DGNSS POSITIONING TECHNIQUES FOR FLIGHT INSPECTION

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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 Kalman filters with and without INS states, and as measurements 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 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. The key to a successful inspection is a very accurate estimation of aircraft position during these profiles.

Several estimation techniques and sources of aircraft position data are currently in use. Previously delivered Sierra Automatic Plight Inspection Systems (AFTS) 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 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 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 (reference 1) 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, some flight inspection agencies have relaxed this requirement and will permit deployment of a GNSS reference receiver and associated data link at an accurately surveyed point near the facility. The camera system can be supplemented or replaced by a high accuracy Differential GNSS system which would maintain, or even improve, system accuracy.

This paper describes three methods of using DGNSS data for position estimation and compares the results with smoothed positron data from an AFIS which was previously proven to provide Category III accuracy (reference 2). The

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comparison is based on flight tests which were performed at the Niagara Falls International Airport using NovAtel 2151R GPS receivers. These receivers employ narrow-correlator spacing techniques and are capable of carrier tracking (reference 3). Analysis shows that each of the DGNSS techniques meets 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 localizer 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 to the ground antennas, and thus determine the average angular difference. The averages are computed over specified inspection regions as the aircraft attempts to follow the ILS signals.

The International Civil Aviation Organization (ICAO) 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 III 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 4. 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 REQUIREMANTS IN DEGREES

	Cat I	Cat II	Cat III
Localizer Alignment	0.042	0.028	0.014
Localizer Displacement Sensitivity	0.035	0.035	0.021
Glide Path Alignment	0.063	0.063	0.035
Glide Path Displacement Sensitivity	0.025	0.021	0.014

THE ALGORITHMS

Three different techniques that generate estimates of aircraft position versus time were evaluated: DGPS integrated with INS (DGPS/INS) a nonlinear least squares solution with DGPS only, and an estimate based on a polynomial coefficient Kalman filter of DGPS only. These techniques were compared with a fourth technique: the smoothed aircraft position estimate.

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 NS 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 NS 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 l), which has

numerical stability superior to 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.** 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 from the **airborne** range and satellite location data corrected by the corresponding reference data 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. Aircraft attitude information is again employed to align coordinate systems.

The Kalman filter technique of DGPS positioning is based on a description of aircraft motion as three polynomials in time. For each instant, the aircraft motion is described as quadratic in time for north and east, and linear in time for vertical. When post processing. the polynomials are applicable to a window of data samples both before and after the time of interest, 6. When processing in real time, the data samples are restricted to before 6. The argument of each polynomial is delta time, which is the difference between the time in the window and t_0. The estimation at each point uses the fact that the aircraft motion and GPS receiver clock errors are not independent from one time to a nearby time, so that, in effect, several seconds of DGPS data are used to estimate position at each individual time t_0. The estimation processing at each one second of real time consists of a Kalman filter whose states are errors in the 10 polynomial coefficients in (time - t_0): three states each for east and north, two states for vertical, and two states for GPS receiver clock bias and drift rate. The Kalman measurement is the difference between the polynomial model of a range from each satellite to the aircraft and the differentially corrected pseudorange measurements for each satellite, for each time/ For example, if there are M satellites tracked, and the window size of the polynomial is $\pm N$ seconds, there are $(2N+1)*M$ Kalman measurements to estimate position at time t_0. Since the Kalman filter is recursive, the estimation may start at t_0, and expand one second at a time until the polynomial motion description is determined to not be an appropriate model, by correlation of residuals.

The difference between both DGPS-only techniques and the DGPSANS technique is that the DGPS-only techniques solve 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. The polynomial coefficient Kalman filter technique makes it possible to obtain some benefit from correlated aircraft motion without the expense of an INS as long as there are sufficiently many closely spaced DGPS samples. This technique is equivalent to the nonlinear least squares technique for zero-length windows, and it is more adaptive and robust than a straight feed-forward Kalman filter based on classic dynamic models.

Carrier phase data were available from the NovAtel receivers, and use of these data was investigated in the DGPS solutions. Carrier data was used to extrapolate range from an initial value, and also to smooth the pseudoranges, which is of value for estimating the ILS structure (roughness). The nonlinear least squares solution became less noisy, but the two Kalman filter versions were inherently smooth, hence carrier smoothing was unnecessary. The accuracy varied for each profile depending on the accuracy of the initial pseudorange and the amount of extra carrier smoothing employed. The table and plots in this paper use pseudorange data with no additional carrier smoothing.

ALGORITHM VERIFICATION PROCEDURE

Tests of the flight inspection system's performance were conducted at the Niagara Falls International Airport. 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 PDOP during these flight tests ranged from abour 2.5 to 4.0, except during one profile with poor satellite geometry when the PDOP increased to greater than 9.0. For a more detailed description of the test procedure, see reference 5.

Ideally, the verification of a position-determination technique relies on a reference position that is even more accurate than the one in test. As the position estimation 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 three different DGPS estimates with the smoothed aircraft position estimates. The errors in the nonlinear least squares position estimates and the Kalman filter polynomial curve tit 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 among these three solutions verifies 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 INSPECTION ACCURACY

The plots in figures 1,2 and 3 compare the DGPS/INS nonlinear least squares and polynomial coefficient Kalman filter 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 inspection regions. These plots show better than one meter agreement in the critical 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). Table II shows the differences between results for each DGPS technique and the smoothed aircraft position estimates for the three most important parameters: bearing angle for Category III localizer alignment, bearing angle for localizer displacement sensitivity, and elevation angle. 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 combined to extract a median difference value, while half their difference defined a spread, which is an index of consistency. The ICAO accuracy requirements are also tabulated.

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 an 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 two DGPS-only techniques and the corresponding smoothed 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 of jointly tracked satellites intermittently decreased to four. The nonlinear least squares results are better than the polynomial coefficient Kalman filter results because the nonlinear least squares only computes a solution when at least five satellites are available, and interpolates over intervals of fewer than rive satellites. In any event, these differences include error components from the DGPS technique and the reference technique. 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.

Accuracy and integrity of the DGPS solution are primarily functions of very accurate survey of GPS reference antenna location relative to the ground IL.5 antenna locations, as described in reference 5, and ILS 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 6) in order maintain solution integrity. Besides these tests, GDOP and the number of satellites jointly **tracked have** been the strongest indicators of performance. Relevant DGPS performance information will be supplied to the flight inspector

as an index of solution reliability.

TABLE II. AVERAGE CATEGORY III ANGLE DIFFERENCES

Profile Number	Azimuth Angle Differences Alignment			Displacement Sensitivity			Elevation Glidepath Angle Differences		
	A	B	C	A	B	C	A	B	C
040806	0.011	0.012	0.010	0.002	0.003	0.002	-0.003	-0.002	0.000
Oil0827	0.000	0.005	0.005	0.000	0.000	-0.001	0.013	0.018	0.018
010827	-0.003	-0.005	-0.007	-0.004	-0.004	-0.005	0.005	0.005	0.001
020827	0.003	-0.008	-0.009	0.007	0.007	0.007	-0.014	-0.012	-0.012
030827	-0.012	-0.017	-0.022	0.003	0.004	0.002	-0.003	-0.005	-0.005
040827	0.009	0.008	0.010	0.016	0.015	0.016	0.000	-0.001	0.000
050827	-0.004	-0.002	-0.001	0.015	0.014	0.015	0.000	-0.011	-0.012
Median	-0.001	-0.003	-0.006	0.006	0.006	0.006	-0.001	0.003	0.003
Spread(=)	0.012	0.015	0.016	0.010	0.010	0.011	0.014	0.015	0.015
ICAO Spec.	0.014			0.021			0.035 - Alignment 0.014 - Disp. Sens.		

A - DGPS/INS Minus Smoothed Aircraft Position
B - Nonlinear Least Squares Minus Smoothed Aircraft Position
C - Polynomial Coefficient Kalman Filter (± 10 seconds) Minus Smoothed Aircraft Position

SUMMARY OF THE ALTERNATE APPROACHES

The DGPSANS system, the nonlinear least squares solution, and the polynomial coefficient Kalman filter solution can provide position estimates that are consistent with ICAO specifications over all categories of 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.

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 stripes. 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. It 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 and the polynomial coefficient Kalman filter technique share most of the advantages of the DGPS/INS technique. In addition, they permit the replacement of the INS unit with an inexpensive attitude sensor for coordinate alignment. Their 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. The use of a

Kalman filter for extracting aircraft position at one second intervals and for smoothing and interpolating between updates provide improved outputs for defining near-continuous estimation of aircraft position and provides required data for monitoring structure (roughness) of the electronic guidance signals.

While the achievable angular accuracy is a function of the runway length, all four systems are capable of meeting ICAO and FAA requirements for inspecting all currently installed categories of precise landing aids. Therefore, any of these DGPS techniques 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 appropriate to use both the camera system and DGPS.

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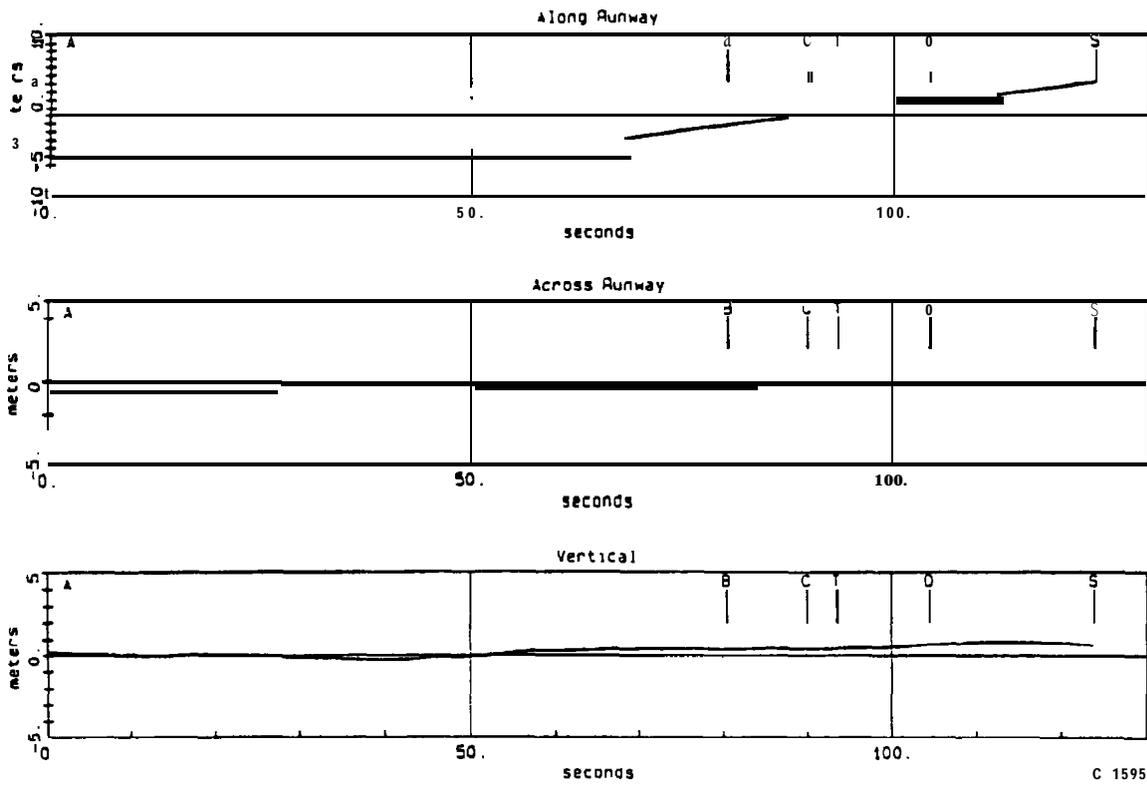
Figure 1. Profile 010827 Differences Between DGPS/INS and Smoothed Aircraft Position Estimates as a Function of Time
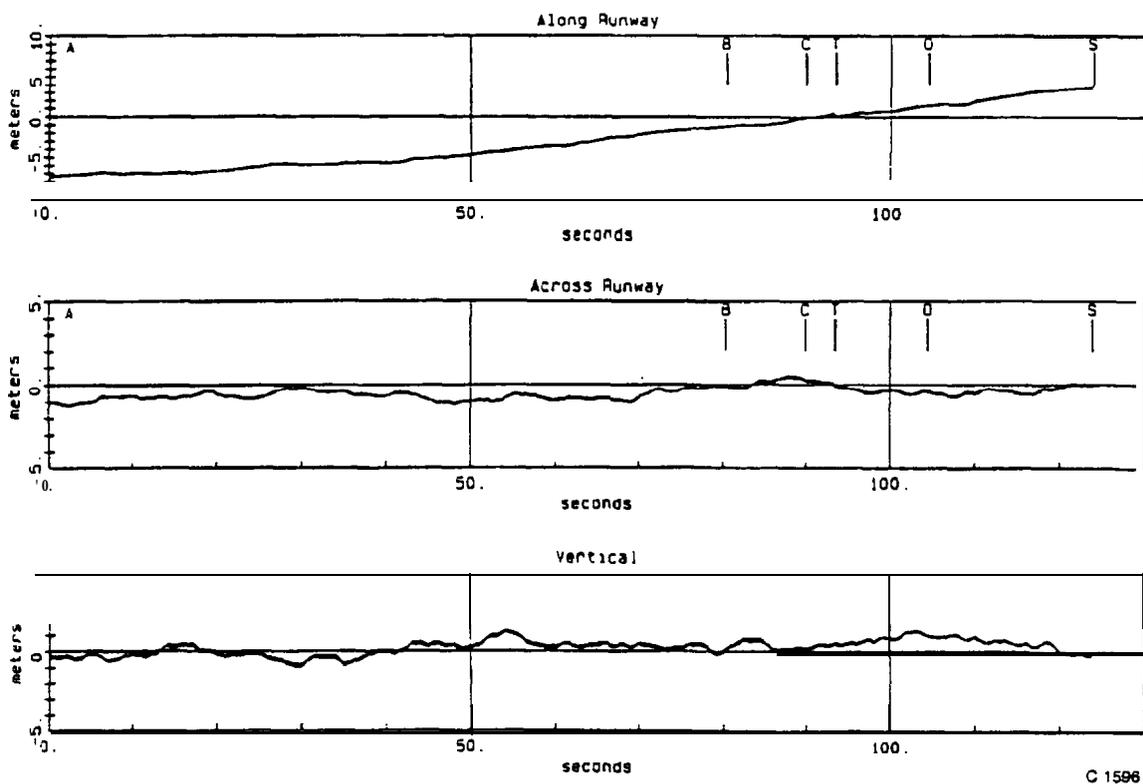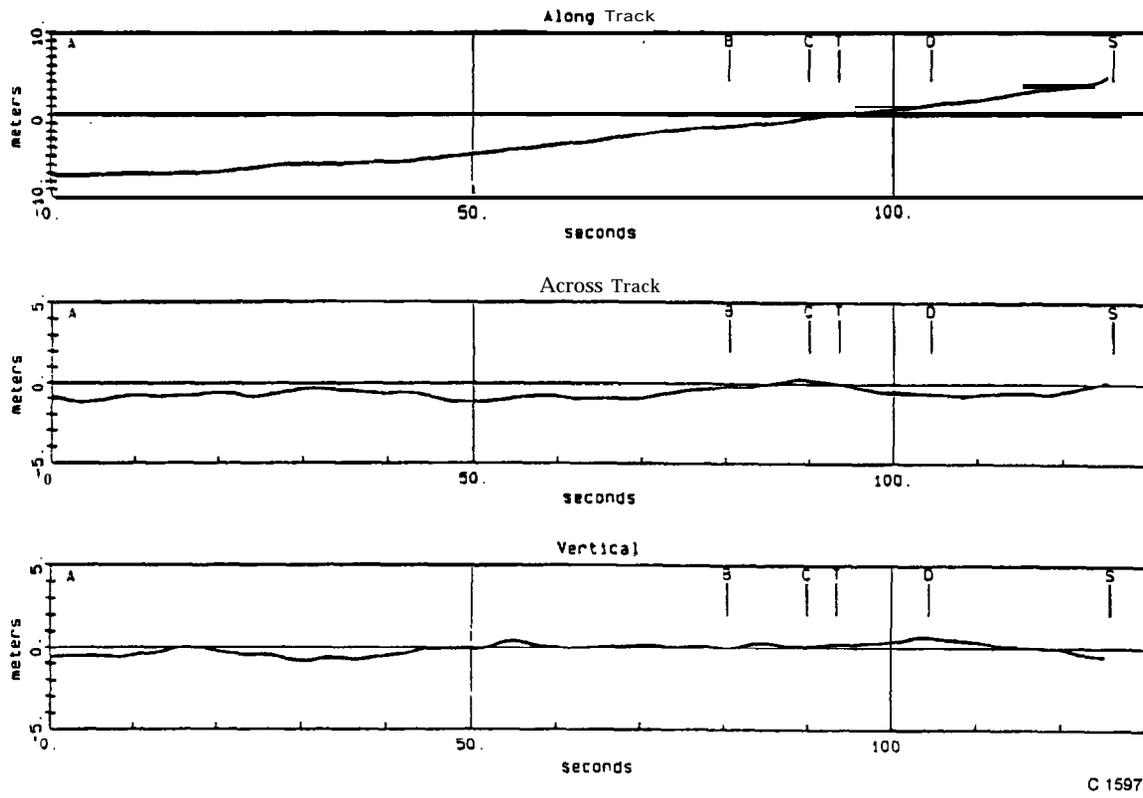

Figure 2. Profile 010827 Differences Between Nonlinear Least Squares and Smoothed Aircraft Position Estimates as a Function of Time

Figure 3. Profile 010827 Differences Between Polynomial Coefficient Kalman Filter and Smoothed Aircraft Position Estimates as a Function of Time