A Kinematic Carrier Phase Tracking System for High Precision Trajectory Determination

Dr. Wang Tang, Mr. Dale Turley & Mr. Gene Howell
ARINC ***Research Corporation***

Ms. Linda Wilkinson
Hughes Aircrafr Company

BIOGRAPHIES

Wang Tang joined ARINC Research Corporation in 1992 and currently is Technical Director of the Aerospace Systems Department. He has 16 years experience in the field of navigation and guidance systems including six years with The Analytic Sciences Corporation (TASC) and eight years with General Dynamics, Convair Division. He received a B.S. degree from National Cheng Kung University, Taiwan, an M.S. degree from University of Texas at El Paso, and a Ph.D. degree from Iowa State University, all in electrical engineering. He is a registered Professional Engineer in the Commonwealth of Massachusetts.

Dale Turley is a Senior Principal Engineer at ARINC Research Corporation. He has over ten years experience with GPS, ranging from control and space segment operations to military and civil receiver applications. He has B.S. and M.S. degrees in aeronautical engineering from California Polytechnic State University in San Luis Obispo.

Gene Howell is also a Senior Principal Engineer at ARINC Research Corporation. He has worked in the field of aided navigation systems for 14 years, primarily with General Dynamics, Convair Division. He has B.S. and MS. degrees in mathematics from Southern Illinois University in Carbondale.

Linda Wilkinson is a Systems Engineer at Hughes Aircraft Company. She has worked in the field of flight test data processing and evaluation for 9 years and the field of software engineering for over 11 years. She has a B.S. degree in mathematics from Miami University in Oxford, Ohio.

ABSTRACT

The processing of GPS carrier phase is a subject that has enjoyed a great deal of attention. For double differenced phase measurements, the integer ambiguities may be resolved by performing a swap of the reference and user receiver antennas or a survey if the baseline is unknown. **A variety** of techniques have also been proposed for resolving the ambiguities on-the-fly (OTF). The phase observable allows relative positioning accuracies to the centimeter level.

Another subject that is the center of intense interest is the terminal homing system. These systems include target recognition/classification algorithms and aimpoint selection. The accuracy requirements for weapon systems employing terminal seekers are quite stringent, usually on the order of a meter. This suggests that relative position derived from the GPS carrier phase is a natural source to evaluate the accuracy of a terminal sensor system.

This paper describes the scoring system developed by ARINC Research Corporation for a terminal homing system testbed being developed at Hughes Aircraft Company. An overview of the system configuration is described and flight test results given. The flight test results were obtained from two cases that differed in trajectory dynamics. In both cases, the results indicate that the scoring system will support the accuracy requirements.

1. INTRODUCTION

Hughes Aircraft Company is developing an A-3 aircraft as an airborne sensor and avionics testbed for integration and evaluation of terminal seekers. The on-board navigation system consists of a Litton strapdown inertial sensor assembly (ISA) and a Rockwell GPS receiver 3A. The GPS Precise Positioning Service (PPS) position and velocity data are loosely coupled with the ISA via a Kalman filter. A Missile Radar Altimeter (MRA) is used to calibrate and verify the altitude derived from the barometric pressure transducer. All test data are recorded on a Test Control Workstation (TCW) for post-flight processing (Figure 1). The design requirement of the navigation system is 10 meters with respect to WGS-84 throughout the mission. In order to evaluate the position accuracy of the testbed navigation system, it is desirable to have a scoring system that is at least an order of magnitude better. As the result, the scoring system should have an accuracy better than a meter. For determining the performance of a terminal seeker, the accuracy required by a scoring system is even more stringent. In the past, the photoscoring technique has been applied successfully for this purpose [l]. Another alternative is to use laser trackers. However, due to the recent constellation maturity, GPS becomes a very cost-effective alternative. Early this year ARINC Research Corporation took the responsibility of designing and developing a GPS-based high precision scoring system, which is subsequently caged Sub-Centimeter Offset Recording Equipment (SCORE). The primary function of the SCORE is to evaluate the accuracy performance of the Hughes' A-3 avionics suite at a much lower cost and **higher** accuracy than either the photoscoring technique or laser tracking systems.

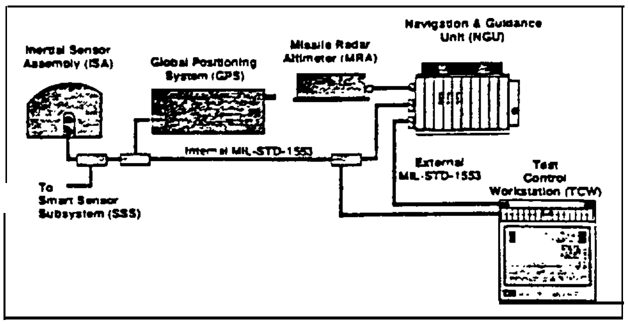


Figure 1. Hughes A-3 Avionics Suite

The accuracy of differential GPS, usually on the order of 1 to 5 meters, is considered marginal to meet the scoring system accuracy goal. In order to maximize the positioning accuracy, GPS carrier phase measurements should also be processed. The GPS carrier phase is not a well-known observable though. In fact, when GPS was conceived a while ago, the carrier phase was not even designed as an observable. The benefits of using carrier phase were largely ignored by most of military and commercial receiver manufacturers. Only recently have the receivers with carrier phase tracking and reporting capability become abundant.

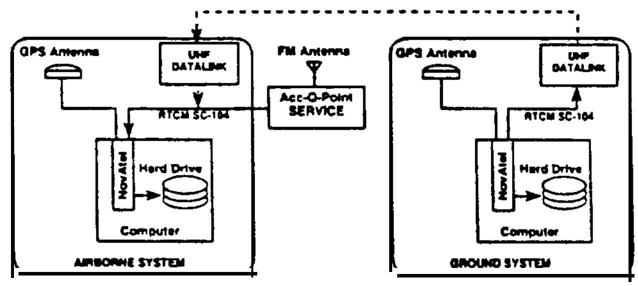
The carrier phase measurements are primarily processed in two different ways. One is to smooth the code tracking pseudoranges and the other is to compute the kinematic relative position based on the double difference operation principle [2]. The focus of this paper is on the latter. We will show how carrier phase measurements are processed to obtain the high precision relative position information. We will then demonstrate that the centimeter positioning accuracy is achievable by evaluating results from two flight tests conducted early this year.

This paper is organized in four sections. Following the introduction, Section 2 describes the configuration of the ARINC GPS-based SCORE system. Section 3 documents results of two flight tests conducted this year. **A** summary is provided in Section 4.

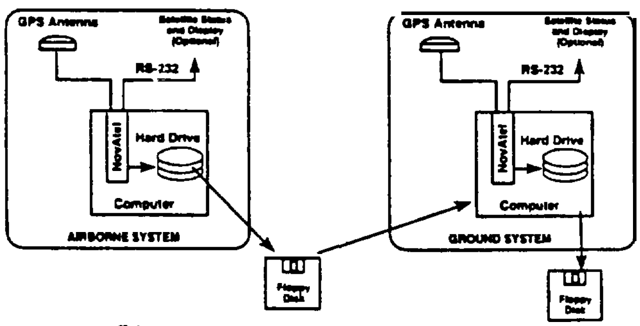
2. SYSTEM DESCRIPTION

2.1 Hardware Confirmation

Figure 2 illustrates the SCORE system configuration. The SCORE can operate in two modes: real-time differential GPS mode and post-processing kinematic GPS mode. As shown, it consists of two NovAtel951R GPSCards housed in two PCs, an Act-Q-Point FM DGPS receiver, and a datalink with two Pacific Crest RDDR-% UHF data modems. A comprehensive description of the theory and performance of NovAtel GPSCards is presented in [3] and features of the Acc-Q-Point DGPS service are documented in [4]. Wherever it is available, the Act-Q-Point service will be used to obtain DGPS pseudorange corrections. Otherwise, the differential corrections computed by the reference station are linked to the roving unit via data modems.



(a) Real Time Differential GPS



(b) Post Processing Kinematic GPS

Figure 2. System Configuration

3.2 Software Development

For real time differential GPS operation, the NovAtel receivers possess the capability of processing differential corrections directly. The positions are computed by using differentially compensated pseudorange measurements. No software development is required.

For kinematic GPS **trajectory reconstruction,** a computer program has been developed to perform the following functions:

1. Align the carrier phase measurements.
2. Compensate the tropospheric delay using the algorithm described in [5]
3. Monitor the quality of carrier phase measurements. Delete those with doubtful quality.
4. Form double differences at each epoch of carrier phase measurements.
5. Compute the integer ambiguities for each pair of satellites and receivers using survey results.
6. Process double differences to compute the offset from the base station antenna to the roving antenna.
7. Compute the geodetic position (latitude, longitude, altitude) of the roving antenna.

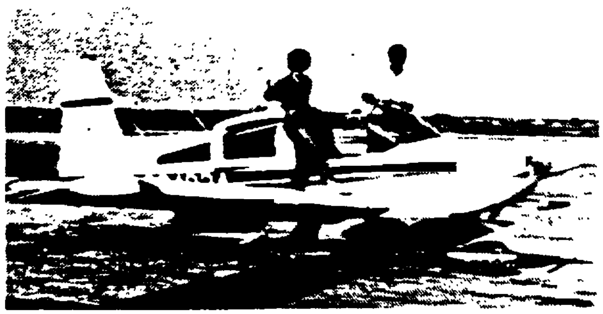
3. FLIGHT TEST RESULTS

Two flight tests were conducted this year. The primary objective of these tests was to evaluate the relative positioning accuracy of the SCORE system by performing an end-to-end check, i.e., to start and end the test at a precisely known location to confirm the loop closure. One test was performed at Gillespie Field, El Cajon, CA on 25 February, and the other at Van Nuys Airport, Van Nuys, CA on 8 July. For the Gillespie Field test, the SCORE system was installed in a four-seat Grumman Tiger aircraft while at the Van Nuys Airport the aircraft involved was the Hughes' Navy A-3 aircraft. In both cases, an initial static survey of 30 minutes was performed in order to expedite the integer ambiguity resolution for the flight segment. During the survey phase , the reference station antenna was located within 100 meters from the survey location. For the Van Nuys test, a post-test survey of 30 minutes was also conducted in order to compute integer ambiguities of some satellites which were not seen initially. The data sampling rate was **1** second.

Table 1. Locations of Reference Station Antennas

	Lat(deg)	Lon(deg)	Alt(m)
Gillespie	32.86008241	-116.97010090	96.874
Van Nuys	34.20974552	-118.48783719	238.863
Act-Q-Point	33.98757183	-118.45265333	-26.517

Two aircraft involved in the flight tests, a Grumman Tier and a Navy A-3 Skywarrior are shown in Figure 3 and 4 respectively. The locations of reference station antennas are listed in Table 1.



Fiie 3. Grumman Tiger

Figure 4. Navy A-3 Skywarrior

3.1 Gillespie Field Test

After the completion of the initial survey near the hangar, the aircraft taxied to the runway, took off, reached I500 ft altitude, flew a circle, descended and executed a touch-and-go, made another circle, landed and then returned to the same spot where the initial survey was performed. The roving portion of the test lasted about 30 minutes. The main purpose of the touch-and-go operation was to check the repeatability of the generated trajectory. The altitude profile and horizontal trajectory are shown in Figures 5 and 6 respectively. The phase center of the reference station antenna is considered to be the origin of these figures.

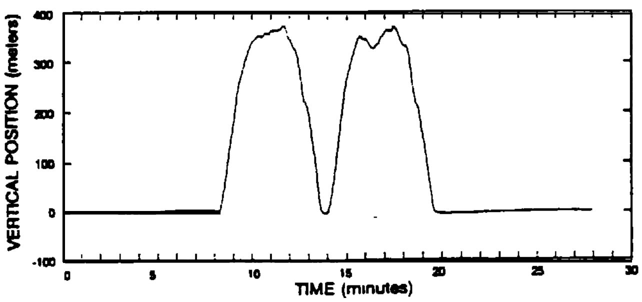


Figure 5. Altitude Profile

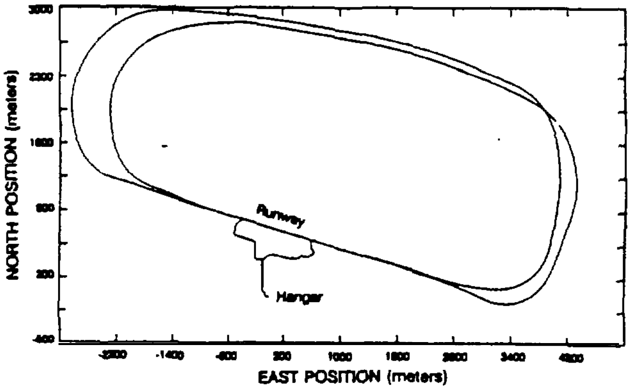


Figure 6. Horizontal Trajectory

Although the GPS antenna was mounted inside the cabin above the dashboard - an undesirable location due to potential signal shadowing, five satellites were continuously tracked during the flight without cycle slips. Their associated integer ambiguities were computed using the initial survey results. For two other satellites which appeared after take-off, the integer ambiguities were computed using the best known position at their corresponding initial tracking time. **At** the end of the test, the aircraft was manually pushed and pulled in order to align it to the marks on the tarmac made prior to the test. The purpose of this maneuver is to make the antenna return to the same location as close as possible so that the closure accuracy can be evaluated. It is estimated that the true final position is within a few centimeters from the initial position.

The reconstructed trajectory near the initial starting and final ending position is shown in Figure 7. The separation of two clusters includes two types of error. One is the SCORE system relative positioning error and the other is the true separation of the starting and ending positions of the roving antenna. As can be seen, the separation is about 5 cm in east and less than a centimeter in north, which is on the same order of magnitude of our ability to return the aircraft to the same position. Based on these results, we can conclude that the SCORE system accuracy is on the order of centimeters as currently configured.

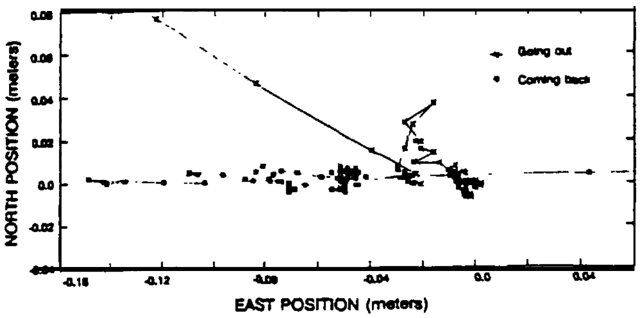


Figure 7. Initial Survey Area

The ground portion of the reconstructed trajectory near the runway area is presented in **Figures** 8 and 9. Note that the vertical axis does not have the same scale as the horizontal axis in these two figures Three segments were identified as take-off, touch-and-go, and landing. **Figure** 8 shows how closely the aircraft follows the runway center line. The wiggling of about a meter was apparently due to the wind. Figure 9 shows a side view of the vertical profile. Several highlights are worthwhile to note: (1) the overlapping touch-and-go and landing segments are close to within centimeters, (2) the take-off segment is also consistent with the other two segments with minor difference in slope, and (3) the flare maneuver executed by the pilot just prior to the physical touch-down is clearly observed.

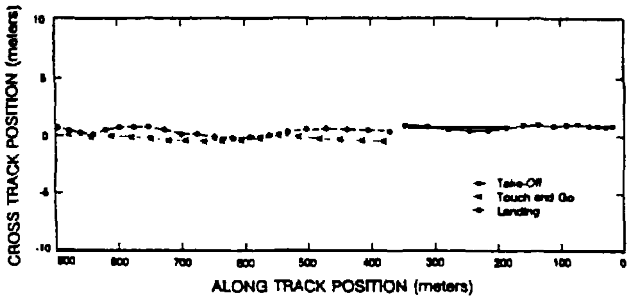


Figure 8. Runway Center Line

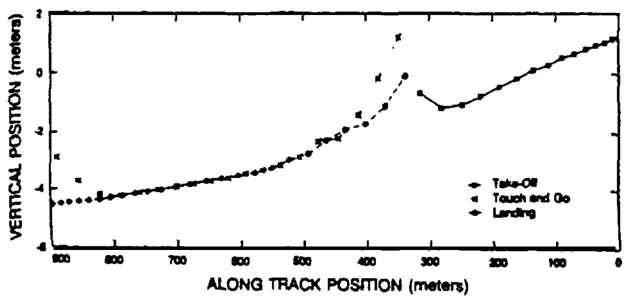


Figure 9. Runway Slope

3.2 Van Nuvs Aimort Test

The SCORE system was later installed in the Hughes' A-3 aircraft stationed at the Van Nuys Airport. A flight test was conducted on 8 July. At the beginning of the test, the aircraft was parked on a grid of 6 ft by 6 ft and an initial survey of 30 minutes was performed in order to resolve the integer ambiguities. The aircraft then took off, climbed to 7000 feet, reached Point Mugu, made three circles, and proceeded to two off-shore islands: San Nicolas Island and-San Clemente Island. The objective was to repeatedly fly over VOR stations on both islands. The weather at San Nicolas Island prevented an over flight of the VOR, but the aircraft was able to duck under the weather upon the approach to San Clemente Island and three overflights were recorded. Total flight time was a little over two hours and the flight **covered an area** of 2.3 deg in latitude and L2 deg in longitude (Figure 10). After returning to the airport, the aircraft was parked on the same grid again and another survey of 30 minutes was performed.

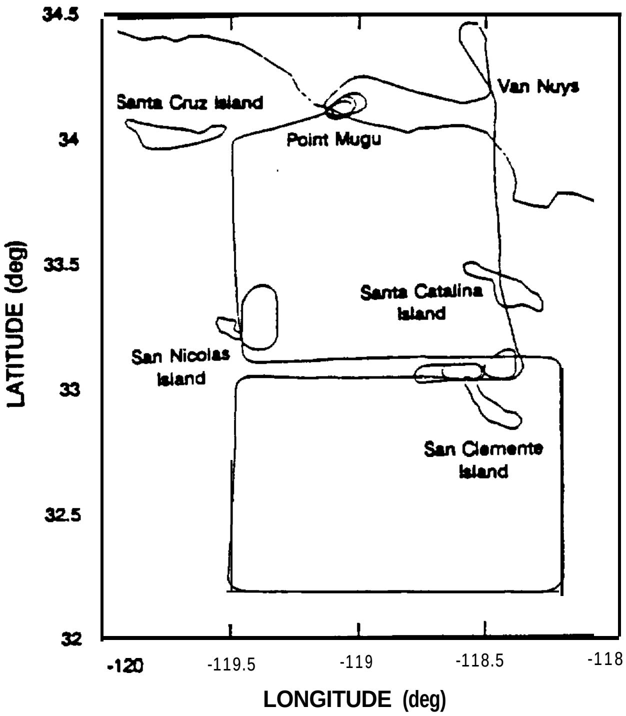


Figure 10. Flight Trajectory

Three repeated trajectory segments near the San Clemente VOR station are shown in Figure 11. The trajectory segments near the grid where the initial and final surveys were conducted are shown in Pie 12. The initial and ending positions of the test aircraft are separated by 14 cm based on the survey results. This offset was confirmed by using a video camera looking down at the grid painted on the tarmac. The clusters of the SCORE reconstructed trajectory are within centimeters from the surveyed results.

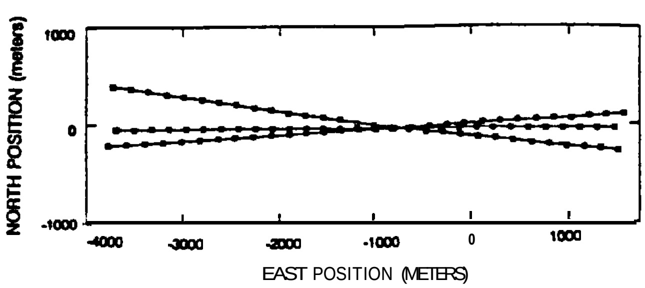


Figure 11. Trajectory Segments near the San Clemente VOR Station

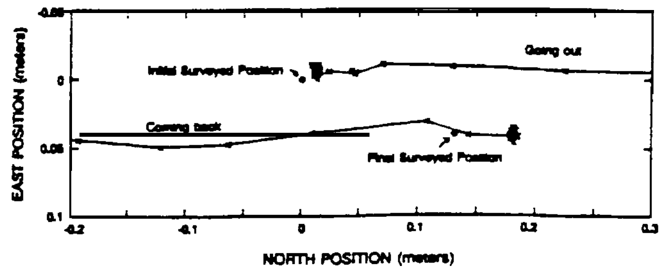


Figure 12. Trajectory Segments near the Grid

Throughout the flight, Act-Q-Point differential GPS corrections were available and used by the onboard receiver to compensate the pseudorange measurements. The post processed trajectory, constructed using carrier phase measurements, is compared to the code tracking differentially corrected position data and the differences are shown in Figure 13. The rms values for east, north and up are 1.15 m, 1.50 m and 3.19 m respectively. The corresponding mean values are 0.36 m, 0.90 m, -1.03 m. Note that the Ace-Q-Point reference station of is located in Long Beach, about 15 miles south of the Van Nuys Airport.

During the same flight, the A-3 GPS/INS navigation suite also provided latitude and longitude data which were compared to the SCORE post possessed trajectory. The differences are shown in Figure **14. The rms values** for north and east are 2.81 m and 251 m respectively. The corresponding mean values are -1.65 m and 1.83 m.

4. SUMMARY AND FUTURE ENHANCEMENTS

Features of the ARINC GPS-based SCORE system have been discussed. Based on the flight test results, the SCORE system has potential to achieve centimeter relative positioning accuracy with minimum recurring cost per flight. The dominating factor of accuracy degradation is the separation of the reference and the roving antennas due to spatially decorrelated ionospheric and tropospheric delays. Using a conservative rule-of-thumb of one centimeter per kilo-meter (10 ppm) [6], centimeter accuracy can be assured if the separation is limited to 10 kilometers.

Additional features/capabilities to be incorporated into the ARINC scoring system are being considered. They include:

1. Real-time trajectory determination,
2. Integer ambiguity resolution on-the-fly (OTF),
3. Wide-!ane operation,
4. RAIM-like data quality control, and
5. Azimuth/Pitch determination.

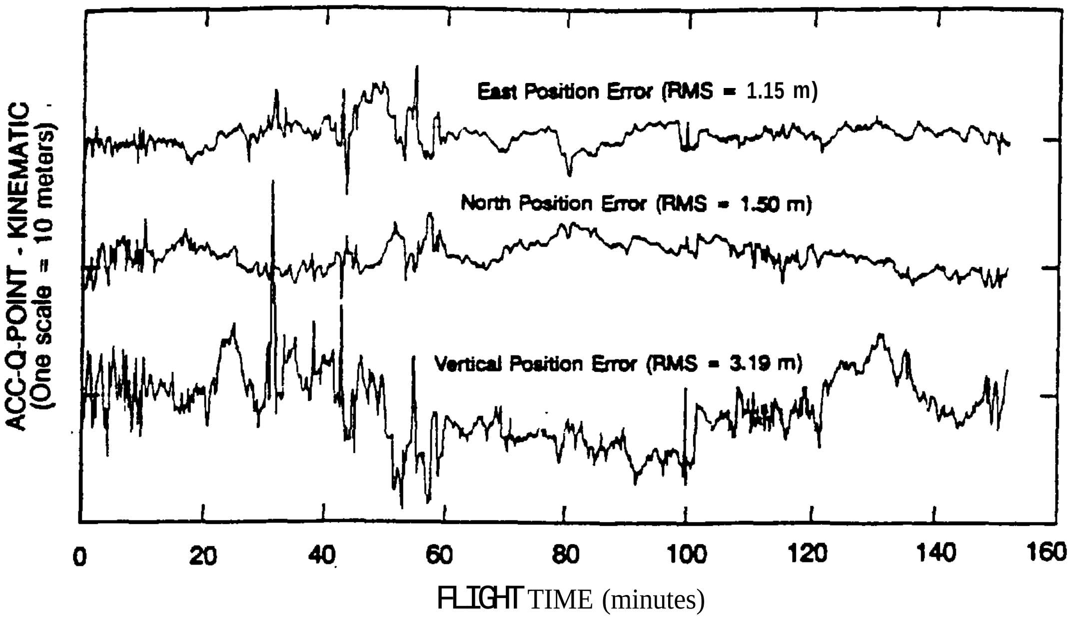


Figure 13. Position Differences between Kinematic and Differential GPS

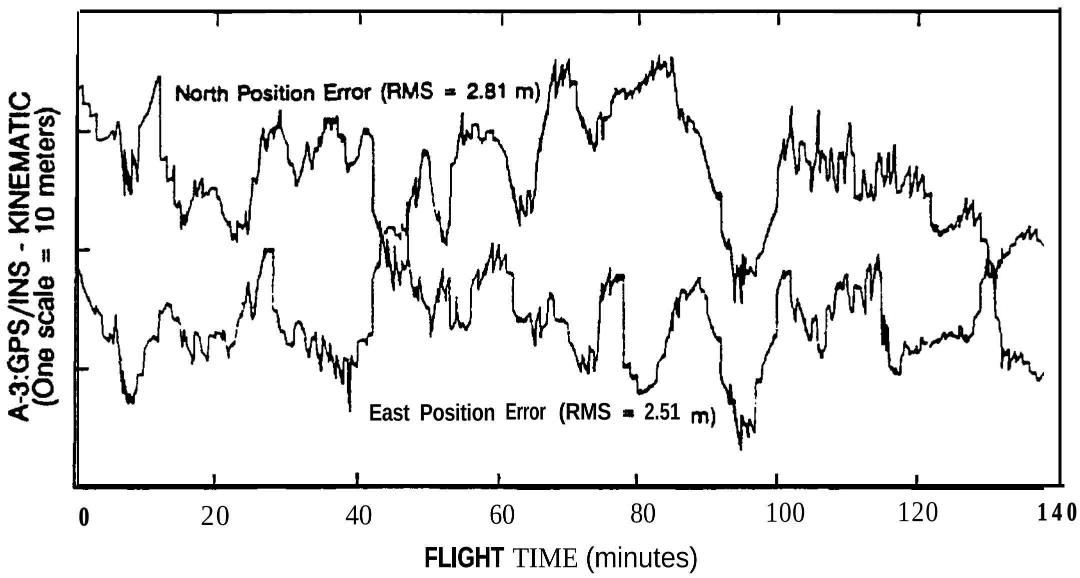


Figure 14. Position Differences between Kinematic and A-3 GPS/INS Navigation Suite

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