THE USE OF DIFFERENTIAL SATELLITE NAVIGATION SYSTEMS IN AN AUTOMATIC FLIGHT INSPECTION SYSTEM

Cecelia M. Feit
Martin R. Bates

Sierra Technologies, Inc.
Sierra Research Division
P.O. Box 222
Buffalo, New York, USA 142250222

ABSTRACT

This paper presents current and future uses of Differential Satellite Navigation Systems in Sierra Research's Automatic Flight Inspection Systems (AFIS). The purpose of an Automatic Flight Inspection System is to inspect and calibrate ground-based aircraft navigation and landing aids. In Sierra's inertial-based flight inspection system, a square root Kalman filter estimates the navigation errors in real time, and a modified Bryson-Frazier smoother improves these estimates immediately post profile to provide the most accurate aircraft position for calibration of en route and final approach navigation aids.

Current uses of DSNS include performing differential GPS techniques post mission to test the accuracy of the aircraft position estimate during flight tests of Sierra's AFIS installed on a BAe 125-800. These results will be presented. DSNS has the accuracy potential to be used in real time for ICAO Category III final approach flight inspection. This paper will present the results of a simulation and analysis performed to determine the appropriateness of DSNS technology in an Automatic Flight Inspection System.

KEYWORDS

Accuracy
Automatic Flight Inspection
Differential Satellite Navigation Systems
ICAO Category III ILS
Simulation

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INTRODUCTION

The purpose of an Automatic Flight Inspection System (AFIS) is to inspect and calibrate ground-based aircraft navigation and landing aids to ensure performance to specifications. Sierra's AFIS has 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. All data necessary to assess the operational status of a facility is collected and processed during specific aircraft flight profiles in the vicinity of the facility under inspection.

The flight inspection of en route navigation aids, such as VORTAC or DME, and terminal approach aids, such as ILS and MLS, requires the flight inspection platform to have a reference position estimate significantly more accurate than that of the facility under inspection. The accuracy requirement for en route flight inspection is that 95 percent of the total horizontal errors must be less than 100 meters. The accuracy requirement for final approach flight inspection is on the order of 1 meter or less. For more detailed information on Sierra's position estimation technique, see references 1, 2 and 3.

The first part of this paper describes the current Sierra Research AFIS System, which includes GPS updates for flight inspection of en route navigation aids. It also describes the DGPS-based flight test of this en route inspection capability.

Inspection of terminal approach aids requires very high accuracy and is performed with a camera system and laser altimeter in Sierra's current AFIS. The next generation Sierra AFIS must consider a high accuracy Differential GPS or joint GPS/Glonass receiver capable of near real-time flight inspection of Category III terminal approach facilities. The last part of this paper describes the simulation analysis performed to specify the accuracy requirements of such a system.

CURRENT USES OF DSNS IN SIERRA'S AUTOMATIC FLIGHT INSPECTION SYSTEM

The first implementation of Sierra Research's Automatic Flight Inspection System (AFIS) was the C-29A developed for the U.S.A.F. and now in use by the FAA. This AFIS was used extensively during Desert Shield/Desert Storm. The Spanish Air Force received the next AFIS, which included a line scan camera for runway updates. Sierra's first AFIS to use a satellite navigation system (GPS) was developed under contract to British Aerospace for the u-125 Flight Inspection Aircraft for the Japanese Defense Agency.

Flight tests of the U-125 were conducted in order to assess the accuracy of the aircraft position estimate using GPS range updates in the en route facility inspection mode. **The** accuracy requirement for en route flight inspection is that 95 percent of the total horizontal errors must be less than 100 meters. Four five-nMi orbits were flown around the Buffalo VOR facility in July 1992. Five to seven satellites were tracked and HDOP ranged from 1.0 to 1.5 during these flights.

The flight test instrumentation was based cn Differential GPS (DGPS) techniques. A sequential C/A-code GPS receiver was used in both the aircraft and at the reference station. Error analysis consisted of a processing-intensive technique, computed post-flight, to provide the best available estimate of true aircraft position to be used as the reference. The accuracy of this DGPS reference process was proved by performing a calibration over a surveyed point. The total **DGPS** reference horizontal error was less than 4.4 meters 95 per cent of the time. A total of 1755 seconds of one Hz. errors were obtained during flight test. Ninety-five percent of the horizontal position errors were less than 57.8 meters in real time, and 30.6 meters post profile. 95 percent of the post profile total horizontal error is less than 35 meters even if the entire 4.4 meter error in the DGPS reference system is assigned to aircraft error. For more detailed INFORmation on the flight test and the DGPS processing technique, see reference 3.

DSNS IN TERMINAL APPROACH FLIGHT INSPECTION

REQUIREMENTS

The most critical accuracy requirements involves checking the alignment and displacement sensitivity of high precision (Category III) Instrument Landing Systems (ILS). The alignment values are defined as the average differences between the instantaneous localizer or glide path angles defined by the **ILS** receiver, and the true angles, measured from the relevant ILS antenna on the ground. The averages are extracted as the aircraft attempts to follow the ILS signals. The AFIS must monitor the received signals, and must estimate the position of the airborne ILS antennas in order to extract the true angles to the ground antennas, and thus determine the average angular difference. Displacement sensitivity (angle offset to produce a given electronic signal level) gives rise to even tighter angular accuracy requirements in the case of glide path.

The International Civil Aviation Organization (ICAO) requires the inspection device to have a two-sigma (95%) error that is not more than one third of the specified alignment accuracy. The overall one sigma angular accuracy requirements are summarized in paragraph 6.1.6 on pp 59-60 of reference 4, 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 divide 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, as shown in Table I.

TABLE I. ICAO ACCURACY REQUIREMENTS (Degrees)

	One-Sigma Total	Allocated to Position	95% Position Accuracy
Localizer Alignment	0.010	0.007	0.014
Localizer Displacement Sensitivity	0.015	0.011	0.021
Glide Path Alignment	0.025	0.018	0.035
Glide Path Displacement Sensitivity	0.010	0.007	0.014

Previously delivered Sierra AFIS systems, which have proven Category III accuracy, rely on an airborne video camera which provides precision horizontal position relative to the runway stripes at each end of the runway. These camera positions are computed within seconds of over-flight and, together with vertical measurements from a **laser** altimeter, and inputs from a Honeywell LaSeref Inertial Navigation System (INS), are sent to a Kalman filter and associated Bryson-Frazier smoother to provide accurate position estimation in flight. An important requirement driving this system design was that no equipment specific to flight inspection could be placed on the ground. The corresponding cost of this requirement is that each pass must consist of low level flight over the entire length of the runway. It is believed that some flight inspection agencies will relax the requirement precluding ground equipment in order to avoid overflight of the whole runway, and would permit deployment of a GPS reference receiver and associated data link at a very accurately surveyed point near the glide path antenna. This possibility for a ground-based update system has motivated an evaluation, by simulation, **of** DSNS in flight inspection.

SIMULATION

This simulation examines the required Differential GPS (DGPS) ranging accuracy that permits use of the DGPS data for real-time positioning of an Automatic Flight Inspection aircraft. In particular, the accuracy predictions of a system simulation that employs the performance parameters of a Laseref Inertial Navigation System (INS) together with correlated random noise inputs that simulate the range errors to the various satellites that are in view are summarized.

The analysis focused on the impact of the resulting aircraft positioning errors on the estimates of the most sensitive Flight Inspection parameters, glide path alignment and displacement sensitivity and localizer alignment. The reference GPS receiver must be located at a point on the airport property whose location relative to the ILS antennas has been accurately surveyed. Measured pseudorange error data at the reference GPS receiver on the ground are relayed to the aircraft to permit real-time correction of the aircraft's range measurements to the GPS satellites.

An examination of typical GPS differential range errors indicates that the errors have an almost cyclic pattern, reminiscent of correlated random noise (see figure 1 of reference 5). These residual errors are approximated by a random noise signal with an **autocorrelation** time of 100 seconds, or more, in the current simulation, see figure 1. Since various manufacturers advertise a DGPS ranging accuracy of 10 cm to several meters, it was decided to examine the impact of one-sigma **DGPS** pseudorange errors that varied between 20 cm and 5 meters. Corresponding autocorrelation times varied from 100 to 1000 seconds.

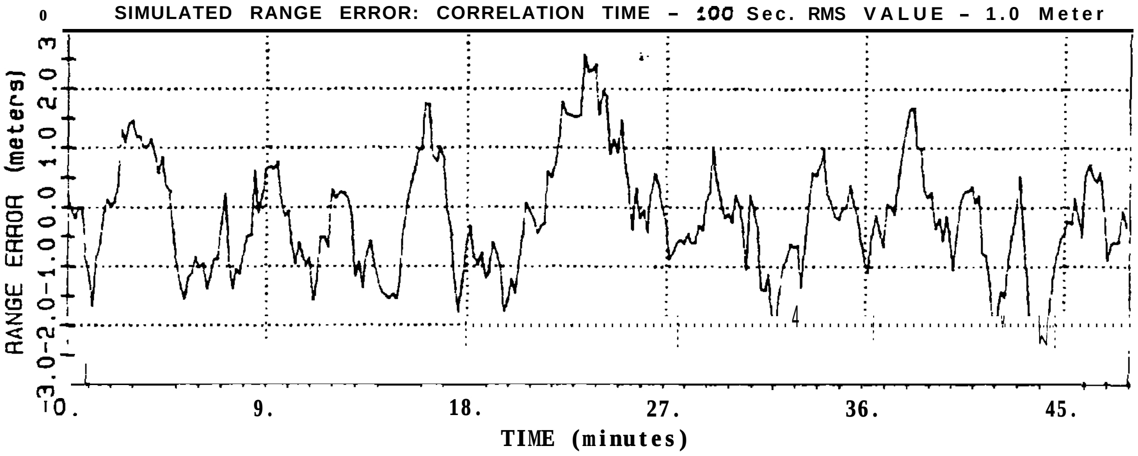


Figure 1. Simulated Residual DGPS Range Error

The Kalman filter simulation propagates the INS data at a 10 Hz. rate, and performs DGPS pseudorange updates every 10 seconds for every satellite in view. The resulting real-time Kalman filter position estimates were used to compute the simulated angular accuracy over the flight inspection regions of interest for localizer and glide path alignment. These angular accuracies may also be used for displacement sensitivity.

PLIGHT INSPECTION ALIGNMENT ERROR ESTIMATE

The localizer angle is the arctangent of the ratio of cross-runway displacement to the along-runway distance from the localizer installation on the ground. The glide path angle is defined as the arctangent of the height above the reference datum (on the runway centerline alongside the glide path antenna) to the horizontal distance from this point.

The Category 111 localizer alignment is measured between a point where the nominal ILS glide path brings the aircraft to **a** height of 30 meters above the reference datum to a point above the runway that is 900 meters past the runway threshold. Since the ILS typically defines a 3° glide path, and since the resulting aircraft trajectory passes at a height of 15 meters above threshold, the localizer alignment is measured from a distance of $15/\tan(3^\circ) = 285$ meters before threshold to a point that is 900 meters past threshold. For the purpose of this analysis, it is assumed that the runway is 3660 meters long, and the localizer antenna is 340 meters past runway end. Similarly, the glide path alignment is measured between points that are 4 nMi, (7411 meters) to 1050 meters before threshold.

The residual alignment angle errors that result from use of the DGPS-corrected INS position data, in lieu of the true airborne antenna positions, is equal to the mean difference between the alignment angles measured with the corrected INS coordinates and the true angles (measured with the true antenna coordinates).

RESULTS

For each selected combination of RMS ranging errors and correlation times, 100 simulated passes were run, and the mean, and root mean square (one sigma) alignment errors were extracted. In addition, the absolute errors were sorted to define the magnitudes that were not exceeded in 95% of all cases. Except where marked, the simulated data corresponded to the final satellite configuration with HDOP of approximately 1.0 and VDOP ranging from about 1.3 to 1.4. The simulation was repeated for the satellite configuration that was visible in the Buffalo, New York area, on 31 January, 1993. One set corresponded to the satellite configuration after midnight GMT with HDOP of approximately 1.3 and VDOP of approximately 2.4. The second data set was taken at 07:00 GMT, with HDOP of approximately 0.9 and VDOP ranging from 1.2 to 1.3. Table II shows the sigma and 95% error for all the cases simulated. An “A” in the "Accuracy OK?” column means that this case passed the alignment accuracy requirement. A “D” in that column means that this case passed the accuracy requirement for displacement sensitivity.

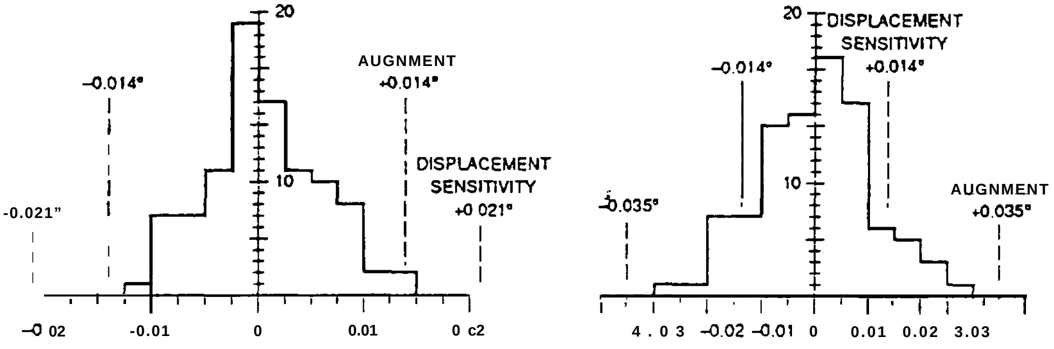
TABLE II. IMPACT OF AIRCRAFT POSITION ERROR ON LOCALIZER AND GLIDE PATH ALIGNMENT AND DISPLACEMENT SENSITIVITY ACCURACY REQUIREMENTS

RMS DGPS		Localizer			Glide path		
Rng Error (meters)	Tcor (sec)	Sigma (deg)	95% Err (deg)	Accur.' OK?	Sigma (deg)	95% Err (deg)	Accur.' OK?
0.2	100.0	0.00213	0.00393	A D	0.00415	0.00799	A D
0.3	100.0	0.00321	0.00613	A D	0.00630	0.01205	A D
0.5	100.0	0.00535	0.00996	A D	0.01064	0.02003	A
1.0	100.0	0.01064	0.02147		0.02155	0.03961	
2.0	100.0	0.02110	0.04197		0.04252	0.07795	
3.0	100.0	0.03135	0.06353		0.06213	0.12093	
5.0	100.0	0.05110	0.10143		0.09964	0.19287	
0.3	200.0	0.00286	0.00527	A D	0.00706	0.01238	A D
0.5	200.0	0.00481	0.00862	A D	0.01193	0.02131	A
1.0	200.0	0.00989	0.01834	D	0.02394	0.04500	
0.3	500.0	0.00303	0.00552	A D	0.00631	0.01355	A D
0.5	500.0	0.00506	0.00961	A D	0.01056	0.02268	A
1.0	500.0	0.01011	0.01955	D	0.02149	0.04411	
0.3	1000.0	0.00319	0.00581	A D	0.00781	0.01578	A
0.5	1000.0	0.00521	0.00928	A D	0.01199	0.02486	A
* 0.2	100.0	0.00321	0.00622	A D	0.00701	0.01452	A
* 0.3	100.0	0.00473	0.00927	A D	0.01045	0.02298	A
* 0.5	100.0	0.00777	0.01453	D	0.01711	0.03642	
** 0.2	100.0	0.00162	0.00355	A D	0.00378	0.00738	A D
** 0.3	100.0	0.00244	0.00537	A D	0.00582	0.01120	A D
** 0.5	100.0	0.00414	0.00883	A D	0.00997	0.01878	A

* Week 682 (31 Jan - 6 Feb 1993) time 0:00
** Week 682 (31 Jan - 6 Feb 1993) time 7:00

The 95% error values have been compared with the aforementioned ICAO limits, and it can be observed that the cases where the DGPS ranging errors do not exceed 20 to 50 cm yield sufficient accuracy to meet ICAC requirements for localizer alignment and displacement sensitivity during Category 111 inspections, when the associated GPS DOP values are appropriately constrained. Similarly, these accuracies generally suffice to meet glide path alignment accuracy specs, but 30 cm ranging accuracy or better is generally required to meet ICAO's glide path displacement sensitivity specifications.

Figure 2 shows histograms of localizer and glide path alignment errors for the final satellite configuration case where satellite range noise is 50 cm and autocorrelation time is 100 The x-axis represents error intervals in degrees, and the y-axis indicates the number of occurrences of Monte Carlo simulated errors in each interval. The corresponding ICAO flight inspection alignment and displacement sensitivity requirements are indicated on these plots.



Localizer

Glide Path

Figure 2. Error Histogram of 50 cm/l00 second Case

The exact value of HDOP and VDOP appears to have a significant impact on the resulting angle accuracy, but increasing the autocorrelation time constant has minor impact on the alignment error statistics. Good satellite coverage is imperative to ensure small HDOP and VDOP values. An examination of final and actual satellite coverage in Buffalo, NY indicates that HDOP values are currently below 1.52 and may be expected to fall to below 1.2 (95% of the time) with final coverage. Similarly, VDOP values are currently below 2.25 and may be expected to fall below 1.82 (95% of the time) with final satellite coverage.

From the definitions of localizer and glide path angle, the angle errors are almost entirely a function of cross-runway and vertical position errors, respectively. Thus the angular errors are respectively a function of HDOP and VDOP. Since similar angular accuracies are required for localizer alignment and for glide path displacement sensitivity, and since VDOP is generally larger than HDOP we may have more difficulty in meeting the glide path requirements with DGPS alone. Our IR&D plans include evaluation of a single laser altimeter update at threshold to meet ICA0 specifications with a good quality DGPS.

CONCLUSION

Flight test of Sierra Research's AFIS in en route mode, with GPS range updates implemented, took place in July of 1992. The position estimation accuracy was tested using Differential GPS techniques performed post flight using data from sequential C/A-code receivers. The Differential GPS reference system was calibrated and the total horizontal error was less than 4.4 meters 95% of the time. Flight test results showed the accuracy of the parameter of interest to en route flight inspection, post profile total horizontal error, is better than 35 meters 95 percent of the time.

The simulation of achievable accuracy that results from use of real-time DGPS corrections of the Flight Inspection aircraft's INS data is encouraging. However, it will be necessary to use the best quality DGPS units that provide 10 to 50 cm pseudorange accuracy. It may be necessary to use Differential Glonass in addition to DGPS, and/or a single threshold update, to provide sufficient accuracy to meet ICAO requirements for glide path displacement sensitivity verification.

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