A Differential Global Positioning System for Flight Inspection of Radio Navigation Aids

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BIOGRAPHY

Dr. Stratton is an engineer with Parker Hannifin Corporation's Gull Electronics Division, a leading manufacturer of avionics and fuel systems. His responsibilities include research and development of avionics navigation systems for flight inspection. His interests include satellite navigation, aircraft guidance and control, and flight safety. He received a B. Sci. degree in Aeronautical Engineering from Rensselaer Polytechnic Institute in 1985, and he received an M.A. in 1989 and a Ph.D in 1992 in Mechanical and Aerospace Engineering from Princeton University.

ABSTRACT

This paper describes a unique application of Global Positioning System (GPS) technology to the flight inspection of radio navigation aids. Ground and flight test results validate that Differential GPS (DGPS) technology can meet the stringent accuracy requirements of flight inspection, including those for Category III landing systems. A unique method of highly-accurate aircraft positioning is described that uses commercial GPS receivers and does not require P-code, the L2 frequency, or ambiguity resolution "on-the-fly." A new generation of portable flight inspection system designs based on this technology can replace cumbersome ground tracking equipment commonly used for flight inspection outside the united States. Flight test results of this paper show that DGPS provides positional accuracy equivalent to the highest-quality flight inspection systems in use today.

INTRODUCTION

The Federal Aviation Administration (FAA) and international agencies perform flight inspection of their radio navigation aids to comply with International civil Aviation Organization (ICAO) requirements [1]. Flight inspection systems require a highly accurate aircraft tracking capability – the system's accuracy must be at least three times more accurate than the navigation aid itself. Over the years, many governments have adopted manually-operated optical theodolites for aircraft positioning which are limited by visibility, turbulence, and *operator performance.* Portable laser and infra-red tracking systems, which offer improved features at higher cost, are used occasionally. With requirements to inspect thousands of radio navigation facilities world-wide, the FAA has abandoned ground-based tracking systems in favor of Automatic Flight Inspection Systems (AFIS). These systems, first developed by Parker Gull engineers in 1973, use on-board Inertial Navigation Systems (INS) and *other airborne* sensors for positioning thereby eliminating weather dependency, visibility limitations, and *ground* equipment [2,3]. Parker Gull AFIS in service with the FAA perform the bulk of all flight inspection in the US. today, and Parker Gull AFIS are used by *several international* governments, including the Japan Civil Aviation Bureau.

Differential GPS technology provides a new alternative for flight inspection that offers many of the advantages of AFIS at lower cost. A DGPS-based Flight Inspection System (DGPS-FIS) employs a ground unit at a fixed location that telemeters GPS measurements to an airborne unit (Fig. 1). The airborne unit uses the telemetered data to correct its on-board GPS measurements, whose errors are highly correlated to those experienced on the ground. Previous research employing specialized dual-frequency GPS receivers and "pseudolites" has shown that DGPS can track aircraft in real time with centimeter-level accuracy [4-7]. systems based on simpler single-frequency receivers with narrow correlator spacing have achieved sub-meter accuracy in real time [8,9]. Differential GPS has been tested for a variety of applications, notably for use in combination with INS for flight inspection [10,11].

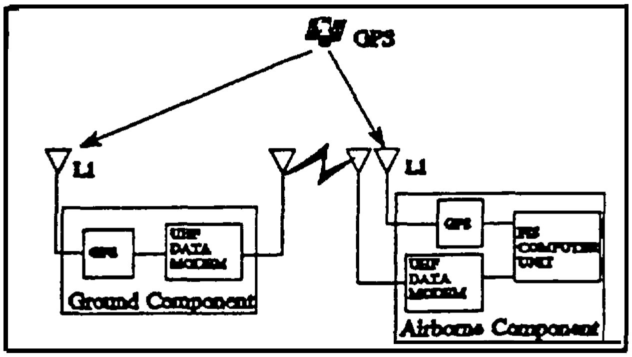

Figure L DGPS-Based Plight Inspection System Configuration.

This paper describes a different approach to highly-accurate aircraft positioning for flight inspection. The approach uses commercial single-frequency GPS receivers, and it provides robust accuracy without INS, laser trackers, or theodolites. This paper presents the results of an independent research and development program that is proving the viability of the DGPS-FIS concept. Flight tests have been performed comparing a prototype DGPS-FIS with dual-frequency survey-grade DGPS equipment and a theodolite tracker. The results establish that the prototype's accuracy clearly is sufficient for flight inspection of Category III landing aids. The high accuracy and portability of this technology make it suitable for a variety of emerging flight inspection requirements [12].

INERTIAL NAVIGATION SYSTEM POSITIONING

The effective use of INS is critical to successfully flight inspecting Instrument Landing Systems (ILS) without ground equipment. The error characteristics of ring laser gyro INS are quite stable, making it feasible to measure its errors in flight [13]. The highest-quality INS error estimates are ma& from position fixes ma& during low-altitude passes over surveyed runway threshold markings. Two such fixes can be obtained as the aircraft is flown over each end of the runway following an ILS approach. Vertical position bii is determined to an accuracy of one ft using a radio altimeter, whik similar accuracy is obtained in the horizontal plane using a camera positioning system (or a manual procedure that provides somewhat less accuracy) [14]. A second fix enables determination of drift rate to approximately two ft per minute. These corrections enable accurate analysis of ILS immediately following the approach

DIFFERENTIAL GPS POSITIONING TECHNOLOGY

A new approach to DGPS derives more from the system's stability (ix., its repeatable accuracy) than it does from absolute accuracy. Parker Gull's approach uses the excellent stability of the *GPS L1 carrier phase* to meet all flight inspection accuracy criteria without INS or ground trackers. DGPS position solutions combii airborne GPS measurements with ground GPS data telemetered to the aircraft as it flies a precision approach. Like the INS solutions of AFIS, the DGPS solutions are improved with the aid of a single runway fix, providing an immediate past-approach evaluation of the landing system. Plight test results have established that this new approach easily meets the required accuracy criteria – in fact, it exceeds them by wide margins. Furthermore, the carrier-phase solutions are immune to multipath and to adverse satellite geometry that affect conventional approaches to DGPS.

Conventional GPS Positioning

The GPS is designed to enable accurate geodetic positioning with a low-cost receiver. GPS receivers lock on to a set of satellites and demodulate their ranging C/A codes, producing range estimates called *pseudo-ranges*. Quality receivers also can provide *accumulated carrier phase* of integrated Doppler measurements that art based on the received phase of the satellite carrier signal. The conventional method for positioning with GPS is to use the pseudo-ranges from four or more satellites to triangulate position and precise time. Because of deliberate errors introduced into GPS as well as secondary environmental effects, the horizontal positional accuracy of the C/A code ranging is limited to about 100 m. GPS can be used alone for inspection of en-route navigation aids, but higher accuracy is needed to provide the accuracy for precision landing aid verification (e.g. for ILS).

Differential positioning provides increased accuracy because errors experienced by nearby receivers are almost identical A receiver fixed at a known position can telemeter pseudo-range corrections to nearby GPS users, or the ground component can telemeter its pseudo-ranges directly to an airborne component that computes the corrections. By using telemetered pseudo-ranges, an airborne system can position with an accuracy of one to three meters in the horizontal plane and two to six meters in altitude, depending on satellite geometry. These code DGPS solutions do not provide sufficient vertical accuracy for flight inspection. Multipath reflections from obstructions near the antennas de-correlate the pseudo-ranges. Multipath can be mitigated by using receivers with narrow correlator spacing but the multiplicative effects of adverse satellite geometry can not be. A more substantial accuracy improvement is obtained by using the accumulated carrier phase measurements.

Carrier Phase Tracking

A GPS receiver accumulates the difference between the phase of the carrier from each satellite and the phase of its local oscillator. **Accumulated** carrier phase can be viewed as a bii **estimate** of the **satellite** to receiver distance, with an unknown integer ***ambiguity*** **(i.e.,** bias) that **equals** the integer number of **19-cm.** wavelengths **from** the satellite to the receiver at the time *of* **lock-on.** If these integer ambiguities can be ***resolved*** **(i.e., determined** exactly), the position solutions are accurate **to a small fraction of the carrier wavelength for as long as the receivers maintain satellite lock. One way to** resolve **ambiguities** is to **make** several **guesses** as to the **correct ambiguity values using pseudo-ranges and single out the correct guess based on successive** measurement **epochs.** The simplest **"static"** resolution methods rquirc that both antennas are stationary during this process. Improved 'On-The-Fly" **(OTF)** ambii **resolution** techniques can work in **real time with one** antenna in motion The most reliable **OTF** methods rquirc **dual-frequency** receivers **[4,5,7]** or GPS-like **transmissions** from ground **"pseudolites" [6].**

Fortunately, flight inspection **does** not **require** these computationally-intensive techniques, **Instead,** the ambiies **can** be **fixed (i.e.,** estimated) at the runway **threshold,** and the stabii of the carrier phase can be used to position backwards from the **fix** point. While incorrect **ambiguity** estimates cause a slight divergence over time, the divergence is at the **sub-decimeter** level over several minutes. On the other **hand,** conventional position **fixes** can be exploited in an (optional) ambiguity resolution process **that,** once **successful,** eliminates the **need** for runway fixes while lock is maintained. Because they do not use the ranging **codes,** tier-phase solutions are **virtually** immune to multipath This also enhances their **capability** to detect GPS multipath errors during flight inspection of GPS **approaches.** Furthermore, carrier-phase degradation is so small that these solutions are accurate even when the satellite **geometry is poor.**

Carrier-Smoothed Code

A hybrid **positioning** approach, carrier-smoothed code, exploits the low noise of the **carrier phase and the long-term accuracy of the ranging codes.** Acarrier-smoothed code solution combines the **carrier** phase and pseudo-ranges using a complementary **filter.** The complementary **filter reduces multipath substantially, and it has no ambiguities to resolve. Carrier-smoothed code solutions have sufficient accuracy to be used with** a radio altimeter to fix the carrier-phase ambii

Laboratory Tests of DGPS

Laboratory test results verify the high level of repeatable accuracy available from the carrier **phase,** and they also indicate the difficulty in relying on code DGPS for flight inspection. Static and **low-dynamic** tests were performed at Parker Gull in April, **1994.** The laboratory test **configuration** consisted of two **NovAtel** Model **951R** GPS installed in two desk-top computers **(Fig.** 2). GPS antennas were installed on the roof of Gull Plant **8,** located on Marcus Blvd., Smithtown, NY.

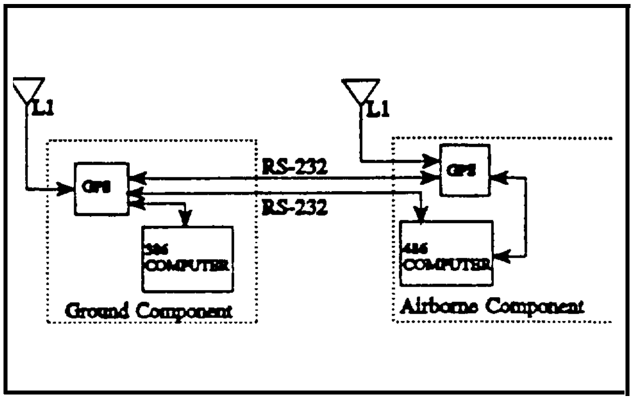

Figure 2 Laboratory Test Configuration.

Static test results for repeatable accuracy of carrier phase DGPS and absolute **accuracy** of code and **carrier-smoothed solutions** are **summarized in** Table L **Centimeter-level** repeatable accuracy was seen for **all tests** of carrier-phase positioning. **Cycle slips (a** potential source of carrier phase error) were not observed during the entire **test** period. Code and carrier-smoothed code solutions were **affected** by multipath **reflections** from nearby air conditioning ducts As later flight test results **confirm,** an accuracy improvement is **gained** when the antennas can be placed away **from obstructions. Figure** 3 compares the relative accuracy of code and carrier-phase solutions in North and East **position.** The code **solutions** for North and East position **(solid** and dashed lines, respectively) exhibit noise **levels** at the meter level. The **centimeter-level errors of the** carrier-phase solutions are not **distinguishable on Fig. 3.**

Test Parameter	Result Obtained (2σ)
Carrier-Phase DGPS Repeatable accuracy	Horizontal 2D: 2 cm Vertical: 3 cm
Carrier cycle slips	Zero slips over 60 min.
Carrier drift rate	6 cm/min worst case
C/A Code DGPS Accuracy	Horizontal 2D: 3 m* Vertical: 4 m*
Carrier-Smoothed Code DGPS Accuracy	Horizontal 2D: 1.5 m Vertical: 2 m*

Table 1. Static Test Results.
("*" indicates quantity not used by Parker Gull system)

Carrier-Phase Circle Test

To test the dynamic tracking capabilities of the carrier-phase solutions, a turntable was positioned on the roof with a GPS antenna mounted 6" from the center of rotation. The second antenna was mounted in a choke ring ground plane 24' away. Carrier-phase measurements were made as the potter's wheel was spun manually. Figure 4 compares the calculated North vs. East position of the moving antenna (each denoted by an "X") with the actual antenna position (the circle). The solution tracks within 2 an throughout the test. Figure 5 contains the time responses. The antenna experienced an average of approximately 1/6 g and a maximum of 1/2 g acceleration during the fastest spin sequence (the last five spins).

Sensitivity to Runway Fix Bias

A sensitivity analysis shows that the accuracy of carrier-phase solutions is not degraded even when the threshold fix is poor. A matrix of solutions was computed with horizontal fix errors of 0, 2, and 4 meters, and with vertical fix errors of 0, 1, and 2 meters. (These are much greater errors than would normally occur). While a bias in the fix causes a corresponding bias in the ambiguity-fixed Solution, no further significant degradations are experienced. Figure 6 presents two-sigma residual drift errors ova a fourteen-minute test period; for the worst case the 2dRMS horizontal position error is 17 cm, while the maximum vertical position error is 24 cm. Thus, an occasional bad fix will manifest itself as a hyperbolic error that is easily identified by an experienced flight inspection technician.

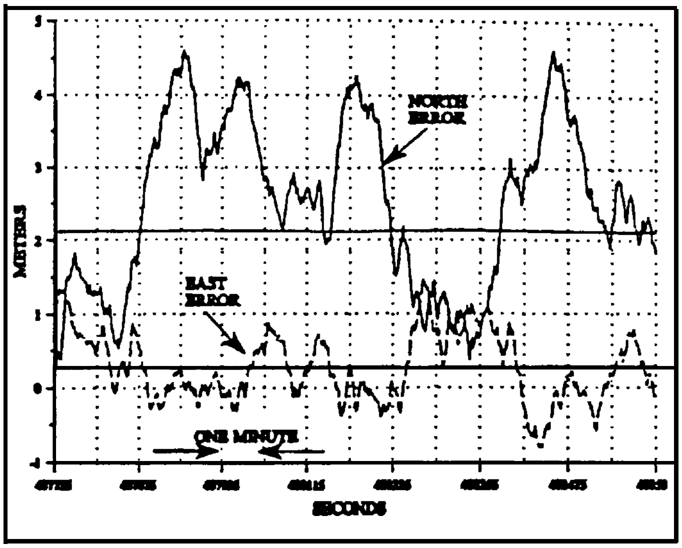

Figure 3. Code and Carrier-Phase DGPS Solutions.

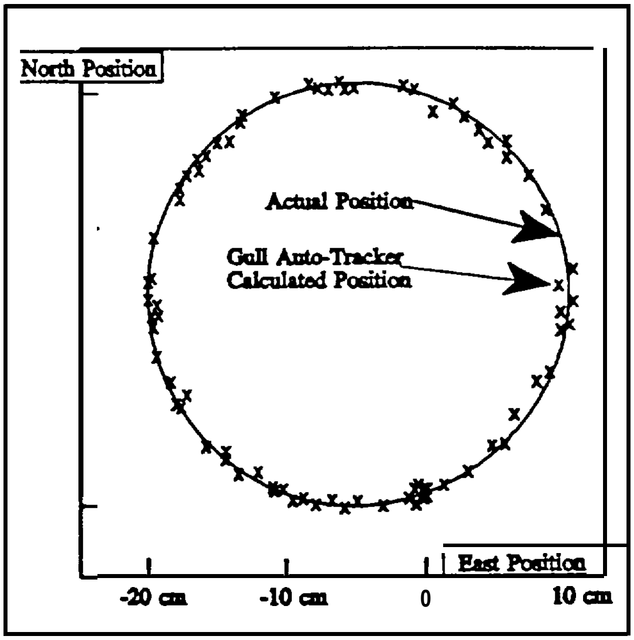

Figure 4. North Vs. East Position for Circle Test.

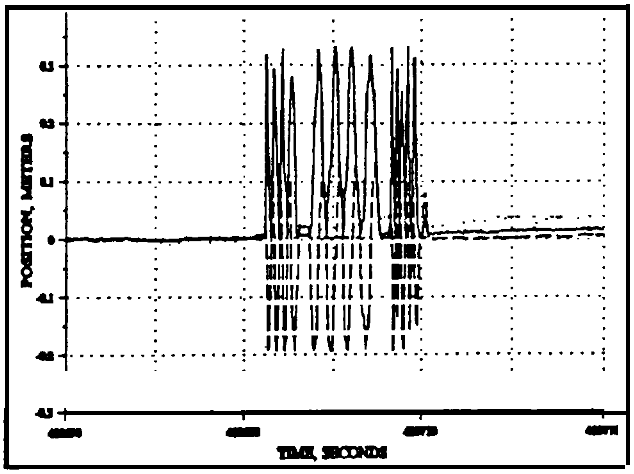

Figure 5. Time response for Circle Test.

DGPS FLIGHT TESTING

A prototype DGPS flight reference system was assembled and flight tested at the Ohio University Airport on September 1-2, 1994. The prototype's airborne module consisted of a 486 notebook computer and docking station containing a NovAtel 951R 10-channel GPSCard and a Synthesized Netlink Radio Data System (SNRDS) provided by GLB Electronics. The ground station consisted of a NovAtel 2151R receiver, 386 notebook computer, and a second SNRDS. The Ohio University Avionics Center (OUAC) was contracted to provide au aircraft, pilot., truth system, and technical assistance for the tests. The Center has a twenty-year history of research, development, installation, and preliminary flight inspection of navigation aids and avionics systems.

DGPS Flight Guidance

For these tests, the Center's Piper Saratoga was outfitted with Parker Gull's prototype DGPS and Ohio University's Interferometric Flight Reference/Autoland (IFRA) system [4], which provided vertical and lateral flight guidance. For the first portion of the tests, the IFRA used data from an Ashtech Z-12 dual-frequency P-code tracking GPS receiver for positioning [5]. For the second portion of the test, the NovAtel receiver in Parker Gull's DGPS provided GPS data to the IFRA for positioning, using a separate ground station set up by OUAC Dr. Bob Lilley, Director of OUAC, piloted the Saratoga through six sets of low approaches to Runway 25. Dr. Lilley noted that the IFRA provided excellent guidance with both configurations. Real-time DGPS solutions were tested, and data was logged for post-test analyses. Figures 7, 8, and 9 present the vertical, lateral, and longitudinal flight profiles.

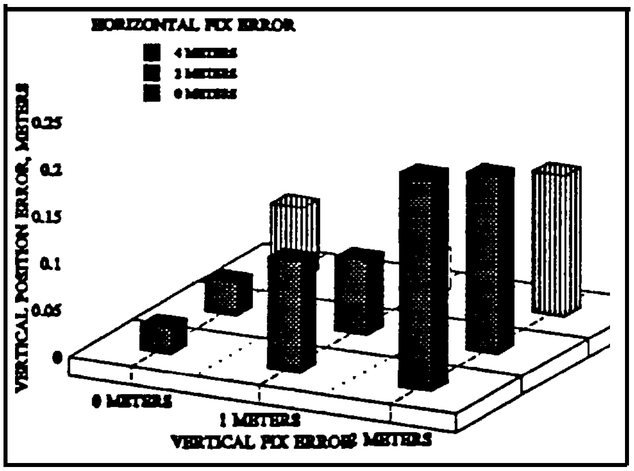

Figure 6. Effect of Large Fix Errors on Ambiguity-Fixed Solutions.

Truth Systems

The OUAC operated two tracking systems to provide truth data: Ashtech Z-12 GPS receivers in the aircraft and on the ground logged data throughout the test period for post-flight DGPS positioning. A tracking theodolite also was operated during some of the approaches. The Ashtech DGPS solutions have been used as the primary source of truth data for the accuracy evaluations of this paper. The Ashtech system has been selected because of its proven high accuracy as well as its continuous tracking capabii. The Ashtech system has been evaluated at the FM Technical Center's laser range, confirming its accuracy to the limit of the laser-tracker's performance (about 1 meter) [5]. Ashtech's PNAV post-processing software provides centimeter-level accuracy by resolving the exact integer ambii in the L1 carrier data. Currently, OUAC is evaluating the tracker data to confirm that good agreement was obtained between the Ashtech DGPS and the tkodolite tracking system. The OUAC uses this theodolite system regularly for Bight inspection of ILS and Microwave Landing Systems (MLS).

ACCURACY EVALUATIONS

Post-processed DGPS solutions of the Parker Gull system have been compared to the Ashtech PNAV solutions. Summary statistics are presented in Table 2 Overall accuracy (2uRM.S for all statistics) of carrier-smoothed code solutions is 0.75 meters cross-track and 03 meters along-track. Along-track error is somewhat smaller because GPS geometry is more favorable in the East-West direction. Accuracy of ambii-fixed carrier phase solutions over a two-minute propagation the is equal to the fix bias plus a few centimeters. Figure 10 presents the composite residuals of carrier-smoothed

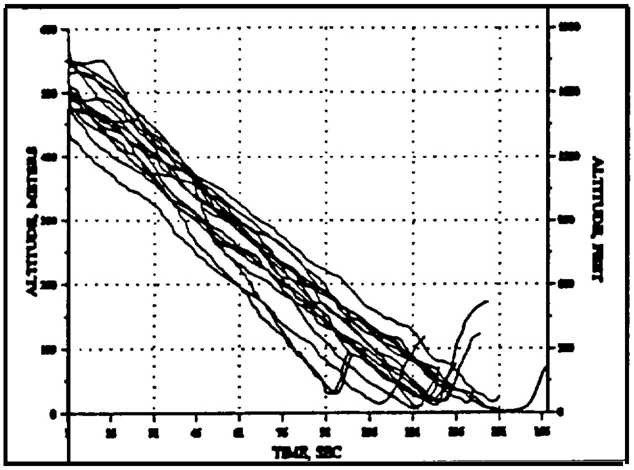

Figure 7. Composite Vertical Flight Profiles.

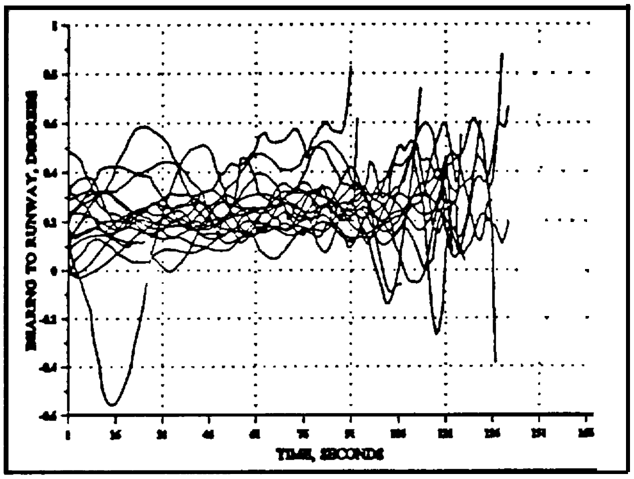

Figure 8. Composite Lateral Flight Profiles.

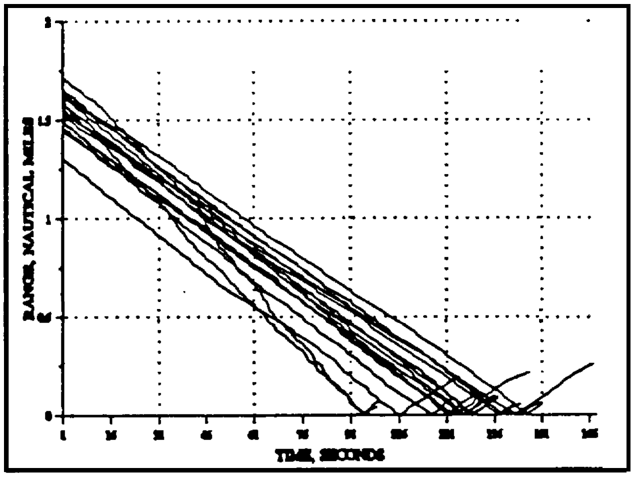

Figure 9. Composite Longitudinal Flight Profiles.

code solutions in cross-track direction. Figures 11 and 12 present composites of the change in residuals of the carrier-phase solutions in cross-track and vertical directions, respectively. The worst-case drift in the vertical carrier-phase solution over sixteen runs is 13 centimeters, which occurs at 1.5 nm from the threshold. Even with a one-ft radio altimeter bias added, this represents an error of 0.01' -- equivalent to the best tracking systems in use for flight inspection today.

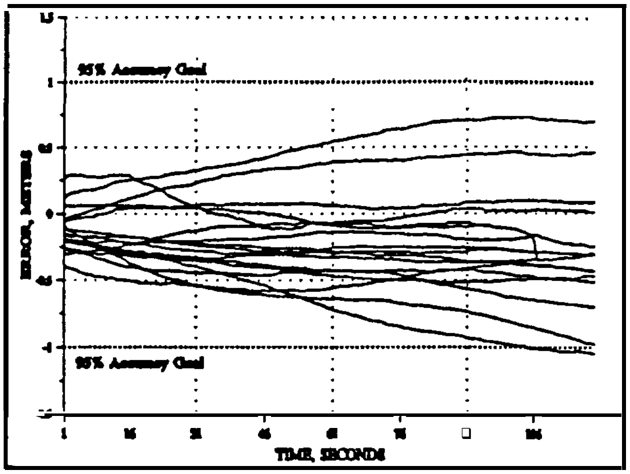

Figure 10. Composite Cross-Track Error of Carrier-Smoothed Code Solutions.

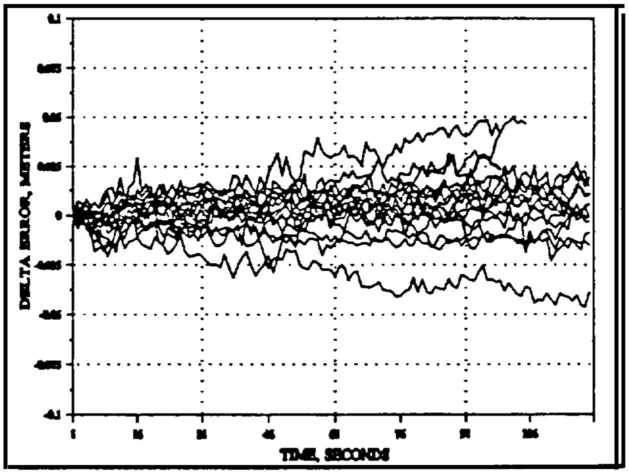

Figure 11. Composite Change in Cross-Track Error of Carrier-Phase Solutions.

As a robustness test of the ambiguity-fixed solutions, a solution is initialized with a one-meter vertical bias *(far greater than* is normally experienced). *The* carrier-phase solution is propagated over a six-minute period consisting of a downwind turn, outbound flight, turn on final, and return to the threshold (Fig. 14, altitude is shown as a dotted line). Upon return to the threshold, the solution has drifted by only ten centimeters (Fig. 14). This indicates that the receiver maintained continuous lock on the carrier phase throughout the maneuver. It also suggests that repeated runway fixes may be unnecessary for a DGPS-based flight inspection system once the ambiguities have been resolved.

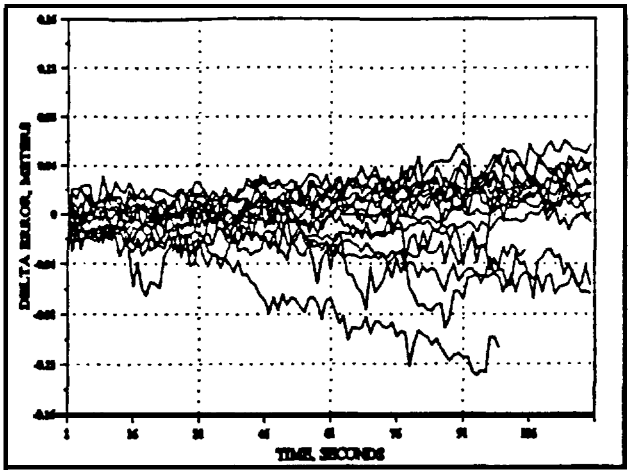

Figure 12. Composite Change in Vertical Error of Carrier-Phase Solutions.

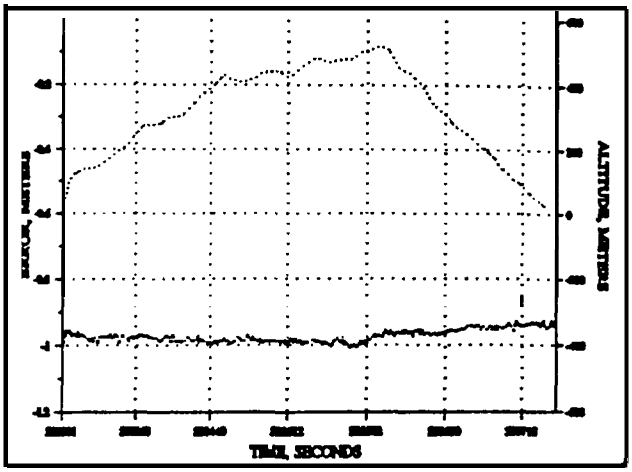

Figure 13. Robustness of Vertical Carrier-Phase Solution to One-Meter Initial Fix Error.

Solution Evaluated	**Cross-track** 2σ accuracy	**Along-track** 2σ accuracy	vertical 2σ accuracy	**Worst-case** cross-track **error**	**Worst-case** vertical error
Carrier-Phase	**Fix + 2 cm**	**Fix + 3 cm**	**Fix + 6 cm**	**Fix + 5 cm**	**Fix + 13 cm**
Carrier- smoothed code	0.75 m	030m	**1.8 m***	1.07 m	1.87 m*
Code*	1.47 m*	0.63 m*	**2.52 m***	211 m*	3.95 *

Table 2 Static Test Results.
("*" indicates quantity not used by Parker Gull system)

CONCLUSIONS

Taken together, these results confirm that differential GPS can meet all flight inspection requirements, without inertial systems or survey-gade equipment. A new approach to precise positioning offers considerable operational advantages compared to theodolites and lasertrackers. Once a base station is established near the airport under inspection, a DGPS-based FIS can provide the same capabilities as a fully-automatic flight inspection system. Combining DGPS with established runway fix procedures greatly increases the system's robustness over conventional DGPS techniques, particularly when the satellite geometry is sub-optimal. In combination with established fix procedures, a DGPS-FIS can compute position accurately without any use of ranging codes. This independence can be exploited by a new generation of portable tracking systems designed for flight inspection of global navigation satellite systems.

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