ACD 330 -

DOT/FAA/CT-ACD-33093/11

# FAA /OHIO UNIVERSITY PRECISION APPROACH FLIGHT TEST (ON-THE-FLY KINEMATIC GPS)

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AVIATION TECHNOLOGY DIRECTORATE REPORT

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## EXECUTIVE SUMMARY

Recent technological advancements in Global Positioning System (GPS) receivers have resulted in an increased level of accuracy than previously attainable with commercially available code tracking receivers. Algorithms are being developed which can accomplish the difficult task of carrier phase tracking in real-time, or on-the-fly kinematic GPS (OTF-KGPS). This highly accurate technique of positioning uses the carrier of the propagated message for range measurements rather than the code which is superimposed on the carrier. The flight tests were conducted to demonstrate the potential of OTF-KGPS to achieve category II/III instrument approach accuracy.

Ohio University used an Ashtech receiver for the necessary GPS signal measurements. A personal computer (PC) with a Intel 486 processor was used to compute the calculations necessary to resolve the integer ambiguities of phase measurements, make position measurements and generate guidance commands to the course deviation indicator (CDI). OTF-KGPS is only possible after the ambiguities have been resolved. Normally at least five satellites are desirable to maintain KGPS in real-time. A vertical dilution of precision (VDOP) constraint of 10 was set since KGPS is not as limited by the DOPs because of the more accurate carrier phase measurements (opposed to code tracking techniques). Two different mechanizations of OTF-KGPS were provided by Ohio University, designated as OU1 and OU2.

Laser tracking provided truth data. Straight in "ILS look-alike" approaches were flown to runway 13 at Atlantic City International Airport.

Table 1 provides conservative estimates of the 95% probable error (|mean| + 2 standard deviation) of the sensor and total system errors. Comparisons to the Federal Radionavigation Plan (FRP) and the Satellite Operational Implementation Team [1] (SOIT) Tunnel are provided. The crosstrack sensor error of 1.8 m for OU1 and 0.5 m for OU2 easily meets the FRP CAT II / III accuracy requirements. The vertical sensor accuracy of 2.7 m for OU1 fell short of the FRP requirement of 1.7 m for CAT II. However, the OU2 sensor accuracy of 0.9 m is good enough for CAT II but not CAT III which requires 0.6 m.

The accuracy data presented in this table does not include all approaches flown. Only the approaches in which the ambiguities were resolved en route to the final approach fix (FAF) were used in the analysis.

## TABLE 1. SUMMARY OF RESULTS
## OU1 - 25 Approaches, OU2 - 18 Approaches

| | HIGHEST ERROR OVER FINAL 2 NMI | 95% ERROR AT 100' DH (0.2 NMI FROM RWY THR) | 1992 FRP RQMTS. AT 100' DH $2\sigma$ | 1992 FRP RQMTS. AT 50' DH $2\sigma$ | SOIT TUNNEL RQMTS. AT 100' DH $2\sigma$ |
|---|---|---|---|---|---|
| OU1 Vertical Sensor Error | 2.7 m | 2.7 m | 1.7 m | 0.6 m | |
| OU2 Vertical Sensor Error | 1.8 m | 0.9 m | 1.7 m | 0.6 m | |
| OU1 Crosstrack Sensor Error | 2.5 m | 1.8 m | 5.2 m | 4.1 m | |
| OU2 Crosstrack Sensor Error | 1.3 m | 0.5 m | 5.2 m | 4.1 m | |
| OU1 Vertical FTE | 12.7 m | 6.5 m | | | |
| OU1 Crosstrack FTE | 19.6 m | 4.2 m | | | |
| OU1 Total System Vertical Error | 12.3 m | 7.9 m | | | 4.6 m |
| OU1 Total System Crosstrack Error | 19.6 m | 3.5 m | | | 22.9 m |

## 1. INTRODUCTION.

The FAA Satellite Program Office invited Ohio University (OU) to flight test a precision approach system they developed based on carrier phase tracking techniques with the Global Positioning System (GPS). This is known as on-the-fly kinematic GPS (OTF-KGPS), and requires very fast microprocessors to complete the immense number of calculations necessary in a short period of time.

This report covers the test configuration, the flight test, and provides complete results with a brief analysis.

## 2. DESCRIPTION OF TEST.

### 2.1 TEST EQUIPMENT.

KGPS is a relative navigation system based on differences between the carrier phases as measured by the airborne GPS antenna and the ground reference station antenna. This technique provides very high accuracy because the resulting range differences are scaled by the carrier wavelength (19 cm for the GPS L1 carrier). However, as with all phase measurements, the proper carrier cycles or lanes must be correctly identified. This is usually done within a "search volume" of space about a coarse estimate of the aircraft's position. In the OU system, the center of the search volume was estimated by conventional DGPS pseudorange measurements. Then a cubic volume about the center was searched for the most probable position solution. OU provided two different mechanizations of OTF-KGPS. OU1 operated with only the L1 Coarse Acquisition (C/A) code and its carrier, and OU2 operated with both the L1 and L2 Precise (P) code and carriers. OU1 and OU2 used two separate Ashtech receivers for the necessary GPS signal measurements. Personal computers (PC) with Intel 486 processors were used to compute the calculations necessary to resolve the ambiguities, make position measurements and generate guidance commands to the course deviation indicator (CDI). OU1 provided guidance commands to the CDI at a 2 Hz rate. The guidance was angular and replicates what an ILS would look like (i.e. +/- 0.7° vertical deviation = 150 mV and +/- 1.8° horizontal deviation = 150 mV). While OU2 could generate guidance, only the sensor error was measured. The test bed for flying the OTF-KGPS system was an OU owned Piper Saratoga.

The GPS reference station utilized the same Ashtech GPS receiver. To help reduce multipath, the GPS antenna was placed a few centimeters above a surveyed point on the ground. A signal splitter from the ground reference station allowed for separate data links with the airborne receivers. OU1 and OU2 used VHF data links to transmit differential corrections, carrier phase information, and other necessary data.

### 2.2 FLIGHT SCENARIO.

All of the approaches were flown to runway 13. The personal computer (PC) which did the position calculations was also used to monitor the status of the ambiguity resolution process. At the termination of each approach, the PC was reinitialized to begin the

ambiguity search. A record of the time to resolve was kept and continuation of the approach was contingent of the search being completed prior to the final approach fix (FAF).

Typically the aircraft was established on the extended runway centerline 6- 7 nmi from the airport at an altitude of 1800 - 2000 ft. Once the 3 degree glide path was intercepted, the pilot would begin to descend the aircraft based on the CDI information provided by GPS. The final approach fix is 4.3 nmi from the runway threshold. Before the FAF point was reached, the aircraft was configured for landing. All approaches were flown with the pilot under the hood.

The vertical dilution of precision (VDOP) constraint provides that VDOP < 10 is acceptable. Additionally, the mask angle is set at 5 degrees. However, OU1 did not use satellites below 10 degrees. VDOP was not a major consideration as far as accuracy is concerned. However, a minimum of 5 satellites in view were required for the OTF-KGPS algorithm to be successful. Five satellites allows for a quick recovery from cycle slips as long as the carrier is continuously maintained on at least four satellites.

### 2.3 TRUTH SOURCE.

The FAA Technical Center's Laser tracker is the truth source for precision approach tests. The aircraft is tracked via a retroreflector mounted on the landing gear of the aircraft. Refer to appendix A for details on the location of the retroreflector and the GPS antenna on the test aircraft.

## 3. DATA REDUCTION.

Ensemble means and standard deviations are computed at 0.1 nmi increments from the runway threshold out to the FAF point (4.3 nmi). The upper limit for the 95 percent confidence interval is based on the number of approaches. Statistical analysis is provided in terms of total system, sensor errors, and flight technical error (FTE).

## 4. DATA ANALYSIS AND RESULTS.

### 4.1 FLIGHT TEST RESULTS FOR 25 APPROACHES, OU1 RECEIVER.

#### 4.1.1 SENSOR ERROR, OU1.

Vertical sensor errors in the final 2 nmi are less than 2.7 m (95%). Both along-track and crosstrack sensor errors are less than 2.5 m (95%). The small along-track error indicates good time synchronization in the data. The crosstrack sensor accuracies meet the Federal Radionavigation Plan (FRP) 2 Sigma requirement of 5.2 m (100' DH) and 4.1 m (50' DH), respectively, for a CAT II/III approach. The vertical sensor accuracies, however, fell short of the FRP 2 Sigma CAT II/III requirements of 1.7 m (100' DH) and 0.6 m (50' DH), respectively. Figures 1 and 2 show the error trajectories for all 25 approaches for vertical sensor error and crosstrack sensor error from 2 nmi to the runway threshold. Notice in figure 2, one particular approach was consistently 3 - 4 m offset. There is no apparent explanation for this, other than possibly mismatched ephemeris data, as

mentioned below. Figure 3 shows the vertical height in sensor error (|mean| + 2 SD) from the final approach fix (FAF), which is at 4.2 nmi, to the runway threshold.

In addition to the 25 approaches analyzed, 1 other approach was eliminated because the data recorder was not on and 2 more were eliminated due to air traffic. Also, 14 more approaches were eliminated because the ambiguity search was not complete upon reaching the FAF point. However, 7 of the previous mentioned 14 approaches were eliminated either because of cycle slips or the FAF point had been crossed before the search was complete. Therefore, 14 of 39 approaches (36%) were lost either because of an incomplete ambiguity search or cycle slips.

While the OU1 system fell short of the CAT II/III 2 Sigma FRP requirements, the noise of the sensor measurements were very low (figure 4). During autocoupled flights, this is very important for feedback control and providing a smooth descent of the aircraft. The variation for 25 approaches ranged from 0.25 - 0.61 m, 2 Sigma. Keeping in mind that the laser tracker contributes a certain amount of error, this is a significant result when compared to the previous mentioned FRP CAT III requirement of 0.6 m. OU has indicated that mismatched ephemeris data may have been the cause of the bias errors. Further investigation where the flights will be rerun, post-flight, should provide more insight into the problem. The results in section 4.2 provide somewhat better sensor accuracies, but fewer initializations to begin the ambiguity search were done. For OU 1, the search was reinitialized at the termination of each approach. In either case, these accuracies are at a level never previously attained with GPS in real-time and provide confidence that CATII and CATIII accuracy requirments are within reach.

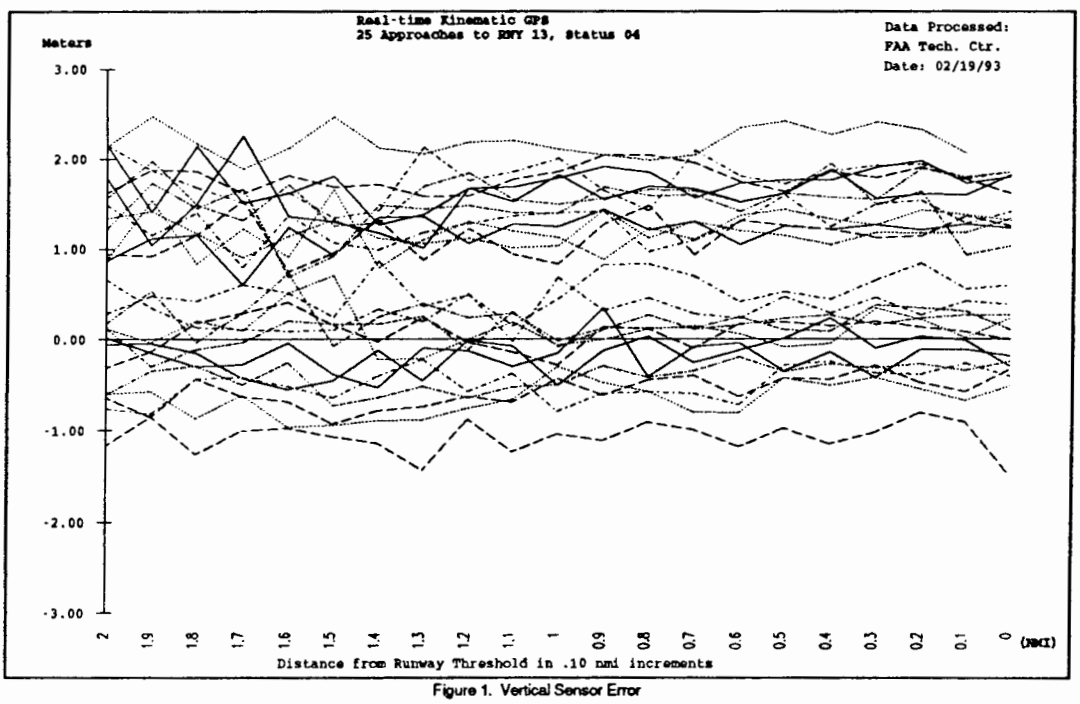



Figure 1. Vertical Sensor Error

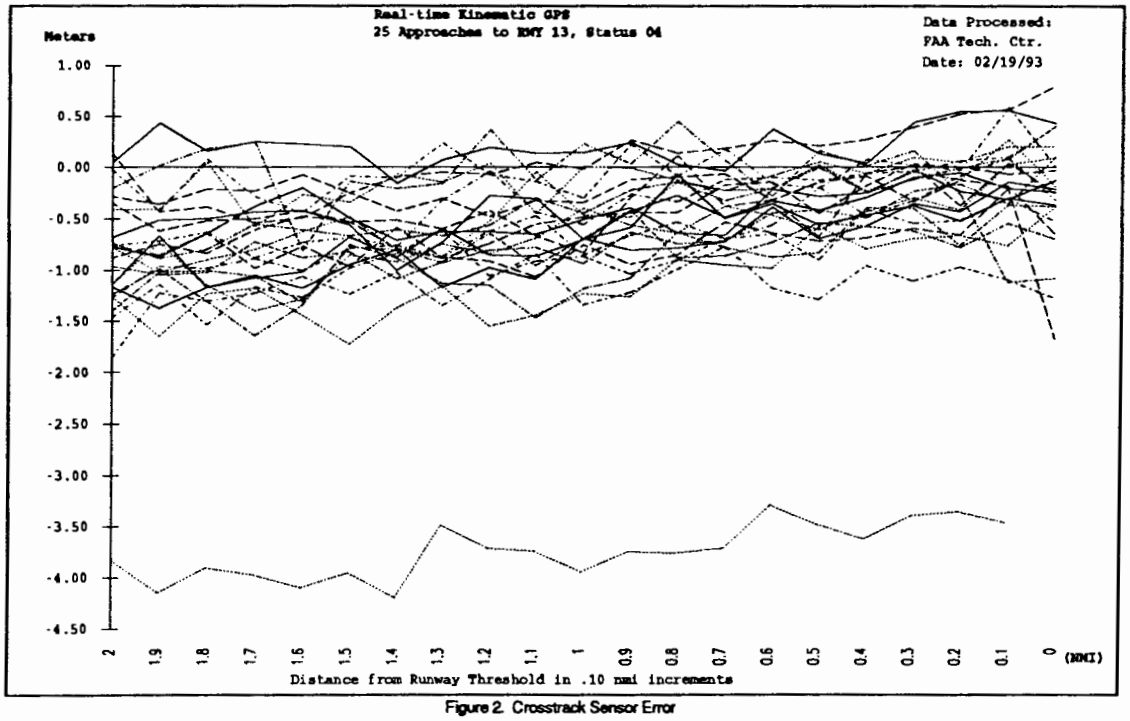



Figure 2. Crosstrack Sensor Error

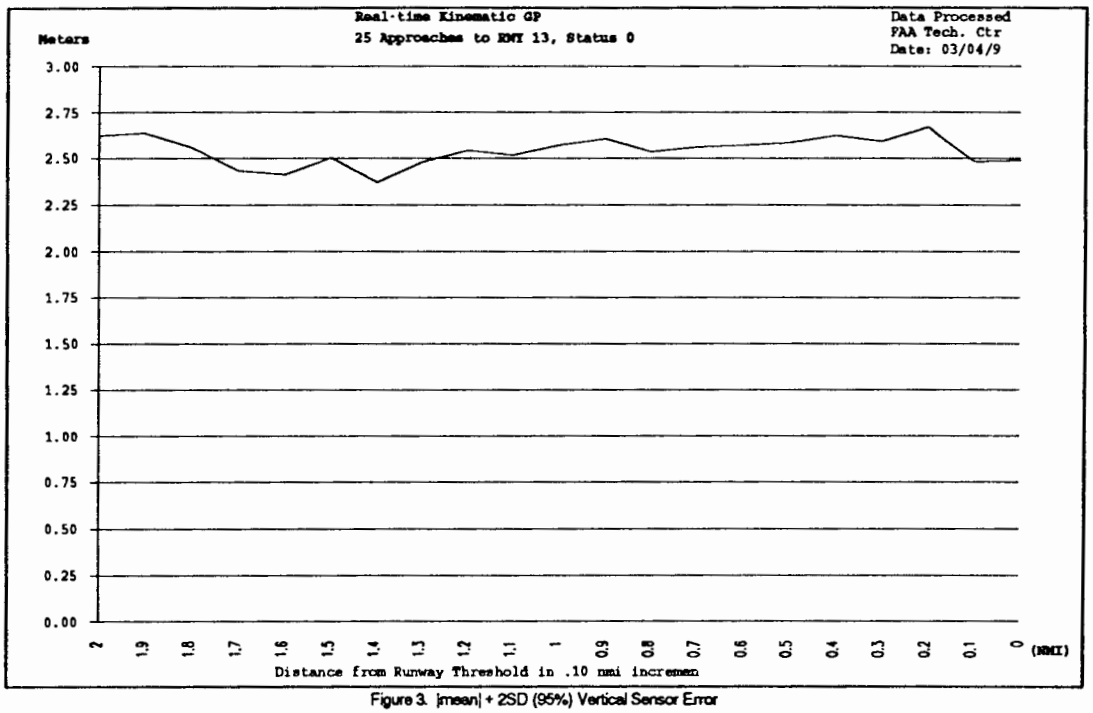



Figure 3. |mean| + 2SD (95%) Vertical Sensor Error

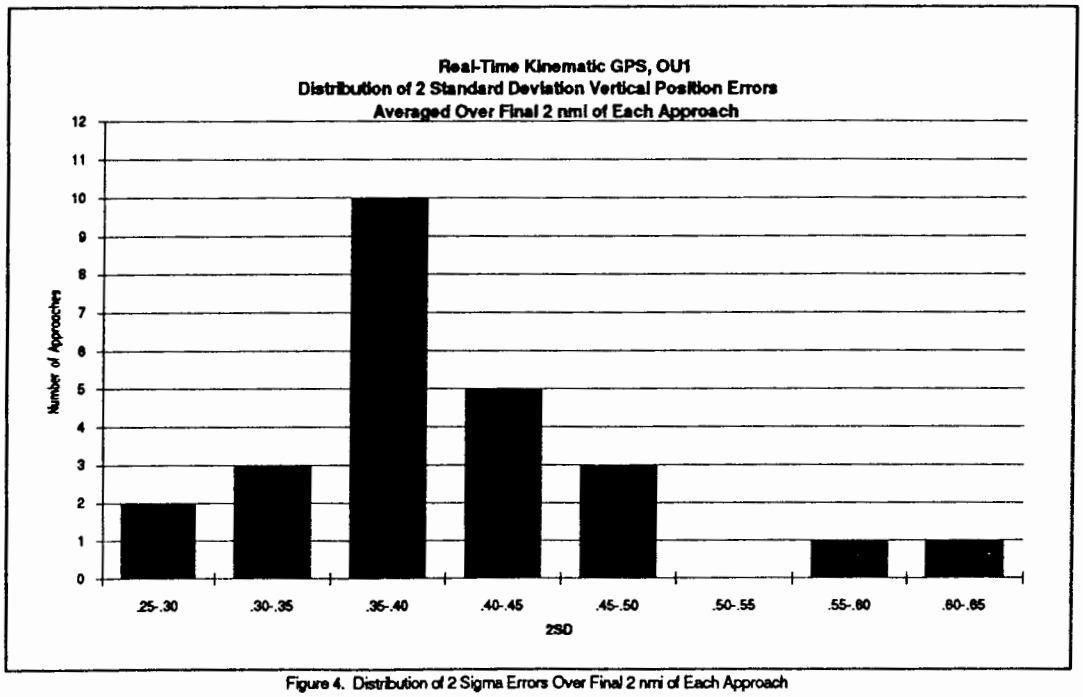



Figure 4. Distribution of 2 Sigma Errors Over Final 2 nmi of Each Approach

## 4.1.2 FLIGHT TECHNICAL ERROR.

Figures 5 and 6 show the error trajectories from 2 nmi to the runway threshold for vertical FTE and crosstrack FTE. All approaches were flown to RWY 13 over a 3 day period and thus various wind conditions were encountered. The same subject pilot flew all approaches under the hood.

Flight technical error (FTE), as shown here, is as a measure of the deflection of the needle on the CDI as derived from GPS positions. Vertical FTE is 6.5m (95%) 0.2 nmi from the runway threshold (approximately the 100 ft DH). Crosstrack FTE is 4.2 m (95%) at the same location. A 6.5 m vertical error is a 4 dot deflection on a 5 dot CDI. A 4.2 m lateral error is less than 1/4 dot on a 5 dot CDI.

The crosstrack FTE indicate guidance good enough for CAT III operations (however, CAT III operations are generally auto-pilot coupled) . The vertical FTE is high when compared to the requirements for CAT II. However, it should be pointed out that flying "raw" CDI needles would not be typical of CATII operations. While FTE can tend to dominate total system error, with the use of enhancements such as flight director, improved pilot performance would be expected. Additionally, the project pilot who flew all of these approaches (under the hood) indicated that every single approach could have resulted in a successful landing.

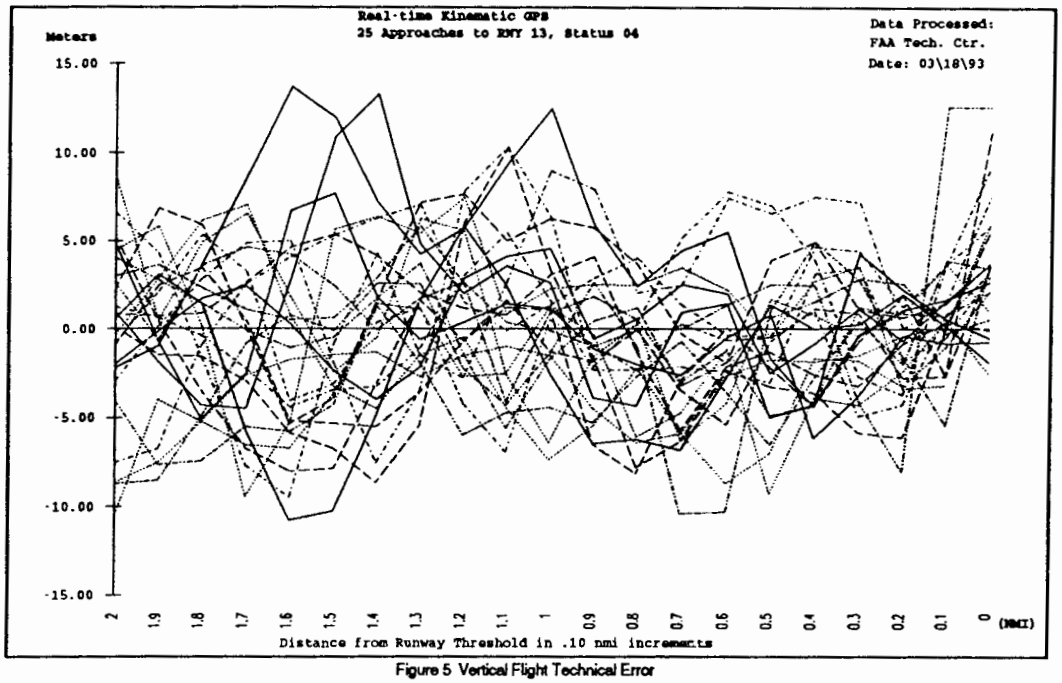



Figure 5 Vertical Flight Technical Error

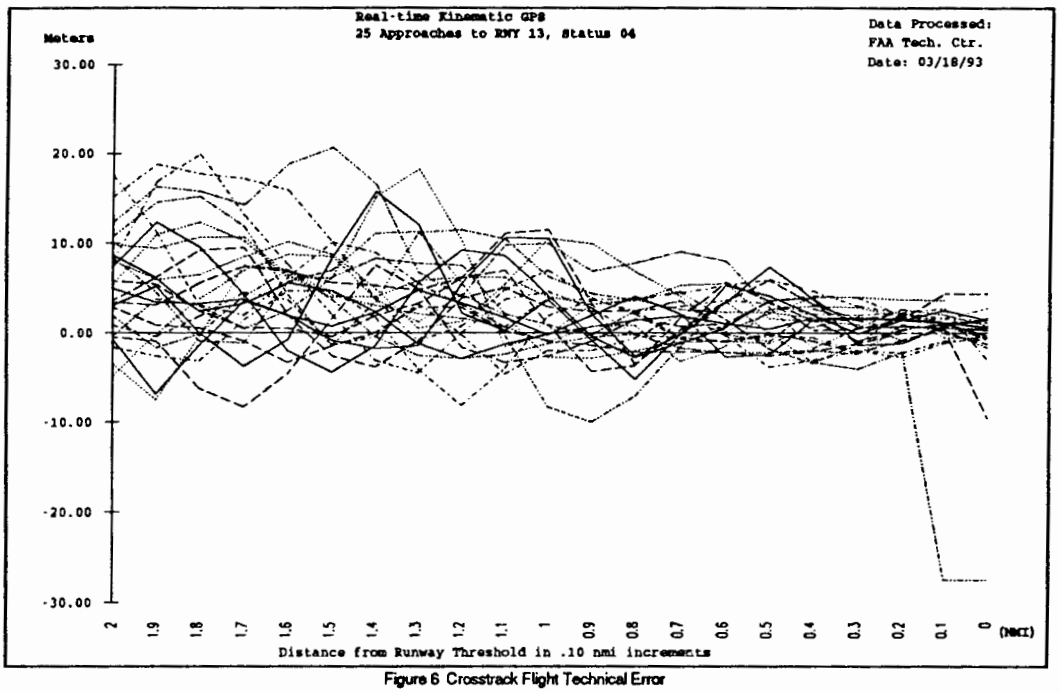



Figure 6 Crosstrack Flight Technical Error

## 4.1.3 TOTAL SYSTEM ERRORS.

Total system errors are derived from the laser tracker truth referenced to the desired flight path. Since all the approaches were manually flown, the total system vertical error is expected to be larger than if autocoupled. Additionally, CAT II/III operations would require at least a flight director which was not employed during these flight tests. At 0.2 nmi from

the runway threshold (approximately the 100 ft DH), the total system vertical error is 7.9 m (95%). This is larger then the developing SOIT "tunnel" [3] requirement of 4.6 m for CAT II. The total system crosstrack error is 3.5 m (95%) at 0.2 nmi from the runway threshold. At a CAT II DH, the SOIT tunnel requires 22.9 m. Thus, as expected, the crosstrack total system errors easily fall within the SOIT tunnel requirements with plenty of margin.

Figures 7 and 8 below show the error trajectories from 2 nmi to the runway threshold for total system vertical errors and total system crosstrack errors. Additionally, figures 9 and 10 show the 95% total system vertical and crosstrack error for all approaches combined (35 total ) from the FAF point down to the runway threshold.

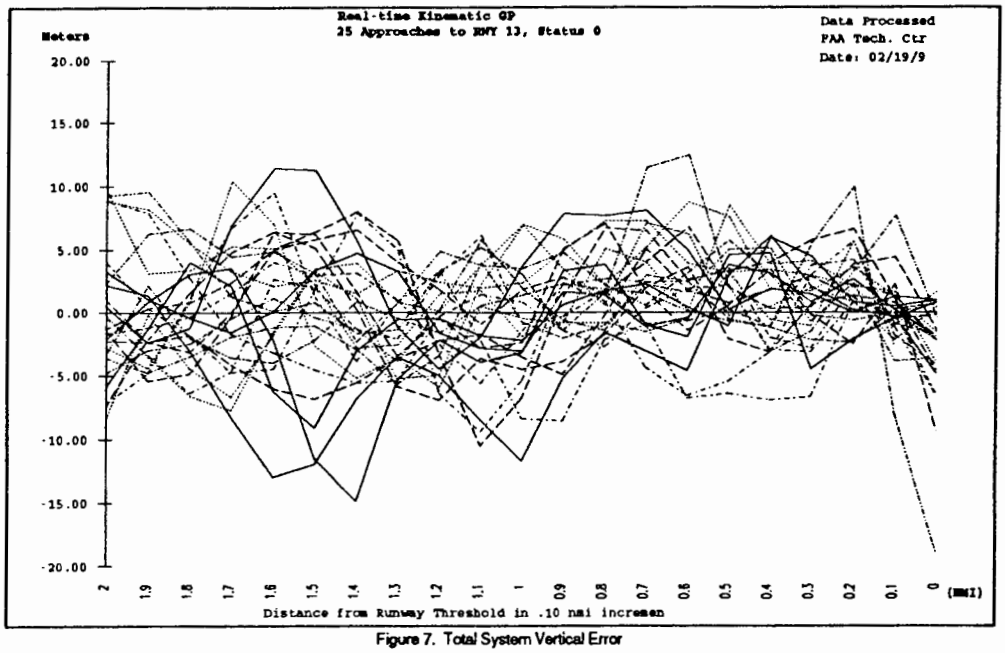



Figure 7. Total System Vertical Error

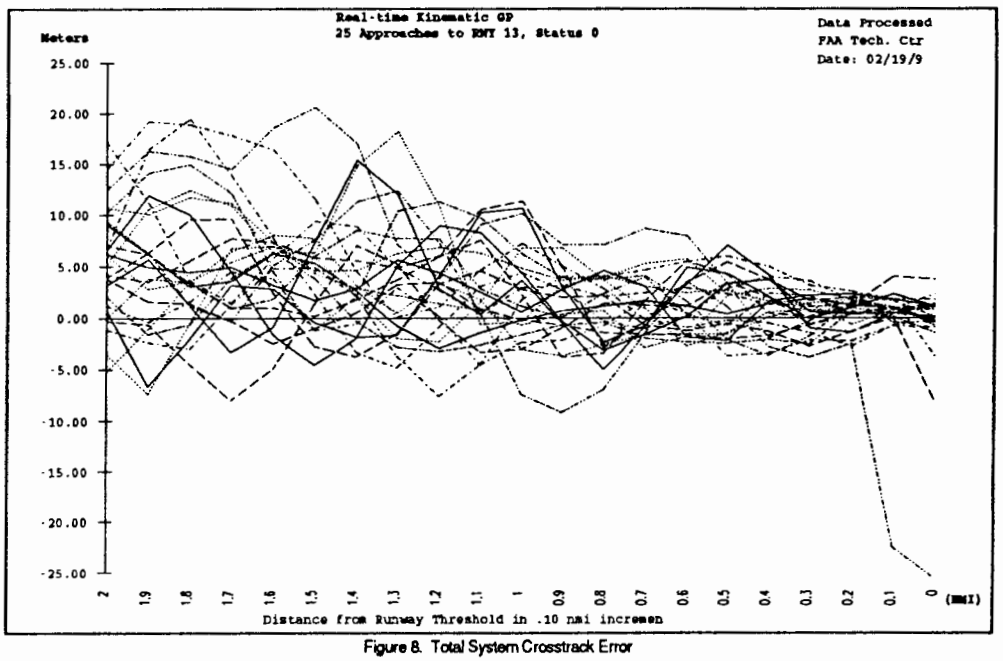



Figure 8. Total System Crosstrack Error

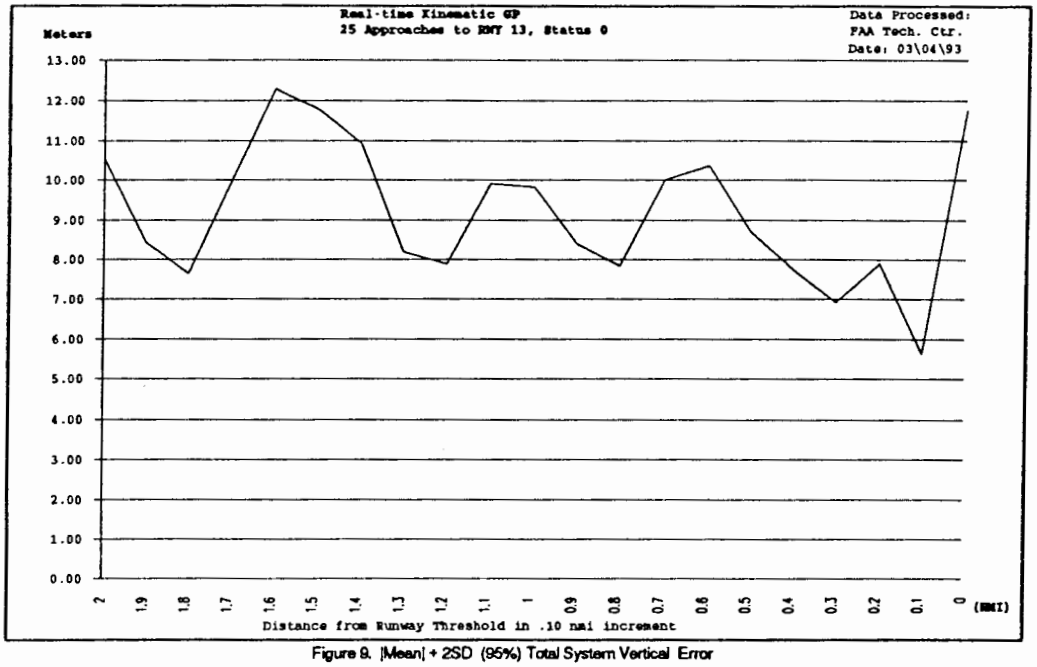



Figure 9. |Mean| + 2SD (95%) Total System Vertical Error

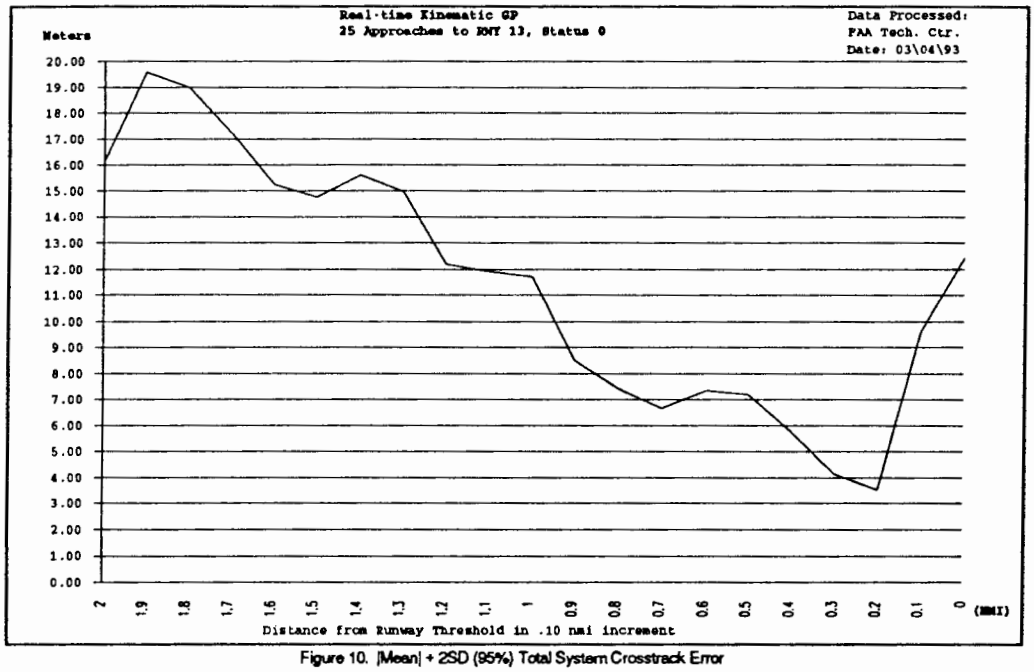



Figure 10. |Mean| + 2SD (95%) Total System Crosstrack Error

## 4.1.4 TIME TO RESOLVE AMBIGUITIES.

Figure 11 provides the distribution of the time to resolve the ambiguities for all 39 approaches including the approaches not analyzed previously as described in section 4.1.1. As can be seen, the largest number of approaches (13) fell in the 100-125 second range. The least amount of time in which the search was completed equaled 93 seconds. The bar at the far right represents the 7 approaches which were declared unsuccessful indicating the search was not complete at the time the approach was broken off.

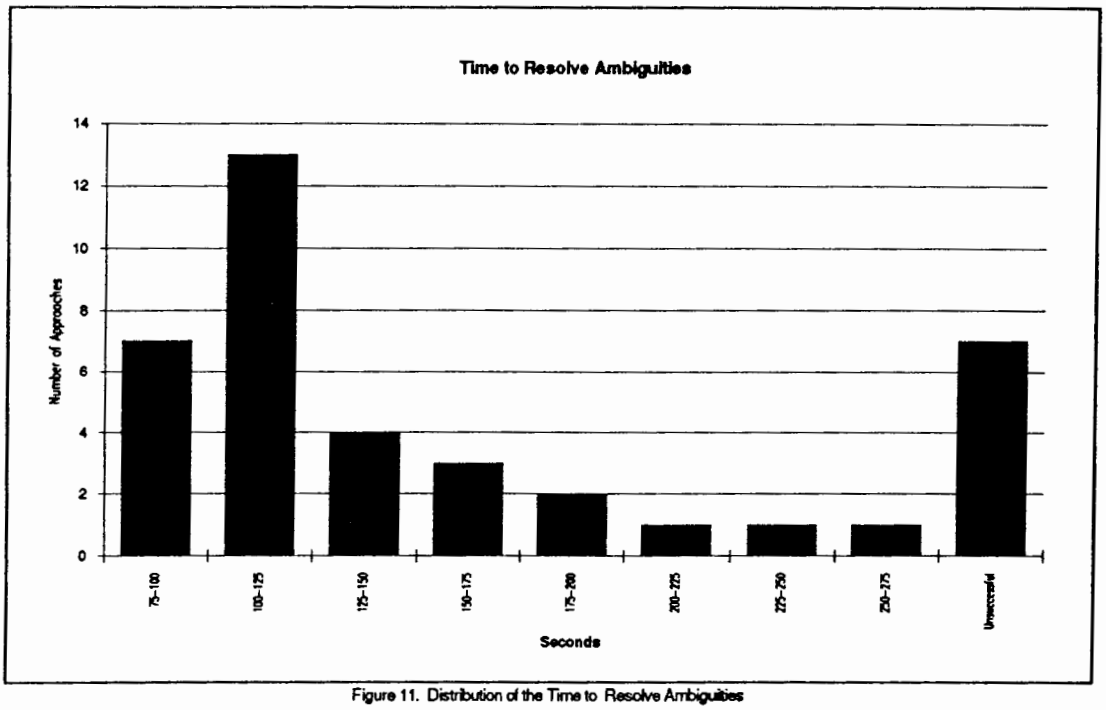



Figure 11. Distribution of the Time to Resolve Ambiguities

## 4.2 FLIGHT TEST RESULTS FOR 18 APPROACHES, OU2 RECEIVER.

### 4.2.1 SENSOR ERROR, OU2.

Vertical sensor errors varied from 0.56 m up to 1.83 m (95%) in the final 2 nmi . However, a poor VHF data communication link contributed errors which have been removed since it is believed this problem can be remedied. Of the twenty-one ensemble points in the final 2 nmi, 57% were less than 1 m (95%), 90% were less than 1.25 m and 100% were less than 2 m. Thus, 90% of the sensor errors in the final 2 nmi were below the FRP CAT II requirement of 1.7 m (95%). The FRP CAT III requirement of 0.6 m (95%) was only attained at one point, 1.7 nmi from the runway threshold where 0.56 m (95%) was the measured error (the mean was 0.03 m and the standard deviation was 0.27 m).

Crosstrack sensor errors were less than 1.3 m (95%) and along-track errors were less than 2.21 m (95%). The small along-track error indicates good time synchronization in the data. The sensor accuracies for crosstrack sensor error meet the DH FRP 2 Sigma requirement for a CAT I I/III approach of 5.2 m and 4.1 m, respectively.

Figures 12 and 13 show the error trajectories for all 18 approaches for vertical sensor error and crosstrack sensor error from 2 nmi to the runway threshold. Figure 14 shows the vertical sensor |mean| + 2 SD for the final 2.0 nmi, to the runway threshold.

In addition to the 18 approaches analyzed, 18 other approaches were eliminated because of data recorder problems; 1 was eliminated due to the data link, and 2 more were eliminated due to air traffic. Also, 6 more approaches were eliminated because the root mean square (RMS) of the north, east and up errors, which is an indication of whether or not the ambiguities have been resolved, was not acceptable. Apparently cycle slips

caused the OU2 receiver to restart the search because it was not reinitialized after each approach as was the OU1 receiver.

As with the OU1 data, the noise of the sensor measurements was very low (fig 15). The time to resolve data was not available for the OU2 configuration.

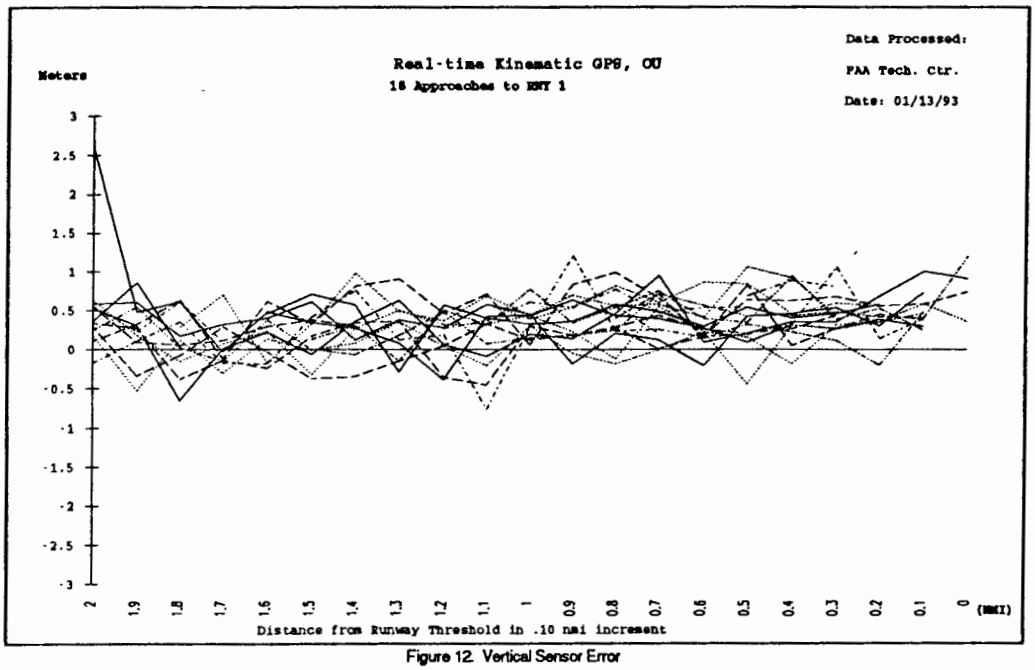



Figure 12. Vertical Sensor Error

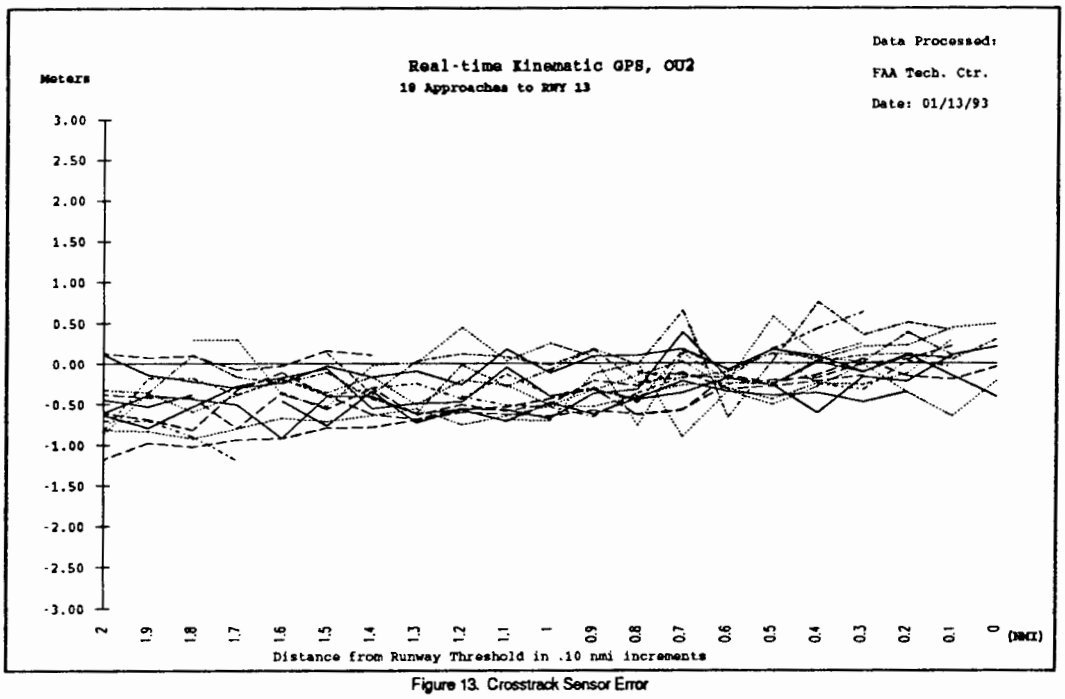



Figure 13. Crosstrack Sensor Error

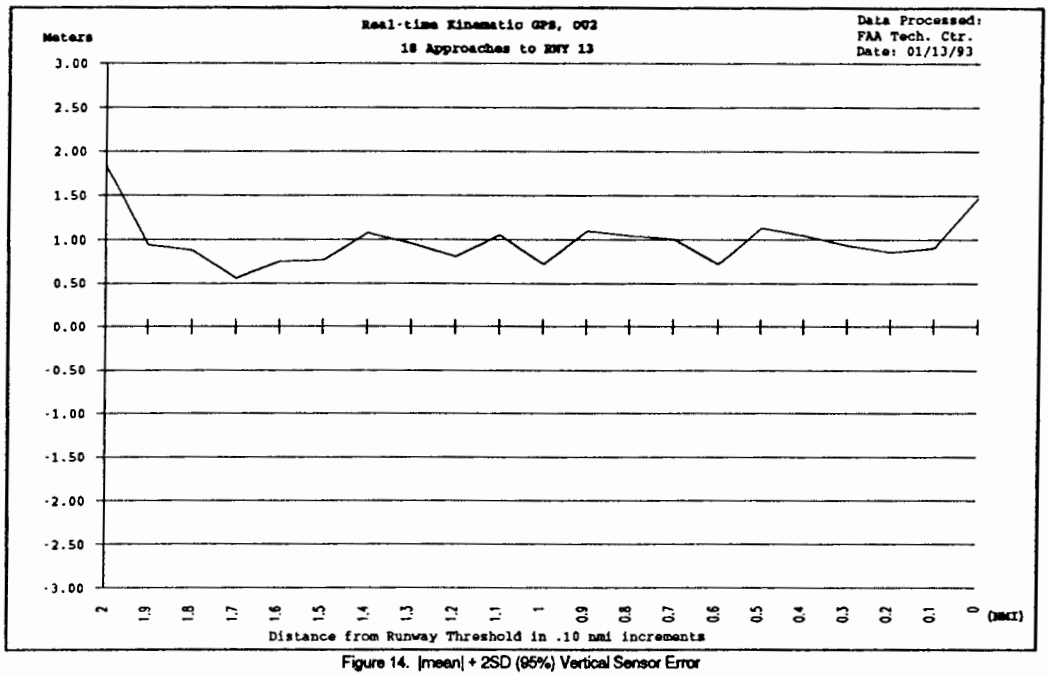



Figure 14. |mean| + 2SD (95%) Vertical Sensor Error

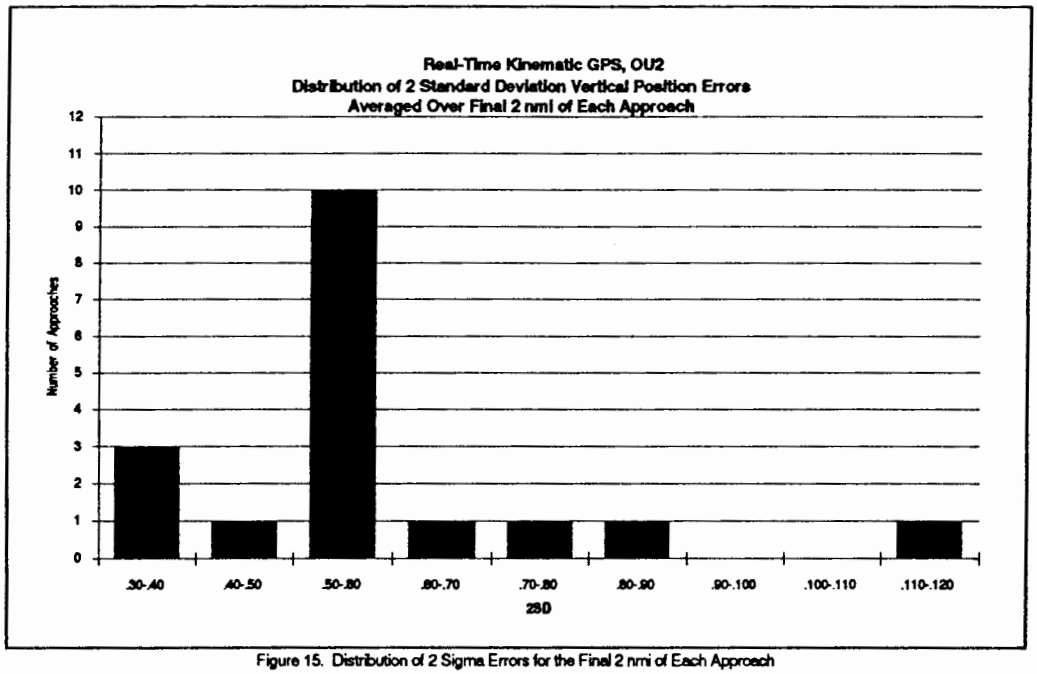



Figure 15. Distribution of 2 Sigma Errors for the Final 2 nmi of Each Approach

## 6.0 CONCLUSIONS.

Because of the speed of 486 microprocessor, algorithms for on-the-fly kinematic GPS are becoming a reality. As faster processors and more efficient algorithms are developed, less time will be required for the ambiguity search. The on-the-fly kinematic GPS (OTF-KGPS) systems tested were not robust enough for implementation. They were not robust in the sense that they only indicated successful ambiguity resolution 82 percent of the time. They require further development to improve their robustness.

However, the low noise position measurements (0.6 m, 2 standard deviation) indicate that the accuracy required for Category II and Category III operations may be possible. Additionally, a 2 hertz (HZ) update rate to the course deviation indicator resulted in flight technical error (FTE) (for the pilot flying "raw needles") of less than 6.5 meters (m), |mean| + 2 standard deviation (SD), at the 100' decision height (DH) for 25 approaches manually flown. It is assumed that a faster update rate and enhancements such as a flight director will improve pilot performance and lower the flight technical error.

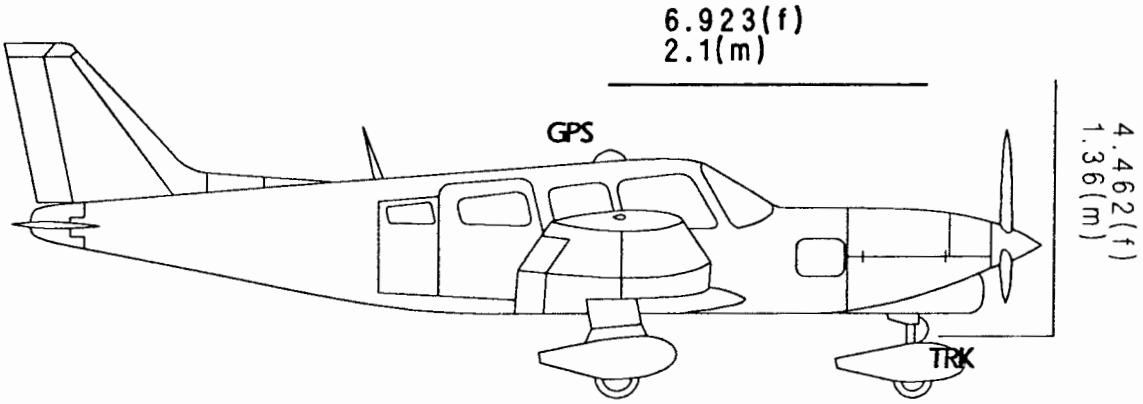
**REFERENCES**

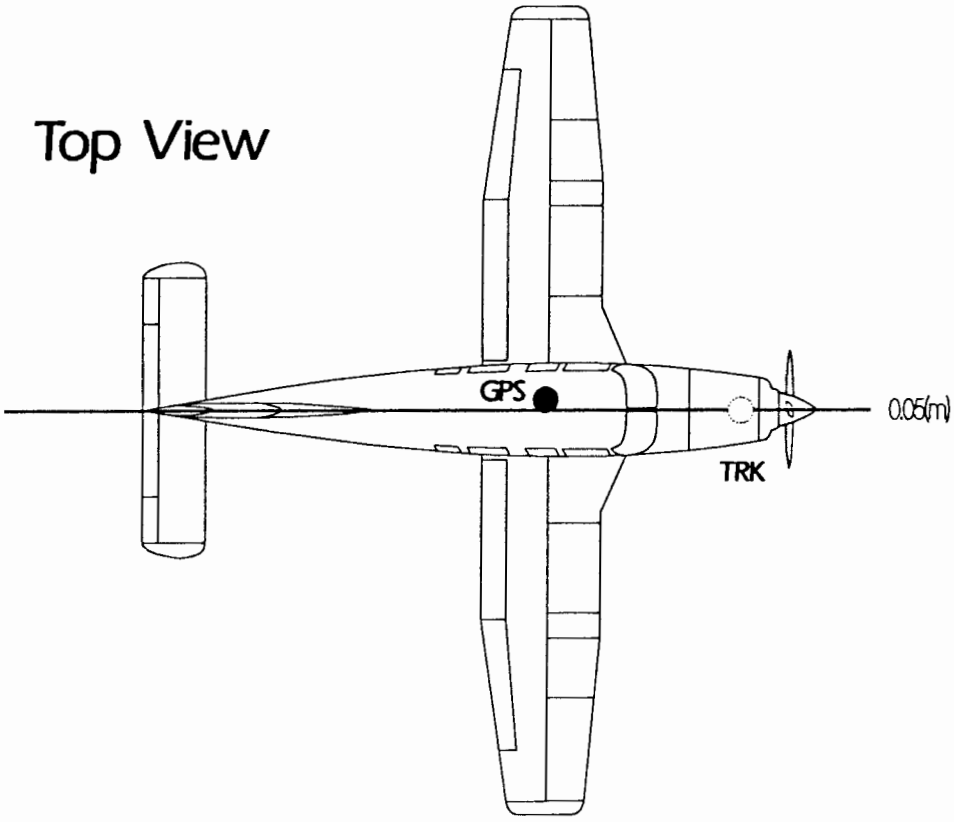
1. Federal Aviation Administration (FAA) Satellite Operational Implementation Team (SOIT) Special Technical Committee (STC), *The Tunnel Concept, The Path to the Future; A RNP Standard for Precision Approaches*,paper approved by FAA SOIT STC on 11/19/92.

APPENDIX A

# OHIO Univ. Flight Test

## Side View




## Top View