Flight Evaluation of a Basic C/A Code Differential GPS for Category I Precision Approach

Mr. Warren Hundley, Dr. Stephen Rowson & Mr. Glenn Courtney
Wilcox Electric, Inc.

BIOGRAPHIES

Warren Hundley received his BS degree from Columbia University and MS degree from Polytechnic Institute of New York He has over 40 years experience in the analysis and development of airborne and ground based navigation and guidance systems. For the past 14 years he has been at Wilcox Electric where his assignments have included Manager of Advanced Development and Manager of Technology.

Stephen Rowson received his BS, MS and Ph.D in electrical engineering from the University of Kansas. For the past 12 years he has been at Wilcox Electric where he has had major hardware, software and system design responsibility including Manager of System Engineering. His assignments have included 2nd Generation VORTAC, MLS, Solid State Radar Beacon Decoder. Airport Remote Monitor System, Wide Aperture ILS Distribution Unit and more recently DGPS Category I Landing System.

Glenn Courtney received his electrical engineering education at the University of Missouri. During his 11 years at Wilcox where he is an Engineering Specialist he has been responsible for numerous hardware projects primarily involving digital circuit design. Among his assignments have ,been remote control and status display equipment for airport towers: prototype hardware and software for MLS beam steering; CPUs. modems, A/D converters, communication interfaces for MLS, 2nd Generation VORTAC and airport remote maintenance systems, Most recently he has worked on the DGPS Category I Landing System.

ABSTRACT

Flight tests are being conducted by Wilcox Electric to evaluate the capability of local area C/A Code DGPS to provide accuracy suitable for precision approach operations under Category I conditions - 200 ft. decision height (DH), 2600 ft. runway visual range (RVR).

The Wilcox King Air 300 aircraft which is instrumented for flight inspection of ILS and MLS Landing Systems is equipped with DGPS receiving equipment and additional computing capability which derives GPS based instrument approach paths. converts DGPS latitude/longitude/altitude position information to lateral/vertical deviations from the approach path and drives the appropriate aircraft flight instruments. A mobile ground station using identical DGPS receiving equipment and a VHF data transmitter is employed to send differential corrections to the aircraft system. Other than the differential corrections no other augmentation of the airborne data is employed.

Approximately 50 ILS-like approaches have been flown under various I-IDOP and VDOP conditions using the DGPS derived path deviations as guidance to the aircraft. Data is taken simultaneously on aircraft position relative to the desired approach path as determined by a conventional ground based radio telemetering theodolite (RTT), by the DGPS system and by the ILS system installed at the site.

In addition to collecting information on the guidance accuracy of the basic DGPS system during landing approaches as well as comparative performance data with respect to ICAO standard ILS the tests are designed to provide information on a number of other factors which are important to the landing requirement. These include the following:

- The data is characterized in terms of path following noise (PFN). path following error (PFE) and control motion noise (CMN). This is required in order to define the ability of any system to provide guidance inputs suitable for precision approach.
- Data is collected at position update rates of 4 to 5 Hz which is more suitable for precision approach than the conventional 1 Hz update rate common to most GPS receivers today.
- The data represents what can be achieved by a

minimally equipped aircraft using DGPS alone. The aircraft is flown manually without benefit of augmentation from radar altimeter. inertial reference system or flight management system. This would be typical of most of the general aviation fleet. air taxi and commuter operations as well as older air transport aircraft and helicopters.

- The impact on performance of improved receiver signal processing which reduces receiver noise errors and multipath effects over that achieved by most current GPS receivers is evaluated. These are the principal residual errors after local area differential corrections are applied and any improvement will reflect directly into improved accuracy on approach.

INTRODUCTION

There is a broad based effort taking place across the civil aviation community to capitalize on the benefits that can be obtained from the implementation of a Global Navigation Satellite System (GNSS). This effort has been sparked by the deliberations of the ICAO FANS committee, the declaration by the United States and Russian governments of the guaranteed free use of GPS and GLONASS for 10 and 15 years respectively following operational availability, the establishment of a special FAA Satellite Operational Implementation Team and the recent impetus provided by the RTCA GNSS Task Force. One of the key early implementation goals defined by the Task Force is to achieve an initial operational capability for a Special Category I GNSS precision approach by 1994. This paper describes one of many efforts which industry and the rest of the aviation community are conducting in order to reach that goal.

REQUIREMENTS FOR PRECISION APPROACH AND LANDING SYSTEMS

Precision approach and landing systems, as opposed to non-precision approach systems, provide positive vertical guidance information in addition to lateral guidance information. Because of this they are able to provide guidance to much lower minimums including all the way to touchdown. Typically the guidance for non-precision approaches is provided by various standard navigation aids such as VOR. DME or NDB. For precision approach the Instrument Landing System (ILS) has served the worldwide aviation community admirably for over forty years. The Microwave Landing System (MLS) is the designated successor to ILS although not implemented as yet-

The requirements for both these systems--lLS and ,MLS--have evolved over the years and are documented by ICAO (International Civil Aviation Organization) in Annex 10. International **Standards** and Recommended practices (SARPS).' Many of the requirements are categorized in terms of operational capability, i.e. runway visual range (RVR) and decision height (DH) at which the runway approach end must be visually acquired or a missed approach procedure be executed. This has resulted in the familiar Category I. II and III classifications. (Refer to Table 1). The specific requirement becomes increasingly stringent as the operational capability increases. An exception to this occurs in the case of accuracy for MLS in that all MLS systems are required to provide a signal in space with precision suitable for Category III operations.

TABLE 1
OPERATIONAL CATEGORIES
FOR PRECISION APPROACH

CATEGORY	DH	RVR
I	200 ft	2600 ft*
II	loo ft	1200 ft
IIIA	**	700 ft
IIIB	**	150 ft
IIIC	**	0 ft

*Can be 1800 ft for appropriately equipped runway.
**NO decision height although some authorities require 50 ft for Category IIIA.

Although many facets of the ILS and MLS systems are specified in the SARPS the key requirements are contained in the triad of:

Accuracy
Integrity
Continuity of Service

Most but not all of the work done to date on the suitability of DGPS for precision approach and landing has concentrated on the first of these, i.e.-accuracy. This is also true of this paper and is not an illogical approach since if a particular system concept cannot deliver the required accuracy then integrity and continuity of service become moot However. the converse is not true. That is, even if a system satisfies all the accuracy requirements but fails to provide satisfactory integrity and continuity of service it will not be suitable for precision approach. In this case it is important to note that the integrity and continuity of service requirements for Category III operation are typically 1 to 2 orders of magnitude more stringent than for Category I.

New ways of looking at the accuracy requirement which may eventually blur the distinctions between the traditional operational categories are presently being developed. most notably RNP. the Required Navigation Performance. RNP is a measure of the navigation system performance in a defined airspace. In the case of accuracy the RNP is defined by the Total System Accuracy (also known as System Use Accuracy) which is the root sum square of the navigation source error, airborne receiving error and flight technical error. The combination of navigation source error and airborne receiving error leads to the position fixing error of the navigation system. For precision approach the total system accuracy can be defined by a “tunnel in space” within which an aircraft must fly on its descent to the runway and whose rectangular cross section shrinks in a linear manner as the aircraft approaches touchdown. For a navigation system with a given position fixing capability, application of the tunnel in space concept has the potential of rewarding the well equipped aircraft (e.g. one with a high quality flight control system) with operation to lower minimums than a lesser equipped aircraft.

However, the position fixing accuracy requirement for a precision approach system cannot be adequately specified by a single number. The modem approach for specifying landing system precision is to specify accuracy in terms of three parameters: 1) path following error (PFE). 2) path following noise (PFN) and 3) control motion noise (CMN). ICAO Annex 10, in specifying accuracy for MLS, defines PFE as that portion (spectral component) of the guidance system error which will result in an actual aircraft displacement from the desired flight path. It includes both a bias term and a noise term (PFN). CMN is defined as that portion of the guidance system error which during coupled flight results in control surface, wheel and column motion and possibly attitude angle change, but does not cause aircraft displacement from the desired flight path. Annex 10 also defines the guidance error aircraft response spectral regions for PFE and CMN.

In the case of the ILS which is an older system, the error is specified in terms of course structure or bends in the flight path which can be considered equivalent to PFN and bias errors which taken together with the structure error can be considered to be the path following error, PFE.

CMN is not specified for ILS. however, Attachment C to Annex 10 stresses the desirability of roll and pitch attitude changes of less than 2 degrees in the final phases of the approach.

The question that arises then is to what accuracy performance standard shall we hold the Category I capable DGPS system and how shall it be specified? Based on its outstanding safety record and long history of satisfactory performance it is both logical and prudent to use the current ILS standards as the initial measuring stick. Employing ILS specifications for DGPS on an exact one for one basis does have some disadvantages. These arise from the fact that not only do many of the principal error mechanisms differ but also that ILS is basically an angular system and is specified as such while GPS is a linear system. The angular specifications for ILS do not reflect the naturally superior accuracy of GPS further out on the approach path which could be turned to advantage for obstacle clearance and general airspace planning purposes. On the other hand the fact that the linear accuracy of ILS improves as the runway is approached is advantageous for a landing system and is reflected in the ILS standards. In any event meeting the current ILS standards down to the 200 foot decision height provides a proven benchmark. A system that meets these standards has the advantage of allowing minimally equipped but IFR capable pilot/aircraft to execute precision approaches to present Category 1 minimums while not restricting more sophisticated aircraft from achieving lower minimums under the tunnel in space concept when that concept is implemented.

The ILS standards are found in ICAO Annex 10. Since CMN is not specified for ILS we have used the value specified for MLS which is a Category III requirement. Tables 2 and 3 show the required accuracies for a Category I capability assuming a 3 degree glideslope approach to a 10.000 foot runway with a 50 foot threshold crossing height (TCH).

SYSTEM APPROACH

The initial system development effort established a set of characteristics which were to be incorporated if at all possible in the Wilcox DGPS Precision Approach System. Among the most important are:

1) Achieve an accuracy at least equivalent to present day ILS Category I performance.

2) The DGPS shall provide both the required lateral and vertical guidance. It shall accomplish this without requiring special equipment on the aircraft such as inertial reference units, radar altimeters, terrain contour maps, heads up displays, flight management systems, etc.

3) System shall be suitable for less sophisticated aircraft as well as new jet transports. Less sophisticated aircraft would include those typically used by commuters and regional airlines as well as a wide variety of older transports. rotary wing and general aviation aircraft.

4) Vertical performance should be achieved with VDOP of at least 4,

5) An independent ground monitor will provide the required integrity.

6) Ground equipment will provide an independent check of the integrity of the airborne flight path data base.

7) Airborne equipment will provide self test integrity

TABLE 2

ICAO ANNEX 10 CATEGORY I LATERAL ERROR REQUIREMENTS - IO.000 FT RUNWAY

Height Above Threshold Ft.	Distance From Threshold Naut. Mi.	Alignment/Bias Para. 3.1.3.6.1a Para. 2.2.3.1. Attach C		Path Following Noise - PFN Para 3.1.3.4.1		Path Following Error - PFE $(Bias^2 + PFN^2)^{1/2}$		Control Motion' Noise - CMN Para 3.11.4.9.4C	
		FT.	DEG.	FT.	DEG.	FT.	DEG.	FT.	DEG.
100	0.16	43.4	0.227°	37.3	0.195°	57.2	0.299°	11.7	0.061°
200	0.47	51.0	0.227°	43.8	0.195°	67.2	0.299°	13.7	0.061°
400	1.10	66.1	0.227°	67.5	0.232°	94.5	0.324°	18.0	0.062°
700	2.04	88.8	0.227°	112.6	0.288°	143.4	0.367°	25.0	0.064°
1000	2.98	111.5	0.227°	169.4	0.345°	202.8	0.413°	32.0	0.065°

* CMN is a Category III MLS requirement

TABLE 3

ICAO ANNEX 10 CATEGORY I VERTICAL ERROR REQUIREMENTS - 3" GP, 50 FT TCH

Height Above Threshold Ft.	Distance From Threshold Naut. Mi.	Alignment/Bias Para. 3.1.5.1.2.2A Para 2.2.12.1 Attach C		Path Following Noise - PFN Para. 3.1.5.4.1		Path Following Error - PFE $(Bias^2 + PFN^2)^{1/2}$		Control Motion' Noise - CMN Para 3.11.4.9.4C	
		FT.	DEG.	FT.	DEG.	FT.	DEG.	FT.	DEG.
100	0.16	5.6	0.168°	4.8	0.144°	7.37	0.221°	2.0	0.061°
200	0.47	11.2	0.168°	9.6	0.144°	14.8	0.221°	4.1	0.061°
400	1.10	22.4	0.168°	19.2	0.144°	29.5	0.221°	8.3	0.062°
700	2.04	39.1	0.168°	33.6	0.144°	51.6	0.221°	14.9	0.064°
1000	2.98	55.9	0.168°	48.0	0.144°	73.7	0.221°	21.6	0.065°

* CMN is 3 Category III MLS requirement

checks.

8) Data link, subject to future standardization by the aviation community, shall be VHF data link radio with suitable *message* integrity checking.

PROGRAM OBJECTIVES

'The objective of Phase I of the Wilcox program was to determine what precision approach performance in terms of lateral and vertical deviations from a typical straight-in 3 degree glide path approach to ILS minimums could be achieved when all parameters available to the system designer are optimized. To this end it was decided to employ the latest state of the art receivers. In a field in which the technology is still evolving rapidly this is important if one is to obtain a current benchmark. Some of the earlier test programs [2,3] employed receivers which by today's standards are relatively crude.

The flight evaluation utilized the following receivers: 1) Ashtech Ranger and 2) Novatel Model 911. Both these receivers have features which are desirable for the precision approach application. In addition to being parallel multi-channel (10 or 12 channel) both receivers have higher position update rates than the conventional 1 Hz. The Ashtech has a 4 Hz update rate and the Novatel had 5 Hz. At an update rate of 1 Hz an aircraft on approach will typically travel about 200 feet and sink 10 feet between position fixes. Update rates of at least 5 Hz are necessary for good dynamic performance and smooth auto coupling. In addition the Ashtech receiver achieves noise reduction through carrier smoothing of the code" while the Novatel receiver minimizes the effect of receiver noise through a novel narrow cot-relator width tracker[5] which also promises to reduce multipath effects. Another technique for reducing multipath which was evaluated was the use of a choke ring on the ground antenna. Since receiver noise and multipath are the two error contributors which cannot be corrected by differential techniques reducing them to a minimum will result in a direct improvement in performance.

Another objective was to obtain data on what performance improvement if any might be obtained with a high speed data link operating at 9600 bps providing differential corrections at an update rate of 1 Hz versus a lower speed link at 1200 bps providing updates at l/3 Hz. The question troubling us in this case is the rate at which SA may be disturbing the signal and our uncertainty concerning this parameter.

In summary the overall thrust of the program is that within the boundaries of a code tracking local area DGPS. what are the parameters that can be optimized in order to achieve a solid performance equivalent to ILS Category I. All observed errors are to be expressed in terms of PFN, PFE and CMN to facilitate that determination.

FLIGHT EVALUATION EQUIPMENT

The flight evaluation equipment consisted of *several* configurations of the local area differential GPS (LADGPS) landing guidance system which was evaluated, plus a tracking system used as a reference against which the guidance *system was compared. The* guidance *system* consisted of a DGPS ground reference station that computed and transmitted differential pseudorange corrections over a VHF data link, plus DGPS receiving, processing and display equipment installed in a Beechcraft King Air 300. The tracking system comprised a radio telemetering theodolite (RTT) on the ground, as well as equipment in the King Air that received and processed the theodolite data

The ground reference station, depicted schematically in Figure 1, used an Ashtech Ranger, 12 channel, standard correlator spacing GPS receiver with carrier aided tracking for the first phase of testing. and a Novatel Model 911.10 channel, narrow correlator spacing GPS receiver card installed in a laptop PC for the second phase. Differential corrections were input serially to a VHF transmitter/modem (136.2 MHz that transmitted them to the aircraft at 1200 bps once every three seconds. This data link provided corrections at the aircraft receiver with ages tanging from 3.5 to 6.5 seconds. It was later replaced with a 9600 bps data link transmitting once per second and reducing correction ages to 0.5 to 1.5 seconds. The L-band antenna was mounted on a seven-foot pole located directly over a survey marker situated about 600 feet to the side of the stop end of the runway. During phase two. a choke ring was mounted under the L-band antenna to reduce the effects of multipath.

The ground component of the tracking system consisted of an RTT, also shown in Figure 1. An operator kept the theodolite crosshairs pointed at the nose of the aircraft at all times during approaches, and the angular deviation of the aircraft from runway centerline or three degree glideslope was transmitted to the airborne tracking equipment over a UHF data link. For horizontal angle measurements. the RTT was located on the extended runway centerline. 850 feet beyond the stop end. For vertical angle measurements, the RTT was located adjacent to the runway, 195 feet from centerline and 1330 feet from the threshold RTT accuracy was ± 0.02 degree plus an operator pointing error of about 1 foot.

The airborne guidance and tracking systems are shown in Figure 2. The airborne L-band antenna (Sensor Systems) was mounted in the top of the fuselage. about midway between the nose and tail. The airborne GPS receiver was initially an Ashtech Ranger and subsequently a Novae1 .Model 911 GPS receiver card. Differential **corrections** were input directly to the GPS receiver from a VHF receiver/modem.

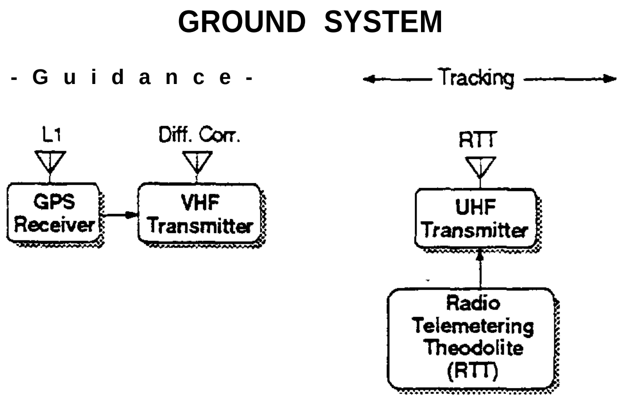

Figure 1

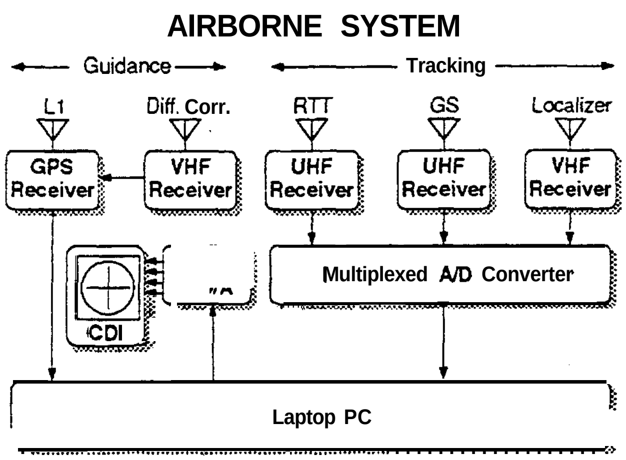

Figure 2

The airborne GPS receiver computed three-dimensional position at a 4 Hz (Ashtech) or 5 Hz (Novatel) ratel The laptop PC converted position data in real time to angular deviation from the desired approach path, using a file of runway coordinates and elevations. Horizontal and vertical deviations from the desired flight path were output in real time as analog voltages from the D/A converter which drove the course deviation indicator (CDI) located in the cockpit.

The airborne equipment recorded GPS position. ILS localizer angle. ILS glideslope angle. and RTT angles on the PC's hard disk for postprocessing and plotting. **RTT** glideslope and localizer data ***were*** received on three separate receivers (two UHF and one VHF), and provided as analog voltages to a multiplexed A/D converter mounted in the PC. RTT, glideslope and localizer angle were sampled and recorded on disk at 4 or 5 Hz. synchronized with GPS position measurements.

Postprocessing software computed and plotted instantaneous angular deviation from approach path, path following error (PFE) and control motion noise (CMN). DGPS errors could be plotted using either the theodolite or ILS signals as reference. Errors were plotted in both degrees and feet.

Since the RTT angular measurements were not supplemented by independent distance measurements, one may question the accuracy of the conversion of angular errors (degrees) to cross-track errors (feet). Although this conversion was accomplished using distance from the RTT as measured by DGPS, the along track DGPS distance errors are bounded and contributed little to the calculated cross-track errors since the distance to the RTT was always large compared to the cross-track distance from the desired glide path. The worst case occurred **when the** aircraft was closest to the RTT. For example, if the aircraft was 1908 feet from the RTT (the closest for which Cat I vertical accuracy limits exist) and 0.3 degree above the glide path. then it was 9.99 feet above glide path. If the DGPS measurement of distance to the RTT were 1928 feet (a 20 foot error. larger than any seen in our tests) then the displacement from glide path would have be-en calculated to be 10.09 feet, an additional error of 0.11 feet. Clearly, angular measurements are sufficient for establishing the accuracy of a DGPS Category I landing system; independent distance measurements are not required.

DESCRIPTION OF TESTS

Flight tests were conducted at Richards-Gebaur Airport, a former Air Force base located on the southern edge of Kansas City. This facility was chosen because it has an operational ILS and light traffic. All approaches were flown to runway 36. which provides the ILS approach. Figure 3 shows a simplified map of the airport.

The purpose of the tests was to collect DGPS position in three dimensions, plus true aircraft position based **on** RTT measurement. in order to determine DGPS accuracy during landing approaches under a variety of DOP conditions. ILS localizer and glideslope deviation angles were collected simultaneously so they could be used either with the RTT reference for comparison purposes. or as a secondary reference in place of the RTT.

AIRPORT MAP

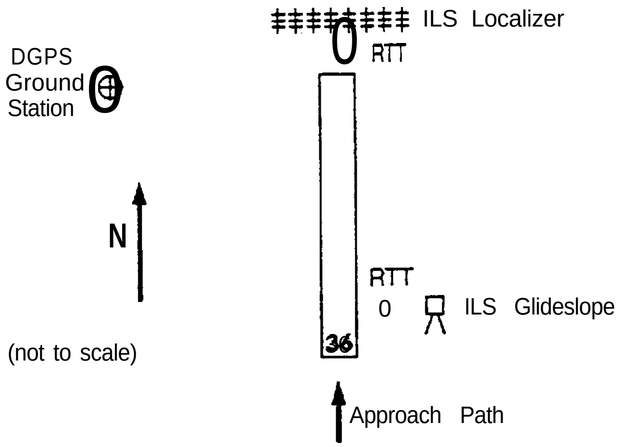

Figure 3

The pilot flew the approaches manually using the DGPS-driven CD1 as the primary guidance instrument, although ILS indications as well as visual cues were also present at all times.

Twenty-one approaches were flown for which lateral error data was collected: 8 with the standard correlator receivers and 13 with the narrow correlator receivers. All these approaches were flown with the 1200 bps data link. Data was recorded beginning approximately 6 nautical miles from threshold (at the outer marker) and ending atthe stop end of the runway. It was discovered after the fact that SA was turned off during these narrow correlator receiver tests. but this is not believed to have materially affected the results.

Twenty-six approaches were flown for which vertical error data was collected: 7 with the standard correlator receivers and 1200 bps data link, 7 with the narrow correlator receivers and 1200 bps data link, and 12 with the narrow correlator receivers and 9600 bps data link. SA was turned off during the 9600 bps data link tests, but was in effect during the other narrow and standard correlator receiver tests.

TEST RESULTS

Data from each approach was plotted graphically. All plots shown in this paper were obtained with the narrow correlator receivers, and the 9600 bps data link inthe case of vertical plots. Figures 4. 5 and 6 show typical lateral results plotted in degrees. The effects of the PFE and CMN filters are evident. The inner and outer limits drawn on the PFE plot correspond to PFN and PFE requirements respectively. The limits drawn on the CMN plot are the ones specified for MLS, which provides a Category III signal in space.

LATERAL UNFILTERED ERROR (degrees)

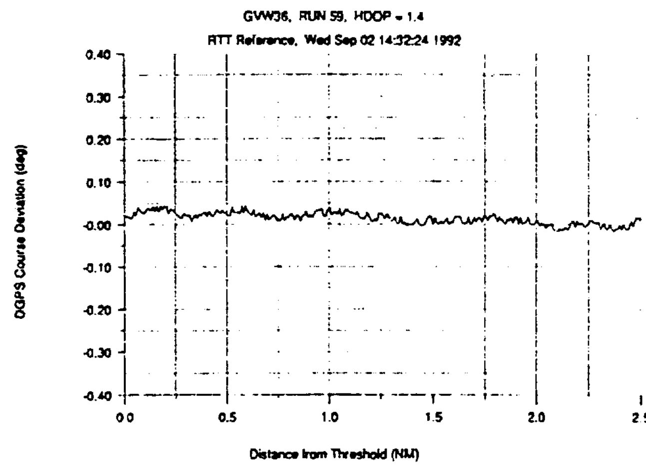

Figure 4

LATERAL PATH FOLLOWING ERROR (degrees)

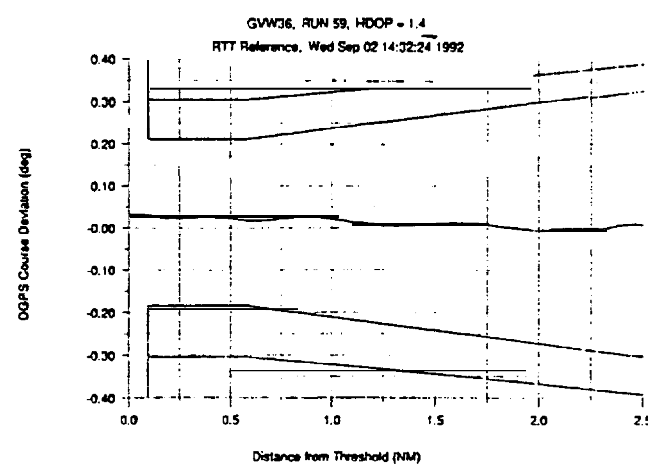

Figure 5

LATERAL CONTROL MOTION NOISE (degrees)

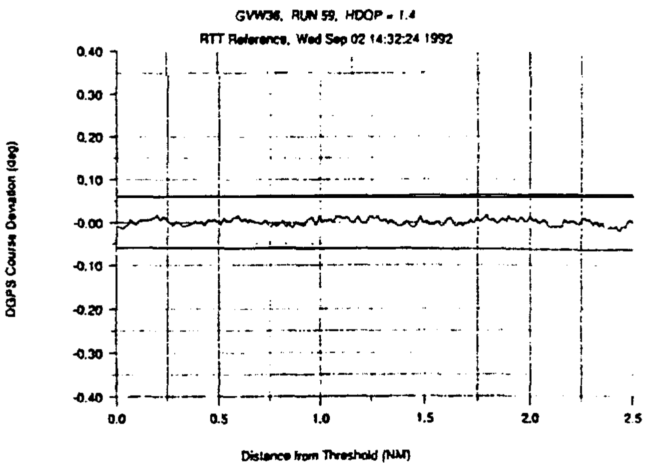

Figure 6

VERTICAL UNFILTERED ERROR (degrees)

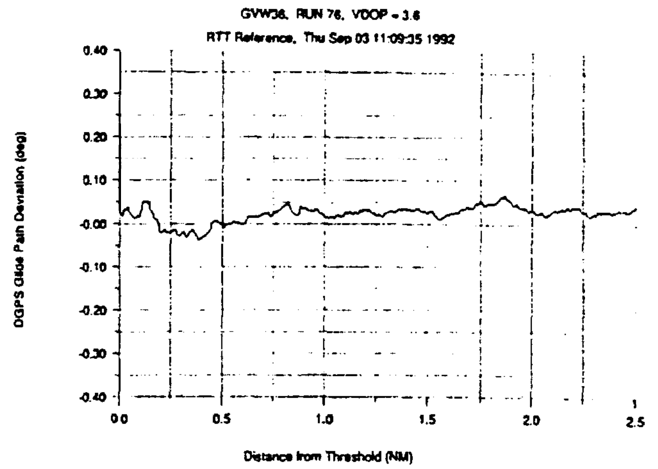

Figure 7

Figures 7 through 11 show typical plots for vertical data. In this case PFE and CMN are plotted in feet as well as degrees. These graphical presentations are very useful in portraying what is actually going on in a dynamic sense during the approach. The plots show the relationship of the aircraft vertical flight path to both the total allowable path following error (PFE) and the course structure requirement (PFN) Figure 8 represents the DGPS navigation error in terms of degrees. This is consistent with ILS requirements and provides a direct comparison to current landing system specifications. Figure 9 represents the navigation error in terms of feet which is very indicative of the DGPS performance characteristic and shows its wide performance margins farther out on the approach path where it is completely clear of current ILS limits. Actually the major error component beyond 2 to 3 miles is the theodolite tracking error. Figures 10 and 11 represent the CMN error in degrees and feet Figures 12 and 13 show vertical PFE in degrees and feet for the worst case approach using the narrow correlator receivers and the 9600 bps data link.

While the data plots provide excellent visibility into the dynamic performance achieved on each individual approach it is necessary to analyze the data on a statistical basis in order to quantify both the overall performance of the DGPS system and the effect on that performance of varying individual parameters of the system such as type of receiver, data rate. and **absence or** presence of a multipath choke ring.

VERTICAL PATH FOLLOWING ERROR (degrees)

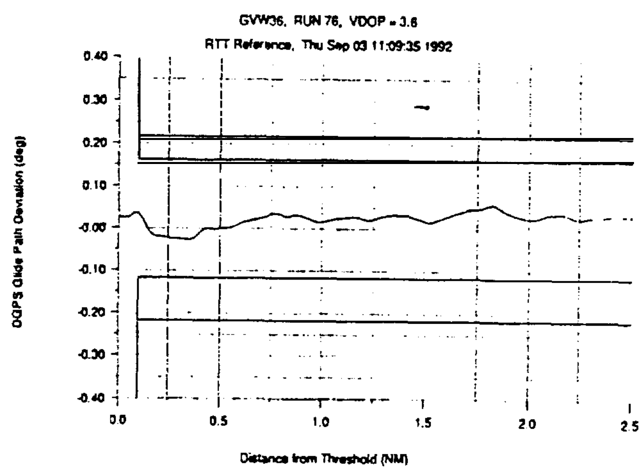

Figure 8

VERTICAL PATH FOLLOWING ERROR
(feet)

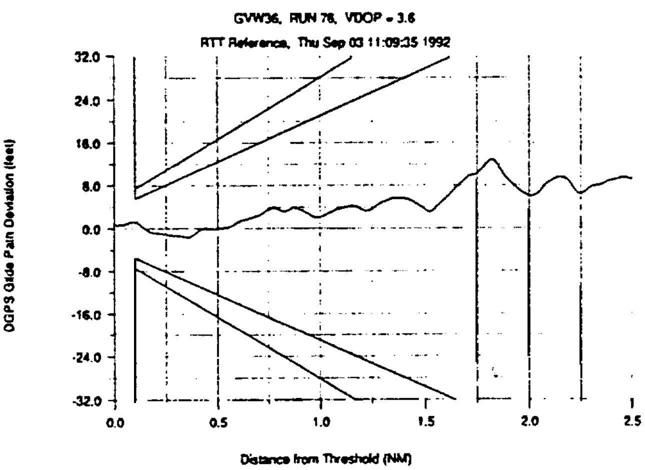

Figure 9

VERTICAL CONTROL MOTION NOISE
(feet)

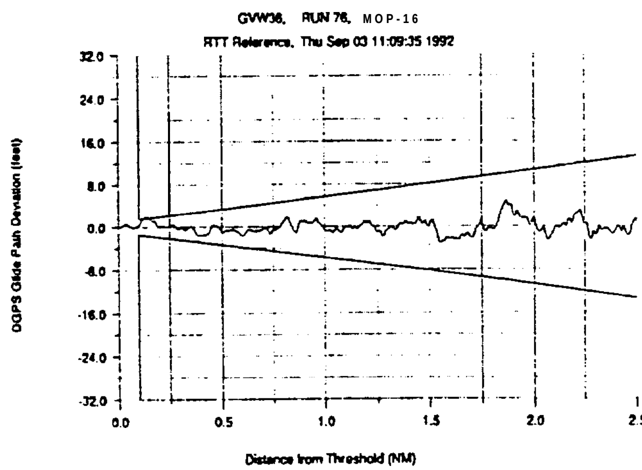

Figure II

VERTICAL CONTROL MOTION NOISE
(degrees)

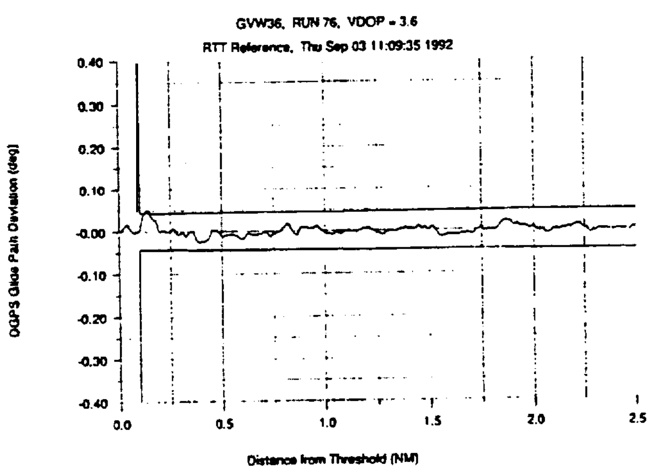

Figure 10

VERTICAL PATH FOLLOWING ERROR
(degrees)

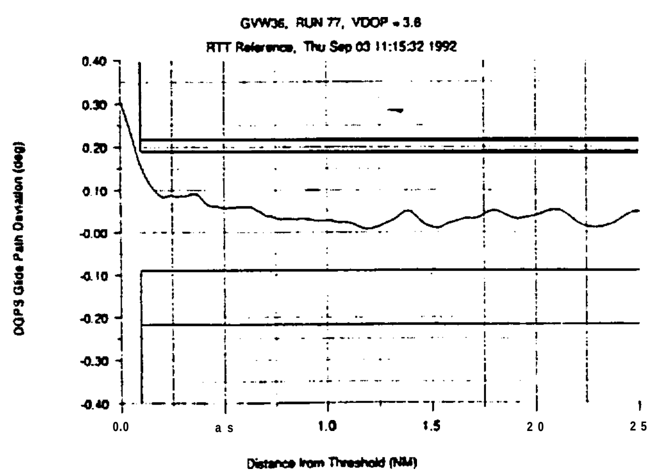

Figure 12

VERTICAL PATH FOLLOWING ERROR (feet)

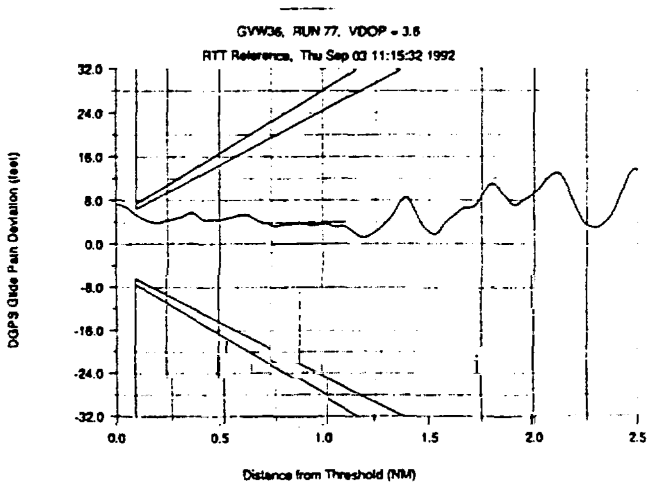

Figure 13

We have utilized two methods of data analysis. The first is a series of snapshots of the PFE taken on the approach at 100 ft. 200 ft, and 400 ft height above threshold for the various groups of approaches. Table 4 shows the 2 sigma values of the PFE at each of the sampled heights for the lateral and vertical deviations respectively as they compare with the ICAO limits. In the case of lateral deviations, Table 4 shows all approaches and all configurations tested are well within Category I ILS accuracy tolerances. In fact. all approaches for all equipment configuration cases met Category III tolerances.

In the case of the vertical deviations from flight path the situation as shown by Table 4 is more complex. It is recalled that although the angular tolerances for lateral and vertical deviations are approximately the same. the linear requirement for vertical deviation is roughly 8 times more restrictive than the lateral requirement at the 100 ft point and 4% times at the 200 ft decision height. Nevertheless the 2 sigma dispersion of all configurations met the Category I requirement at the 200 foot decision height with the narrow cot-relator spacing Novatel receiver meeting the requirement by a wide margin. The configurations with the narrow correlator receiver also met the extrapolated tolerance at 100 feet above threshold although the Ashtech receiver with carrier aided code tracking did not The 100 foot values are referenced even though they are **beyond the decision height** since ICAO specifies ILS Category I course structure (PFN) as an angular tolerance down to 100 feet. This is probably not appropriate for a linear system such as DGPS but is included for completeness.

TABLE 4

LATERAL PFE "SNAPSHOTS" RESULTS (feet, 2σ)

Configuration	Approaches	100'	200'	400'	Avg. HDOP
ICAO Limit		57.2*	67.2	94.5	
Std, Slow, NC	8	10.1	8.1	8.2	1.9
Narrow, Slow, C	13	8.9	10.3	8.7	1.2

VERTICAL PFE "SNAPSHOT" RESULTS (feet, 2σ)

Configuration	Approaches	100'	200'	400'	Avg. VDOP
ICAO Limit		7.8	14.8	29.5	
Std, Slow, NC	7	15.2	11.8	13.3	2.3
Narrow, Slow, C	7	6.1	4.0	5.9	2.4
Narrow, Fast, C	12	4.8	4.1	5.8	3.0

Std = standard spacing corrdator receivers
Narrow = narrow spacing eorrelator receivers
Slow = 3.5 - 6.5 sec differential corrections age at aircraft
Fast = 0.5 - 1.5 sec differential corrections age at aircraft
NC = no choke ring on base station L1 antenna
C = includes choke ring on base station L1 antenna

*** Only PFN component of PFE defined at 100' level**

The second method of analyzing the data for purposes of quantifying the performance was to calculate the 2 sigma error values for each of the approaches from the data collected over a distance on the approach of one mile. This has the effect of providing many more samples with which to validate the statistical analysis. The one mile section of approach was selected so as to optimize the tracking angle accuracy. For analyzing vertical errors in degrees the data taken from 1.5 nautical miles from threshold (approximately 500 ft height above threshold) to 0.5 nautical miles from threshold (200 ft DH) was used. For vertical errors in feet the data from 1.0 nautical miles from threshold down to the threshold (50 ft crossing height) was analyzed. For the case of lateral errors in degrees the identical part of the approach path that was used for vertical errors in degrees was also used. However. in order to obtain improved tracking angle accuncy when analyzing lateral errors in feet the one mile segment that was analyzed started at 6576 feet from the runway stop end and terminated 500 feet from the stop end.

Summaries of the results of these analyses for PFE. PFN and CMN errors are presented in Table 5 for the lateral errors **and** Table 6 for the vertical errors. As in the case of the snapshot analysis. inspection of the Tables shows

TABLE 5

LATERAL PFE "1 NM" RESULTS (2σ)

Configuration	Apps.	Spls.	Degrees	Feet	Avg. HDOP
ICAO 2σ Limits			0.299*	67.2*	
Std, Slow, NC	8	446	0.031	9.2	1.9
Narrow, Slow, C	13	1333	0.034	7.6	1.2

LATERAL PFN "1 NM" RESULTS (feet, 2σ)

Configuration	Apps.	Spls.	Min	Med	Max	Avg. HDOP
ICAO 2σ Limit					43.4*	
Std, Slow, NC	8	436	0.6	1.8	2.4	1.9
Narrow, slow C	13	1420	0.6	1.4	5.8	12

LATERAL PFN "1 NM" RESULTS (degrees, 2σ)

Configuration	Apps.	Spls.	Min	Med	Max	Avg. HDOP
ICAO 2σ Limit					0.196'	
Std, Slow, NC	8	446	0.006	0.012	0.022	1.9
Narrow, Slow, C	13	1333	0.004	0.010	0.014	1.2

LATERAL CMN "1 NM" RESULTS (feet, 2σ)

Configuration	Apps.	Spls.	Min	Med	Max	Avg. HDOP
ICAO 2σ Limit					113.7'1	
Std, Slow, NC	0					
Narrow, Slow, c	13	7420	12	1.6	3.0	12

LATERAL CMN "1 NM" RESULTS (degrees, 2σ)

Configuration	Apps.	Spls.	Min	Med	Max	Avg. HDOP
ICAO 2σ Limit					0.061*	
Std, Slow, NC	0					
Narrow, Slow, C	13	1333	0.010	IO.014	0.018	1.2

Std = standard spacing corrdator receivers
Narrow = narrow spacing correlator receivers
Slow = 3.5 - 6.5 sec differential corrections age at aircraft
Fast = 0.5 - 1.5 sec differential corrections age at aircraft
NC = no choke ring on base station L1 antenna
C = includes choke ring on base station L1 antenna

- Limit at 200' decision height

TABLE 6

VERTICAL PFE "1 NM" RESULTS (2σ)

Configuration	Apps.	Samps.	Degrees	Feet	Avg. VDOP
ICAO 2σ Limits			0.22-l	14.8*	
Std, Slow, NC	7	660	0.115	12.7	2.3
Narrow, Slow, C	7	986	0.066	6.1	2.4
Narrow, Fast, C	12	14%	0.049	5.0	3.0

VERTICAL PFN "1 NM" RESULTS (feet, 2σ)

Configuration	Apps.	Spls.	Min	Med	Max	Avg. VDOP
ICAO 2σ Limit					9.6*	
Std, Slow, NC	7	662	2.6	3.2	18.2	2.3
Narrow, Slow, C	7	1006	1.4	3.2	6.4	2.4
Narrow, Fast, C	12	1457	1.8	2.4	6.8	3.0

VERTICAL PFN "1 NM" RESULTS (degrees, 2σ)

Configuration	Apps.	Spls.	Min	Med	Max	Avg. VDOP
ICAO 2σ Limit					0.144	
Std, Slow, NC	7	660	0.016	0.048	0.074	2.3
Narrow, Slow, C	7	986	0.014	0.030	0.048	2.4
Narrow, Fast, C	12	1446	0.018	0.032	0.056	3.0

VERTICAL CMN "1 NM" RESULTS (feet, 2σ)

Configuration	Apps.	Spls.	Min	Med	Max	Avg. VDOP
ICAO 2σ Limit				-	4.1*	
Std, Slow, NC	4	495	1.8	2.2	2.6	2.3
Narrow, Slow, C	7	1006	1.8	2.4	2.8	2.4
Narrow, Fast, C	12	1457	1.6	2.2	2.6	3.0

VERTICAL CMN "1 NM" RESULTS (degrees, 2σ)

Configuration	Apps.	Spls.	Min	Med	Max	Avg. VDOP
ICAO 2σ Limit					0.061*	
Std. Slow. NC	4	492	0.016	0.020	0.022	2.3
Narrow, Slow, C	7	986	0.016	0.024	~0.030	2.4
Narrow, Fast, C	12	1446	0.014	0.022	0.028	3.0

Std = standard spacing correlator receivers
Narrow = narrow spacing condator receivers
Slow = 3.5 - 6.5 sec differential corrections age at aircraft
Fast = 0.5 - 1.5 sec differential corrections age at aircraft
NC = no choke ring on base station L1 antenna
C = includes choke ring on base station L1 antenna

- Limit at 200' decision height

all configurations on all approaches met the lateral requirements by a wide margin. In the case of the vertical performance the narrow width correlator receiver met all Category I requirements by a significant margin. For example referring to Table 6 the 2 sigma vertical path following error as computed for the 12 approaches with the 9600 bps data link was only 5.0 feet, and 6.1 feet with the 1200 bps link, against a requirement of 14.8 feet. The standard width correlator receiver also met all requirements (except one) but by smaller margins. In this case Table 6 shows 2 sigma PFE of 12.7 feet against the 14.8 foot requirement, The out-of-tolerance exception was PFN on one approach with a VDOP near 4.

Since the narrow correlator ground reference station Ll antenna was installed with a choke ring to reduce multipath effects and the standard correlator reference station antenna was not, a series of ground tests were. run on successive days under identical DOP conditions to measure the relative effects of receiver design and antenna configuration. These tests determined that approximately 90% of the improved performance obtained with the narrow correlator receivers was a result of the receivers themselves, with the remaining 10% attributed to the choke ring.

CONCLUSIONS

For all cases tested the local area DGPS landing system provided the equivalent of ILS Category I accuracy for lateral guidance by wide margins.

For vertical guidance which has always been the difficult case for satellite based systems the most interesting result was the solid Category I performance provided by the narrow spacing correlator design exemplified by the Novatel Model 911 GPS card.

Future areas of endeavor will concentrate on collecting additional DGPS test data on landing approaches under varying site conditions, auto-coupled approaches and curved approaches. Additional work needs to be accomplished by the aviation community in specifying and standardizing the differential corrections data link.

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