Performance of Category IIIB Automatic Landings Using C/A Code Tracking **Differential GPS**

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BIOGRAPHIES

Stephen Rowson received his B.S., M.S. and Ph.D. in electrical engineering from the University of Kansas. For the past 13 years he has worked 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 Landing Systems.

Glenn Courtney received his electrical engineering education at the University of Missouri. During his 12 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; hardware and software for MLS beam steering; CPUs, modems, signal synthesis, communication interfaces for MLS, 2nd Generation VORTAC, MK10 ILS and airport remote maintenance systems. Most recently he has worked on DGPS Landing Systems.

Richard Hueschen received the B.S. degree in electrical engineering from the University of Nebraska and the M.S. degree in electrical engineering from George Washington University. He joined NASA Langley Research Center in 1965. He has conducted research in the development of navigation, guidance, and control systems for transport aircraft which utilize the Microwave Landing System (MLS). One such system was an advanced modern-control-designed digital integrated automatic landing system and another an automatic guidance and control system for turnoff onto a high-speed runway exit after landing. He has conducted research in the use of Artificial Intelligence (AI) programming methods for the design and implementation of aircraft guidance and control systems. Since 1990 he has been conducting research and flight tests of differential GPS systems in transport aircraft applications. He is an Associate Fellow of the American Institute of Aeronautics and Astronautics.

ABSTRACT

An experimental DGPS precision approach and landing system was installed and flight tested on the NASA Langley Transport Systems Research Vehicle (TSRV), a Boeing 737-100.

The GPS ground station and avionics units used Novatel 10-channel, narrow correlator, C/A code tracking receiver engines. Differential corrections generated in the ground equipment were adjusted using a carrier phase smoothing algorithm prior to being transmitted once every two seconds to the aircraft via a 2400 baud VHF data link.

The GPS avionics converted DGPS position to vertical and horizontal angular deviations from the desired flight path. These deviations drove the aircraft flight control system in a manner emulating an instrument landing system (ILS) receiver. The GPS avionics did not make use of kinematic carrier phase tracking with on-the-fly cycle ambiguity resolution techniques, and was not enhanced with input from other systems such as barometric altimeter, radar altimeter, terrain mapping or inertial reference unit (IRU). However, the TSRV autoland flight control system included a radar altimeter (used for vertical flare guidance below 42 ft) and IRU (implemented to filter the "bends" in the glide path sometimes seen with ILS).

A total of 40 DGPS-guided approaches and landings were performed at the NASA Wallops Flight Facility, 31 of them hands-off, automatic landings.

Aircraft position was measured using a laser tracker. Total system error me: the proposed Category III Required Navigation Performance (RNP) or "tunnel concept"

accuracy requirements by a 300 percent margin laterally and 35 percent vertically. Touchdown dispersion for the 31 automatic landings also met Category III R!! requirements by approximately a 3-to-1 margin laterally and 2-to-1 longitudinally.

OBJECTIVES

Wilcox Electric has been developing and flight ● Esr.in$ DGPS precision approach and landing systems since early 1992. Prior to performing the tests described in this paper. the system was configured to drive a course deviadon indicator/glideslope indicator (CDI/GSI) on a Beechcraft King Air 300 twin turboprop aircraft. Xbouc 100 approaches were flown manually, with emphasis on meeting sensor accuracy requirements established for ILS under Category I conditions. i.e. 200 ft decision height (DH), 2600 ft runway visual range (RVR)[1].

It has been generally assumed that a Category III GPS landing system would necessitate use of kinematic carrier phase tracking techniques with cycle ambiguity resolution on the fly in order co achieve the required accuracy. This might be true, given current receiver performance, if it were necessary to meet the ILS vertical sensor accuracy requirement of ±2 ft (95%) at runway threshold[2]. However. the Required Navigation Performance[3] (RNP) or "tunnel concept", which is expected to become the new standard for defining landing system accuracies, specifies system accuracy in terms of total system error (TSE) rather than navigation sensor error (NSE) as currently specified for ILS. TSE is related to NSE and flight technical error (FE), i.e. autopilot error. by the expression:

$$TSE=\sqrt{NSE^2+FTE^2}$$

ILS accuracy requirements specified by the International civil Aviation Organization (ICAO) were established in an era when fairly large FTE had to be assumed. Since RNP specifies accuracy in terms of TSE, the user is permitted to perform a trade-off between NSE and FTE, allowing relaxation of the required sensor error for aircraft with modern, highly accurate flight control systems, i.e. typical autoland-equipped airliners in service today.

The purpose of the Wilcox/NASA Langley tests was to demonstrate chat an aircraft equipped with a modern autoland-capable flight control system could perform automatic landings meeting RNP accuracy requirements when driven by avionics using straightforward C/A code tracking differential GPS. Tine flight tests were also intended to demonstrate that such an avionics system could be configured to emulate an ILS avionics receiver, therefore allowing installation with an unmodified flight control system designed for ILS autolands.

ACCURACY REQUIREMENTS

ICAO specifies that a Category III ILS approach does not have a well-defined DE. but that a Category III landing system must provide guidance all the way to touchdown and along tie runway surface. Category III approaches are divided into three subcategories, A B and C. each having a minimum RVR as shown in Table 1.

Category	RVR
IIIA	750 ft
IIIB	150 ft
IIIC	0 ft

Table 1 - CAT III Definitions

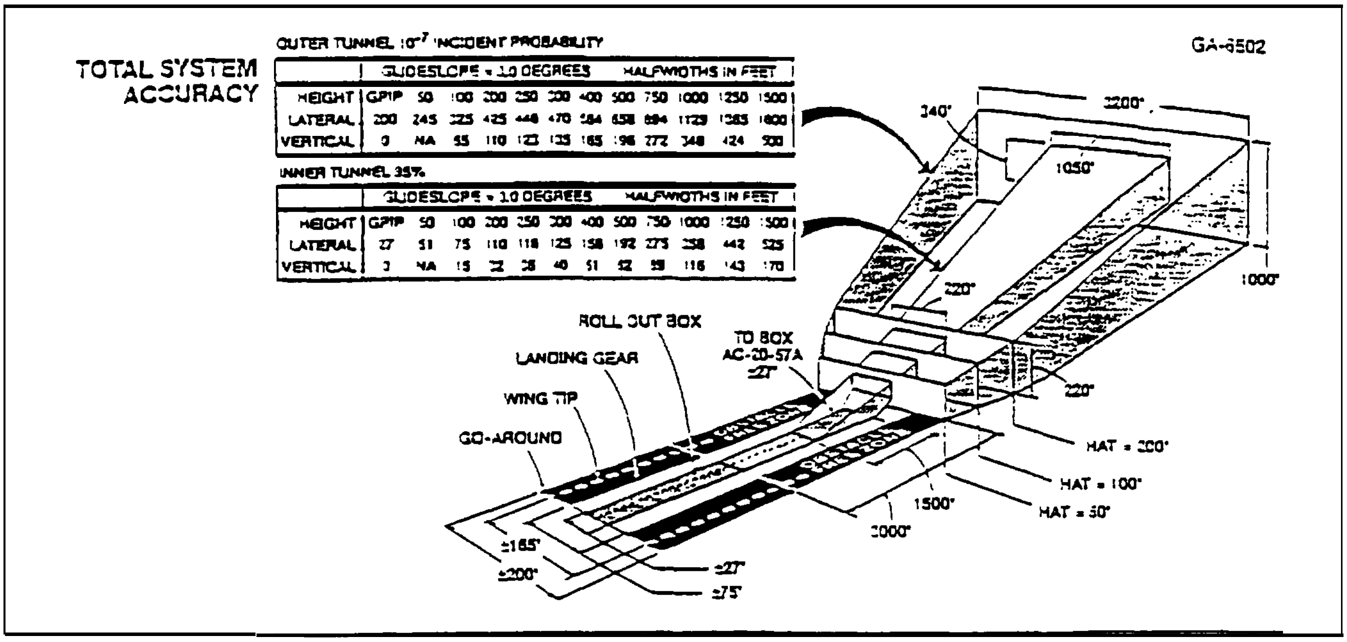
No Category IIIC ILS approaches have been commissioned since no means has yet been implemented to provide zero-visibility taxi guidance.

RNP establishes requirements for accuracy, integrity and continuity of function. all of which must be me: by a landing system to be certified for operational use. However, the tests described in this pacer were concerned only with accuracy.

For precision approach, RNP describes the required accuracy in terms of two concentric rectangular tunnels that surround the approach path to the runway. (Set Figure 1.) The tunnels are centered around a 3-degree glide path chat intercepts the runway surface about 1000 ft from threshold. The dimensions of both tunnels become smaller in tie vertical and lateral diicdons as the intercept point is approached_

The inner tunnel defines a region within which the aircraft's center of gravity (CG) must 'be contained at least 95 percent of the rime. The smallest vertical dimension for the inner nmne! is ±15 ft, centered about the 3 degree glide path at a height of 100 ft above runway threshold elevation. The minimum lateral dimension is ±27 ft from runway centerline at the glide path intercept point

Associated with the inner tunnel is a two-dimensional touchdown dispersion box on the runway. The aircraft CG must lie within this box at touchdown on a 95 percent basis. The touchdown dispersion box extends 27 ft either side of the runway centerline, and is 1500 ft long. Also,



OUTER TUNNEL 10^{-7} INCIDENT PROBABILITY

	GLIDESLOPE = 3.0 DEGREES						HALFWIDTHS IN FEET					
HEIGHT	GPIP	50	100	200	250	300	400	500	750	1000	1250	1500
LATERAL	200	245	325	425	448	470	584	658	894	1129	1365	1600
VERTICAL	0	NA	55	110	123	135	165	196	272	348	424	500

INNER TUNNEL 95%

	GLIDESLOPE = 3.0 DEGREES						HALFWIDTHS IN FEET					
HEIGHT	GPIP	50	100	200	250	300	400	500	750	1000	1250	1500
LATERAL	27	51	75	110	118	125	158	192	275	358	442	525
VERTICAL	3	NA	15	22	28	40	51	52	59	116	143	170

Figure 1 - RNP Category III Concept

during rollout in auto-coupled mode the aircraft CG must stay within ±27 ft of the runway centerline.

The outer tunnel defines a containment surface beyond which no part of the aircraft is allowed to extend with a probability greater than one in 10^7 landings. If any portion of he aircraft penetrates the outer tunnel, the plane runs a significant risk of collision with an obstacle or the ground. The smallest vertical dimension of the outer tunnel is ±65 ft around the glide path at 100 ft height. The minimum lateral dimension is 200 ft at the glide path intercept point.

SYSTEM APPROACH

Although Category III imposes stringent accuracy limits on a landing system. Category III integrity requirements may be even more difficult for a GPS landing system to satisfy. Both ICAO ILS specifications and RNP require that the probability of undetected guidance error be extremely small. in the case of RNP 3.3×10^{-9} per landing for the entire system, ground and airborne.

Continuity of Function (COF) is also an importttt requirement for a Category III landing system. Executing a missed approach in a large. jet aircraft from low altitude (i.e. less than 100 ft) under conditions of low visibiiicy (i.e. Category III) may be hazardous. Therefore. once an approach is begun the probability of loss of guidance from the landing system must be low. The proposed RNP Cat III COF requirement is a loss of continuity probability of less than 4×10^{-6} for the final 30 seconds of approach commencing at 100 ft height above threshold.

Given the present state of the art. Wilcox believes that C/A code tracking receivers are more likely to provide the integrity and COF performance required for a Category III GPS landing system than other approaches such as kinematic carrier phase tracking with cycle ambiguity resolution on the fly. For instance, a C/A code tracking receiver behaves robustly under conditions of momentary loss of satellite signals. A kinematic carrier phase tracking receiver may require complex and expensive augmentation by other systems, e.g. a tightly coupled IRU, in order to cope with cycle slips and achieve the required integrity and COF.

Because of the relative simplicity and robusmess of C/A code tracking, Wilcox chose to design this type of receiver into the GPS autoland system described in this paper.

FLIGHT EVALUATION EQUIPMENT

A block diagram of the ground reference station is shown in Figure 2. The ground system was based on a Novatel Model 951R GPS receiver engine installed in a laptop PC. This receiver has 10 parallel channels and uses narrow correlator technology to achieve very low noise and low susceptibility to multipath distortion of satellite signals.

The GPS receiver calculated differential pseudorange corrections and range rates based on its known antenna location (about 400 feet to the side of runway 28 at the NASA Wallops Flight Facility). Corrections and range rates, along with measured pseudoranges and accumulated carrier phase, were output to the PC once every two seconds.

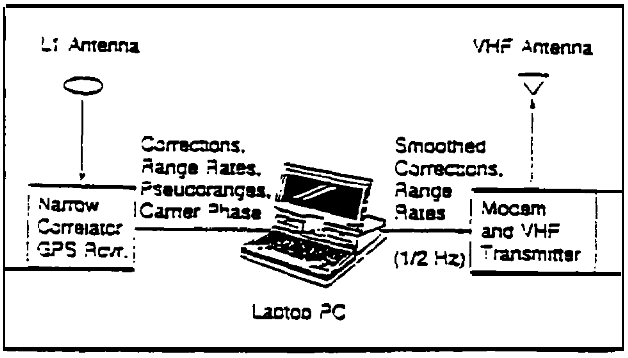


Figure 2 - Ground Reference Station

In an attempt to further reduce the effects of multipath on the accuracy of the pseudorange corrections, a came: phase smoothing algorithm was implemented in software in the PC. The difference between Me-based pseudorange and a range based on accumulated carrier phase, i.e. ΔR = PR - AC?, was calculated once every two seconds for each satellite in view. Each differential correction was then adjusted by the difference between the current ΔR and the average ΔR over the previous 300 seconds.

The adjusted differential corrections were transmitted in a proprietary ASCII format to the aircraft via a 2400 bps modem and VHF transmitter.

The L1 antenna was mounted a few inches above the ground in order to further minimize multipath effects. The ground station GPS receiver mask angle was set to 7 degrees.

The test aircraft was the NASA Langley Transport Systems Research Vehicle (TSRV), a Boeing 737-100. This aircraft is equipped with an autoland-capable flight control system and is instrumented for recording a large number of system measurements (e.g. attitudes, velocities, accelerations, wheel spin, squat switch, etc.) and is therefore an ideal platform for testing landing systems. The TSRV has previously been used to test other GPS landing systems[4,5] and the microwave landing system MS;.

The DGPS avionics was designed to operate as an ILS "look-alike" system, i.e. to output angular deviations and flags emulating ILS receivers outputs. Figure 3 shows a block diagram of the avionics equipment. Satellite signals were received at a Sensor Systems L-band antenna mounted in the top of the fuselage, about 7 feet in front of the aircraft CG.

The GPS receiver, a Novatel Model 2151R Performance Series unit, was housed in a DZUS-rail enclosure which was mounted to the front panel of a 19-inch rack Like the receiver on the ground, this receiver has 10 parallel channels and narrow-width correlator circuitry. The GPS receiver used pseudorange corrections and range rates input from a 2400 'bps data link to compute differentially corrected position and velocity at a 5 Hz rate. Position and velocity were output to a notebook PC (486 based) via a 37.4 kbps RS-232 serial link.

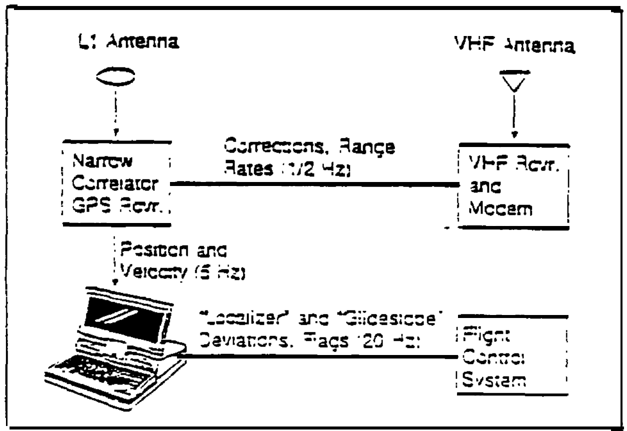


Figure 3 - Avionics Equipment

Since the TSRV's flight control system required updates at a 20 Hz rate, the notebook PC software used velocity to project the last computed position ahead in time in 50 msec increments. Each position was projected ahead in time an additional 200 msec in order to reduce the overall system latency to approximately 50 msec. Latencies greater than 100 msec can cause flight control system instability, especially in the presence of turbulence.

Using a database of runway coordinates, each computed position was converted to lateral (localizer) and vertical (glideslope) angular deviations from the 3-degree ideal glide path. Deviations were output to the flight control system at 20 Hz via the aircraft's DATAC digital dam bus. DATAC was a forerunner of the ARINC 629 data bus. The notebook PC also computed localizer and glideslope flags which were set or cleared according to aircraft position with respect to imaginary ILS localizer and glideslope antennas on the ground. An "ILS valid" flag was set whenever all DGPS self-test bin were set valid. Flags were output to the flight control system at 20 Hz.

The DGPS avionics also output time-tagged GPS latitude, longitude and altitude to the DATAC bus at 5 Hz. These data were recorded on magnetic npe and optical disk, along with deviations and flight control system data, and were used by the TSRV area navigation computer to Steer the aircraft around the pattern prior to intercepting the final approach glide path. However, only deviations, scaled to emulate ILS deviations, and flags, not raw GPS position, drove the flight control system during the final approach and landing.

The TSRV autoland system is an inertially augmented ILS system. The system was designed to use inertial measurements and complementary filtering to improve localizer and glideslope tracking in the presence of ILS beam bends. For the flight tests described in this paper the ILS-like localizer and glideslope inputs to the autoland system were of course provided by the DGPS avionics. Figures 4 and 5 show block diagrams of the lateral and longitudinal portions of the autoland system.

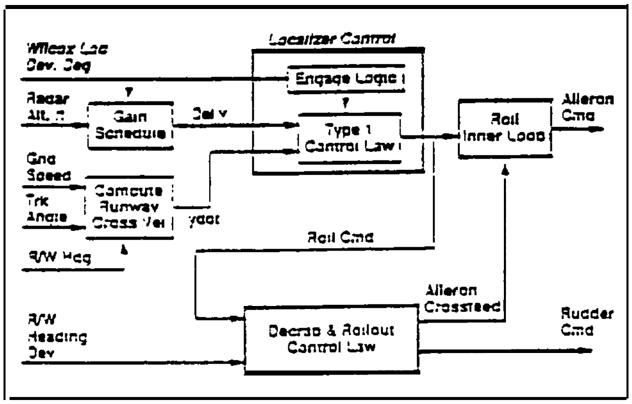


Figure 4 - TSRV Lateral Autoland System

The lateral portion consists of two control laws: localizer and decrab/rollout.

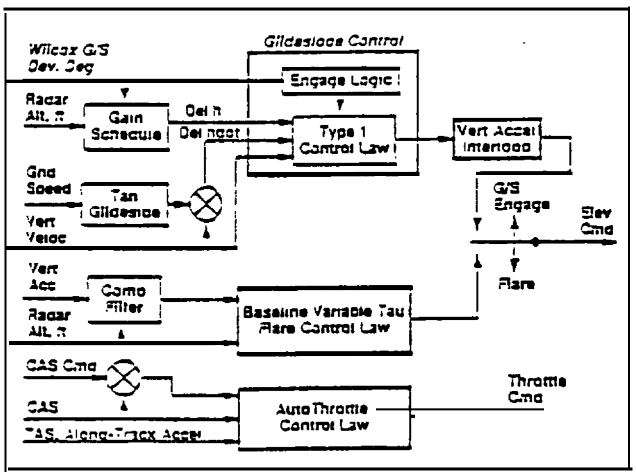


Figure 5 - TSRV Longitudinal Autoland System

The longitudinal portion consists of three control laws: glideslope, flare and autothrottle.

The localizer and glideslope control laws are both "type 1" control laws in the tracking mode, i.e. they use integrators to produce zero tracking error in steady-state conditions.

The TSRV autoland system uses four measurements from the onboard laser-gyro IRU. The localizer control law uses inertial ground speed and track angle to compute cross-runway velocity ("ydot") for path damping and complementary filtering of the localizer signal. The glideslope control law uses inertial ground speed and complementary filtered vertical velocity (obtained from the IRU vertical acceleration and barometric altitude measurements) for path damping and complementary filtering of the glideslope signal. The flare law uses vertical acceleration from the IRU and radar altitude to compute a vertical velocity relative to the runway surface. The autothrottle control law uses along-track acceleration to improve calibrated airspeed hold tracking performance.

The TSRV autoland system has several control modes. These modes are localizer capture, glideslope capture, localizer track, glideslope track, decrab, flare and rollout. The decrab mode is engaged at radar altitude of 150 ft and aligns the aircraft heading with the runway heading in the presence of crosswinds. The flare mode is engaged at radar altitude of 42 ft and rollout engages when one of the main gear squat switches is set.

A radar/laser tracker was used to provide a reference position measurement of the aircraft. The fundamental measurements of the tracker are azimuth, elevation and range. The accuracy specifications for the measurements are given as 0.005 degrees (0.1 mrad) rms for the angle measurements and ±1.5 ft rms for the laser range measurement. Boresight measurements obtained on each flight test day showed bias errors in the azimuth measurements varying from 4.011 degrees to -0.012 degrees. The bias errors in the elevation measurements varied from 0.029 degrees to 0.031 degrees. The tracker is located at the Wallops Flight Facility (WFF) on Virginia's eastern shore and has visibility to all of the runways at WFF. The tracker is situated 452.4 ft to the right of runway 28, 1993.7 ft from its threshold. The tracker provides valid measurements up to 2 nautical miles (nmi) in range. Tracker position relative to the runways is shown in Figure 6.

DESCRIPTION OF TESTS

The flight tests consisted of approaches and landings primarily to runways 22 and 28 at WFF. The same flight path profiles were used for each runway and are shown in Figure 7. These paths are typical right and left hand ILS approach and landing paths. The course-cut to localizer

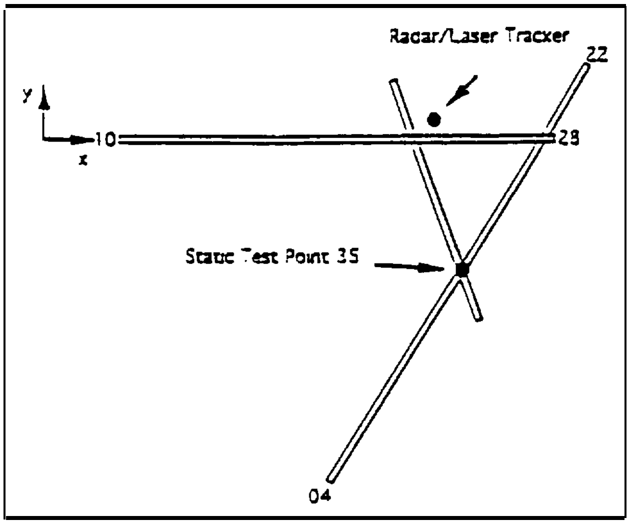


Figure 6 - Wallops Flight Facility Runway Layout

centerline was 30 degrees and the final straight path segment was 5 nmi *long* and descended along a 3 degree glideslope. Tracking data was recorded along the entire flight path, but valid laser range data was only obtained when the aircraft was less than approximately 2 nmi from the tracker. Prior to that the range measurement was made by the tracker radar.

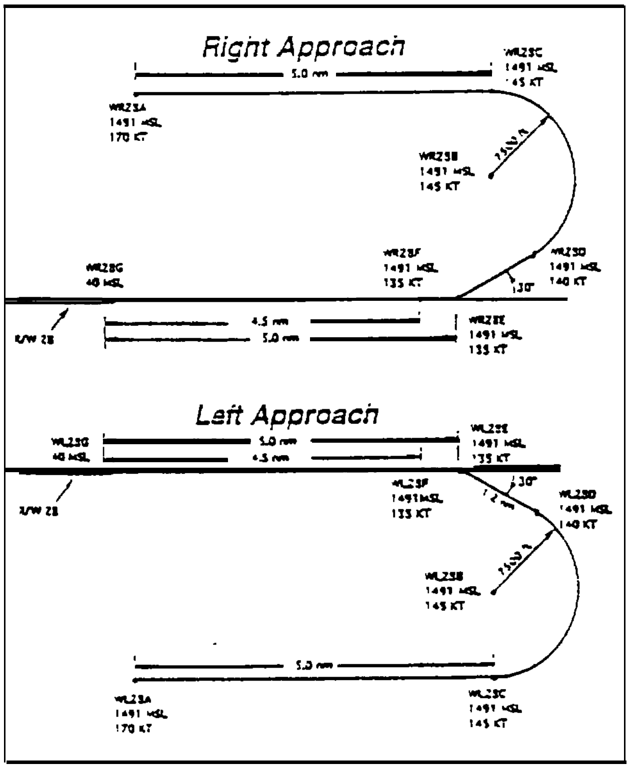


Figure 7 - Flight Test Paths

A total of 40 airborne test runs were flown. The test runs used three fly-by-wire control modes selected in the research flight deck of the TSRV. Prior to the final approach and landing, the aircraft was positioned on *the* 30 degree course-cut segment of the flight path using either the VCWS or 3D modes with position information from the DGPS avionics. VCWS is a Velocity Control Wheel Steering piloted mode in which the pilot commands the aircraft flight path angle and track angle through a sidearm controller. The 3D mode automatically maintains the airplane *on* a horizontal and vertical profile generated from stored path waypoints. The final approach and landings were accomplished using either the VCWS *or* autoland modes. Figure 8 shows the vertical profile for the final segment of an autoland approach and landing.

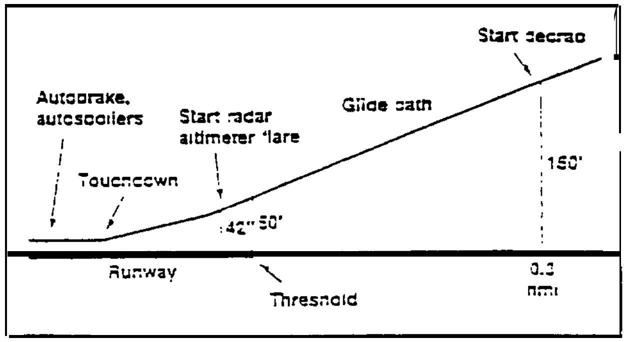


Figure 8 - Vertical 3 Degree Approach Profile

Most landings were followed by an immediate takeoff (touch and go-around) to make more time available for approach and landings. When a touch and go was not performed after landing, the DGPS avionics localizer signal was used by the automatic rollout mode to maintain the aircraft on runway centerline and automatic braking was used to slow the aircraft to taxi speed.

The first approach and landing to each runway was flown using the VCWS mode to ensure proper operation of the research system prior to engaging the autoland mode. Seven VCWS and 33 autoland test runs were performed on two flight test days. Thirty-one of the autolands were completely "hands-off" landings. The forward flight deck pilots put in slight wheel inputs (roll control only) near touchdown for two autoland runs because crosswinds had exceeded the autoland system crosswind limits.

Because use of the 7-degree mask angle provided good DOPs throughout both flight test days (September 15 and 21, 1993), the landings were not scheduled to optimize satellite geometry. Maximum HDOP during the tests was 1.7; maximum VDOP was 3.7.

TEST RESULTS

Using the laser tracker as ground truth reference, both navigation sensor errors (NSE) and total system errors (TSE) were measured and analyzed for the 33 autoland approaches and landings. Although the principal intent of the study was to compare TSE with RNP tunnel accuracy requirements, NSE was also examined to determine the effect of the carrier phase smoothing algorithm applied in the ground station to the differential corrections.

Figures 9 and 10 show superimposed plots of lateral NSE for 18 autolands to runway 28 and 16 autolands to runway 22. One of the autolands to runway 22 was accidently aborted near the threshold when the pilot bumped the autopilot disengage button. That approach is included in the Figure 10 plots although it was reclassified as a manual approach. Because of its proximity to the runway, the laser tracker slew rate was insufficient to keep up with the aircraft starting about 500 ft prior to the threshold of runway 28. The consequent loss of valid tracking data in that region is apparent in Figure 9. The path between the laser tracker and aircraft was blocked at several points on the runway 22 approach by airport structures. Figures 10 and 12 have been adjusted to fill these gaps in coverage with interpolation between valid segments on the approach path.

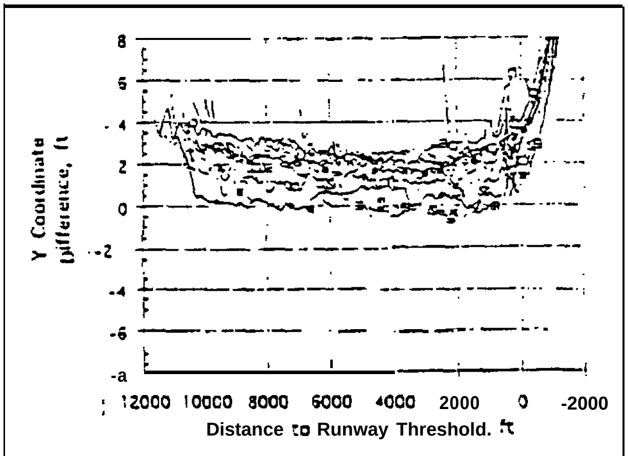


Figure 9 - Lateral NSE, Runway 28

Figures 9 and 10 illustrate the effects of the carrier phase smoothing algorithm. The plots show that NSE for any single approach 'was more constant throughout the approach as compared to previously obtained data for the unsmoothed case'. In other words, the carrier phase smoothing as implemented in this system caused the DGPS NSE to look like a slowly varying bias. The overall difference in bias between the two figures is most likely not related to the geometric differences between runways 28 and 22, but rather is the result of most of the

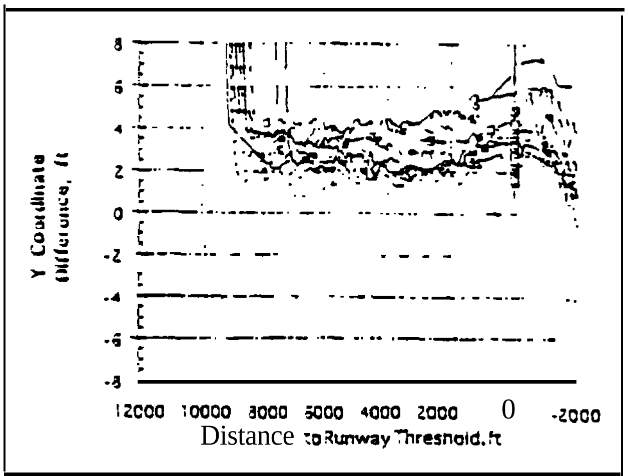


Figure 10 - Lateral NSE, Runway 22

runway 22 landings being flown on the first test day and most of the runway 28 landings being flown on the second day because of prevailing wind directions.

An NSE that varies slowly is desirable so that FTE is not increased as a result of the flight control system trying to follow a flight path containing bends.

Figures 11 and 12 show vertical NSE plots for the same set of approaches. Note that the overall spread in error is larger than for the lateral case, and that there is a corresponding difference in bias between runways 28 and 21.

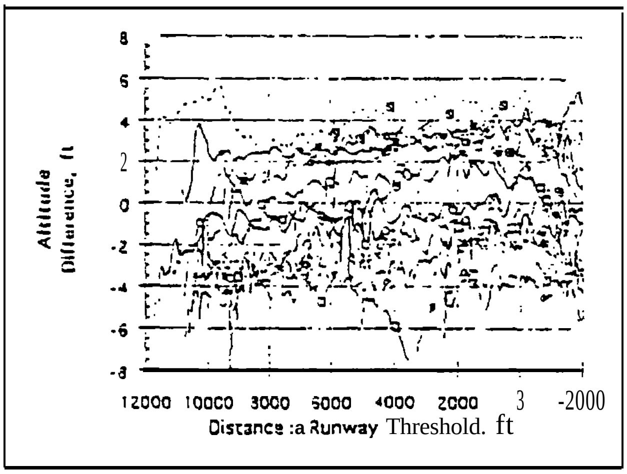


Figure 11 - Vertical NSE, Runway 28

NSE statistics were calculated for the point at 150 ft altitude (1300 ft from threshold) for 33 autolands to runways 22 and 28. This point was chosen because it is near threshold, prior to the decrab and flare maneuvers, and corresponds to a segment between laser tracker obstructions on the runway 22 approach. NSE results are

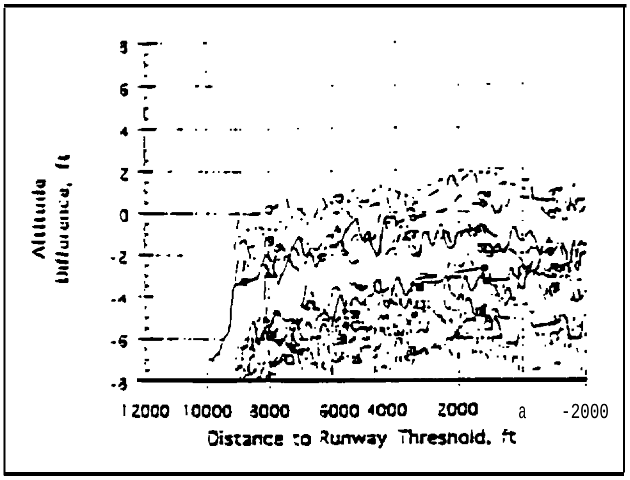


Figure 12 - Vertical NSE, Runway 22

compared to ICAO ILS accuracy requirements in Table 2. Since ICAO specifies limits at the 95 percent level, we have calculated 95 percent estimates of measured NSE using the conservative formula $|\mu| + 2\sigma$.

	Measured NSE	CAT III ICAO Limit
Lateral ($|\mu|+2\sigma$):	4.8 ft (1.5 m)	*20.0* ft (*6.1* m)
Vertical ($|\mu|+2\sigma$):	*7.1* ft (2.2 m)	*2.0* ft (0.6 m)

Table 2 - Navigation Sensor Error, 33 Autolands, 95%

The NSE obtained with these flights easily meets Category III ILS localizer (lateral) requirements as specified by ICAO[2] but does not meet the ICAO Category III ILS glideslope (vertical) requirements. These error estimates are also slightly higher than those obtained from earlier flight tests at the FAA Technical Center (FAATC) using similar equipment without the smoothing function applied to the differential corrections[1]. However, improvements introduced by the carrier phase *smoothing* may have been masked by differences between the highly accurate FAATC laser tracker and the WFF laser tracker which had 2σ errors of 3 ft range. 4 ft vertical and 1.4 ft lateral at the measurement point Also, the NSE (and TSE) data measured against the laser tracker were not compensated to remove the measured tracker biases of 0.8 ft (azimuth) and -.! ft (vertical) at the 150 ft measurement point.

However, as discussed earlier, FAA and ICAO are moving toward eventual acceptance of the RNP tunnel as the standard for accuracy, integrity and continuity of function. RNP specifies accuracy in terms of TSE, not NSE.

Since the inner tunnel (see Figure 1) specifies limits at the 95 percent level, we have calculated 95 percent estimates of TSE the same as for NSE, using the conservative formula $|\mu| + 2\sigma$. Although TSE was measured throughout approximately the last nautical mile of each approach using the laser tracker, TSE statistics were calculated for the point at 150 ft altitude (1800 ft from threshold) for 33 autolands to runways 28 and 22, ie. the same measurement point used for NSE statistics. The lateral and vertical TSE results are compared to Category III RNP accuracy limits in Table 3.

	Measured TSE	CAT III RNP Limit
Lateral ($|\mu|+2\sigma$):	8.9 ft (2.7 m)	27.0 ft (8.2 m)
Vertical ($|\mu|+2\sigma$):	11.1 ft (3.4 m)	15.0 ft (4.6 m)

Table 3 - Total System Error, 33 Autolands, 95%

The lateral requirement was satisfied by a 3-to-1 margin. The measured vertical TSE was about 35 percent better than required by RNP.

Because the laser tracker could not provide valid data at touchdown for runway 28, touchdown dispersions based on laser tracker ground truth are only available for 15 autolands flown to runway 22. RNP specifies a 95 percent touchdown dispersion zone 1500 ft long extending ±27 ft from the runway centerline. Figure 13 graphically depicts the location of the aircraft CG at touchdown for the runway 22 autolands with respect to the RNP touchdown limits. Clearly, the touchdown points fell within the limits with substantial margin.

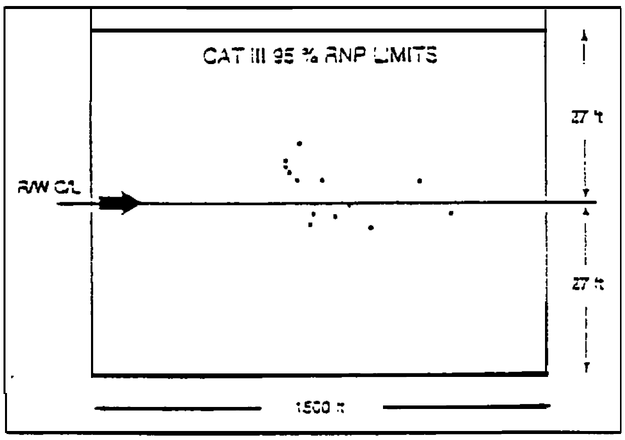


Figure 13 - Aircraft CG Touchdown Dispersion

Table 4 gives the statistics for the touchdown dispersion. Lateral dispersion was estimated using $|\mu| + 2\sigma$. Since the

RNP zone is defined longitudinally as a total length rather than in half lengths, 4σ was used to estimate the longitudinal dispersion.

	Measured	CAT III RNP Limit
Lateral (|u|+2σ):	9.3 ft (2.5 m)	27.0 ft (8.2m)
Longitudinal (4σ):	686 ft (209 m)	1500 ft (457 m)

Table 4 - Touchdown Dispersion Statistics

As would be expected the lateral touchdown dispersion is approximately the same as the lateral TSE measured at the 150 ft height above threshold on the approach path (see Table 3). Table 4 shows that the longitudinal dispersion satisfies the RNP requirement by about a *1-to-1* margin. a larger margin than was seen for vertical TSE at the 150 ft point This is not surprising, since longitudinal dispersion is affected at least as much by the autoland flare laws and wind conditions as by vertical TSE. A 3-degree glide path angle is equivalent to a 19-to-1 slope. Therefore, the 3.4 ft standard deviation measured for vertical TSE in these tests translates into only 258 ft (3.4 x 4 x 19) of total longitudinal dispersion (95%).

CONCLUSIONS

A C/A code tracking differential GPS landing system, using narrow correlator receivers in the ground reference station and avionics, and configured to drive an ILS autoland flight control system with ILS "look alike" deviation signals, successfully guided a Boeing 737 to 31 successful "hands off" landings. No landings were aborted because of equipment failure, and conservative estimates of lateral and vertical total system error fell within Category III RNP tunnel requirements for both the approach and touchdown segments *of the* landings with *substantial* margin. The number of landings provided a sufficient sample size to ensure high confidence in the statistical error estimates.

The TSRV pilots commented that the DGPS approach paths seemed noticeably straighter than what they had experienced with ILS coupled approaches.

ACKNOWLEDGMENTS

The authors would like to thank Cary Spitzer at NASA Langley and Wayne Dohlman at Wilcox Electric for initiating the organizational cooperation that resulted in this test program. Special thanks are due to Clint Lee, Charles Howell and Dave McLuer of NASA Langley for their unflagging efforts to get the Wilcox equipment installed in the TSRV on schedule. We would also like to express our gratitude to the managers, flight crews and ground support personnel at NASA Langley without whose enthusiastic support this project would have been impossible.

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Performance of Category IIIB Automatic Landings Using C/A Code Tracking Differential GPS

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BIOGRAPHIES

Stephen Rowson received his B.S., MS. and Ph.D. in electrical engineering from the University of Kansas. For the pas; 13 years he has worked at Wilcox Electric where he has had major hardware. software and system design responsibility, including Manage: 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 Landing Systems.

Glenn **Courtney** received his electrical engineering education at the University of Missouri. During his 12 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; hardware and software for MLS beam steering; CPUs, modems. signal synthesis. communication interfaces for MLS, 2nd Generation VORTAC, MK10 ILS and airport remote maintenance systems. Most recently he has worked on DGPS Landing Systems.

Richard Hueschen received the B.S. degree in electrical engineering from the University of Nebraska and the M.S. degree in electrical engineering from George Washington University. He joined NASA Langley Research Center in 1965. He has conducted research in the development of navigation. guidance, and conuol systems for transport aircraft which utilize the Microwave Landing System (MLS). One such system was an advanced modern-control-designed digital integrated automatic landing system and another an automatic guidance and control system for turnoff onto a high-speed runway exit after landing. He has conducted research in the use of Artificial Intelligence (AI) programming methods for the design and implementation of aircraft guidance andcontrol systems. Since 1990 he has been conducting research and flight tests of differential GPS systems in transport aircraft applications. He is an Associate Fellow of the American Institute of Aeronautics and Astronautics.

ABSTRACT

An experimental DGPS precision approach and landing system was installed and flight tested on the NASA Langley Transport Systems Research Vehicle (TSRV), a Boeing 737-100.

The GPS ground station and avionics units used Novatel lo-channel. narrow correlator, C/A code tracking receive: engines. Differential corrections generated in the ground equipment were adjusted using a carrier phase smoothing algorithm prior to being transmitted once every two seconds to the aircraft via a 2400 baud VHF data link.

The GPS avionics converted DGPS position to vertical and horizontal angular deviations from the desired flight path. These deviations drove the aircraft flight control system in a manner emulating an instrument landing system (ILS) receive:. The GPS avionics did nor make use of kinematic carrier phase tracking with on-the-fly cycle ambiguity resolution techniques. and was not enhanced with input from other systems such as barometeic altimeter, radar altimeter, terrain mapping or inertial reference unit (IRU). However, the TSRV autoland flight conuol system included a radar altimeter (used for vertical flare guidance below 42 ft) and IRU (implemented to filter the "bends" in the glide path sometimes seen with ILS).

A total of 40 DGPS-guided approaches and landings were performed at the NASA Wallops Flight Facility, 31 of them hands-off, automatic landings.

Aircraft position was measured using a laser tracker. Total system error met the proposed Category III Required Navigation Performance (RNP) or "tunnel concept"

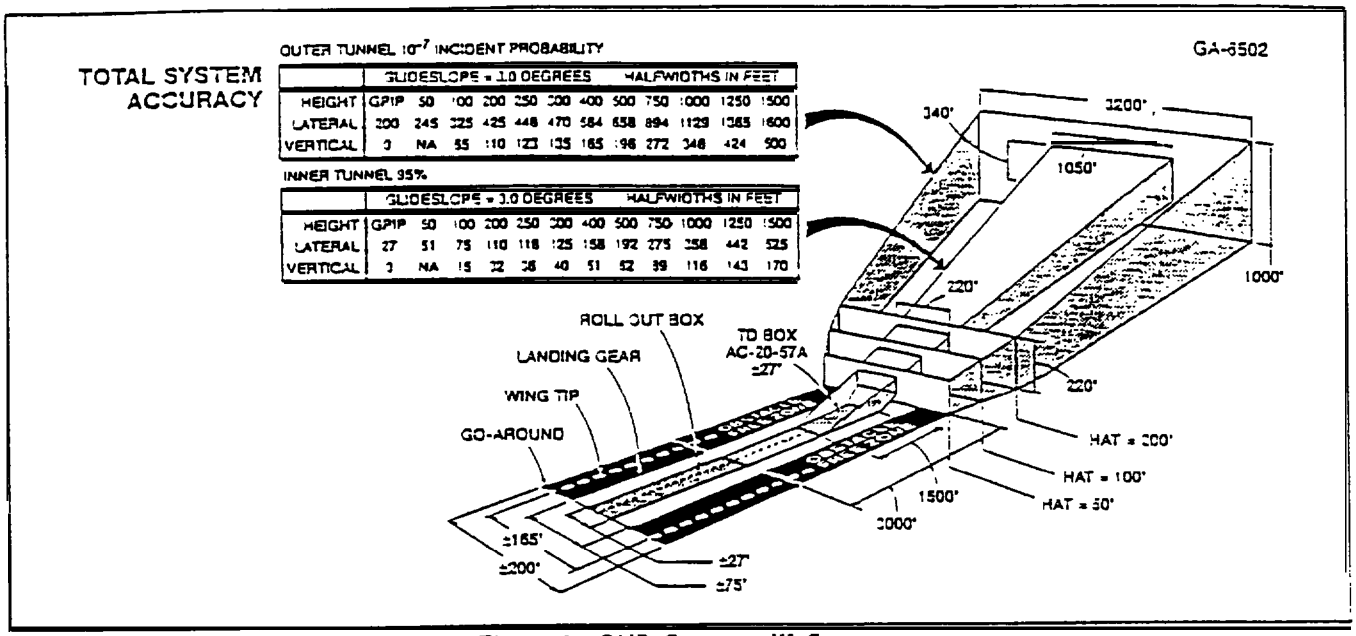

Figure 1 - RNP Category III Concept

during rollout in auto-coupled mode the aircraft CG must stay within ±27 ft of me runway centerline.

The outer tunnel defines a containment surface beyond which no part of the aircraft is allowed to extend with a probability greater than one in 10’ landings. If any potion of the aircraft penetrates the outer tunnel, the plane runs a significant risk of collision with an obstacle or the ground. The smallest vertical dimension of the outer tunnel is ±65 ft around the glide path at 100 ft height. The minimum lateral dimension is 200 ft at the glide path intercept point.

SYSTEM APPROACH

Although Category III imposes stringent accuracy limits on a landing system, Category III integrity requirements may be even more difficult for a GPS landing sysrem to satisfy. Both ICAO ILS specifications and RNP require that the probability of undetected guidance error be extremely small. in the case of RNP 3.3 x 10^{-9} per landing for the entire system, ground and airborne.

Continuity of Function (COF) is also an important requirement for a Category III landing system. Executing a missed approach in a large, jet aircraft from low altitude (i.e. less than 100 ft) under conditions of low visibility (i.e. Category III) may be hazardous. Therefore, once an approach is begun the probability of loss of guidance from the landing system must be low. The proposed RNP Car III COF requirement is a loss of continuity probability of less than 4 x 10^{-6} for the final 30 seconds of approach commencing at 100 ft height above threshold.

Given the present state of the art, Wilcox believes that C/A code tracking receivers are more likely to provide ‘he integrity and COF performance required for a Category III GPS landing system than other approaches such as kinematic carrier phase tracking with cycle ambiguity resolution on the fly. For instance, a C/A code tracking receiver behaves robustly under conditions of momentary loss of satellite signals. A kinematic carrier phase tracking receiver may require complex and expensive augmentation by other systems, e.g. a tightly coupled IRU, in order to cope with cycle slips and achieve the required integrity and COF.

Because of the relative simplicity and robusmess of C/A code tracking, Wilcox chose to design this type of receiver inro the GPS autoland system described in this paper.

FLIGHT EVALUATION EQUIPMENT

A block diagram of the ground reference station is shown in Figure 7. The ground system was based on a Novatel Model 951R GPS receiver engine installed in a laptop PC. This receiver has 10 parallel channels and uses narrow correlator technology to achieve very low noise and low susceptibility to multipath distortion of satellite signals.

The GPS receiver calculated differential pseudorange corrections and range rates based on its known antenna location (about 400 fee: to the side of runway 28 at the NASA Wallops Eight Facility). Corrections and range the aircraft around the pattern prior co intercepting the final approach glide path. However. only deviations, scaled to emulate ILS deviations, and flags. not raw GPS position, drove he flight control system during the final approach and landing.

The TSRV autoland system is an inertially augmented ILS system. The system was designed to use inertial measurements and complementary filtering to improve localizer and glideslope tracking in the presence of ILS beam 'bends. For the flight tests described in this paper the ILS-like localizer and glideslope inputs to the autoland system were of course provided by the DGPS avionics. Figures 4 and 5 show block diagrams of the lateral and longitudinal portions of the autoland system.

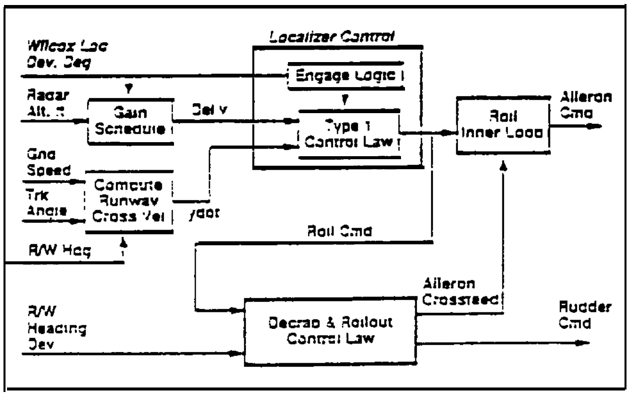

Figure 4 - TSRV Lateral Autoland System

The lateral portion consists of two control laws: localizer and decrab/rollout.

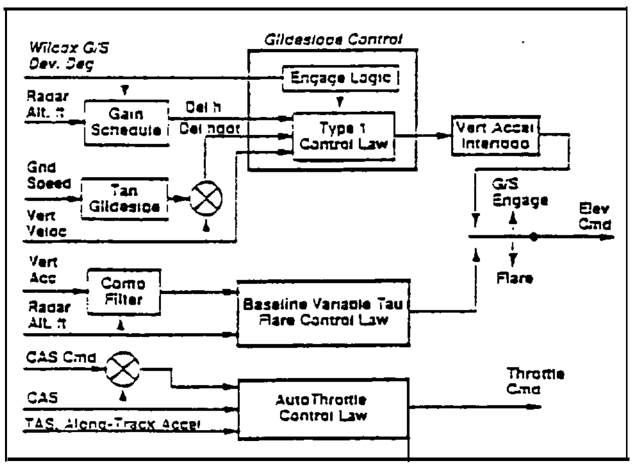

Figure 5 - TSRV Longitudinal Autoland System

The longitudinal potion consists of three control laws: glidesiope, flare and autothrottle.

The localize: and glideslope control laws are both "type 1" control laws in the tracking node. i.e. they use integrators to produce zero tracking error in steady-state conditions.

The TSRV autoland system uses four measurements from the onboard laser-gym IRU. The localizer control law uses inertial ground speed and track angle to compute cross-runway velocity ("ydot") for path damping and complementary filtering of the localizer signal. The glideslope control law uses inertial ground speed and complementary filtered vertical velocity (obtained from the IRU vertical acceleration and barometric altitude measurements) for path damping and complementary filtering of the glideslope signal. The flare law uses vertical acceleration from the IRU and radar altitude to compute a vertical velocity relative to the runway surface. The autothrottle control law uses along-track acceleration to improve calibrated airspeed hold tracking performance.

The TSRV autoland system has several control modes. These modes are localizer capture. glideslope capture. localize: track. glideslope track. decrab, flare and rollout. The decrab mode is engaged at radar altitude of 150 ft and aligns the aircraft heading with the runway heading in the presence of crosswinds. The flare mode is engaged at radar altitude of 42 ft and rollout engages when one of the main gear squat switches is set.

A radar/laser tracker was used co provide a reference position measurement of the aircraft. The fundamental measurements of the tracker are azimuth, elevation and range. The accuracy specifications for the measurements are given as 0.0057 degrees (0.1 mrad) rms for the angle measurements and ±1.5 ft rms for the laser range measurement Boresight measurements obtained on each flight test day showed bias errors in the azimuth measurements varying from -0.011 degrees to -0.012 degrees. The bias errors in the elevation measurements varied from 0.029 degrees to 0.031 degrees. The tracker is located at the Wallops Eight Facility (WFF) on Virginia's eastern shore and has visibility to all of the runways at WFF. The tracker is situated 162.4 ft to the right of runway 28, 1993.7 ft from its threshold. The tracker provides valid measurements up to 2 nautical miles (nmi) in range. Tracker position relative to the runways is shown in Figure 5.

DESCRIPTION OF TESTS

The flight tests consisted of approaches and landings primarily to runways 22 and 28 at WFF. The same flight path profiles were used for each runway and are shown in Figure 7. These paths are typical right and left hand ILS approach and landing paths. The course-cut to localizer

TEST RESULTS

Using the laser tracker as gound truth reference, both navigation sensor errors (NSE) and total system errors (TSE) were measured and analyzed For the 33 autoland approaches and landings. Although the principal intent of the study was to compare TSE with RNP tunnel accuracy requirements. NSE was also examined to determine the effect of the carrier phase smoothing algorithm applied in the ground station to the differential corrections.

Figures 9 and IO show superimposed plots of lateral NSE for 18 autolands to runway 28 and 16 autolands to runway 22. One of the autolands to runway 22 was accidendy aborted near the threshold when the pilot bumped the autopilot disengage button. That approach is included in the Figure 10 plots although it was reclassified as a manual approach. Because of its proximity to the runway, the laser tracker slew rate was insufficient to keep up with the aircraft starting about 500 ft prior to the threshold of runway 28. The consequent loss of valid tracking data in that region is apparent in Figure 9. The path between the loser tracker and aircraft was blocked at several points on the runway 22 approach by airport structures. Figures *10* and 12 have been adjusted to fill these gaps in coverage with interpolation between valid segments on the approach path.

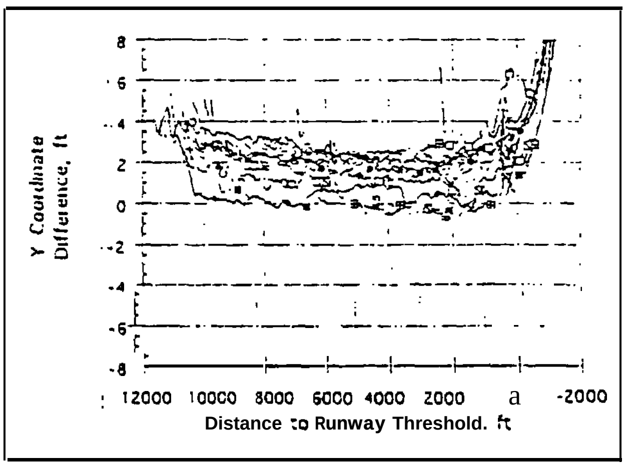

Figure 9 - *Lateral NSE, Runway* 28

Figures 9 and *10* illustrate the effects of the carrier phase smoothing algorithm. The plots show that NSE for any single approach was more constant throughout the approach as compared to previously obtained data for the unsmoothed case[1]. In other words, the carrier phase smoothing as implemented in this system caused the DGPS NSE to look like a slowly varying bias. The overall difference in bias between the two figures is most likely not related to the geometric differences between runways 28 and 22, but rather is the result of most of the

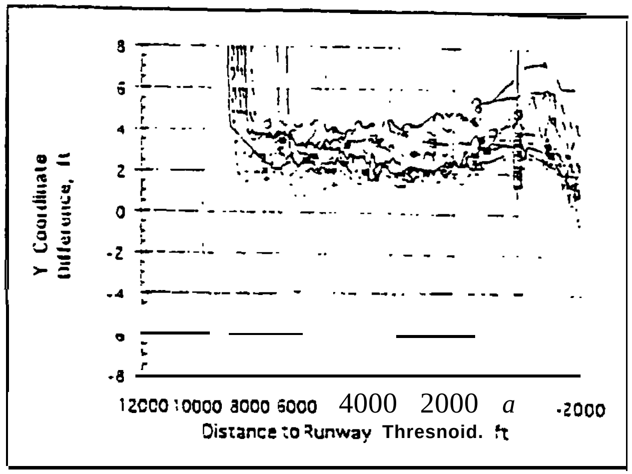

Figure 10 - Lateral NSE. Runway 22

runway 22 landings being flown on the firs: test day and most of 'he runway 28 landings being flown on the second day because of prevailing wind directions.

An NSE that varies slowly is desirable 30 that FTE is not increased as a result of the flight control system trying to follow a flight path containing bends.

Figures 11 and 12 show vertical NSE plots for the same set of approaches. Note that the overall spread in error is larger than for the lateral case, and that there is a corresponding difference in bias between runways 28 and 22.

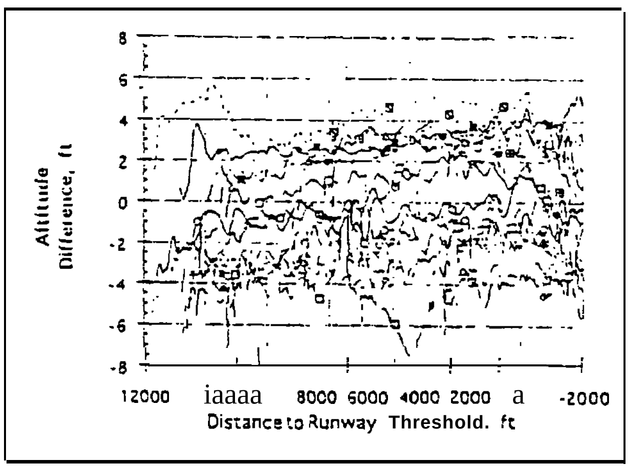

Figure 11 - Vertical NSE, Runway 28

NSE *statistics* were calculated for the point at 150 ft altitude (1800 ft from threshold) for 33 autolands to runways 22 and 28. This point was chosen because it is near threshold, prior to the decrab and flare maneuvers, and corresponds to a segment between laser tracker obstructions on the runway 22 approach. NSE resuits are

RNP zone is defined longitudinally as a total length rather than in half lengths, 4σ was used to estimate the longitudinal dispersion.

	Measured	CAT III RNP Limit
Lateral ($|u|+2\sigma$):	9.3 ft (2.8 m)	27.0 ft (8.2m)
Longitudinal (4σ):	686 ft (209 m)	1500 ft (457 m)

Table 4 - Touchdown Dispersion Statistics

As would be expected, the lateral touchdown dispersion is approximately the same as the lateral TSE measured at the 150 ft height above threshold on me approach path (see Table 3). Table 4 shows that the longitudinal dispersion satisfies the RNP requirement by about a 2-to-1 margin, a larger margin than was seen for vertical TSE at the 150 ft point. This is not surprising, since longitudinal dispersion is affected at least as much by me autoland flare laws and wind conditions as by vertical TSE. A 3-degree glide parh angle is equivalent to a 19-to-1 slope. Therefore, the 3.4 ft standard deviation measured for vertical TSE in these tests translates into only *358* ft *(3.4 x 4 x 19)* of total longitudinal dispersion (95%).

CONCLUSIONS

A C/A code tracking differential GPS landing system, using narrow correlator receivers in rhe ground reference station and avionics, and configured to drive an ILS autoland flight control system with ILS "look alike" deviation signals, successfully guided a Boeing 737 to 31 successful "hands off" landings. No landings were aborted because of equipment failure, and conservative estimates of lateral and vertical total system error fell within Category III RNP tunnel requirements for both the approach and touchdown segments of the landings with substantial margin. The number of landing provided a sufficient sample size to ensure high **confidence in the statistical** *error* estimates.

The TSRV pilots commented that the DGPS approach paths seemed noticeably straighter than what they had experienced with ILS coupled approaches.

ACKNOWLEDGMENTS

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