DOT/FAA/CT-81/201

Navigation System Using Time and Ranging (NAVSTAR)/Global Positioning System (GPS) Fixed Wing Z-Set Testing

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Project Plan

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1. INTRODUCTION.

1.1 OBJECTIVE.

The overall objective of the Federal Aviation Administration (FAA) Global Positioning System (GPS) test program is to define and determine the potential role of GPS as a civil aviation navigation system. The objective of the GPS Z-set receiver test and evaluation program is to gather information to help determine the eventual role of GPS in civil aviation by providing timely data to formulate the FAA decision on future navigational standards. The Z-set test program is designed as a series of tests to evaluate the suitability of GPS to meet the objectives of the July 1980 Federal Radionavigation Plan (FRP). These objectives include investigation of both technical and operational considerations as they impact suitability of performance. Emphasis will be placed on en route navigation and nonprecision approaches to airports when the aircraft is at low altitudes in the terminal area in a maneuvering configuration.

The objective of the Z-set test program is to totally evaluate the GPS Z-set system performance including accuracy, reliability, integrity, responsiveness, accquisition time, resultant flight technical error, pilot confidence in displayed information, and the effects of signal variations due to aircraft dynamics, weather, atmosphere delays, multipath, radiofrequency interference (RFI), satellite availability, and satellite geometry. Emphasis in the test will be directed toward evaluating the potential of GPS navigation for the single-piloted, low performance, general aviation class aircraft utilizing a low cost GPS system. Modifications to the standard Z-set configuration will be employed to accomplish these objectives (e.g., low cost preamplifiers, low cost antennas, and different control display indicators (CDI's)). Results of the test will be compared with total system requirements specified in FAA Advisory Circular (AC) 90-45A and the July 1980 FRP.

1.2 BACKGROUND.

Very high frequency omnidirectional radio range (VOR)/distance measuring equipment (DME) is the current worldwide civil short range air navigation system which provides fixed radial course lines from VOR ground stations. When an aircraft is within the coverage area of the VOR/DME ground station, the aircraft bearing and distance information provided is readily usable for navigation. However, not all geographic regions permit effective VOR/DME service. For long range navigation, Loran, Omega, and inertial navigation systems have been utilized. Each system has its advantages and disadvantages.

The Navigation System Using Time and Ranging (NAVSTAR) GPS is a candidate replacement for these systems. It is a satellite-based navigation and positioning system which provides accurate position, velocity, and time information. When the GPS system is fully operational, a GPS receiver will select signals from several GPS satellites, decode and process those signals to determine three-dimensional user position in any weather, 24 hours a day, anywhere on or near the surface of the earth. The system is passive with no danger of system saturation.

A complement of six satellites in two circular, orbital planes presently provide three-dimensional coverage (4-hour interval when all satellites are in a healthy operational status) over selected geographical areas. Full operational capability, to include 18 to 24 satellites, is scheduled for the late 1980's.

The FAA has initiated an extensive program to define and determine the potential role of GPS as a civil navigation system. This plan outlines the initial test objectives and utilization of the GPS Z-set receiver in a fixed wing aircraft to help determine the eventual role of GPS in civil aviation. This plan complements the Z-set plan on the helicopter.

1.3 RELATED DOCUMENTATION/PROJECTS.

a. Federal Radionavigation Plan, July 1980, published by the Department of Defense and the Department of Transportation.

b. Approval of Area Navigation Systems for Use in the U.S. National Airspace System, Advisory Circular 90-45A, February 1975.

c. Results of Joint Service Field Tests, Validation Phase 1 Concept Developmental Test and Evaluation, NAVSTAR GPS Joint Program Office.

d. Evaluation of NAVSTAR GPS as a Rotary Wing Navigation Aid Using Magnavox Z-Set, FAA, Report No. FAA-CT-81-160, April 1981.

e. Institute of Navigation, GPS Special Issue, Summer 1978, Volume 25, Number 2.

f. User's Manual (Computer Program) for User Equipment Z-Set of the NAVSTAR Global Positioning System, Draft, CDRL Item AOOX, Magnavox Government and Industrial Electronics Company.

g. USCG/MARAD Static Tests of the GPS Navigation Z-Set (Low Cost), U.S. Coast Guard, Report No. CG-D-18-80.

1.4 CRITICAL ISSUES.

In the FRP, the GPS is being considered for the following phases of navigation:

a. Oceanic en route phase.

b. Domestic terminal and en route phase.

c. Special en route phase (remote and helicopter).

d. Nonprecision approach and landing phase.

The critical issues, as identified in the FRP, volume IV, page A6, for any candidate navigations system, other than the present VOR/DME, are:

a. Concurrent operations of multiple navigations systems and standards during the transition period (paragraph 2.2.3 contains the compatibility test).

b. Reliability of the signal in space and signal status information dissemination to pilots and controllers (paragraph 2.1.3 addresses the ground truth monitor; paragraph 4.4 cites the method and plans to evaluate this issue).

c. Flight inspection method to be carried out for the alternative system. (FAA surveillance/participation in GPS ground monitoring stations to satisfy flight inspection requirement is not addressed in this document.)

Key technical factors concerning civil use of the GPS are:

a. Operational feasibility in the air traffic control (ATC) environment for navigation phases listed (paragraph 2.2.3 contains operational tests).

b. Signal level and accuracy (paragraph 2.2.2 contains accuracy tests; the GPS set will be flown when three to six healthy satellites are available).

c. Operational suitability of low cost, single frequency user equipment. Operational suitability will be assessd in the operational test of the Aero Commander with the Z-set as cited in paragraph 2.2.3.

d. RFI susceptibility. (RFI tests are contained in paragraphs 2.1.2 and 2.2.2. RFI instrumentation equipment are listed in paragraph 3.0 and in figure 4; data analysis is addressed in paragraph 4.4.)

e. Multipath problems during approach. (Existence and effect of multipath problems will be evaluated as detailed in paragraphs 2.2.3 and 4.4.)

f. Aircraft antenna coverage during normal maneuvers. (Aircraft antenna coverage will be analyzed during post-analysis, as cited in paragraph 4.4.)

g. Initial acquisition time and acquisition time during flignt. (Acquisition time in flight will be measured and analysis performed, as cited in paragraphs 2.2.2 and 4.4.)

h. Human factors of the man/machine interface such as pilot workload, flight technical error, blunder rate, cockpit automation, and pilot confidence when performing approaches. (Human factors aspects that will be evaluated in the operational test program are outlined in paragraph 2.2.3.)

i. Satellite constellation failure modes detection and restoration time. (Satellite signals will be monitored during the test program, as outlined in paragraph 2.1.3.)

j. System integrity and reliability. (System integrity and reliability will be evaluated as outlined in paragraph 2.1.3.)

k. System capability to meet present and potential future navigation needs. (The system will be evaluated against the requirements cited in FAA AC 90-45A dated February 21, 1975, and the FRP. The system will be evaluated in quantitative terms allowing for realistic projections of future navigation requirements.)

1.5 SYSTEM DESCRIPTION.

The Z-set GPS receiver is a single channel production prototype navigation receiver capable of processing the course/acquisition (C/A) signal sequentially from four chosen satellites on L-Band frequency 1575.42 megahertz (MHz). The information is processed into a three-dimensional position, ground track, ground speed, and system time.

The major components of the set are an L-Band antenna, RF amplifier, receiver/processor, and a control/indicator (C/I). The C/I front panel is shown in figure 1. The set is provided with an optional Z interface module (ZIM) to interface barometric altitude with the Z-set for three-satellite navigation and a buffer box providing isolation and accessibility of the sets memory by an external data processor. Barometric altitude is used as a substitute range measurement only when less than four satellites are available for navigation. The set data are displayed on a single line readout (one parameter at a time displayed) selectable by the operator to set initial input conditions or monitor output parameters. The selectable parameters are listed in table 1. The physical and general performance characteristics of the Z-set, although presently unverified by FAA tests, are shown in table 2.

Position information for nine waypoints plus current location can be entered into the system. The waypoint number (0 to 9) is displayed in a separate window; waypoints (other than waypoint 0 - current position) have only two dimensions — latitude and longitude. Current position is referenced to altitude as well as latitude/longitude. Position data displayed by the set is referenced to the Department of Defense World Geodetic System 1972, commonly referred to as a WGS-72 ellipsoid surface.

In addition to the microwave specialty antenna delivered with the Z-set, an FAA developed Ball Brothers microstrip antenna will be evaluated. A low cost GPS preamplifier has also been procured for evaluation.

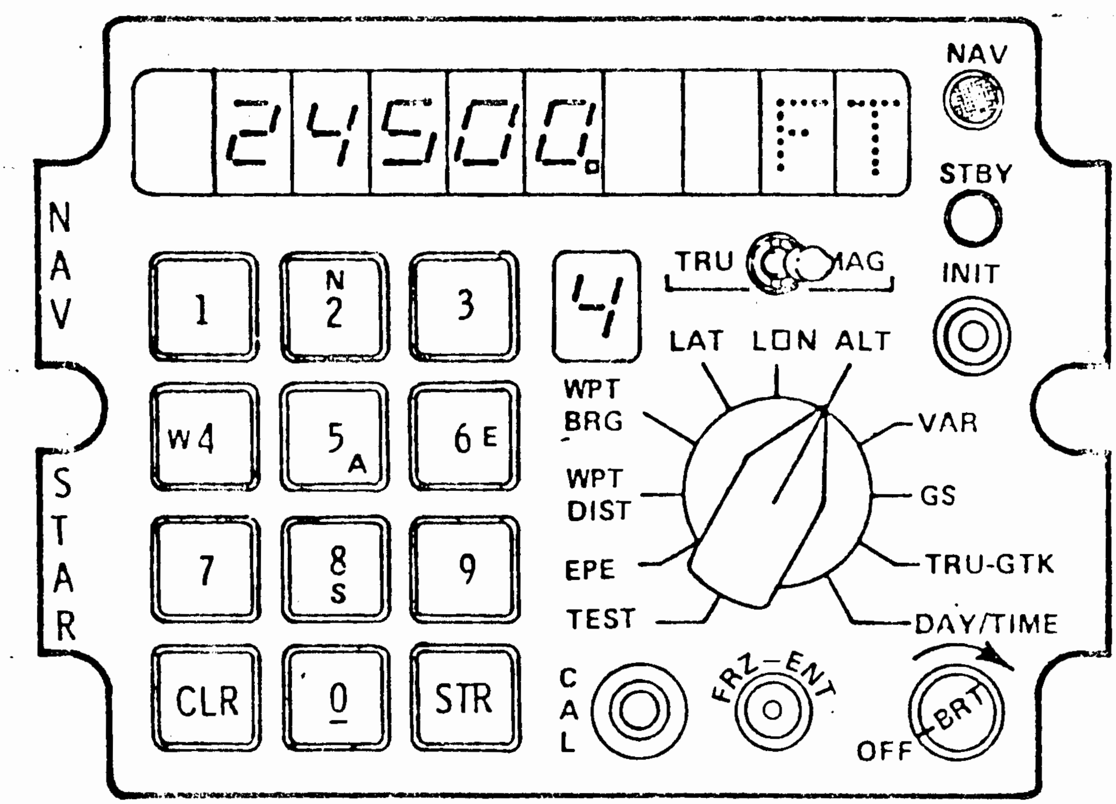

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FIGURE 1. Z-SET CONTROL/INDICATOR PANEL

TABLE 1. Z-SET CONTROL/INDICATOR DISPLAY PARAMETERS

Displayed Parameters	Characteristics
Distance to waypoint	Resolution of 0.1 nautical mile
Bearing to waypoint	Resolution of 0.1°
Latitude	Resolution to 1 second
Longitude	Resolution to 1 second
Altitude	Resolution to 1 foot
Waypoint magnetic variation	Resolution to 0.1°
Ground speed	Resolution to 1 knot
True ground track	Resolution to 0.1°
Day/time	GPS epoch time to 1 second
Receiver/processor faults	Fault messages and satellite data
Test mode	Checks LED operation
Estimated position error	Calculated from the Kalman filter covariance matrix; $\sqrt{x^2 + y^2 + z^2}$ where values are differences between predicted Kalman output and actual position; resolution to 0.01 nautical mile.

TABLE 2. PHYSICAL AND PERFORMANCE DETAILS

Parameters	Characteristics
ENVIRONMENTAL	
Temperature	
Operating:	
Receiver/processor and C/I	0 to +49° C
RF amplifier	-40 to +50° C
Antenna	-40 to +85° C
Storage:	
Set	-40 to +85° C
Relative humidity	
Receiver/processor and C/I	95% (0 to 49° C)
RF amplifier	95% (-40 to +55° C)
Altitude (Operating)	-1,000 to 44,000 feet
OPERATIONAL	
RF signal input level	-163 to -150 dBW, L_1 1575.42 MHz
Maximum dynamics	
Velocity	0 to 400 meters per second
Acceleration	0 to 5 meters per second (between 5 m/s^2 and 10 m/s^2 set will enter HOBYT)
Antenna coverage	Reception of satellite signals more than 5° above horizon
Equipment stabilization period	Less than 15 minutes from turn-on to the start of data acquisition between 0 to +49° C
Static propagation delay error (GDOP less than 5)	Error in displayed navigation solution less than 180 meters
Fix accuracy	500 meters
Pseudorange measurement accuracy	15 meters (C/A signal)
Jamming-to-signal power ratio	Up to 25 dB
Data recovery	Undetected bit error rate less than 0.00001 with jamming-to-signal ratio of 25 dB
Time to first fix	
Normal (wide) acquisition mode	Less than 300 seconds
Narrow acquisition mode*	Less than 215 seconds
Digital output signal	2.4 kilobits per second
PHYSICAL	
Volume	0.016 cubic meter
Weight	15 kilograms
Power	53 Watts

*Position uncertainty 13 km - Initial velocity uncertainty <17 m/s

1.6 LOCATION OF TEST.

Most of the test will be conducted at the FAA Technical Center utilizing its instrumented range and laboratory facilities. Some test may be conducted in Alaska with the Loran-C program to help determine what future navigation systems will be used in that area. The test will be conducted with the Loran-C program in mountainous areas and over oceans to investigate possible multipath problems, and in areas with high RFI environments. The exact RFI areas to be flown are now under study and will consider inputs/recommendations from outside organizations, such as Electromagnetic Compatibility Analysis Center (ECAC), Aeronautical Radio, Inc. (ARINC) and MITRE Corporation.

1.7 OVERALL TEST SCHEDULE.

The Z-set test schedule is a cohesive schedule that takes into account the limited FAA resources in aircraft, fuel, navigation test items, instrumentation equipment, manpower, and money. It is developed with the understanding that other navigation systems such as Loran, Omega, DME, etc., will be flown concurrently, when possible, to minimize the number of flights necessary to evaluate all systems, and to keep the test conditions identical for evaluation of various systems. The overall test schedule is shown in figure 2. This schedule assumes that the Z-set will be reliable and that GPS testing will not be delayed due to unavailability of other navigation systems or their interface equipments.

2. TEST PROGRAM.

The tests to be conducted under the auspices of this project plan include both laboratory testing and flight testing. The activities associated with flight testing involve assessment of the test platform itself as well as data collection through use of the platform. Laboratory testing provides information on the basic preformance of the system such as static accuracy, acquisition time, stability, and system response to external inputs (erroneous initialization data and simulated RFI inputs). In addition, testing in the laboratory supports flight testing by providing a reference for accuracy comparisons and a means for establishing familiarization with the GPS Z-set and associated test equipment.

The evaluation of GPS performance requires the separation of characteristics due to two dynamic mediums. The foremost concern is the GPS performance as affected by the flight dynamic environment. But just as important, the effects of transient satellite position on the received signal must also be evaluated.

2.1 LABORATORY TEST PROGRAM.

Laboratory testing is intended for the purpose of characterizing those effects on GPS performance which occur independently of flight dynamics and can, therefore, be measured in a stationary environment.

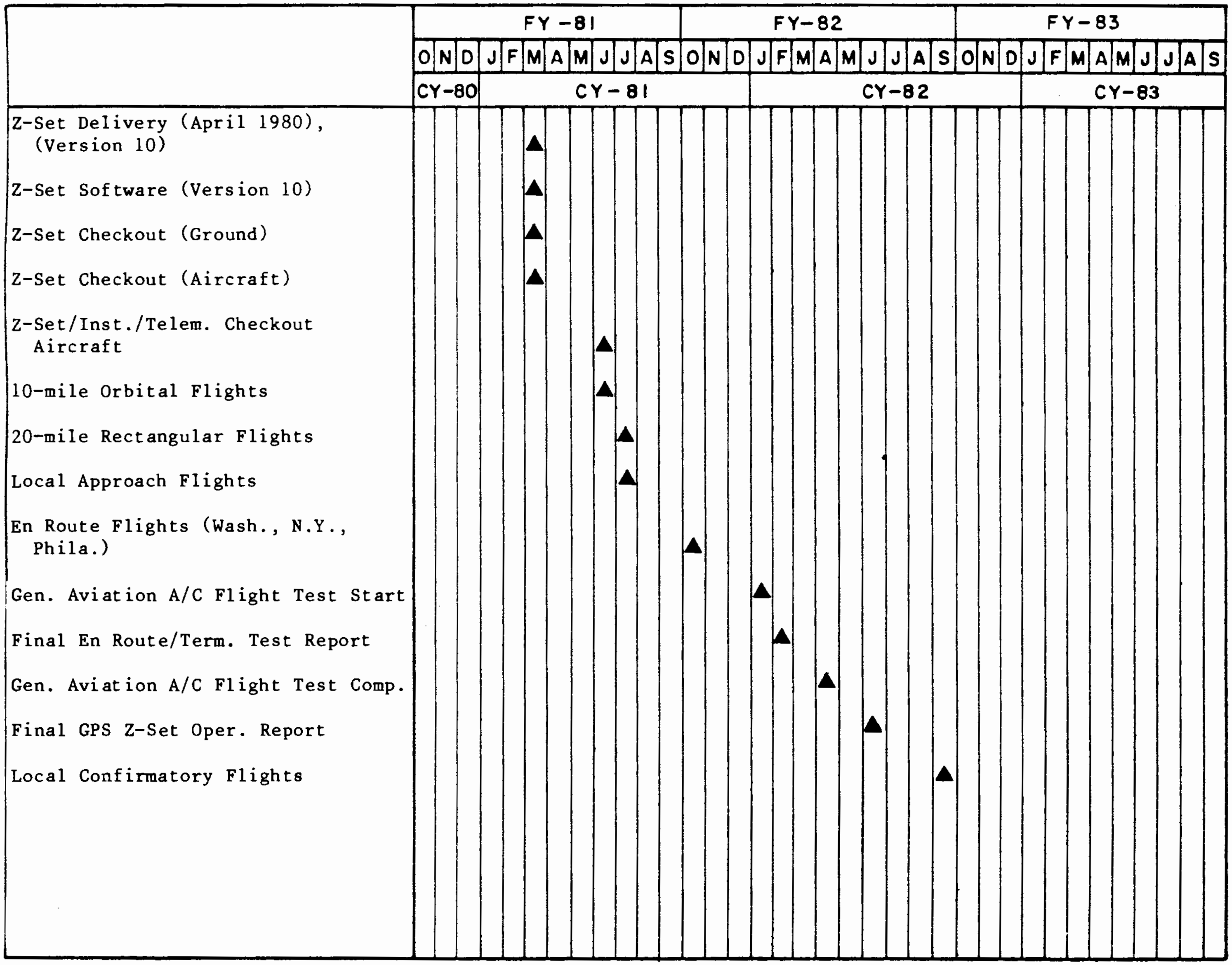

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FIGURE 2. Z-SET TEST SCHEDULE

Although the primary means of characterizing the ability of GPS to satisfy airborne navigation requirements is through flight testing, there are definite benefits to be derived from conducting laboratory tests:

Lower cost than flight testing.
Fixed site for precise accuracy determination.
Semicontrolled environment.
Easy access to all equipment.

For these reasons, the laboratory is an ideal environment for familiarization testing and static GPS performance evaluation.

2.1.1 Laboratory Familiarization Test.

Flight testing creates an environment which can be unforgiving of operator errors, especially with evaluations involving limited test windows. It is, therefore, essential that all personnel involved in the GPS test program become familiar with the operation of the equipment prior to its installation in the aircraft. Areas of operation to be emphasized are the mechanics of data entry, proper interpretation of output parameters including diagnostics, and different modes of initialization. Tests to be conducted to familiarize personnel with operation of the Z-set prior to installation in the aircraft include:

Set turn-on.
Entering and storing initialization data.
Entering and storing waypoint data.
Selection of all display parameters.
Almanac update.
Fault isolation.
Operation with less than four satellites.
Signal acquisition.

2.1.2 System Performance Laboratory Test.

The GPS antenna will be mounted at a surveyed position on the top of building 301 at the FAA Technical Center and connected to the Z-set. The Z-set will be monitored and the data will be analyzed to determine the following:

a. Static Accuracy Test. Accuracy of the Z-set will be effected by the position of the satellites as reflected by geometric dilution of precision (GDOP) values. The Z-set position readings will be compared against the survey position to determine the amount they are affected by various GDOP values. In addition, the estimated position error (EPE) will be compared to GDOP and the measured position values.

The Z-set accuracy will be monitored to determine if it is affected by the daily updates of the satellite by the Master Control Station and, if so, the amount by which it is affected. The accuracy of the set is determined in part by the satellite constellation chosen by the set to use for navigation. The set will be monitored to determine the ability of the set to select the proper constellation at the right time.

b. Acquisition Time. Acquisition time will depend on the status of the equipment prior to turn-on and the information provided to the set during initialization. Acquisition time will be measured with a combination of different initial conditions. These initial conditions will include:

1. Cold Start (RF oscillator cold).

2. Hot Start (RF oscillator stable and at operating temperature).

3. With and Without Calibration Mode (calibration mode, when activated, set the Z-set velocities to zero to indicate the set is not moving).

4. Erroneous Initialization Inputs. set will be intentionally operated with the incorrect inputs to determine the effects on acquisition time. These inputs would be those mistakes a pilot could be expected to make. Local time instead of Greenwich Mean Time (GMT), wrong day code (like four instead of five), east longitude instead of west, etc.

5. Different Almanac Ages. The use of old almanac data may cause the actual rejection of satellite signals and prevent the set from acquiring. It is the purpose of this test to determine the set sensitivity to the age of the almanac data.

6. Almanac Collection. Starting in almanac collection mode, measure the length of time it takes to collect an almanac and acquire.

7. Search the Sky Mode. Starting in search the sky mode, measure the length of time it takes to locate a satellite, collect an almanac, and acquire.

8. Almanac/Ephemeris Comparison. The almanac and ephemeris data are basically the same; however, there is a difference based largely on elapsed time from last almanac update. Almanac data will be compared with current ephemeris data from each satellite.

c. Altitude Input Test. The Z-set accuracy is affected by the altitude input to the system when less than four satellites are available for navigation. The optimum condition would be a continuous accurate input of altitude; the minimum condition would be an incorrect or zero input of altitude at the time of initialization. The purpose of this portion of the test would be to measure the effects on position information with different methods of inputing altitude — one time input, manual input every x number of minutes, continuous digital altimeter input, and continuous digital altimeter input with manual input.

d. RFI Lab Test. The Z-set performance will be monitored in the presence of RFI. An RF signal generator output (below 163 decibels above 1 watt (dBW) at 1575.42) will be connected to the input line of the preamplifier when the antenna is connected and receiving GPS satellites' signals. The RF signal generator output will be increased to a level where the signal effects the Z-set position output as compared to the surveyed position or the system loses track.

Interference signals that simulate tactical air navigational aid (TACAN) and other RF sources will be coupled into the line at various signal levels to determine the effect on the Z-set. The most severe RF environments that are measured and recorded during flight test will be simulated as near as possible during lab test; the Z-set output will be monitored and analyzed. Z-set multipath rejection and susceptibility will be investigated by use of two antennas, couplers, and delay lines in the lab until the FAA simulator is assembled and operational.

At the major airports in the local area (New York, Philadelphia, and Wilmington), RFI measurements will be taken and the Z-set performance will be monitored. RFI measurements will be taken at airports in the northeast and Alaska when the flight test program brings us to these airports. As listed in section 3, the aircraft will be equipped with an RF spectrum analyzer and recorder which will permit RFI measurements in the air and at selected airports. Other airports will be visited as determined by RFI studies and as the GPS program evolves.

2.1.3 GPS Ground-Based, Fixed Monitor.

A GPS ground-based, fixed site monitor system in the vicinity of the actual flight test will provide valuable data to allow determination of the accuracy of the GPS signals in space during the actual conduct of airborne flight test on the Z-set. This data (commonly referred to as ground truth data) will enable the separation of effects caused by aircraft maneuvers alone from those effects resulting from GPS satellites' position, clock errors, and ionospheric delays. The Y-set will be utilized as a ground monitor during the Z-set flight test. Its antenna will be located at a survey position and the Y-set will be connected to the ground-based Hewlett-Packard (HP)-1000, model 45 instrumentation computer. The data from the Y-set will be recorded continuously during the Z-set airborne testing, provided the Y-set is available and operating. The Y-set, when available, will be used to monitor the satellites continuously so that GPS system accuracy, integrity, and reliability can be assessed.

2.2 AIRBORNE TEST PROGRAM.

Airborne testing of GPS may be placed in two categories: GPS performance testing and operational suitability testing.

Performance testing involves a measure of GPS accuracy during varying aircraft maneuvers. Performance tests will verify the accuracy of the particular Z-set being tested, the velocity and ground track data provided by the Z-set, and will investigate such parameters as satellite shielding during maneuvers, the effects of aircraft dynamics, and the benefits that may be derived from altimetry-aiding. Additionally, it will provide an evaluation of system initialization and acquisition times under various conditions.

Operational testing involves an evaluation of the man/machine interface and the total system performance under operational conditions. It provides an evaluation of the ability of the operator to use GPS for navigation throughout the airspace. Although a navigation system may be capable of meeting all accuracy requirements, it is not sufficient to judge acceptability on accuracy alone. The operational capability of a system in terms of the man/machine interface is highly significant and, therefore, must be evaluated.

The Airborne Test Program will be flown in an Aero Commander, a Gulfstream, and a Convair 580, depending on aircraft availability and test to be conducted. The objective of the test program is stated in section 1.1. The test flight schedule is shown in figure 2 and is highly dependent on adequate satellite coverage (4 hours per day in the Atlantic City area when five satellites are healthy). The program will consist of the following:

Instrumented Range Flights	Data Flight Hours
Familiarization/checkout flights (four flights)	4
10-mile orbital flights (eight orbits)	3
20-mile rectangular flights (10 patterns)	10
30 constant bank angle orbits	5
Terminal approach flights (40 approaches)	10
Five RFI check flights	10

Operational En Route/Terminal Nonprecision Approach Flights	Data Flight Hours
Local (N.Y., Phila., Wash.) (five flights)	10
Northeast flights (five flights)	
Northwest and Alaska flights (five flights)	10
North Atlantic Oceanic flight	10

2.2.1 Familiarization/Checkout Flights.

After system checkout in the laboratory and on the ramp, the Z-set will be test flown in the local area with approaches to Atlantic City Airport (FAA Technical Center) runways, en route flights to Millville, Cape May, and Monmouth County as well as local flights utilizing the Technical Center's instrumented range. Approximately four 1-hour flights will be required to checkout the interface of the Z-set with the airborne instrumentation system.

2.2.2 Instrumented Range Flights.

To establish a baseline performance for the Z-set and to make certain the system meets its requirements before extensive testing, the Z-set will be flown over the instrumented range in the following manner:

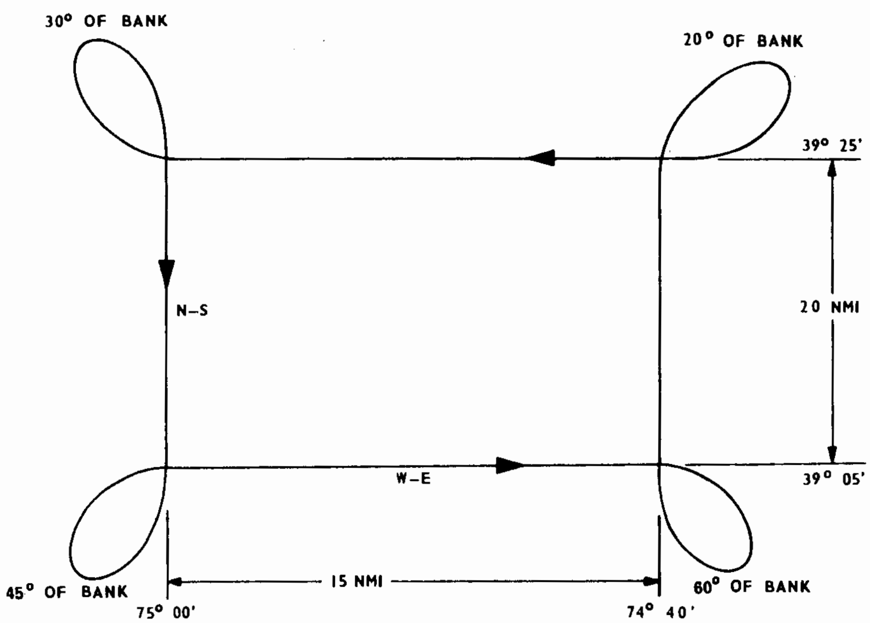
a. Eight 10-nautical mile orbits around the Atlantic City VOR terminal area chart (VORTAC) to access the effects of different satellite configurations and aircraft bank angles. System will be reinitialized during some flights to measure acquisition time in flight.

b. Ten 20-mile rectangular patterns (two north/south legs and two east/west legs) with outside turns of 20°, 30°, 45°, and 60° banks at altitudes of 5,000 to 25,000 feet (see figure 3). Some flights will be flown with and without altimeter aiding when receiving only three satellites. Z-set performance will also be evaluated with manual insertion of altitude. Several flights will be flown with changes in the flight altitudes during various legs of the rectangular.

c. Constant bank angle orbits (15 orbits with each of the two GPS antennas) with bank angles from 5° to 40° at an altitude of 5,000 feet.

d. Forty terminal approach flights will be made to the Technical Center runways including six instrument landing system (ILS) approaches. The ILS is being used as a positioning system for the test. This test is not intended to demonstrate the existence of a landing system capability for the Z-set.

e. Five RFI check flights will be made in the area of known transmitters to determine the susceptibility of the GPS signals, if any, to known existing local high RF environments, such as channel (CH)-23. These flights will be scheduled when the GPS satellite window coincides with the high RF environment. (For instance, during the spring the satellite window is in the middle of the night when CH-23 is not broadcasting.) Detail information on test flights will be developed after consultations with ECAC, ARINC, MITRE, and other FAA organizations.



NOTES:

1. FLIGHTS TO BE CONDUCTED AT 5,000 TO 25,000 FEET. NO ANTICIPATION OF TURNS UNTIL CORNER POINT IS PASSED. TIME FOR ONE PASS IS APPROXIMATELY 1 HOUR.
2. FLIGHTS TO BE TRACKED BY RADAR.

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FIGURE 3. RECTANGULAR FLIGHTPATH SKETCH

2.2.3 Operational En Route/Terminal/Nonprecision Approach Flights.

The Z-set will be flown under Instrument Flight Rules (IFR) procedures on established VOR routes and as an area navigation (RNAV) system to Washington, D.C., Norfolk, Va., Philadelphia, Pa., Wilmington, Del., New York, N.Y. (JFK Airport), and Monmouth County Airport, N.J., with Nike/Hercules range tracking wherever possible within 200 nautical miles. The Z-set will be flown to major airports in selected regions of the country to ascertain that specific geographic locations, RF environments, aircraft density, and air traffic patterns can be flown safely utilizing a GPS receiver. The equipment will be flown with the Loran-C program in the Northeast and Northwest, including Alaska. Flights in each area will be required to make certain that specific locations and environment do not significantly degrade the performance of navigation system so that the minimum requirements of FAA AC 90-45A cannot be satisfied.

One oceanic flight will be conducted when satellite coverage is available for the entire flight to assess its performance in the established North Atlantic routes. Approximately 10 flight hours will be flown over the ocean. GPS is a candidate system, as identified in volume 1, table I-4.1 of the FRP for remote area en route/terminal navigation and the oceanic en route navigation. The purpose of the Alaska, Northeast, and North Atlantic oceanic routes is to demonstrate that the GPS is a worldwide system that satisfies these requirements.

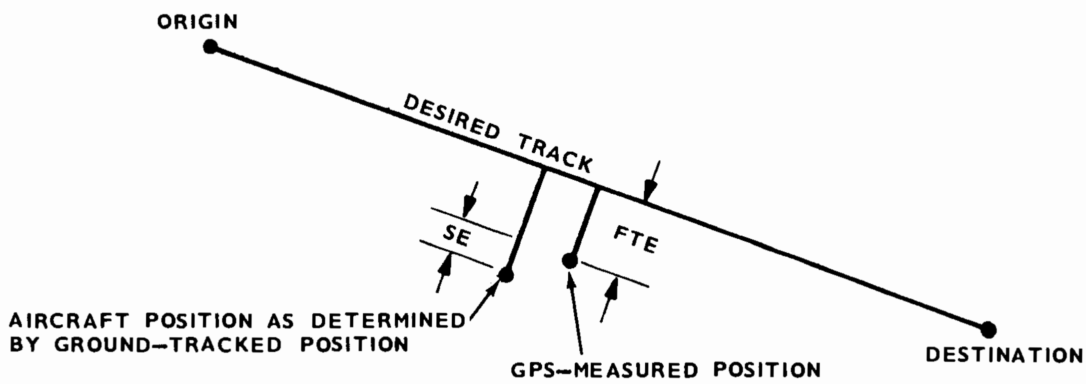
The Z-set information will be used in many flights to provide the navigation guidance to the pilot. Positional data from the Z-set will be utilized to compute crosstrack information reference to the desired track. This crosstrack information will be displayed to the pilot on a CDI. The Z-set control indicator will be installed in the cockpit, if space permits, so that the pilot can utilize it to check range and bearing to destination or to various waypoints along the route. On some flights, GPS will be used as the prime navigation system for the pilot to utilize. Other navigation systems onboard at the same time will be used to maintain safety of flight and to abort the GPS mission if necessary.

During operational test, ILS will be utilized as a positioning system; ILS approaches will be accomplished whenever possible to evaluate the Z-set position information, reliability, integrity, and the affects, if any, of multipath. A minimum of two flights will be made to each airport.

Although the GPS Z-set accuracy may be acceptable and exceed specifications, the main concern from a human factor and navigator's viewpoint is whether the system can provide the proper navigation guidance to the pilot so that he can arrive at his destination safety. Flight technical error is a measure of how well an average pilot can accomplish this. It is the error contribution of the pilot in using the presented information to control aircraft position.

It is important to associate a value of flight technical error with GPS system accuracy since the combination of flight technical error and system accuracy, referred to as system use accuracy, is the parameter on which operational suitability is based.

The following illustration shows how the components of system use accuracy relate to each other.



SE = SYSTEM ERROR = ACTUAL POSITION – GPS MEASURED POSITION

FTE = FLIGHT TECHNICAL ERROR

SYSTEM USE ERROR = SE + FTE

The most basic test pattern which can be flown to measure flight technical error and, thereby, system use accuracy, is a great circle path connecting a specified origin and destination. The pilot is told to simply fly the aircraft in such a way as to minimize crosstrack deviation as indicated by the CDI. A reference flight-path is established through selection of an origin and destination and input of the corresponding latitude and longitude coordinates into the GPS receiver/processor waypoint list. Three different parameters relating to aircraft position will be recorded:

Ground-based aircraft tracking data.
GPS airborne receiver position data.
Aircraft CDI data.

The aircraft CDI will be calibrated to provide a desired resolution of X number of nautical miles per "dot" of deflection of the CDI needle. This calibration can be accomplished by associating, through software and/or the digital analog (D/A) converter, a particular equivalency of course deviation in nautical miles to the analog representation of the "value" of a "dot" of deflection (either 75 μa or 150 μa depending on the CDI being used). The input to the CDI will be recorded on tape.

2.2.3.1 GPS Aero Commander Test.

The GPS system will initially be flown in a Gulfstream to accomplish the accuracy, basic Z-set performance test, and to develop the crosstrack presentation to the pilot. Since a major intent of the FAA GPS test is to evaluate GPS for the single piloted, low performance general aviation aircraft operations, it is desirable that an aircraft like the Aero Commander be utilized for some of the operational tests. Therefore, the Z-set will be installed in an Aero Commander and operational testing will be conducted. Approximately 40 nonprecision approaches and approximately 5 en route/terminal/nonprecision approach flights will be made to New York (JFK), Philadelphia, Wilmington, Washington, and Norfolk. Flight technical error will be measured when the aircraft is being tracked by radar.

2.2.3.2 Multipath Investigations.

During this phase of the operational test, the Z-set will be monitored to determine if multipath affects the set. The system will initially be flown low over the ocean when the satellite angles are relatively low and the conditions are conducive to the occurrence of multipath. Several parameters in addition to position, such as pseudorange and delta pseudoranges, will be monitored and analyzed to determine if multipath exist. Results of a forthcoming lab test will be beneficial in determining the threshold levels of various parameters at which multipath effects occur. The Z-set will also be flown in mountaineous areas to ascertain if multipath exist in those areas and if it seriously degrades the navigation capability of the Z-set so that the aircraft cannot meet the AC 90-45A requirements for nonprecision approach.

2.2.3.3 In Flight GPS Monitor.

On flights away from the center, there is a definite need to monitor the satellites' signals independent of the Z-set at the locations where the Z-set test is being conducted. Since the Z-set will be flown from one location to the next on a continuous basis during the off-Center test, it is advisable to have an in-flight monitor of the satellites signals that is more accurate than the Z-set. Based on previous Government tests at Yuma, the Y-set is more accurate than the Z-set and is air-worthy. The Y-set, when available, will be interfaced with instrumentation computer, installed in the aircraft, and checked out in local flights in preparation for flights away from the center.

3. EQUIPMENT REQUIREMENTS.

a. Test item - GPS Z-set:

1. Control/indicator
2. Receiver/processor
3. Preamplifier

b. Ancillary equipment:

1. GPS antennas (microwave speciality and Ball Brother's microstrips)
2. GPS cockpit indicator
3. Z-Set interface module
4. Altimeter

c. Other navigation systems for comparison:

1. Loran-C
2. Omega

3. VOR (2)
4. DME
5. TACAN
6. ILS
7. Inertial navigation system (INS)
8. GPS Y-set (for flights away from the Center)
9. Aircraft Tracking and Data System (ATADS)

d. Instrumentation equipment:

1. Airborne

(a) HP-1000 computer, model 25
(b) Computer terminal
(c) 9-track tape recorder
(d) Flexible disk drives (2)
(e) Time base generator
(f) Position locating (PL) interface unit
(g) Telemetry unit for range data
(h) RF spectrum analyzer and recorder
(i) Nike/Hercules radar beacon

2. Ground backup support

(a) Nike/Hercules instrumentation radar and/or phototheodolite tracking System.
(b) Ground truth monitor (Y-set)
(c) HP-1000 computer, model 45, with associated equipment (terminal, disk, tape drives, printer, etc.)
(d) Still photograph of equipment installation
(e) Film coverage of several approach flights showing cockpit instruments, test instruments, and pilot's view

3.1 INSTALLATION DATA.

The Z-set will be connected as shown in Z-set user manual (reference section 1.3g). The remaining navigation equipment will be installed in accordance with the manufacturer's instructions. A typical block diagram of the overall airborne instrumentation system for all aircraft other than the Aero Commander is shown in figure 4. The Aero Commander will not have the multiplicity of the navigation system on-board or the airborne HP computer, but will have an instrumentation system to record Z-set parameters, telemetry range information, pitch and roll information, and crosstrack computation capability (as shown in figure 5).

4. DATA REQUIREMENTS.

Parameters to be measured will depend on systems available and the aircraft utilized. In general, as shown in table 3, the following data will be taken when possible from the following systems:

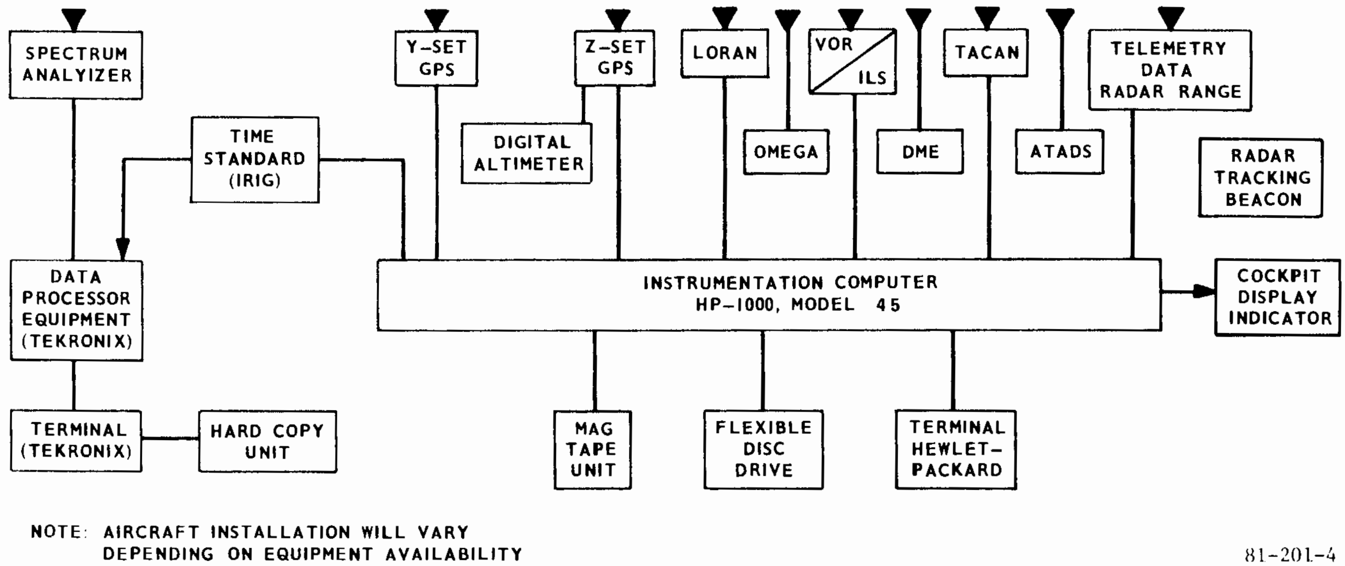


FIGURE 4. TYPICAL BLOCK DIAGRAM OF AIRBORNE SYSTEM

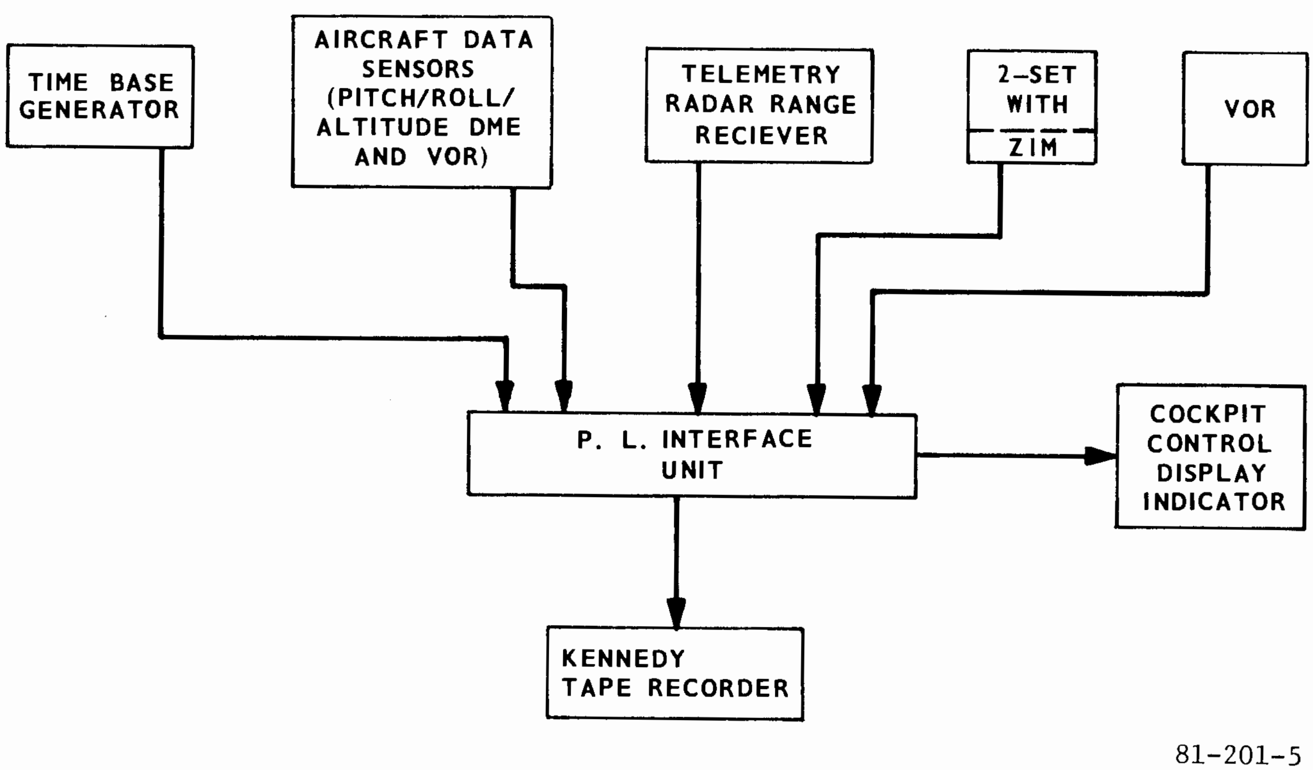


FIGURE 5. AERO COMMANDER AIRBORNE INSTRUMENTATION SYSTEM

TABLE 3. SYSTEM PARAMETERS AND DATA RATES

	GPS Z-Set	Nike/Hercules Radar	VOR	ILS	DME	TACAN	Loran	Omega	INS	GPS Y-Set When Used	ATADS	Altimeter	Data Rates
Latitude	X	X					X	X	X	X	X		1/sec
Longitude	X	X					X	X	X	X	X		1/sec
Altitude	X	X										X	1/sec
Range	X	X			X	X	X	X	X	X			1/sec
Bearing	X		X	X		X	X	X	X	X			1/sec
Crosstrack	X						X	X	X	X			1/sec
Heading								X	X	X			1/sec
Glide Slope				X						X			1/sec
Ground Track	X						X	X		X			1/sec
Desired Ground Track							X	X		X			1/sec
Ground Speed	X						X	X	X	X			1/sec
True Air Speed								X	X	X			1/sec
Wind Speed								X	X	X			1/sec
Wind Direction								X	X	X			1/sec
Time	X	X								X			1/sec
Pitch									X				1/sec
Roll									X				1/sec
Waypoint Station Selected	X		X	X	X	X	X	X	X	X			1/15 min
Waypoint Data Entered	X						X	X	X	X			1/15 min
System Mode Indications	X						X	X	X	X	X		1/sec
Built in Test Indications	X						X	X	X	X	X		1/sec
To/From Indicator			X			X		X					1/sec
AGC Level			X										1/sec
Satellites Selected	X									X			1/min
GDOP	X									X			1/min
Pseudorange	X									X			1/sec
Delta Pseudorange	X									X			1/sec
Position Error Estimate	X									X			1/sec
Almanac Data	X									X			1/15 min
Ephemeris Data	X									X			1/15 min
Satellite Health Status	X									X			1/15 min
Clock Correction Factor	X												1/15 min
Freeze Enter Button Activ.	X						X	X		X			1/event
Signal Noise	X									X			1/sec
Time Difference (TDA)							X	X					1/sec
Time Difference (TDB)							X	X					1/sec
Area Selected							X	X					1/15 min
Triad Selected							X						1/15 min
Blink/Cycle Error							X						1/15 min
Offset Course							X						1/15 min
Calibration Data							X						1/15 min
Velocities X, Y, Z	X								X	X			1/sec

a. Position data (X,Y): GPS, Loran, Omega, INS, ATADS, and Technical Center instrument range.

b. Relative position data: DME, VOR, TACAN, ILS, and systems listed in 4a.

c. Altitude data: altimeter, GPS, and Technical Center instrument range.

d. Attitude data: INS.

e. Wind data: INS.

f. Ambient RF radiation levels: spectrum analyzer, Tektronix 7L13.

The operator will record all pertinent data that will otherwise not appear on the instrumentation tape to include the items listed on the Test Log Sheet, figure 6.

4.1 DATA RATE.

Position and time data for en route, terminal, and nonprecision approach flights will be collected once every second, but accurate to 10 milliseconds of the display. The data rate for all parameters are shown in table 3. All parameters will be recorded before and after each flight. RF environment measurements will be taken in-flight and at various airports throughout the country. As with all other data, RFI measurements will be time tagged with Inter-Range Instrumentation Group (IRIG) time.

4.2 DATA COLLECTING PHILOSOPHY.

The objective is to gather as much meaningful data as possible to make a valid assesment of GPS. Absolute accuracy, reapeatable accuracy, relative accuracy, and system time response are of major concern. Pilot's presentation and human factors considerations will also be evaluated. Pilot's subjective evaluation of system's acceptability will be gathered from monitoring the system's control display unit (CDU) which will be mounted for some flights in the cockpit so that pilots can obtain hands-on operating experience with the Z-set.

ILS will be utilized as a test positioning system and multiple ILS approaches will be made, whenever possible, in different parts of the country because exact coordinates of ILS touchdown points are easily obtained. These approaches will provide data for evaluation of both repeatable and absolute accuracy of the system plus time lag of the system.

Data will be collected and presented so that it can be used to evaluate both present and future system applications. For example, only data from representative satellite configurations (GDOP's less than the value typical for a fully operational GPS system) will be utilized in evaluation. Data from satellites configuration with high GDOP's will be so noted and not used in system evaluation. Data on system performance with only three satellites with different altitude information inputs will also be evaluated.

Flight Test Number____________

Date____________

Aircraft Type____________

Location of Flight____________

Weather Conditions____________

Takeoff Time____________

Type of Mission____________

Local____________

En Route____________

Landing Time____________

Personnel On-Board____________

Pilots:____________

Test Crew:____________

Pertinent Remarks:____________

Pilot Remarks:____________

Satellites Available at Turn On____________

GPS System Turn On____________

Time to First Satellite____________

Time to NAV Light____________

Elapse Time to NAV Light____________

Status of Set (3:3 or 4:4)____________

Time of Almanac Collect____________

Time Almanac Completed____________

Delta Time to Collect Almanac____________

Time When Release From Cal Mode____________

Time of System Turn Off____________

Status of Set at Turn Off____________

(2:2, 3:3, or 4:4)____________

FIGURE 6. TEST LOG SHEET

4.3 DATA ANALYSIS.

In general, the phototheodolite range tracker will be considered the most accurate, followed by the Nike/Hercules radar for the local area, and then the GPS Y-set for flights away from the Center. The orbital and rectangular flights will assess the GPS accuracy, antenna coverage during normal maneuvers, system acquisition time, and time lag using the Technical Center's instrument range as a standard. When outside of the Technical Center's instrumentation range, the GPS derived position will be compared against the ATADS determined position, when available, ILS touchdown points on ILS approaches, and the determined position from ranges to different DME's and bearing to different VOR stations to assess GPS Z-set accuracy. However, the data from all systems, in the final analysis, will be used to evaluate the acceptability of the Z-set. For example, VOR data will be monitored to make certain that navigation with other systems will keep the aircraft on the selected VOR route. The following data will be shown on the Airborne Instrumentation System Terminal for monitoring the navigation system's performance during each flight:

a. Latitude, longitude, and altitude information from GPS, telemetry and INS.

b. Range and bearing to waypoint selected (from GPS data).

c. Crosstrack from desired track (from GPS data).

d. Ground speed from GPS and INS.

e. Pitch, roll, heading, wind speed, wind direction, and northerly and easterly velocities from the INS.

f. Satellite selected and satellites available for selection.

4.4 POST-FLIGHT ANALYSIS.

Data will be analyzed to determine GPS technical compliance to FAA requirements documents and to access GPS operational suitability as presently configured.

4.4.1 Instrumented Range Data.

During post-flight analysis, each system's measured position will be plotted against the instrumented ranges for different GDOP values, different bank angles, different flight profiles, etc. The data will be reduced to determine the system's crosstrack error, along-track error, and altitude. Data will also be reduced to determine northerly and easterly errors regardless of flightpath. The data will be analyzed to determine if aircraft maneuvers, existing RF environment, or aircraft power fluctuations affect the performance of the Z-set. As part of the data analysis procedure, the following data will be plotted and/or tabulated along with altitude information:

a. Orbital Flights.

1. Horizontal distance and altitude for each system recorded: radar range, Z-set, DME, TACAN, Loran, Omega, and ATADS.

2. Delta distance between radar determined range and each system's measured range.

3. Bearing for each system, i.e., VOR, TACAN, and systems listed above that have been installed and interfaced with the instrumentation system.

4. Delta bearing between radar determined bearing and each system's measured bearing.

b. Rectangular/En Route/Approach Flights.

1. Latitude/longitude position and altitude data for each system.

2. Crosstrack error for each system.

3. Delta crosstrack error between radar range and each system.

4. Along-track distance to waypoint for each system.

5. Delta along-track distance between radar and each system.

4.4.2 All Data.

All data will be categorized into the different navigation flight phases (en route, terminal oceanic, and nonprecision approach phases). Data will also be separated into GPS GDOP intervals, Loran, and Omega coverage areas. Data will be analyzed to determine if the systems meet the technical requirements of FAA AC 90-45A and the FRP. Each system's position data (along-track, crosstrack, radial distance, and altitude) will be plotted against the instrumented range, ILS, and Y-set measured position when available. The ILS and Y-set data will be used away from the Center as a baseline when the instrumented range data are not available. The data will also be utilized to evaluate different GPS antennas and preamplifiers. The Z-set will be flown with different antenna over the same patterns with essentially the same satellite configuration; its Z-set performance will be analyzed to determine the effect of different antennas.

Operational data on acquisition time in flight and on the ground will be compiled, tabulated, and included in the final report. The operational en route/terminal/approach data will be analyzed to assess pilot confidence, pilot acceptability, and pilot technical error when flying a GPS crosstrack Indicator. The data will be utilized to assess GPS system integrity, reliability, and operational suitability.

All data will be organized in usable report format to include the following:

a. Individual two-dimensional position plots of each approach.

b. Composite two-dimensional position plots of all approaches.

c. Individual two-dimensional plots of each en route flight.

d. Composite two-dimensional plots of all en route flights.

e. Statistical distribution of plots per system.

f. Statistical comparison plots of all systems for each navigation flight phase.

4.4.3 System Erratic Behavior.

Any system erratic/abnormal behavior will be analyzed with respect to aircraft maneuvers, aircraft antenna pattern, loss of signal strength, multipath, RF environment, equipment malfunction, and overall system malfunction (e.g., erroneous satellites signal information, etc.).

RFI data will be analyzed in detail and threshold values, where interference occurs with the Z-set, will be noted and included in GPS data reports. If multipath interference occurs, it too will be noted and the conditions existing at the occurrence will be fully documented.

4.4.4 Ground Monitor Data.

The data collected by use of the Y-set will be analyzed. The difference between the survey position of the Y-set antenna and the positional data provided by the Y-set will be tabulated and the mean, variance, and root sum square (rss) will be calculated. Periods when the satellites are being uploaded by the Master Control Station will be monitored closely to make certain the output position data is not affected. Any effects will be noted, documented, and contained in the Ground Base Monitor Test report.

5. COORDINATION AND AREAS OF RESPONSIBILITY.

A summary of each organization's responsibility and activities are listed in table 4.

TABLE 4. ORGANIZATIONAL RESPONSIBILITY AND ACTIVITY

Organization	Responsibility/Activity
ACT-63	Installation photographs Film coverage of several flights
ACT-105	Reports processing
ACT-100B	Program Management Engineering/technical guidance Data collection systems Computer programs Test coordination and methods Data collection Data processing and analysis Test reports
ACT-640	Aircraft Project pilots ATC flight coordination
ACT-650	Aircraft engineering
ACT-750	Instrumentation range
ACT-750	Programmer support
ARD-300	Coordination
AEM-300	Coordination
JPO, DOT Point of Contact	Coordination