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Test Plan to Address Technical Issues Associated with GPS Integration into the National Airspace System

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16. Abstract

This test plan describes a project designed to investigate the specific issues which will affect implementation of the Global Positioning System (GPS) within the National Airspace System (NAS). These include development of evaluation criteria, procedures requirements, flight inspection requirements, and identification of any areas of GPS operations or NAS operations which must be changed to integrate the two.

Technical areas to be addressed include masking angles, shielding of the signal, multipath, signal strength, and ionospheric/tropospheric delays. The test will involve both p-code and C/A code receivers.

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EXECUTIVE SUMMARY

This test plan describes a project designed to investigate the specific issues which will affect implementation of the Global Positioning System (GPS) within the National Airspace System (NAS). These include development of evaluation criteria, procedures requirements, flight inspection requirements, and identification of any areas of GPS operations or NAS operations which must be changed to integrate the two.

Technical areas to be addressed include masking angles, shielding of the signal, multipath, signal strength, and ionospheric/tropospheric delays. The test will involve both p-code and C/A code receivers. Flight test and static data will be collected and analyzed to resolve these issues.

Results will be used by various organizations within the Federal Aviation Administration (FAA) with responsibility for certification, flight standards, and air traffic.

INTRODUCTION

OBJECTIVES.

The primary goal of this flight test is to investigate means of implementation of the Global Positioning System (GPS) into the National Airspace System (NAS). In attaining this objective several subgoals must be met.

1. To develop criteria by which GPS may be evaluated.

2. To develop a method for evaluating GPS Instrument Flight Rules (IFR) procedures for approval in the NAS.

3. To determine if the GPS signal requires flight inspection and, if so, identify which parameters must be flight inspected, which must be checked in some other manner, and which do not have to be inspected in order to approve procedures.

4. To identify any changes which must be made in the GPS to incorporate it into the NAS.

5. To identify any additional hardware, procedures, or operational changes in the NAS which must be made to incorporate GPS.

6. To identify areas of responsibility for resolution of issues relative to the certification of GPS and approval for its use in the NAS.

7. To evaluate different receiver technologies to determine the characteristics of each relative to potential certification of these technologies (not necessarily these receivers).

8. To evaluate characteristics of the GPS signal and its use for navigation. In particular, the effects of various ionospheric models, masking angles, and commercially available antennas on receiver navigational performance will be investigated.

Once the proper techniques have been developed, data will be collected using a representative GPS receiver(s). These data will be used to determine the reliability, availability, and accuracy of the GPS signal, and also to evaluate the methods used to gather data. Determination will be made on susceptibility to multipath, signal strength variations, and means of determining masking angle at each test site.

BACKGROUND.

This project is one facet of a complete program to integrate GPS into the NAS. Concurrent efforts by the user segment include development of an operational concept by the GPS user community, and airworthiness and performance standards which will be developed by the Federal Aviation Administration (FAA) in conjunction with user groups, military, and other government agencies. These will be coordinated with the Control Segment where necessary to maintain operational flexibility and viability.

Many other organizations have been and will be involved in GPS development and evaluation. The Aerospace Corporation and the U.S. Army's Yuma Proving Ground have developed a large base of data and expertise which will be utilized, particularly in this project and in developing operational and flight standards criteria.

The FAA has the responsibility to develop flight inspection criteria as well as flight standards and airworthiness standards. It also must approve a Minimum Operational Performance Specification (MOPS), specific IFR flight procedures at airport terminals and en route, and installation of GPS user equipment in aircraft. The agency will also play a primary function in the integration of GPS into the NAS. The FAA is now taking a strong role in developing standards and criteria by working with the U.S. Air Force and various user groups.

Results of this project may be used by the Office of Aviation Standards (AVS) and the regional offices responsible for certification. A complete description of participating and cognizant organizations is provided in the section titled "Areas of Responsibility."

TECHNICAL ISSUES. Primary effects on transmitted signals depend upon frequency of the signal and conditions along the propagation path. L-band signals, such as those utilized by GPS, are susceptible to multipath interference, shielding effects, attentuation, and variable propagation delays. These characteristics will be the subject of the proposed flight test. Secondary effects related to specific user equipment, including antennas and receivers, will be addressed in related testing which will be performed by the FAA Technical Center.

The effects of satellite performance, uploads, and Control Segment actions, including denial of accuracy, will not be investigated except to note their existence and possible effect. Where appropriate, recommendations will be made on ways to produce GPS procedures which conform to current FAA requirements and regulations. In some cases, notably the area of monitor and alarm systems, these will more properly be a topic for a performance standard. However, they are subjects which must be addressed before GPS procedures may be developed and approved.

TEST PROCEDURES.

The GPS signal will be evaluated by collecting airborne data to determine signal coverage and quality. Flights will be conducted in airport traffic areas, terminal areas, and along IFR flight routes. Flight inspection is performed along the published route and beyond the limits of intended coverage to insure that the signal is usable throughout the protected airspace.

Where possible, GPS procedures used in this flight test will be overlaid on existing procedures which are based on conventional navigation and guidance systems. This will facilitate direct comparison of the different systems, minimize the workload associated with implementing a new procedure, and minimize delays during the flight test by maintaining normal air traffic patterns.

Flights will be conducted in the vicinity of the FAA Technical Center, Atlantic City Airport, New Jersey. This will allow use of radar and laser tracking facilities. In some cases, however, the effects of certain site-specific features will be investigated as required to meet test objectives.

Site selection will be made based upon existence of large obstructions such as buildings or mountainous terrain in the area. These may cause signal blockage, multipath, or both. It is expected that flights will, therefore, be conducted over a large city and near a large mountain range, such as the Rockies. Also, flights will be conducted over large areas of flat terrain or large bodies of water where multipath may occur.

The procedures will be flown in an instrumented aircraft which will collect data on signal availability and accuracy. A precision tracking system will be utilized, where possible, to determine accuracy. These data may be used for this project and later projects which will investigate use of GPS as an approach aid.

The separate effects which are of primary interest are identified and discussed below. Included is a short description of each and the means which will be employed to evaluate it. As each group of tests is conducted it will be the subject of an Engineering Division report. These will detail the procedures and results of specific tests. At the conclusion of the test program, a final report will be issued which summarizes individual test results and conclusions, and recommends further steps to be taken as GPS implementation proceeds.

MULTIPATH. Multipath interference may occur when a reflected signal arrives at a receiver in-phase with a nonreflected signal. It can result in inaccurate determination of position. Due to the correlation techniques used to track spread-spectrum signals, multipath can only occur when a reflective obstruction is within 1 1/2 chip lengths of the receiving antenna. This corresponds to a position error of approximately 4 meters for p-code. The effect is magnified for C/A code due to the longer chip length and may result in errors on the order of 15 meters. Conventional antenna siting techniques virtually eliminate the danger of multipath for a fixed-site installation, such as a monitor site. For airborne use, vehicle dynamics greatly reduce the possibility of multipath and insure that any effects, even if they do occur, will exist for only a brief period of time. Again, proper placement of the antenna will minimize the problem.

Multipath is considered to be a minor problem and its effects have not been well documented because of the difficulty in proving its effects. In order to perform a comprehensive investigation, however, it is necessary to accumulate a data base which will be used to form a decision on its potential to affect civil navigation.

In light of the above considerations, an attempt will be made during this flight test to induce multipath interference. The technique employed will be to fly at a family of constant angles relative to a reflective surface, such as a building or large body of water. The angle will be determined geometrically as that which will cause the signal from a particular satellite to be reflected at a constant angle and delayed by 1 to 1 1/2 chip lengths. Flight along this path will result in a biased position measurement if multipath is present. Otherwise, no degradation is expected to occur. C/A code will be used, if a

suitable receiver is available, in order to increase the likelihood of multipath.

SHIELDING. Shielding of the GPS signal will occur wherever obstructions are in the line of sight from the satellite to the user. The result will be complete blockage of the signal and loss of navigational data from the particular satellite being blocked. The blockage may be caused by objects which are very close, such as aircraft structure, or far away, such as terrain or foliage. Vehicle attitude will also cause loss of signal during cases where the aircraft itself causes blockage due to the antenna location.

The method used during this flight test will be to survey each test site for obstructions along the approach path. These will then be combined with mathematical predictions of satellite position, for each site, to determine which satellites are expected to be available for navigation and at what times during the day. Flights will then be conducted during the times and in the areas of expected blockage. This will verify the model of satellite position and the existence of signal blockage. If this method results in acceptable estimates of signal availability, it will be proposed as a method of determining satellite coverage, subject to on-site verification.

MASKING ANGLE. The masking angle is the minimum angle of satellite elevation at which that satellite's signal is usable for navigation. The main issue which must be resolved is to determine a minimum masking angle based upon system performance. This angle may be different for different users and will be determined jointly by the various segments of the GPS community.

Because satellites and antennas are not specified for operation below 5°, this is assumed to be a lower limit. However, conventional flight inspection methods require documentation of signal quality beyond the limits of coverage. It is, therefore, desired that this project provide data on signal quality above and below 5° elevation. Data will be collected at the lowest elevation angle possible with available equipment to help determine whether some other masking angle is appropriate and to document the effects outside the coverage area.

SIGNAL STRENGTH. Signal levels have been determined to be nearly uniform over large areas of GPS coverage. This characteristic will be verified by collecting in-flight data and correlating it with data collected on the ground, in the local vicinity, by a fixed monitor receiver. This will document the signal strength in an area and help determine whether ground-based monitors provide a suitable means of assessing signal quality.

PROPAGATION DELAYS. Another effect is caused by the implementation of the tropospheric and ionospheric models incorporated into the receiver processing software. Variance in actual delays which are based upon changing conditions are difficult to estimate in the receiver. These limitations become a dominant effect between 0° and 5° above the horizon when only one frequency is available. Receivers differ in their implementation due to the lack of a clearly optimal scheme for handling the problem. Use of navigational data from satellites below 5° elevation may be restricted unless some clear operational advantage can be gained. A related MOPS issue may be whether to inhibit use of low-elevation satellites or to prohibit the reselection of satellites for tracking during an approach. Data will be gathered during this flight test which may be used to support decisions of this nature. As a minimum, the

performance of one particular receiver will be documented when satellites near the horizon are in use.

AIRPORT PROCEDURES. Before flying at each subject airport a site survey will be conducted to determine where potential signal blockages may occur. The first step will be to obtain an Obstruction Clearance Chart for the particular airport. It will be verified visually at the site, and any discrepencies will be noted. Parameters of height and position of obstructions will be entered into a computer prediction program which will show areas of expected blockage of signals from particular satellites. Flights will be conducted at those times and in those areas where blockage is expected to occur. Effects of obstructions of various sizes will be investigated. These may include large buildings which may produce intermittant coverge, or mountains which may completely block the signal. The aircraft will be flown off of published routes if necessary to document these effects. Flight test data will be correlated by position with the predicted blockage pattern to determine the conditions under which blockage occurs. This will help refine the model and verify the areas of blockage and signal availability.

Signal-to-noise ratios (SNR) of the GPS signal are subject to small variations due mainly to attenuation resulting from passage through the earth's atmosphere. At lower satellite elevations the path length through air is proportionately greater and SNR goes down. The satellites' antenna patterns are designed to compensate to some degree, but SNR variations due to lower signal levels will occur. They will be documented during this flight test and presented as plot data of SNR versus elevation angle.

TEST EQUIPMENT. Several types of receivers will be made available for this flight test. They include one p-code and two C/A code receivers. The p-code set is a Phase II receiver manufactured by Collins Radio under the U.S. Air Force GPS User Equipment development contract. The C/A code receivers are a Magnavox Z-set built during Phase I, and a commercially available Litton LTN-700.

A number of Phase II receivers have been delivered to the Joint Program Office (JPO). They will be allocated to users based upon need and justification. The units are five-channel p-code receivers built for the high dynamic military environment. They provide simultaneous tracking of four satellites for navigational use, leaving one channel for acquisition of satellites rising over the horizon. The receiver selects the satellites which will give the best navigational performance based upon geometry and signal availability. An instrumentation port is provided for control inputs and data outputs. The default mode outputs a predetermined block of data at a predetermined rate. This mode has been judged to be sufficient for the purposes of this test.

An interface control document for this type receiver is listed as number 1 under "Related Documentation." The interface provided utilizes standardized blocks of data for output. Initial inspection of the types of parameters available has indicated that no modification of the units or their interfaces will be necessary. A list of parameters available from the Time Mark Data Block and the Midcourse Receiver Ephemerides Data Block are provided in table 1.

The Litton LTN-700 is a fast sequencing receiver which utilizes a single channel front end to track up to four satellites simultaneously. This approach was used to keep hardware costs low without sacrificing performance. This type

TABLE 1. DATA FORMAT BLOCK DATA SUMMARY, PHASE II RECEIVER

Time Mark Data Block

Data Item	No. of Parameters	No. of Words	Units
GPS Time	1	4	Seconds
CUT Time	1	4	Seconds
T from GPS Time	1	1	10 Milliseconds
Time Mark Counter	1	1	N/A
Position (Lat, Long)	2	4	Radians
Posiiton (x,y,z)	3	6	Meters
Altitude (m.s.l. and Absolute)	2	4	Meters
Velocity (E, N, Up)	3	6	Meters/seconds
Acceleration (E, N, Up)	3	6	Meters/sec/sec
Attitude (Pitch, Roll)	2	4	Radians
True Heading	1	2	Radians
Magentic Variation	1	2	Radians
Measurement Channel Status	5	10	N/A
Standardized Figure of Merit	1	1	N/A
Expected Horizontal Error	1	1	Meters
Expected Vertical Error	1	1	Meters
Equipment Configuration	1	2	N/A

Midcourse Receiver Ephemerides Data Block

Data Item	No. of Parameters	No. of Words	Units
GPS Time	1	4	Seconds
Satellite Number	1	1	N/A
Satellite Health Word	1	1	N/A
C/N_O	1	1	Decibel
Ephemeris Data (Subframes 1,2,3 without parity)	3 x 15	45	N/A
Ionospheric Correction	1	2	Meters

of design also trades off signal strength for dynamic performance because of its hardware multiplexing technique. Approximately 6 decibels (dB) of signal strength available at the antenna is lost by the use of this architecture. The receiver provides serial data outputs through an RS-232 port and an ARINC-429 port. It may also be controlled through the RS-232 interface. The data available are listed in table 2.

The Magnavox Z-set is a Phase I prototype which uses a single channel and sequential scanning. In this design the receiver tracks each satellite continuously for approximately 1 second at a time. It sequentially tracks up to four satellites which are included in the navigation solution. This design also minimizes hardware at the expense of software. No signal strength is lost, but the receiver will not perform as well in a dynamic environment as one that tracks multiple satellites at once. The Z-set interfaces to the PDP-11 UNIBUS[R] and provides the data listed in table 3.

AREAS OF RESPONSIBILITY

APM-420: Provide funding and program management to ACT-140.

JPO: Provide user equipment hardware and integration support.

USCG: Provide interface to the Control Segment through Space Command.

YPG/GD: Provide technical assistance and supply available data as requested.

ACT-140: Provide aircraft and personnel to conduct flight test, write test plan, perform data analysis, design and build receiver interface and data collection system, and write final reports.

ANALYSIS OF RESULTS

Data will be statistically reduced and presented as mean and standard deviations for parameters of interest. These will include SNR and accuracy in east-north-up (ENU) coordinates where available. Plot data will be provided which show areas of signal blockage due to obstructions and areas of multipath, if they can be identified.

Results obtained using the different receivers will be compared. Characteristics of the receivers which affect these results will also be identified and discussed.

Analysis of the results will be conducted to determine what masking angle is appropriate, based on performance. The performance of different antennas and receiver technologies will also be verified and/or discussed relative to expected theoretical results.

The flight inspection issues will be addressed once the data reduction is complete. In general, flight inspection is performed only where necessary to verify a signal and its performance. It is possible that the GPS signal will not require flight inspection. Signal availability and accuracy will be analyzed to determine whether airborne or ground data collection is required.

Multipath data will be reduced by comparing results with and without multipath interference. The existence of multipath will be verified using correlation techniques or by direct comparison of performance in and out of multipath. Results will be presented which show the areas and times where multipath can occur, relative to an obstruction, and quantify the affects on navigational performance.

RELATED DOCUMENTATION

1. Buchanan, H. and Lehrke, K., Interface Control Document NAVSTAR GPS Instrumentation and Connector Standards, ARINC Research Corporation, ICD-GPS-204A, March 1982.

2. Robbins, J. E., Effects of Multipath on GPS Receivers, General Dynamics/Electronics, Yuma Proving Grounds, June 1979.

3. Litton Aero Products, LTN-700 Interface Control Document, December 1985.

4. Magnavox Government and Industrial Electronics Company, User's Manual (Computer Program) For User Equipment Z-Set of the NAVSTAR Global Positioning System, DCRL item AOOX.

TABLE 2. DATA FORMAT BLOCK DATA SUMMARY, LTN-700

Data Block	Period (sec)	Description
A	30	Almanac data (32 pages)
C	10	Covariances
E	30	Ephemeris data (6 pages)
K	1	Kalman Filter States
L	1	Local level navigation data
M	1	Measurements from RPC
N	30	NAV, RPC, and satellite status
Q	1	CDU Display
S	120	Satellite selection data
T	10	Accumulated delta-range
U	120	UTC and Ionosphere data
Z	10	Kalman filter residuals and

TABLE 3. MAJOR Z-SET RELATED PARAMETERS RECORDED

PZ	Z-set derived position utilizing earth-centered earth-fixed (ECEF) coordinates converted to latitude, longitude, and altitude in WGS-72 coordinate systems.
SN	Number of each satellite in the constellation selected by the Z-set providing data.
NSD	Number of satellites presently providing data.
NSE	Number of satellites for which ephemeris data has been collected.
DX DY, DZ	Difference between Z-set derived position and the radar determined position of the aircraft beacon antenna in three orthogonal directions. DX is the northerly difference, DY is the easterly difference, and DZ is the altitude difference.
2D	Horizontal difference between the Z-set derived position and the radar determined position of the aircraft beacon antenna.
3D	Spacial difference between the Z-set derived position and the radar determined position of the aircraft beacon antenna.
GS	Z-set derived ground speed.
GTK	Z-set derived ground track.
Z (Dwell)	Z-set dwell counters for each satellite (increased for good data quality, decreased for poor data quality).
Z (Count)	Z-set up-down (increased with poor data quality, decreased with good data quality).
HDOP	Horizontal dilution of precision value for satellite configuration selected.
GDOP	Geometric dilution of precision value for satellite configuration selected.
EPE	Estimated position error of the Z-set.
GPS (Time)	GPS time in tenths of seconds from the Z-set.