resetting barometric pressure after selecting a different approach to the same airport.

Prompting or a lack of prompting was a problem with more than one receiver. "Prompts" are cues or messages to help users move to the next step in a task that requires a series of steps. Prompting may involve explicit messages indicating the next task or less explicit cues such as flashing of the next button to be pressed in the task sequence. The GPS receiver evaluators concluded that, for certain receivers, there was not enough prompting. Some receivers did not clearly indicate, through prompting, the next step in a task or it was not obvious whether or not a task had been completed. For one receiver, prompting was used for entering waypoints but the prompts provided were confusing. On one receiver, two buttons flashed simultaneously as a prompt and therefore, it was unclear which button should be pressed first in the sequence. Pressing the incorrect button took the receiver out of the desired sequence and required that the pilot initiate the sequence again.

There were two unique problems related to the logic and sequence required for a task. On one receiver, the method in which the cursor was activated was inconsistent from one situation to another. On another receiver, it was easy to erase a flight plan accidentally while activating it – if the pilot rotated the knob on the receiver 3 clicks too far while activating a flight plan, the erase function was applied. If a busy pilot simply followed the flashing button prompts without reading the messages on the display, the entire flight plan could be erased.

Recommendations:

17. Wherever possible, reduce the number of steps required to complete tasks, especially emergency or critical tasks. Eliminate unnecessary or redundant steps in a task.
18. Buttons dedicated to a single function require fewer steps in a task. Consider the use of dedicated buttons for frequent or time critical functions.
19. Where tasks require several steps in sequence, provide prompts to assist the pilot in completing the next step in the sequence. Ensure that neither explicit nor implicit prompts are ambiguous. One method of determining whether or not the prompts are ambiguous is through user testing to determine whether pilots who are GPS novices can determine, from the prompt alone, the next step in the task.

3.2.6 Navigation Guidance

There were no problems related to navigation guidance that were consistent across receivers. However, there were a number of specific problems that were unique to certain receivers. Examples of problems encountered include:

- Two receivers went into HOLD mode automatically when beginning an approach from a specified angle to the final approach course and did not do so when outside that angle – this may be confusing to pilots.
- In one receiver, on a DME arc assist page, the DTK continued to provide turning guidance, regardless of whether the pilot was on the proper DME arc, and provided no CDI guidance while flying the DME arc.
- On one receiver, the manual advised the pilot to set the inbound final approach course when crossing the IAF outbound, contrary to the common practice of setting the outbound course when outbound.
- On one receiver, when a pilot programmed a new approach, the IAF for the original approach remained selected.
- On one receiver, the CDI needle shifted abruptly (i.e., from a "fly-right" indication to a "fly-left" indication) when inbound in a procedure turn.

Recommendations:

20. Wherever possible, ensure that the navigation guidance provided by the GPS receiver is consistent with pilot expectations and procedures.
21. Where there is a likelihood that the navigation guidance provided or the procedure employed by the receiver is different from other receivers or other methods of navigation guidance, ensure that the display provides adequate visual and auditory feedback to indicate any unique or potentially confusing behavior by the receiver.

3.2.7 Functionality

In performing the flight test tasks, the evaluators found that some GPS receivers lacked certain key functionality. Examples of important functions that were not available include:

- For one receiver, there was no capability to fly a holding pattern on an individual waypoint that is not part of a flight plan or approach.
- For two of the three receivers tested on this task, the evaluators could not add an approach to any airport other than the current destination without clearing the active approach.
- In two receivers, SIDS and STARs were not provided as a string of waypoints by procedure name.
- One receiver did not allow selection of non-turbojet STAR. The non-turbojet pilot was required to select the STAR, delete the turbojet waypoints and insert the non-turbojet waypoints.
- One receiver would not accept a .01' difference in waypoint coordinate.

- Some receivers did not accept ICAO identifiers, some required them.
- In one receiver, the evaluators could not combine a section of an airway or could not combine Victor and Jet airways into a flight plan. In other receivers, airways were not even in the database.
- In one receiver, the evaluators could not change the default RAIM prediction aircraft speed, resulting in inaccurate ETAs.

Recommendations:

22. We recommend that receivers be capable of performing all typical GPS functions that might be required in flight. The tasks performed in these receiver evaluations represent either typical tasks that a pilot would normally perform or tasks that could potentially be required by ATC during a flight.
23. Ensure that the lack of functionality is visible to the pilots as well as the presence of functionality. For example, if a user persists in making a specific mistake, such as trying to enter ICAO identifiers or trying to enter a waypoint coordinate with .01' difference, provide a message that indicates to the pilot why the action is not successful.

3.2.8 Moving Maps

Of the six receivers that were evaluated, two units had moving maps. Most of the problems encountered with the moving maps were similar for the two units. The problems were related to the display of information on the maps, specifically the ease with which needed information could be identified and discriminated from other information. Because a great deal of information is often displayed on moving maps, information clutter can be a problem. Specific problems with these units included:

- Distinguishing the active waypoint was difficult when automatic scale changes placed the active waypoint near other closely spaced waypoints.
- Automatic scale changes did not perform according to pilot expectations and caused display clutter.
- The airplane symbol was not easily differentiated from waypoint symbols.
- There were problems with the priority or hierarchy of the information displayed – important information could be overwritten by less important information.
- No airport diagram or runway map was provided on one of the maps.
- Map orientation (e.g., North up) was not indicated on the display.

Recommendations:

24. Ensure that the active waypoint is distinguishable from other symbols on the display. As a minimum, ensure that the active waypoint and its identifying label are never obstructed.
25. Ensure that all icons are recognizable and distinguishable from each other at all map scales. Review other applications and documentation to determine commonly accepted practice for aviation symbology. SAE G-10 has released a standard symbol set that should be used for all symbols (SAE ARP 4102/7). For unique symbols, test recognition and discrimination of symbols through icon testing with several typical potential users who are not familiar with the system.
26. Denote map orientation on the map display (ex. North up symbol or indicator).
27. Develop a consistent and intuitive way of controlling map scale.
28. When a waypoint identifier can not be displayed in its entirety because of overwriting other information, do not display the identifier. Partial waypoint identifiers are easily mistaken for other waypoints and add to display clutter.

3.2.9 Documentation – Information Format

In the evaluation, one common problem noted for the Pilot's Guides was that it was difficult to find needed information quickly. Also, it was time consuming to read the documentation to understand the system. Much of the information is presented as paragraph text. Unfortunately, reading paragraph text is time consuming and this method of information presentation may not be the best way to convey conceptual information that will help the pilot gain an understanding of how the system operates. Paragraph text also is not a good method of formatting information for later reference.

There are two types of information that should be presented in the pilot's guide – conceptual information and task-based information. Conceptual information provides pilots with a basic understanding of the system and with some general rules for operating the GPS receiver that apply across many situations. Task-based information provides step-by-step instructions for specific tasks that can be performed using the system.

For presentation of conceptual information, different forms of graphical presentation may be helpful. Some manufacturers have made good use of flow charts and receiver diagrams with labels for presenting information. Glossaries also provide conceptual information in a form that allows pilots to quickly locate needed information. Flow diagrams of menus, modes, and receiver functionality provide a general overview that gives pilots a basic understanding of the system and function as a reference after the pilot is familiar with the system. Diagrams that display how the receiver might integrate with the rest of the system (e.g., HSI, CDI, annunciators, fuel flow indicators, etc.) also provide pilots with a basic understanding of the system.

Task-based information should be provided for all major tasks that can be completed using the receiver. Task-based information should be formatted so that it is easy for the pilot to locate and then follow the instructions for a particular task. Referencing of the tasks in a table of contents and an index, as well as providing clear, distinguishable headings for each task within the document, will help pilots locate the needed information quickly. The presentation of the task instructions should include clear, concise instructions in numbered sequential steps.

Recommendations:

29. Limit the use of lengthy paragraph text for explanation of system operation.
30. Provide a graphical presentation of the receiver and how it integrates with other aspects of the systems such as an HSI or CDI, altitude input, fuel flow management system, etc.
31. Provide a graphical presentation of the receiver and the associated controls (knobs and buttons) along with a description of the functionality of the controls.
32. Provide a graphical presentation of the receiver display describing the information displayed at the various locations.
33. Provide flow diagrams indicating menu structure, modes, and/or receiver functionality.
34. Provide task-based instructions for the major tasks that can be completed using the GPS receiver. Include the twenty-three tasks used in this evaluation.
35. Provide quick access to task-based instructions in a table of contents and an index.
36. Use clear distinguishable headings for task-based instructions.
37. Use numbered sequential steps in the task-based instructions.
38. Use clear, concise wording for each step in the task.

3.2.10 Documentation Content

Most of the manufacturers were fairly comprehensive in their choice of content for the manuals. There were two fairly common problems related to the content of the manuals. The first problem was that one or two manuals did not provide enough detail in the information. For example, the manual might say "use the knobs to…" but would not provide enough detail on how to use the knobs to achieve that particular function or the manual might indicate that the display or mode will usually change but will not describe the criteria for change.

The second, more critical, problem was that some of the information was inaccurate. Most of the inaccuracies resulted from a lack of precision in the use of aviation navigation terminology. For example MAHP (missed approach holding point) was used when MAP (missed approach point) was the correct term. Similarly, "guidance to the FAF" (final approach fix) was used when guidance was actually to the final approach course.

Another potential source of inaccuracies occurs when new software changes are released but new manuals or manual changes are not automatically provided with the new software. Also, receiver users seldom receive notices of software upgrades. Only one of the six receivers evaluated incorporates software changes with database updates.

Recommendations:

39. Ensure that the manual provides sufficient detail in task instructions.

40. Use navigation terminology carefully and precisely to avoid confusion and potential inaccuracies.
41. Ensure that the manuals remain up to date with software changes and that manual revisions are distributed with software changes.

3.2.11 Documentation Referencing and Indexing

Probably the most prevalent problems with GPS pilot's guides are related to referencing and indexing. Two types of problems occur – 1) too much cross-referencing is used within the manual text to refer readers to different sections or pages to access needed information and 2) too little referencing is provided in indexes and appendices.

Many of the GPS receiver pilot's guides refer readers to other sections for more information when providing instructions. This causes readers to have to flip around within the manual to obtain information. In one or two cases, these references were circular with neither of the prescribed locations providing complete information. These types of references also tend to be inconsistent in how they reference other parts of the document. Some references provide section numbers, others provide section titles, and some provide page numbers or any combination of the three. If cross referencing is used, the references should always include the page number of the referred section. If the referenced information is minimal, cross references should not be used, rather the information should simply be provided in each place it is necessary.

Because pilots use these manuals as references to quickly locate instructions for specific procedures, good indexes are important. One of the six manuals did not have an index. Some of the manuals that did have indexes did not cross reference common terminology, e.g., they did not provide index entries for both "route" and "flight plan." Some manuals provided glossaries and acronym lists that were useful. An appendix of symbology would also be useful for those receivers that have moving maps.

Recommendations:

42. Minimize cross-referencing within the text of the manual.
43. When cross-referencing is used within the text, ensure that the references include accurate page numbers and are not circular.
44. Cross-reference common terminology within traditional indexes in addition to the terminology used in the manual.
45. Include glossaries, acronym lists, and symbology lists as appendices.

3.2.12 Quick Reference Guide

The documentation provided with GPS receivers should also include Quick Reference Guides (QRGs) that pilots may refer to for in-flight reference. It is even more important with QRGs than with the Pilot's Guides that the information be presented so that it can be quickly read. Unfortunately, the QRGs reviewed presented most of the information as paragraph text, making it difficult for pilots to quickly access instructions for specific tasks.

According to Osborne (1995), the purpose of a QRG for GPS receivers is as follows:

> "A QRG is a document that contains instructions for someone who has read the operating manual for a specific GPS receiver to operate it for en route flight in IFR conditions and for GPS instrument approaches in IFR conditions."

Based on the assumption that pilots using the QRG are familiar with the operating manual, the QRG should be limited to task-based instruction of frequent or emergency procedures. The task-based instructions should have clear distinguishable headings. The instructions should be sequential and numbered and should be written so that it is easy to quickly read the required steps for a given task. Highlighting control actions within the instructions may help pilots quickly access information they need. Emergency procedures such as "Direct to the nearest airport" should be the easiest to locate. Osborne (1995) created a sample standard format for QRGs (see Appendix C). The AOPA Air Safety Foundation also has created quick reference guides for Bendix-King, Trimble and Apollo receivers (see reference list for details).

Recommendations:

46. Limit the content of the quick reference guides to task-based instructions of frequently used and emergency procedures.
47. Ensure that emergency or critical procedures can be located quickly.
48. Highlight task headings so that they are easy to locate.
49. Present task steps in numbered sequential lists. (See Appendix C)
50. Highlight control actions within the task steps so that they can be read quickly.
51. Minimize the use of paragraph text and lengthy explanations.

3.3 Building a Dream GPS Machine

Throughout this testing, and particularly once the final evaluation was completed, the authors have repeatedly been asked to identify their "favorite" receiver. Which receiver would we buy for ourselves or recommend others buy? In response to this question we generally point out that each receiver has advantages and disadvantages, and if we could, we would design our own "dream GPS" unit, combining the best features of each, plus adding some of our own. Throughout the evaluation process, we recorded both problems and positive features of the receivers. This section describes some of the good features of the various GPS units that would be implemented in a "dream GPS." Some potentially desirable features that have not been seen in any of the units also are described.

3.3.1 Controls

Buttons dedicated to a single function were among the nice features of the evaluated receivers. Obviously there are size and space constraints that limit the addition of buttons on the receiver panels. If there are too many buttons, it can be difficult for the pilot to find the necessary button. However, the pilots who evaluated these receivers believed that the benefits of additional buttons outweighed the added complexity. . Additional buttons that are grouped well and clearly labeled on the receiver may improve the usability of the receivers. The ideal GPS receiver might have the following dedicated buttons:

- An INFO button or knob function as is provided on the Apollo 2001 or Northstar M3. This dedicated function retrieves information on a waypoint including complete airport information, VOR or NDB information, intersection information, etc.
- A NRST or EMG button, similar to those provided on the Garmin 155 and the Apollo 2001, to quickly access Nearest waypoints (e.g., the nearest airport in an emergency).
- A dedicated MSG button for retrieving messages. Multiple messages can be retrieved by pressing the button multiple times. Messages are displayed in order of importance. Most of the receivers evaluated had a MSG button.
- A cancel, escape, or undo button to undo the last pilot action. None of the tested receivers had this type of control.

3.3.2 Messages/Prompting

An ideal GPS receiver would have clear, concise, and consistent messages and prompting. The following table displays messages or prompts that are examples of easily understood and useful information provided by the receivers:

Table 3. Examples of Useful Messages

Message	Receiver	Required Action
"hold or Nearing PT safe limit"	Northstar M3	When flying a full approach with a procedure turn or holding pattern for a course reversal, the receiver warns the pilot when the prescribed safe distance (e.g., 10nm) from the facility is about to be exceeded.
"Turn to 277^{o} : 0.3nm" (distance counts down) "Turning now → 277^{o}" "Turn back to 155^{o}"	Northstar M3	During turn anticipation, for course changes of greater than 2^{o} and less than 150^{o}, beginning about 15 seconds prior to the turn, the first and then second prompts are provided. For turns of over 150^{o}, the third prompt is given.
"Adj Nav Ind Crs to XXX°" and "Adj Nav Crs to XXX"	Bendix/King KLN-90B and 89B	When the receiver is interfaced with an external HSI or CDI, this message tells the pilot what course to set for the next leg in a flight plan or approach.
"GPS course is XXX°"	Bendix/King KLN-89B	The desired track has changed and disagrees with the HIS/OBS setting by more than 5°
Ceil: 8000' MSL Floor: 500' MSL BRG 008° ↑ 58.4nm	Apollo 2001 NMS	This message provides the pilot with the floor and ceiling of the upcoming SUA as well as bearing, relative bearing, and distance.

3.3.3 Information Display

Three desired information display characteristics would include the following, two of which are present in current receivers:

- In the Northstar M3, when outbound from the IAF to a procedure turn, with ground speed and TAE (track angle error) displayed, the display for ground speed is replaced with a helpful count-up time display (e.g., "Out 0:57 $\leftarrow 0^{o} \rightarrow$").
- In the Bendix King KLN-89B, when selecting an approach, if there is more than one IAF, a list of IAFs is presented on the same page. This removes any pilot doubt about multiple IAF availability.
- In an ideal GPS receiver, moving map display symbology would be the same or similar to symbols used on paper approach plates and paper charts.

3.3.4 Navigation Guidance and Programming Features

The following navigation guidance features were favored by the evaluators:

- Auto arming of approach as was provided in the Bendix King KLN-89B, KLN-90B and Northstar M3 receivers.
- In the Trimble 2000, when programming a flight plan, the receiver defaults to aircraft present position for the first waypoint. This saves the pilot one programming step.
- In the Northstar M3, to fly an approach, the pilot merely follows receiver and/or CDI guidance. The M3 has no "OBS" or "HOLD" function. There is no necessity to "hold" the receiver for a procedure turn or other course reversal. This reduces pilot workload and memory requirements.
- The Northstar M3 also has a "Vectors to Final" feature. This feature automatically makes the final approach fix the active waypoint and provides guidance to the final approach course.
- Also in the Northstar M3, no altimeter setting is required for an approach.
- In an ideal receiver, guidance for a DME ARC would lead the pilot around the actual arc, not between designated points on the arc. The Bendix-King and Northstar receivers provided this type of DME guidance.
- Provide an extension of the inbound track and distance from the missed approach point and allow automatic missed approach sequencing at a specified distance after the missed approach point, unless terrain considerations dictate otherwise (this requires the integration of a multi-function display for situational awareness as stated in TSO C-129a). This would provide pilot guidance for continuation to a landing, or for performing the clean-up phase of the missed approach, and would require no additional pilot actions for missed approach guidance

3.3.5 Functionality

The following functions were unique to one or two units and were especially useful. We would implement the following additional functions in a "dream GPS":

- A SmartComm feature, such as in the Northstar M3, that provides center, approach, tower, ground, FSS, AWOS, and ASOS frequencies. This SmartComm feature will automatically tune a dedicated transceiver, if installed.
- As in the Apollo 2001, the capability to simultaneously select an approach and an IAF.
- Capability to easily return to the departure airport in the case of an emergency. The Northstar M3 enables the pilot to program the departure airport and approach in use separate from the active flight plan. This allows the pilot to return to the departure airport and fly an approach in an emergency with a minimum of control actions.
- As in the Bendix King KLN-89B, a default page on receiver boot-up that provides the frequencies for the airport where the aircraft is located.

3.3.6 Database

The following database characteristics were favored by the evaluators:

- A database that includes both Victor and Jet airways like the database in the Northstar M3, if airway segments can be programmed an a flight plan.
- Capability to load the database without pulling the receiver out of the aircraft. The Northstar M3, the Apollo 2001 and the Garmin 155 all provided this capability.
- As provided in the Trimble 2000, a database that includes traffic pattern information for airports.
- If there are duplicate waypoint identifications in the database, the nearest waypoint to the aircraft will be listed first as is done in the Bendix King KLN-89B.

3.3.7 Standardization

Another desirable characteristic of the ideal GPS receiver would be that the terminology, symbols, and operation of the most basic functions be standard across all receivers. Examples of areas where GPS receiver standardization would be helpful include:

- Timing of waypoint alerting
- Algorithm for turn anticipation
- Sensitivity changes
- Arming approach
- Direct-To function
- Return to departure airport function
- Methods of data input (e.g., ICAO format, LAT/LONG input)
- Database organization

- Messages
- Knob and button labels
- Primary NAV page display
- Dedicated MSG, D (Direct-To), and NRST buttons.

3.3.8 Usability Testing

The final important characteristic of a dream GPS unit is that the pilot interface demonstrate proven success through usability testing. Usability testing is a process by which a new product is evaluated by typical users doing typical tasks with the product. Trained human factors professionals observe the performance of tasks by test participants and record errors, requests for assistance, and any problems that occur. The usability test process is similar to the evaluation conducted on these six receivers. Ideally, however, a usability test would require the performance of tasks by eight to ten different, unbiased, typical users rather than simply by one pilot as was the case in this evaluation. Rubin (1994) suggests the following six steps in conducting a typical usability test:

Step 1. Develop a test plan.

A test plan should include: 1) the goals of the test, 2) characteristics of the expected product users, 3) the tasks to be covered, 4) test method or design, 5) the test environment and equipment, 6) the role of test monitors, 7) data to be collected, and 8) the expected contents and format of the test report.

Step 2. Select and acquire test participants.

The usability test should include selection of the participants who are typical users of the product tested. Pilots chosen for GPS receiver testing should be representative of the pilots who will actually use the equipment. The participant pool should include both novice and experienced pilots if both types of pilots are expected to use the receiver. The number of test participants will also have to be determined. Fewer test participants may be acceptable for early, iterative bench testing of product design (e.g., 5-6), while more test participants (e.g., 8-10) should be included in final usability tests.

Step 3. Prepare the test materials.

Test materials may include screening and background questionnaires for test participants, scripts for introducing participants to the task, data collection instruments, training or practice scenarios, task scenarios, post-test questionnaires and debriefing guides.

Step 4 Conduct the test.

In the case of evaluating GPS receivers, the test may be conducted on a bench, in-flight or both. Because of safety concerns with using pilots who are unfamiliar with the new equipment, bench testing should usually precede any in-flight testing. However, because of issues such as time sharing and attention management, the flight environment is critical to GPS evaluations and final testing should be conducted in a realistic flight environment. The test monitors should include both a pilot and a human factors practitioner to record the responses of the test participant to the tasks, and in the case of in-flight testing to act as a safety pilot. Data that is collected may be similar to that collected in this evaluation, such as the number of control actions required. Requests from the test participant for assistance as well errors made by the test participant should be recorded. Post-task questionnaires on workload and satisfaction with the steps involved in the task may also be collected.

Step 5 Debrief the participant.

After the test is conducted, the test monitors have an opportunity to collect subjective information from the test participant. This information may include post-test questionnaires as well as in-depth discussion of their performance on the task. This type of discussion will help identify "why" pilots may have taken certain (erroneous) actions during the tasks.

Step 6 Transform the data into findings and recommendations.

The data from the evaluation should be compiled to identify potential problems with the product. This compilation of data may include statistics such as the mean or median number of errors, assistance requests, or control actions. Subjective ratings data should also be analyzed. This type of data should point out problematic tasks. The test observation experiences of the test monitors will help to identify the specific causes of problems and recommendations for design improvement.

This description of the usability test process provides only a high level overview of usability testing. More in-depth coverage of this information is may be found in Rubin (1994), Dumas and Redish (1993), and O'Brien and Charlton (1996). Usability testing methods also may be used to target specific aspects of the GPS receiver design including symbols recognition and discrimination, message comprehension, and ease of use of documentation. In the case GPS, or other avionics interfaces, a flight simulator is an excellent test bed. Also, videotaping the sessions provides both archival data and a rich source of information for subsequent analysis.

Human factors consultants may be hired to perform usability evaluations. Services available from consultants range from relatively inexpensive expert analyses of GPS receivers for adherence to accepted human factors principles, to more costly usability tests and competitive analyses. The Human Factors and Ergonomics Society (HFES) publishes a directory of human factors consultants which can be ordered through their website (http:\\hfes.org\hfes.html).

4. IMPLICATIONS FOR THE FAA

4.1 Pilot Training

The results of the GPS evaluations indicated that pilot training is important for safe use of GPS receivers. Familiarity with controls, messages, and procedures are required prior to flying with GPS receivers. Pilots should become familiar with the receiver on the ground, then practice in VFR conditions with a safety pilot for familiarization. Pilots should not expect to use GPS receivers for IFR flight without training and practice. Rental pilots may encounter more than one type of GPS receiver and must be aware of differences between receivers.

The results of this evaluation of GPS receivers indicated that several procedures are conducted frequently or are important as emergency procedures:

- Fly direct to a waypoint
- Find and fly direct to the nearest airport
- Select and fly an approach
- Create and edit a flight plan

These four tasks represent the most important tasks to be trained and practiced for all pilots. The programming requirements for the last of these four tasks, creating and editing a flight plan, indicate that pilots should do the programming on the ground whenever possible. Pilots should also program alternates on the ground prior to flying. If pilots must program flight plans in flight, they should maintain inside and outside scan while programming. This technique should be practiced.

The evaluation also found that six procedures resulted in a medium to high workload and a high number of control actions for most of the GPS receivers. They include the following:

- Vectors to intercept final approach course
- Missed approach with a vector or heading to intercept a course to a MAHP (missed approach hold point) waypoint
- Diversion to an alternate
- DME arc approach
- Intercept a parallel offset base
- Return to departure airport.

Training programs should highlight these tasks so that pilots understand what makes these procedures difficult and to give pilots an opportunity to practice these procedures. Pilots should be aware that they may have to request vectors from ATC for tasks that require additional programming time, such as the six mentioned above, or for editing flight plans. A standard GPS receiver training syllabus for pilots would be helpful in ensuring that pilots training covers the critical aspects of GPS receiver use.

4.2 Air Traffic Control

Implications of this evaluation for air traffic control are generally related to a need for air traffic controllers to be aware of the workload and programming requirements of GPS receivers, as well as specific maneuvers that may be difficult using GPS receivers. One ATC controller interviewed in this evaluation commented that the workload for using a GPS receiver was similar to that of operating RNAV. This is clearly not the case. It was also pointed out that the operational characteristics can vary widely across GPS receivers, so it is not safe to generalize across receivers regarding pilot workload for any given procedure.

Although different receivers may have problems in different situations, the six procedures described in section 4.1 are problematic for most of the GPS TSO-C129A receivers. In addition, rerouting that requires changes to flight plans, approach procedures, SIDs, or STARs represents high workload for pilots. Therefore air traffic controllers should limit rerouting of general aviation pilots flying single pilot IFR, using stand-alone GPS receivers for navigation. Controllers should also be prepared to issue vectors (or holding) for the procedures described in section 4.1. If possible, the vectors or headings assigned should be of sufficient length to allow the pilot time to accomplish required actions.

In addition to the six procedures mentioned above, there are two procedures that are not only difficult but may be beyond the capabilities of general aviation pilots flying single pilot IFR using GPS. Wherever possible, limit the use of these procedures to two pilot crews:

- extended downwind to intercept a parallel offset base to extended final approach course (ARINC 424-13)
- multi-segmented, short-leg course reversal

4.3 Flight Standards and Training

The FAA Flight Standards representatives are responsible for evaluating GPS receivers and conducting field approvals of GPS installation and operation. A document is available that provides guidance to flight standards for GPS installation and operation approval (Wright, 1996). Information described in section 4.1 on high workload procedures and pilot training should be used as a supplement to this guide for Flight Standards representatives approving GPS operations. Flight standards representatives should be aware of these procedures and should ensure that training programs cover high frequency, emergency, and high workload procedures. Flight standards representatives also should be trained in using GPS receivers.

The two procedures mentioned in section 4.2 may be beyond the capabilities of general aviation pilots flying single pilot IFR with GPS. These procedures also should be evaluated carefully by flight standards before approval is given. Methods that may make these two procedures easier, such as improved receiver design or improved positive guidance through the procedure (e.g., through interface with an RMI), are required before these procedures will be within the capabilities of general aviation single pilot IFR.

One other problem that flight standards personnel must monitor is the currency of the data that is used in GPS receivers. There currently is no system for enforcing the maintenance of up to date data. Flight standards representatives should check to ensure that GPS receiver data is current.

4.4 Certification

FAA Certification representatives are responsible for certifying that manufactured equipment is within the specifications of the appropriate technical standard order and other FAA guidance documents. Documents that provide guidance for GPS Certification specialists include a human factors and operations checklist by Huntley, et al (1995) and a report of GPS human factors design guidance by McAnulty (1995). Nearly all of the design recommendations made in section 3.2, as well as the desirable characteristics of GPS receivers made in section 3.3, should be of interest to FAA Certification representatives as a supplement to existing design guidance. The design recommendations of section 3.2 are summarized in the following table.

Table 4. GPS Receiver Design Recommendations Summary Table

Controls
1. Ensure that controls are positioned so that they are not accidentally activated.
2. Minimize the use of a single control for many different functions.
3. Consider front panel designs that use "soft" labels for buttons, that is, the button labels are electronic, software programmed, labels that change with the associated button function so that the label is always displaying the current button function.
4. Ensure that controls are used in a consistent manner throughout the interface.
5. Choose labels for controls that are descriptive of their functions and positioned so that it is easy to associate the label with the control.
6. Where buttons have multiple functions and labels cannot be completely descriptive, stress these points in training and in manuals.
Messages
7. Write messages using common pilot terminology or plain language. Avoid technical or manufacturer specific terms and phrases.
8. Where possible and applicable, indicate in the message what action the pilot should take following the message.
9. Provide as much information as possible as to the cause of the problem. Where multiple causes may exist, list them in the message or indicate what action the pilot may take to determine the cause.
10. For critical messages, require pilot acknowledgement before the message display is removed. If messages are removed from the display without acknowledgement, light the message annunciator and provide an easy way to recall and read the message.
Display Visibility/Readability
11. Ensure that annunciators, as well as the main GPS display are visible and readable. Consider that annunciators may be installed in different locations in different aircraft cockpits. Annunciators must be readable in the full range of cockpit lighting conditions.
12. Locate annunciators near the pilot's primary field of view.

Information Display
13. Whenever there is more information available related to the current display screen, indicate this, for example, with an iconic symbol such as an arrow or a “more” label. 14. Ensure that essential labels and indications (such as the current database section in use or the “to” or “from” indication of a bearing) are clearly shown on the display. 15. Ensure that the presentation of information (for example the position and appearance of labels and the timing and form of mode annunciations) is consistent throughout the user interface. 16. The primary navigation page should display the following: • active waypoint • distance and ETE to the active waypoint • active waypoint name • bearing to the active waypoint • TO/FROM indicator • desired track (DTK) or track angle error (TAE) • cross track error (XTE) Any other information displayed should be pilot selectable and readily de-cluttered (easy to remove from the display).
Logic/Sequence of Steps
17. Wherever possible, reduce the number of steps required to complete tasks, especially emergency or critical tasks. Eliminate unnecessary or redundant steps in a task. 18. Buttons dedicated to a single function require fewer steps in a task. Consider the use of dedicated buttons for frequent or time critical functions. 19. Where tasks require several steps in sequence, provide prompts to assist the pilot in completing the next step in the sequence. Ensure that neither explicit or implicit prompts are ambiguous. One method of determining whether or not the prompts are ambiguous is through user testing to determine whether novices can determine, from the prompt alone, the next step in the task.
Navigation Guidance
20. Wherever possible, ensure that the navigation guidance provided by the GPS receiver is consistent with pilot expectations and procedures. 21. Where there is a likelihood that the navigation guidance provided or the procedure employed by the receiver is different from other receivers or other methods of navigation guidance, ensure that the display provides adequate visual and auditory feedback to indicate any unique or potentially confusing behavior by the receiver.
Functionality
22. We recommend that receivers be capable of performing any function that might be required in a typical flight. The tasks performed in these receiver evaluations represent either typical tasks that a pilot would normally perform or tasks that could potentially be required by ATC during a flight. 23. Ensure that the lack of functionality is visible to the pilots as well as the presence of functionality. For example, if a user persists in making a specific mistake, such as trying to enter ICAO identifiers or trying to enter a waypoint coordinate with .01’ difference, provide a message that indicates to the pilot why the action is not successful.

Moving Maps

24. Ensure that the active waypoint is distinguishable from other symbols on the display. As a minimum, ensure that the active waypoint and its identifying label are never obstructed. 25. Ensure that all icons are recognizable and distinguishable from each other. Review other applications and documentation to determine commonly accepted practice for aviation symbology. SAE G-10 has released a standard symbol set that should be used for all symbols (SAE ARP 4102/7). For unique symbols, test recognition and discrimination of symbols through icon testing with several typical potential users that are not familiar with the system. 26. Denote map orientation on the map display (ex. North up symbol or indicator). 27. Develop a consistent and intuitive way of controlling map scale. 28. If a waypoint identifier can not be displayed in its entirety because of overwriting other information, do not display the identifier at all. Partial waypoint identifiers are easily mistaken for other waypoints and add to display clutter.
Documentation – Information Format
29. Limit the use of lengthy paragraph text for explanation of system operation wherever possible. 30. Provide a graphical presentation of the receiver and how it integrates with other aspects of the systems such as an HSI or CDI, altitude input, fuel flow management system, etc. 31. Provide a graphical presentation of the receiver and the associated controls (knobs and buttons) along with a description of the functionality of the controls. 32. Provide a graphical presentation of the receiver display describing the information displayed at the various locations on the display. 33. Provide flow diagrams indicating menu structure, modes, and/or receiver functionality. 34. Provide task-based instructions for the major tasks that can be completed using the GPS receiver. 35. Provide quick access to task-based instructions in a table of contents and an index. 36. Use clear distinguishable headings for task-based instructions. 37. Use numbered sequential steps in the task-based instructions. 38. Use clear, concise wording for each step in the task.
Documentation Content
39. Ensure that the manual provides sufficient detail in task instructions. 40. Use navigation terminology carefully and precisely to avoid confusion and potential inaccuracies. 41. Ensure that the manuals remain up to date with software changes and that there is some process in place so that manual changes are distributed with software changes.
Documentation Referencing and Indexing
42. Minimize cross-referencing within the text of the manual. 43. When cross-referencing is used within the text, ensure that the references include accurate page numbers and are not circular. 44. Cross-reference common terminology within traditional indexes in addition to the terminology used in the manual. 45. Include glossaries, acronym lists, and symbology lists as appendices.

Quick Reference Guide
46. Limit the content of the quick reference guides to task-based instructions of frequently used and emergency procedures.
47. Ensure that emergency or critical procedures can be located quickly.
48. Highlight task headings so that they are easy to locate.
49. Present task steps in numbered sequential lists.
50. Highlight control actions within the task steps so that they can be read quickly.
51. Minimize the use of paragraph text and lengthy explanations.

5. CONCLUSIONS

The evaluation of six TSO-C129A1 certified receivers revealed that a few GPS procedures require a high number of control actions to be completed. Some procedures also were rated as medium or high workload by the project pilot. Problematic procedures generally were common across the five receivers, though some GPS receivers handled some situations better than others. Frequent, emergency, and high workload procedures were presented in section 3.1 and discussed in section 4 in terms of the implications of this information to the FAA.

The six receivers also exhibited several common problems that indicate there is a need for human factors improvement in the design of these receivers. Areas that were problematic included button labeling, text messages, display of key information, moving map automatic scaling, and documentation format. Design recommendations were made for dealing with these and other human factors problems.

The receivers also exhibited good design characteristics. Examples of these design characteristics, as well as a few unique ideas for an ideal GPS receiver, were described in section 3.3. Another recommendation that resulted from considering an ideal GPS receiver was that GPS receivers should be “usability tested” following procedures similar to those used in this evaluation and in testing consumer electronics. Usability testing will help identify and correct problems like those described in this report before the product is available on the market.

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APPENDIX A – GPS Receiver Front Panels, Button Labels And Functions

NOTE: The following figures display the front panels of each of the six GPS receivers. The associated tables present each of the buttons and their main functions. The description of functions for each button may not include all of the functions for that button.

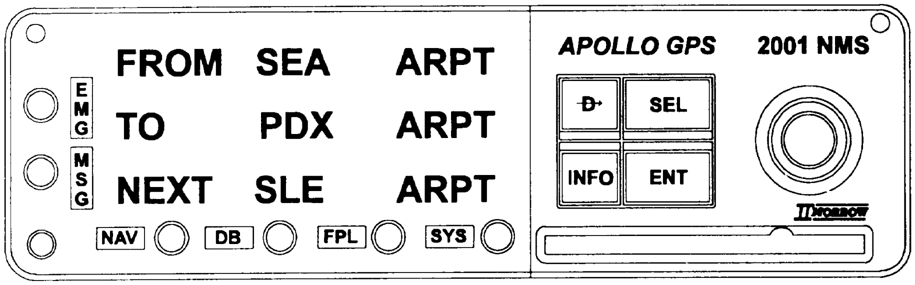

Figure A - 1. Apollo 2001

Table A - 1. Apollo 2001 Button Labels and Functions

Label	Function
D (Direct-To)	Define a direct course from the present position to any waypoint.
ENT	Enters and saves the information flashing on the display. If ENT is not pressed, changes made are not saved.
SEL	Activate editing, pressing the "SEL" turns on and off the "blinking cursor."
MSG	Display messages.
EMG	Find the nearest waypoints and nearest SUAs (Special Use Airspace areas) to your present position, or to find the closest waypoints to a selected waypoint.
NAV	1. Display navigation information, such as the bearing, distance, and the ETE (Estimated Time En route) to the To waypoint. 2. Provide Altitude Assist features, Parallel Track, Current Position Sensor information, a Countdown Timer, and From, To, Next waypoint access.
INFO	1. Accesses supplementary information about the displayed waypoint. 2. Access flight plan comments that you enter.
DB	Access waypoints stored on a data card, and to create, store, and edit up to 500 user waypoints.
FPL	1. Create, store, view, and edit up to 9 flight plans of up to 20 legs each and to edit the Active flight plan. 2. Provide advance information about ETE, ETA, Fuel Usage, and other important flight statistics.
SYS	1. Used to make certain settings and adjustments to the system, such as adjusting the Time and Date, Fuel Units, and Barometric Units. 2. Provides status information for position and other sensors.
Concentric knobs	Large knob 1. Scroll through top-level displays in each mode 2. When part of the display is flashing (i.e., editing is on), used to choose which character or characters on the display will flash. Small knob 1. Used to scroll through displays that pertain to the top-level displays. 2. When editing the display, a character, or series of characters, will flash, the small knob is then used to change the flashing character(s) to the desired character(s).

Figure A - 2. Bendix-King KLN89B

Table A - 2. Bendix-King KLN89B Button Labels And Functions

Label	Function
D (Direct-To)	1. Allow selection of a waypoint for direct routing 2. Allow deselection of a direct-to waypoint
ENT	Complete an action.
CRSR	Control cursor activation and deactivation
CLR	1. Delete flight plans 2. Cycle through information (cyclic) fields (cyclic fields are sometimes changed by use of the concentric knobs) 3. Select controlling frequencies for SUAs (special use airspaces) 4. Return to the prior step in flight plan selection 5. Delete user waypoints from the OTH pages 6. If Direct to has been initiated to a waypoint in a flight plan, to clear the Direct to and return to the flight plan
MSG	View messages.
NRST	Retrieve nearest facilities – airports, VORs, NDBs, SUAs, FSS frequencies, center frequencies
OBS	Switch between the OBS and LEG modes.
ALT	1. Set barometric pressure 2. Set VNAV
Concentric knobs	Outer knob: 1. Rotate through the information page types listed on the bottom of the display 2. Cursor movement Inner knob - IN position 1. Select individual pages within the page types on the bottom of the display 2. Input alphanumerics to enter data Inner knob – OUT position 1. Rapid rotation through database information 2. Rotate through flight plan waypoints in the NAV 4 page

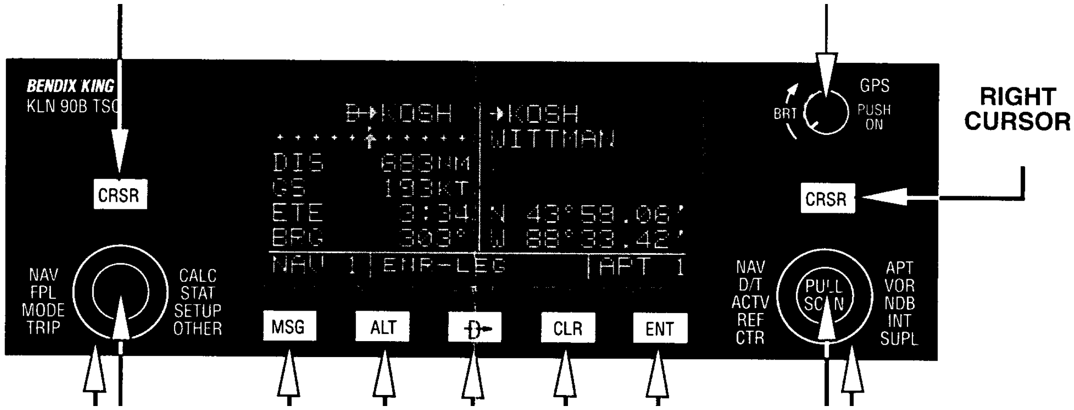

Figure A - 3. Bendix-King KLN90B

Table A - 3. Bendix-King KLN90B Button Labels And Functions

Label	Function
D (Direct-To)	1. Allow selection of a waypoint for direct routing 2. Allow cancellation of direct-to operation
ENT	Complete or confirm an action.
CRSR	Control cursor activation and deactivation
CLR	1. Delete flight plans 2. Delete waypoints and approaches from flight plans 3. If Direct to has been initiated to a waypoint in a flight plan, to clear the Direct to and return to the flight plan
MSG	1. View messages. 2. Displaying nearest airports.
ALT	Set barometric pressure
Concentric knobs	Outer knob: 1. Selects page type 2. With cursor on, controls cursor location Inner knob - IN position 1. Selects specific page 2. With cursor on, makes selection character by character Inner knob – OUT position 1. Selects specific page 2. With cursor on, makes selection by scanning through the database alphabetically (right side only)

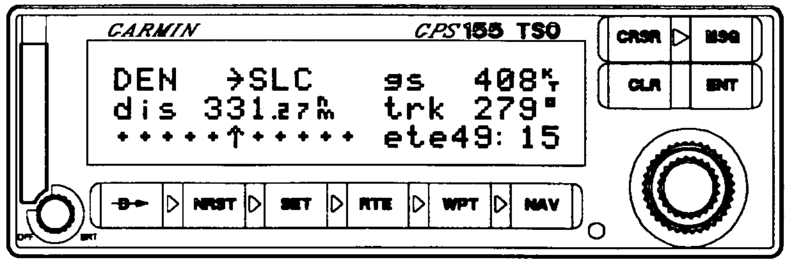

Figure A - 4. Garmin 155

Table A - 4. Garmin 155 Button Labels And Functions

Label	Function
D (Direct-To)	Define a destination waypoint for direct-to operation.
ENT	1. Confirm an operation 2. Complete data entry
CRSR	1. Activate and de-activate cursor 2. Cycle through available options
CLR	Erase information or cancel a previous entry.
MSG	View messages.
NRST	Retrieve nearest facilities – 9 nearest airports, VORs, NDBs, intersections, and user waypoints or 2 nearest FSSs. Displays nearest airport first.
NAV	1. View navigation and position information. 2. Perform planning operations using the navigation function.
WPT	View information about airports, NAVAIDs, intersections, and user waypoints.
RTE	1. Used to define up to 20 routes of up to 31 waypoints each. 2. Approach, SID, and STAR selection 3. Closest point of approach 4. Parallel offset 5. Search-and-rescue operations
SET	1. Customize operation of GPS receiver 2. View satellite status information
Concentric knobs	Outer knob: 1. Select a new information display 2. Move the cursor 3. Enter data Inner knob 1. Select new information of a given category 2. Enter data

Figure A - 5. Northstar M3

Table A - 5. Northstar M3 Button Labels And Functions

Label	Function
D (Direct-To)	1. Define a flight path direct from present position to a waypoint or along a route that is displayed in the primary readout. 2. With the left-hand CRSR button, provides a shortcut for displaying the nearest airport's ID, bearing, distance, and longest runway.
ACK	1. Confirmation of defined flight path – press after the –D button has been pressed. 2. Data entry - to confirm data entry procedures. 3. When an advisory is waiting to be displayed press the blinking button to display the advisory. 4. Save present position.
CRSR	Activates (and deactivates) flashing cursor to enter or change data.
MSG	View messages (when flashing).
ALRT	View airspace alert (or Airalert) messages (when flashing).
Concentric knobs	Outer knob: Selects the functions labeled on the receiver face Inner knob: Selects specific data within the functions.

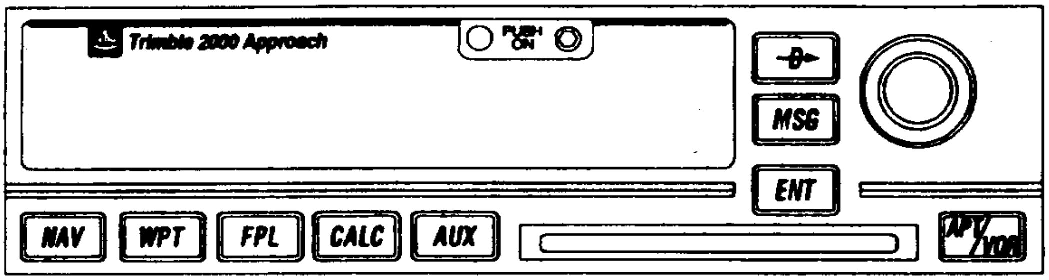

Figure A - 6. Trimble 2000 Approach

Table A - 6. Trimble 2000 Button Labels And Functions

Label	Function
D (Direct-To)	1. Proceed to a waypoint already selected 2. Select a new active waypoint 3. Select a course inbound/outbound to/from current active waypoint 4. Activate approach, SID or STAR 5. Select a user defined DME arc about any active waypoint
ENT	Enter, select, or change the information currently displayed on the LED screen.
MSG	View messages.
NAV	1. Display the primary navigation display as well as supplement navigation information 2. Place the unit in NAV mode.
WPT	1. Provides access to information in the NAVAID and procedure databases 2. Place the unit in waypoint mode.
APT/VOR	Provides information on the 20 nearest airports, approaches, VORs, agencies, NDBs, intersections, and user waypoints.
FPL	1. Create, activate, edit, reverse, and erase flight plans. 2. Allows direct editing of flight plans, including the active flight plan. 3. Plan legs, bearing and distance between waypoints, and ETE (for Active Flight Plan) are available.
CALC	1. Perform many common E6B computer functions. 2. Save present position and calculate VNAV profiles, wind speed and direction, fuel ranges, flight plan summaries and more.
AUX	Provides access to less commonly used functions – checklists, system status information, sensor status information, configuration (e.g., parallel offset), and installation (e.g., display intensity).
Concentric knobs	The small, inner knob can be used to 1. Change any editable field (course, distance, or procedure) located within angle brackets "< >" 2. Change alphanumeric or available option/function of a selected field while editing 3. Scroll through primary pages and top lines of the displayed mode The large, outer knob can be used to 1. Move between editable fields on the displayed page 2. Scroll through secondary pages and bottom lines of the displayed mode

APPENDIX B – Sample Data Sheet for a Test Flight Maneuver

Maneuver: ____

Number of times controls used			Prompts		
Button	Knob	Dedicated	None	Text	Illuminated key

Cursor use		Mode switch		Mode annunciation		Multiple page use	
Yes	No	Yes	No	Yes	No	Yes	No

Pilot memory required			Likelihood of errors			Pilot workload		
High	Med	Low	High	Med	Low	High	Med	Low

Prompts	***Pilot action***	***In order to***	***Buttons***	***Knobs***
		Total:		

([D] = use of dedicated knob, button, or annunciator switch)

Notes:

Most probable error:

Surprises:

What makes it difficult to do?

Problems, consequences, and recommendations:

APPENDIX C – Proposed Format For GPS Receiver Quick Reference Guide

Manufacturer and GPS Receiver Model Names
Quick Reference Guide to Receiver Operations

Creating routes

1. Rotate [left outer knob] to FPL.
2. Rotate [left inner knob] to blank flight plan pages.
3. Press [left CRSR]
4. Rotate [left inner and outer knobs] to input desired waypoint.
5. Press [ENT]
6. Press [ENT]
7. Repeat 4, 5, and 6 until all desired waypoints are entered.

Selecting SIDs

1. Rotate [right outer knob] to airport pages.
2. If the desired airport is not displayed, press [right CRSR]
3. Rotate [right inner and outer knobs] to input desired airport.
4. Press [right CRSR]
5. Rotate [right inner knob] to select APT 7 page.
6. Press [right CRSR]

See next page for more instructions.