ACCURATE POSITIONING IN A FLIGHT INSPECTION SYSTEM USING DIFFERENTIAL GLOBAL NAVIGATION SATELLITE SYSTEMS

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BIOGRAPHIES

Cecelia Feit (Member, IEEE and ION) joined Sierra Research, now a Division of Sierra Technologies, Inc.,in 1983, as a software engineer, and has worked on Radar Bomb Scoring, Station Keeping Equipment, Situational Awareness Avionics, and Flight Inspection. Currently, she is the lead software engineer on Position Estimation for the Flight Inspection System product line and principal investigator of DGNSS applications for special mission aircraft. She is a member of RTCA Special Committee 159 - Minimum Operational Performance Standards for Airborne Navigation Equipment Using GPS.

Martin Bates instructed mathematics at Union College from 1949-1950, and then joined Bell Aircraft Corporation as a Dynamic Analyst. His principal assignments at Bell Aircraft involved development of Ship Motion prediction algorithms and measurement and analysis of ship motion spectrum information. Mr. Bates joined Sierra Research, now a Division of Sierra Technologies, Inc., as Chief Analyst in 1958. He has participated in the design and analysis of Flight Inspection, Stationkeeping, TACAN, Radar, Collision Avoidance Data Link, Ship Motion Instrumentation and Aircraft Landing Systems. He is a co-author of several patents.

ABSTRACT

The purpose of a flight inspection system is to calibrate and evaluate the performance of aircraft navigation and landing aids to ensure conformance to specifications. This mission requires that the flight inspection platform have a reference position estimate significantly more accurate than that of the facility under inspection, i.e., tenths of meter accuracy over a region of many kilometers, in a dynamic environment. Differential Global Navigation Satellite Systems (DGNSS) have the accuracy potential to be used in real time for ICAO Category III final approach flight inspection. However, this requires that the residual pseudorange errors be very small, and that the values of HDOP and VDOP be appropriately constrained.

This paper presents the results achieved by employing several different position estimation techniques for estimating aircraft position during flight tests of an airborne flight inspection system in the final approach mode. These techniques use DGNSS measurements integrated with an Inertial Navigation System (INS), and alone. Measurements from GPS receivers which employ narrow correlator spacing and carrier-phase tracking techniques are used as an update source to a Kalman filter and as inputs for a nonlinear least squares estimation of aircraft position. The accuracy results show that DGNSS-based position estimate techniques are capable of meeting ICAO requirements for flight inspection of even the most stringent category of precise landing aids.

INTRODUCTION

The purpose of a flight inspection system is to calibrate and verify the performance of aircraft navigation and landing aids. All data necessary to assess the operational status of a facility are collected and processed during specific aircraft flight profiles in the vicinity of the facility under inspection.

Previously delivered Sierra Automatic Flight Inspection Systems (AFIS) have been designed to carry out airborne flight inspection independently of ground-based position sensing equipment such as theodolites, specially erected marker lamps, or laser trackers. This significantly eases the flight inspection task and greatly improves flexibility and efficiency. The smoothed aircraft position estimates from these systems, which have proven Category III accuracy (references 1 and 2). rely on an airborne video camera that provides precise horizontal position relative to the threshold stripes at each end of the runway. These camera positions are computed within seconds of overflight and, together with vertical

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measurements from a laser altimeter and inputs from a Honeywell Laseref Inertial Navigation System (INS), are sent 10 a Kalman filter and associated Bryson-Frazier smoother (reference 3) to provide accurate position estimation in flight.

Despite the obvious value of a system design that requires no ground equipment that is specific to flight inspection, there is an associated cost. This is the requirement that each pass must consist of low level flight over the entire length of the runway. It is believed that, in order to avoid overflight of the whole runway, some flight inspection agencies will relax the requirement precluding ground equipment and will permit deployment of a GNSS reference receiver and associated data link at an accurately surveyed point near the facility. Should this requirement be relaxed, the camera system can be supplemented or replaced by a high accuracy Differential GNSS system. The DGNSS system would eliminate the need for departure end overflight and would maintain. or even improve, system accuracy. This possibility for a ground-based system has motivated an evaluation by simulation (reference 4) and flight test of DGNSS in flight inspection.

This paper describes the results of flight tests which were performed at the Niagara Falls International Airport in the summer of 1993 using NovAtel 2151R GPS receivers. These receivers employ narrow-correlator spacing techniques and are capable of carrier tracking (reference 5). Two DGNSS techniques were evaluated and compared with the smoothed aircraft position described above. Analysis shows that all three techniques meet the ICAO accuracy requirements for flight inspection of Category III facilities.

FLIGHT INSPECTION ACCURACY REQUIREMENTS

The most critical flight inspection accuracy requirements involve checking the alignment and displacement sensitivity of high precision (Category III) Instrument Landing Systems (ILS). The alignment values are defined as the average angle from the glide path or localizer antenna to the aircraft, when the ILS signal indicates that the aircraft is on course on path. The ILS alignment errors are defined as the average differences between the instantaneous Iocalizer or glide path angles defined by the ILS receiver and the true angles, measured from the relevant ILS antenna on the ground. Displacement sensitivity is a measure of the scale factor of the associated ILS signal (microamps per degree). Measurement of the glide path displacement sensitivity requires tighter angular accuracy than measurement of glide path alignment.

The flight inspection system must monitor the received signals and estimate the position of the airborne ILS antennas in order to compute the true angles 10 the yound antennas, and thus determine the average angular difference. The averages are computed over specified inspection regions as the aircraft attempts to follow the US signals.

The International Civil Aviation Organization (ICAO), empowered by treaty 10 define system accuracy specifications and flight inspection standards, has specified three categories of ILS runways. These three categories (I, II, and III) permit landings under successively worse conditions of ceiling and visibility, and achieve their purpose by providing successively more accurate signals in space. The accuracy requirements for flight inspection also become more demanding as the specified facility accuracy requirements are tightened. The most demanding accuracy requirements are imposed for inspecting performance of Category HI ILS runways, specifically for verifying the glide path and localizer alignment and the displacement sensitivity.

ICAO requires the inspection device to have a two-sigma (95%) error that is not more than one third of the specified ILS alignment accuracy. The overall one sigma flight inspection angular accuracy requirements are summarized in paragraph 6.1.6 on pp 59-60 of reference 6. These values are provided for a typical glide path angle of 3” with a 4000 meter separation between threshold and the localizer antenna Since that tabulation lists the combined receiver and positioning errors, they must be divided by the square root of two to define the error allocated to the positioning device. The result is then doubled to define the 95% probability values shown in Table I.

TABLE I

95% (TWO SIGMA) FLIGHT INSPECTION ACCURACY REQUIREMENTS IN DEGREES

	Cat I	Cat II	CatIII
Localizer Alignment	0.042	0.028	0014
Localizer Displacement Sensitivity	0.035	0.035	0021
Glide Path Alignment	0.063	0.063	0035
Glide Path Displacement Sensitivity	0.028	0.021	0.014

DIFFERENTIAL GPS OVERVIEW

This flight test program employed the Differential GPS (DGPS) component of DGNSS. DGPS is an enhancement of the U. S. Department of Defense’s Global Positioning

System through the use of differential corrections to the basic satellite measurements from the user's receivers. This DGPS approach to flight inspection uses measurements from a receiver in the flight inspection aircraft and corresponding measurements from a second GPS receiver at a location that has been accurately surveyed relative to the flight inspection facility (e.g., the glide path and localizer antennas) to be inspected.

In the current tests, an all-in-view receiver at the reference site extracts signals from all visible satellites and measures the pseudorange to each. Since the satellite signal contains information on the precise satellite orbits and the reference receiver knows its position, the true range to each satellite can be computed. By comparing the computed range and the measured pseudorange, a correction term can be determined and used to correct each associated pseudorange measurement in the aircraft (reference 7).

The main advantage of employing DGPS as opposed to stand-alone GPS arises from the improved accuracy that can be achieved through use of this relative navigation technique. In particular, those GPS error components that are common to the two sets of satellite-to-receiver links either disappear or are significantly reduced, especially when the two GPS receivers are in close proximity. These errors include range variations introduced by selective availability, atmospheric propagation delays, satellite clock errors, and ephemeris errors (reference 8). Differential corrections can reduce navigation errors from 100 meters (95%) to one meter or less, depending on receiver accuracy and distance from the reference station.

SURVEYING ACCURACY CONSIDERATIONS

A particular problem that governs the attainable accuracy of DGPS measurements is the positioning (survey) accuracy of the reference GPS receiver relative to the landing aid under inspection. The first order effect of any such survey bias error is a corresponding equal shift in the apparent location of the GPS receiver in the flight inspection aircraft and, hence, in the relative coordinates of the navigation aid. The effect of such a bias error on alignment accuracy has been calculated. A one meter offset (bias) in vertical position results in a 0.0147 degree shift in the measured elevation angle over the ICAO-specified inspection region. Similarly, a one meter shift in cross runway position yields an azimuth angle shift of 0.0134 degrees for a Category I runway, 0.0153 degrees for a Category II runway, and 0.0198 degrees for a Category III runway. These different impacts are due to the varying inspection regions associated with the three ILS categories. This analysis emphasizes the need for surveying the location of the reference receiver lo decimeter accuracy relative to the landing aid under inspection. Such survey accuracies are most readily attained if the reference GPS receiver position is within a few miles of the landing aid.

Note that the effects of along runway bias errors on the glide path (elevation) angle are reduced by the descent geometry. For a three degree descent angle, a one meter along runway bias error results in an elevation angle change of 0.00077 degrees. The impact on the localizer (azimuth) angle is almost negligible, since the aircraft is nominally on the runway centerline.

Displacement sensitivity requires subtraction of two angles. Because of the near linearity of the arctangent for small elevation angles, the first order impact of the bias term disappears, and the effect of bias is very significantly reduced.

FLIGHT- TEST PROCEDURE

Tests of the flight inspection system's performance were conducted at the Niagara Falls International Airport during July and August, 1993. The aircraft was a Cessna Citation jet aircraft with Sierra's AFIS installed. Final approaches were flown and relevant flight inspection data were saved to magnetic tape during these approaches. Additionally, NovAtel GPS data were logged in the aircraft and at the reference station. All DGPS processing was performed using these recorded data.

The aircraft installation included a NovAtel GPS antenna located at a precisely defined point, a NovAtel Model 2151R GPS Receiver, a NovAtel evaluation kit, and a Grid laptop personal computer which was able to log GPS data The antenna was not permanently installed in the aircraft since these tests were performed on a noninterference basis. Instead, it was located on the glare shield, tight against the windshield, near the right edge of the cockpit. The GPS data logged in the aircraft included the pseudoranges, the satellite positions, the GPS position solutions, the clock error estimates, and the dilutions of precision (DOP). These data were logged at a 1 Hz rate, except for the DGP message, which was logged whenever it changed.

Sierra's flight inspection computer was installed in the aircraft, and the flight inspector saved data to magnetic tape for each profile. These data included time-tagged, smoothed aircraft position data that were to be used as a reference; raw INS data including velocities, accelerations, and attitude; and UTC time and system time at interrupts for synchronization.

The reference GPS installation included a NovAtel

GPS antenna at a surveyed location on the roof of building SO7 at the Niagara Falls Air Reserve Base adjacent to the airport The antenna was installed inside a choke ring ground plane in order to reduce multipath. The reference site is approximately 1.1 km from the threshold of runway 2SR as shown in figure 1. A NovAtel Model 2151R GPS Receiver, a NovAtel evaluation kit, and a Toshiba laptop personal computer that was able to log GPS data were nearby on the roof. The GPS data logged at the reference station included the pseudoranges, the satellite positions, and the clock error estimates. These data were logged at a 1 Hz rate.

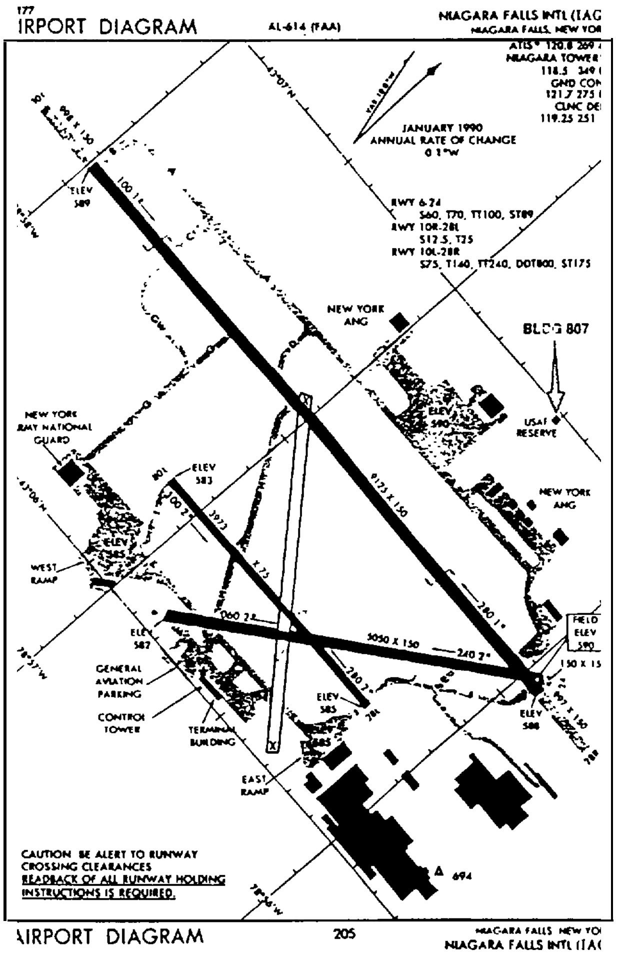

Figure 1. Map of the Niagara Falls International Airport

Data were logged during a number of ILS approach profiles on several different days. Position and average angle data from seven of these profiles have been extracted and compared. The results confirm the accuracy of each of the three position estimation techniques that were employed.

During each profile, the aircraft approached runway 2SR at the Niagara Falls International airport from the east, at a speed of about 150 knots. Data were recorded from a range of about 15000 meters before the runway threshold to about 3700 meters past threshold. The aircraft flew level at an altitude of about 540 meters AGL until the glide path was intercepted, then followed the glide path to a point above the runway threshold. There, the aircraft flew nearly level at an altitude of about 1.5 meters AGL until runway end, where the pilot started to climb, Although the pilot tried to follow the localizer signal to maintain the aircraft on the runway centerline. there was some cross runway wander.

Table II shows the overall geometric dilution of precision (GDOP), the horizontal and vertical dilutions of precision (HDOP and VDOP), and the number of satellites jointly tracked and used for differential GPS updates on seven approaches flown in August, 1993. Seven to eight satellites were continuously tracked in the aircraft and six to seven were continuously tracked at the reference station, however, only about five or six of the same satellites were **tracked by** both receivers simultaneously.

TABLE II

SATELLITE GEOMETRY

Profile	GDOP	HDOP	VDOP	#Sat
040806	2.5	1.2	1.5	7-6
000827	2.7	1.2	1.9	6
010827	3.5	1.5	2.6	5
020827	3.1	1.5	2.1	5
030827	2.5-9.5	1.4-6.8	1 .S-5.0	5-4
040827	3.8	2.2	2.4	5
050827	3.6	1.6	2.7	5

The plot in figure 2 shows the azimuth and elevation of the satellites tracked in profile 040827. The radial coordinate represents elevation: a satellite at the outer edge of the chart is at the horizon and one at the center is directly overhead. Although eight satellites were visible during this time, satellite #I3 was not tracked in the aircraft, probably due to antenna location, and satellites #17 and #26 were not tracked at the reference station, probably due to their low elevation angles and the antenna choke ring ground plane. It is expected that a permanent top-mounted antenna installation on the aircraft and elimination of the choke ring at the reference station will permit at least five satellites to be jointly tracked almost always. Of course, some problems may be anticipated if the line of sight from the reference antenna is blocked by mountainous terrain or tall buildings in the vicinity.

FLIGHT TEST ANALYSIS

Three different techniques were used to generate estimates of aircraft position versus time: the smoothed

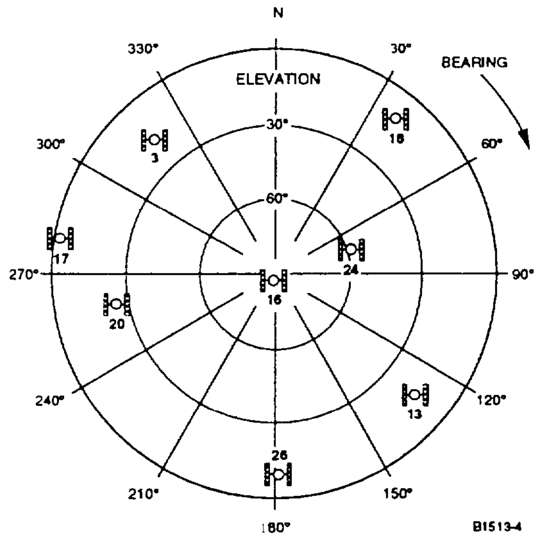

Figure 2. Satellite Bearing and Elevation

aircraft position estimate, DGPS integrated with INS (DGPS/INS), and a nonlinear least squares DGPS solution.

The smoothed aircraft position data are those currently used in Sierra's Automatic Flight Inspection System. They are computed by a Kalman filter that integrates the INS acceleration and attitude information and inserts corrections based on airborne camera scanning of the runway markings and on laser altimeter measurements of aircraft height over the runway. The resulting data are corrected by a modified Bryson-Frasier smoother immediately post profile. Since these data have been previously flight tested and have demonstrated sufficient accuracy for Category III ILS inspections, they are used as a reference for the performance of the other positioning techniques.

The DGPS measurements are integrated with INS data using a Kalman filter that models errors in three positions, three velocities, three attitudes, three accelerometer biases, three gyro biases, user clock phase and frequency, and pressure altitude. The Kalman filter implementation is a U-D factorized Kalman filter, described by Bierman (reference 3), which has the advantageous property of superior numerical stability when compared with conventional implementations. INS acceleration data are integrated to compute the aircraft position. The differentially corrected GPS range measurements are used to generate updates, mapping matrices and measurement variances to the Kalman filter. The measurements for DGPS range updates are the differences between a range computed from the satellites to the estimated aircraft position and the differentially corrected pseudorange measurements (as described in the DGPS Overview). INS attitude data are employed to convert from the aircraft GPS antenna location to the appropriate airborne ILS antenna location.

The nonlinear least squares technique of DGPS positioning computes a solution for aircraft location based on the range and satellite location data provided by the airborne receiver after inserting corrections based on the corresponding data at the reference receiver. This algorithm can employ corrected satellite range estimates from four or more satellites to extract three orthogonal aircraft position coordinates plus a receiver clock error term, Comparison of computed and measured ranges to each satellite provides correction terms for aircraft position coordinates. The solution is iterative, but convergence is rapid when a fairly good initial estimate is provided. The nonlinear least squares technique was derived and summarized in a Sierra Research document, reference 9. Aircraft attitude information is again employed to align coordinate systems.

The difference between the nonlinear least squares technique and the DGPS/INS technique is that nonlinear least squares solves for the actual position coordinates of the GPS antenna, while the DGPS/INS technique employs the range errors to estimate the errors in the INS. Continued good solutions are available from the DGPS/INS technique even if DGPS updates are missed for a moderate time.

Carrier phase data were available from the NovAtel receivers, and use of these data was investigated in both the DGPSANS solution and the nonlinear least squares solution. Carrier data was used to extrapolate range from an initial value, and also to smooth the pseudoranges. In general, the results were less noisy, especially in the nonlinear least squares solution, but the accuracy varied for each profile depending on the accuracy of the initial pseudorange and the amount of extra carrier smoothing employed. All the tables and plots in this paper use pseudorange data with no additional carrier smoothing.

ACCURACY VERIFICATION METHODOLOGY

It is essential to verify the perfomrance of a flight inspection system before employing the system for facility inspection. Ideally, the verification involves use of an even more accurate position-determination technique than the one that is employed for flight inspection. As the flight inspection accuracy improves, the requirements on the verification process grow as well. This can pose a technological and financial problem for the equipment manufacturer and its customers. An alternate approach to such verification is to employ two high quality position-determination techniques with independent error sources, and accept the accuracy of a candidate technique when the two results differ by a sufficiently small amount. Since the statistical magnitude of the difference between independent readings is the root sum square of the individual errors, the process reflects the error in both systems. If the root sum square error is acceptable, each system error statistic must be acceptable.

The flight test analysis used this alternate approach in comparing the two different DGPS estimates with the smoothed aircraft position estimates. The errors in the nonlinear least squares position estimates are entirely due to DGPS and to aircraft maneuvers during interpolation. For the DGPS/INS solution, the INS acts primarily as a high quality interpolator that compensates for aircraft maneuvers; any residual drift has very little impact on the position estimation errors. The residual errors are therefore also due almost solely to DGPS. Close agreement between these two solutions verify this primary dependence on DGPS. In the case of the smoothed aircraft position data the errors depend primarily on the accuracy of the camera and laser altimeter updates that correct the residual INS drift. Therefore, these error sources are independent of the DGPS errors.

When comparing two systems, if the anticipated error statistics for either of the systems is known, the corresponding error of the second system can be deduced after subtracting the square of the known statistical error term from the square of the corresponding statistic of the difference between the two outputs. In any case, the error statistics for each of these position estimates is less than the error statistics of the difference values. The accuracy of the SMOOTHED position estimate was verified earlier by comparison against a laser tracker at Wright Patterson Air Force Base. This provides an upper limit on the coordinate error statistics for the smoothed aircraft position data. If the error statistics for the difference signal are less than the specified flight inspection error values, both systems are acceptable.

FLIGHT LNSPECTION ACCURACY

The DGPS/INS and smoothed position data were available 10 tunes per second while the nonlinear least squares data were available once per second. The nonlinear least squares solution was linearly interpolated to achieve the higher data rate for comparison.

The plots in figures 3 and 4 compare the DGPS/INS and nonlinear least squares solutions, respectively, with the smoothed aircraft position for profile 010827 from the outer marker (Point A) to the departure or stop end of the runway (Point S). Tick marks show when the aircraft was over points B, C, D, and the runway threshold, Point T. These points are used to define the different ICAO flight

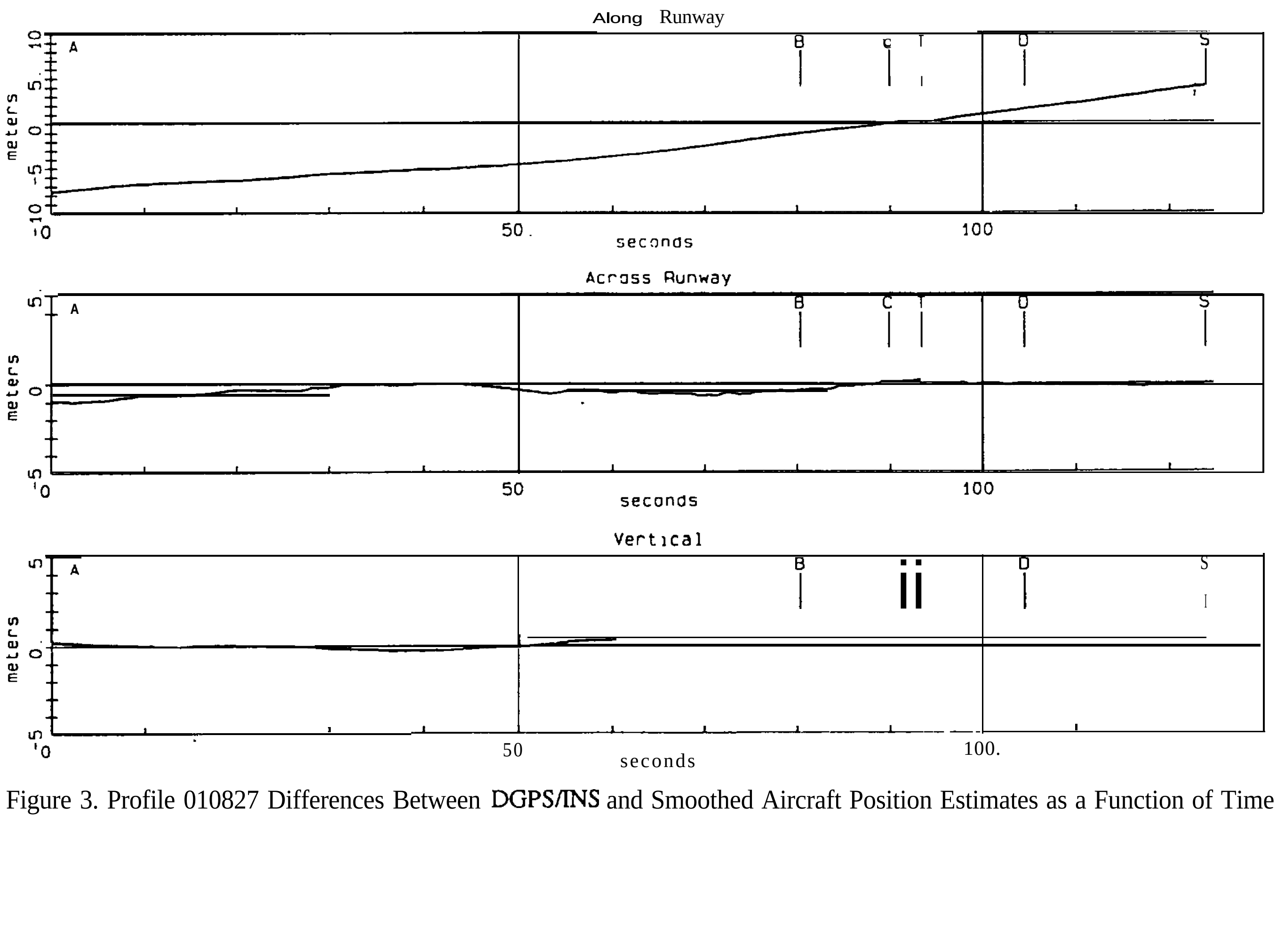

Figure 3. Profile 010827 Differences Between DGPS/INS and Smoothed Aircraft Position Estimates as a Function of Time

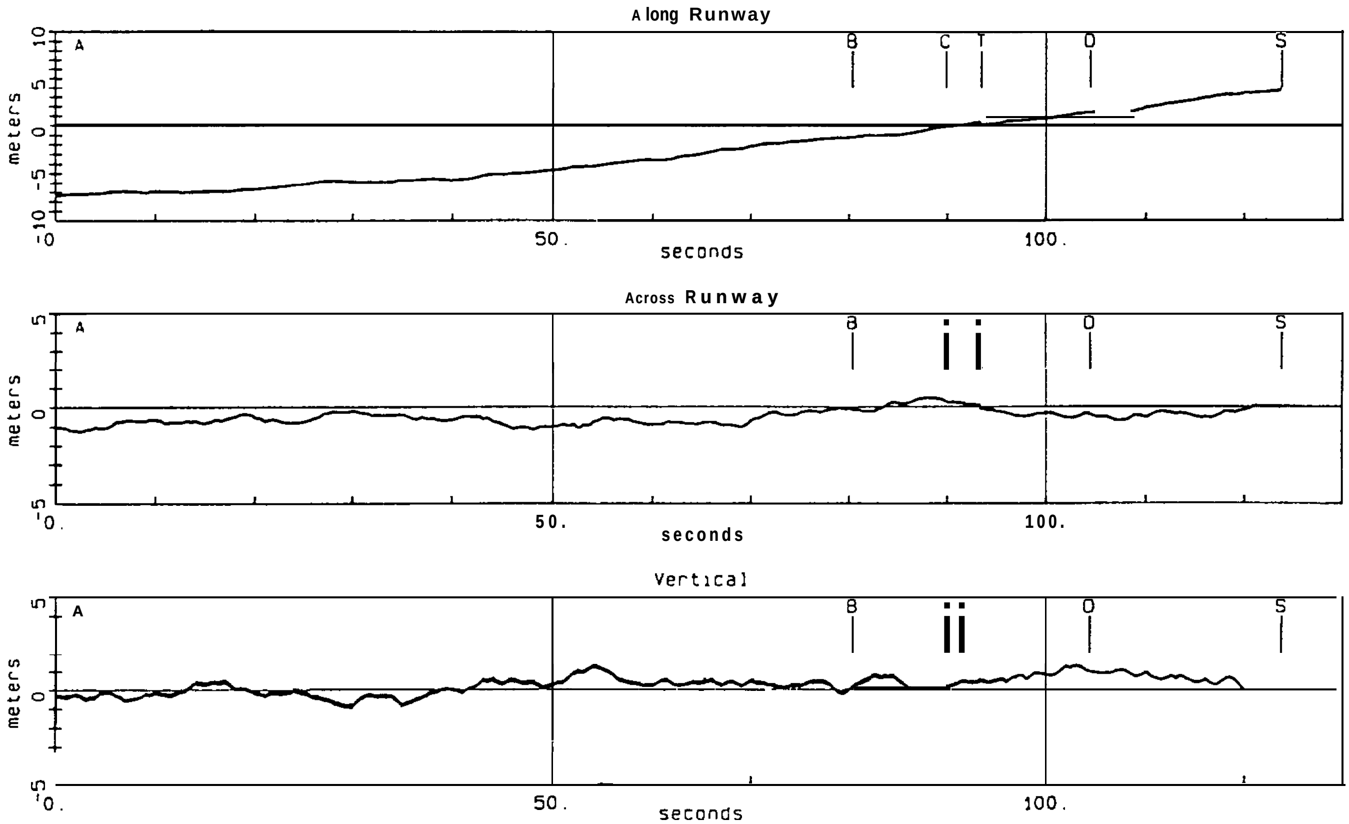

Figure 4. Profile 010827 Differences Between Nonlinear Least Squares and Smoothed Aircraft Position Estimates as a Function of Time

inspection regions. These plots show better than one meter agreement in the across runway and vertical positions. Although the along runway errors are somewhat larger, they can be attributed to the along runway update variations in smoothed aircraft position rather than the DGPS positions, and are well within specifications.

Eight parameters were analyzed: along runway, across runway, and vertical positions, four average bearing angles (three for different localizer inspection regions and one for localizer displacement sensitivity), and one elevation angle (for the glide path alignment and displacement sensitivity inspection region). The differences between the DGPSANS technique and the smoothed aircraft position estimates are presented in Table III. The differences between the nonlinear least squares position estimate and the smoothed aircraft position are presented in Table IV. Again, these differences reflect errors in the DGPS estimate and the smoothed aircraft position estimate, and are greater than the errors in each individual system.

For each parameter, the positive and negative differences of greatest magnitude were tabulated together with the ICAO accuracy requirements. These peak values were combined to extract a median difference value, while half their difference defined a spread, which is an index of consistency.

Excellent agreement was obtained between the DGPS/INS position estimates and the smoothed aircraft position data. All of the tabulated differences are within ICAO specifications. Since at least part of the difference values must be ascribed to the smoothed aircraft position estimate, these difference spreads are consistent with a 0.01 degree uncertainty in both the DGPS/INS and smoothed aircraft position solutions, which is au excellent figure-of-merit for a flight inspection system capable of performing inspections of Category III ILS installations.

Very good agreement was also achieved between the nonlinear least squares position estimates and the corresponding smooothed aircraft position data. However, one absolute azimuth angle difference and one absolute elevation angle difference slightly exceeded the ICAO accuracy specifications. One of the larger absolute differences was observed on profile 030827 where the number ofjomtly tracked satellites intermittently decreased to four. In any event, these differences include both nonlinear least squares and smoothed aircraft position error components. Presuming that the errors are evenly distributed between these two components, the result can be divided by the square root of two, corresponding to an acceptable error in each component.

TABLE III

AVERAGE POSITION AND ANGLE DIFFERENCES: DGPS/INS MINUS SMOOTHED AIRCRAFT POSITION

Profile Number	Position Differences Over Runway (meters) Along	Across	Vertical	Azimuth Differences Over Inspection Region Alignment by Runway Category I	II	III	Displacement Sensitivity	Elevation Glidepath Angle Dif
040806	2.369	0.542	0.302	0.004	0.007	0.011	0.002	-0.003
000827	0.856	0.410	1.318	-0.005	-0.006	0.000	0.000	0.013
010827	1.935	-0.219	0.705	-0.007	-0.002	-0.003	-0.004	0.005
020827	2.718	-0.572	-0.187	0.007	0.008	0.003	0.007	-0.014
030827	2.566	-1.036	-0.143	-0.001	-0.002	-0.012	0.003	-0.003
040827	0.498	0.134	-0.246	0.017	0.011	0.009	0.016	0.000
050827	0.198	-0.467	0.287	0.013	0.010	-0.004	0.015	-0.008
Max Dif	2.718	0.542	1.318	0.017	0.011	0.011	0.016	0.013
Min Dif	0.198	-1.036	-0.246	-0.007	-0.006	-0.012	-0.004	-0.014
Median	1.458	-0.247	0.536	0.005	0.003	-0.001	0.006	-0.001
Spread(t)	1.260	0.789	0.782	0.012	0.009	0.012	0.010	0.014

TABLE IV

AVERAGE POSITION AND ANGLE DIFFERENCES: NONLINEAR LEAST SQUARES MINUS SMOOTHED AIRCRAFT POSITION

Profile Number	Position Differences Over Runway (meters) Along	Across	Vertical	Azimuth Differences Over Inspection Region Alignment by Runway Category I	II	III	Displacement Sensitivity	Elevation Glidepath Angle Dif
040806	2.494	0.468	0.054	0.010	0.012	0.012	0.003	-0.002
000827	-0.307	0.673	0.764	-0.004	-0.006	0.005	0.000	0.018
010827	0.874	-0.379	0.693	-0.001	-0.004	-0.005	-0.004	0.005
020827	1.747	-1.019	-0.501	0.008	0.003	-0.008	0.007	-0.012
030827	0.444	-1.414	0.402	0.002	-0.007	-0.017	0.004	-0.005
040827	-0.767	0.184	-0.455	0.007	-0.002	0.008	0.015	-0.001
050827	-0.583	-0.194	0.306	0.009	0.007	-0.002	0.014	-0.011
Max Dif	2.494	0.673	0.764	0.010	0.012	0.012	0.015	0.018
Min Dif	-0.767	-1.414	-0.501	-0.004	-0.007	-0.017	-0.004	-0.012
Median	0.864	-0.371	0.132	0.003	0.003	-0.003	0.006	-0.003
Spread(*)	1.631	1.044	0.633	0.007	0.010	0.015	0.010	0.015
ICAO Specification - Refer to Table I				0.042	0.028	0.014	0.021-0.035	0.035-0.063[1] 0.014-0.028[2]

[1] Alignment
[2] Displacement Sensitivity

Accuracy and integrity of the DGPS solution are primarily functions of very accurate survey of GPS reference antenna location relative to the ground ILS antenna locations, as described in the Surveying Accuracy Considerations section, and the number and geometry of satellites tracked at both the aircraft and reference station. Several different reasonableness and integrity tests were examined to exclude use of erroneous GPS data. It will be necessary to employ such tests and/or check magnitudes of the residuals (reference 10) in order maintain solution integrity. Besides these tests, GDOP and the number of satellites jointly tracked have been the strongest indicators of nonlinear least squares performance. When five or more satellites were jointly tracked and the GDOP was four or less, there was a small difference between the nonlinear least squares position estimate and the smoothed aircraft position estimate. Such relevant DGPS performance information will be supplied to the flight inspector as an index of solution reliability.

ADVANTAGES OF THE ALTERNATIVE APPROACHES

The current smoothed aircraft position estimation technique provides an excellent reference for flight inspection. Accuracy is highly dependent on laser altimeter, camera, and attitude-sensor performance in determining aircraft antenna coordinates relative to the runway markings, In addition, a high quality INS must be incorporated in the inspection aircraft to ensure adequate positioning accuracy. The major advantage of this technique is its freedom from additional ground aids. The major disadvantages of the system are initial cost, need to overfly both runway ends, and need to observe the runway markings from the aircraft. Use of the camera implies reasonable viewing conditions, which inhibits flight inspection activities when snow covers the runway ends, or when ground fog intervenes.

The DGPS/INS technique can provide excellent accuracy, even when fewer than five satellites are jointly tracked at the aircraft and reference sites. Integrating DGPS with INS takes advantage of the reliability and continuity of the INS and the high accuracy of DGPS. The approach does not require overflight of both runway ends or flight inspector intervention to make sure that the camera has properly selected the point corresponding to the ends of the runway center stripe-s. This approach does not rely on the user organization to control the accuracy of centering of the runway stripes, and does not require optimum visibility conditions for performing critical ILS inspections. INS cost and maintenance are as before. **11** is necessary, however, to position a reference GPS receiver and associated data link at a carefully surveyed location in the vicinity of the airport.

The nonlinear least squares technique shams most of the advantages of the DGPS/INS technique. In addition, it permits the elimination of the INS unit, or perhaps its replacement with an inexpensive attitude sensor for coordinate alignment. Its major advantage is decreased initial and maintenance costs. The disadvantage is that there might be less capability for estimating aircraft position during any intervals of poor satellite geometry.

FLIGHT INSPECTION OF CPS FACILITIES

The policy, techniques and standards for flight inspection of GPS and DGPS approaches are being developed now by the US FAA. The requirements for this mission are to effectively and efficiently verify safe flight operations that are dependent on satellite technology. GPS-based navigation is notably different from conventional navigation. Traditionally, ground-based navaids emanate signals-in-space that provide guidance or navigation through the airspace with a receiver tuned to the guidance signal. GPS, as a positioning system, computes the aircraft position in a geodetic reference system. When another geodetic location, such as a runway threshold or waypoint. is known, course guidance to that location is computed, and the navigation function is accomplished.

The flight inspection mission will not attempt to verify the accuracy of the NAVSTAR GPS satellite constellation since that is the responsibility of the US DoD. For a GPS Non-precision Approach (Stand-alone), the flight inspection requirements include verifying that the waypoints are correctly placed and aligned, validating that the GPS signals-in-space adequately support the instrument flight procedure in the approach environment, and validating that the flight path is operationally safe. For a DGPS Precision Approach, the flight inspection requirements include verifying the integrity of the procedure and waypoints used to develop the flight path, verifying that the GPS, local or wide-area differential data link, and pseudolite marker beacon (if applicable) signals-in-space support the instrument flight procedure in the geographic location, and verifying that the flight procedure is operationally safe (reference 11). A flight inspection system which meets Category III ILS accuracy requirements will be able to meet the accuracy requirements for the flight inspection of GPS and DGPS facilities.

SUMMARY AND CONCLUSIONS

Sierra has conducted simulations and flight tests and has accumulated relevant flight inspection data to permit evaluation of two position estimation techniques, one which integrates DGPS with INS data, and one which uses

DGPS alone for point positioning. The flight test evaluation involved computation and analysis of the differences between the aircraft posi TION coordinate estimates from both DGPS solutions and those provided by Sierra's AFIS smoothed aircraft position, which has been independently tested by the U.S. Air Force, and shown to be accurate to within 0.01" in azimuth and elevation.

Examination of these differences indicates that the smoothed aircraft position, the DGPS/INS system and the nonlinear least squares solution can provide position estimates that are consistent with ICAO specifications over Category III inspection regions. Both DGPS/INS and the smoothed aircraft position are consistent with an even better, 0.01 degree elevation and bearing accuracy over a Category III inspection region. These results also show that the DGPS techniques may be used to verify the performance of camera-based flight inspection systems prior to delivery, or vice versa.

While the achievable angular accuracy is a function of the runway length, all three systems are capable of meeting ICAO and FAA requirements for inspecting all currently installed categories of precise landing aids. Therefore, the DGPS/INS technique or the nonlinear least squares technique can be used at airports where a ground GPS reference system can be deployed in the near vicinity at a carefully surveyed site with an unobstructed view of the satellites. For initial commissioning and conditions of restricted satellite line 'of sight, it may be apporpriate lo use both the camera system and DGPS.

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REFERENCES

1. Feit, C., M. Bates, and B. Scherzinger. "Position Estimation Accuracy of the C-29A Automatic Flight Inspection System." Proceedings of the Sixth International Flight Inspection Symposium. Washington, D.C. June 25-29, 1990.

2. Bates, M. AFIS/Camera Accuracy Analysis, Sierra Research Report, October, 1990.

3. Bierman, G., Factorization Methods for Discrete Sequential Estimation, Mathematics in Science and Engineering Volume 128, Ademic Press. NY, 1977.

4. Feit, C., and M. Bates. "The Use of Diffcrcntial Satellite Navigation Systems in an Automatic Flight Inspection System." Proceedings of the Second International Symposium on Differential Satellite Navigation Systems, DSNS-93. March 28-April 2. 1993. Amsterdam, The Netherlands.

5. Van Dierendonck, A. J., P. Fenton and T. Ford. "Theory and Performance of Narrow Cot-relator Spacing in a GPS Receiver." Proceedings of the Institute of Navipation National Technical Meeting. San Diego, CA. January 27, 1992.

6. Mannual On Testing Of Radio Navigation Aids, Volume II, ILS (Instrument Landing Sysrem), ICAO Document 8071, Third Edition, 1972.

7. Design Document for Differential GPS Ground Reference Station Pseudorange Correction Generation Algorithm. Interim Report DOT-CG-N--03-86, Wright Aeronautical Labs, WPAFB, Ohio, December 1986.

8. Blackwell, E. "Overview of Differential GPS Methods." Global Positioning System, Papers published in Navigation Volume III. Reprinted by The Institute of Navigation, Washington, D.C. 1986.

9. Bates, M. R. "Part 4: An Alternate Derivation Of the Non-Linear (Least Squares) Multilateration Equations." Research/Development Report RDR-0807: Additional ACMR Mathematical Topics. Sierra Research Corporation, July 1970.

10. Parkinson, B. W. and P. Axelrad. "Autonomous GPS Integrity Monitoring Using the Pseudorange Residual." Navigation. Journal Of The Institute Of Navigation, Vol. 35, #2. Summer 1988.

11. Donaldson, E. 'Flight Inspection Policy and Standards for the Global Navigation Satellite System (GNSS). Proceedings of the Eighth International Flight Inspection Symposium. Denver, CO. June 6-10, 1994.