Performance Evaluation of On-Airport Local Area Augmentation System Architectures

David Lawrence, Stewart Cobb, Boris Pervan, Guttorm Opshaug,
Per Enge, J. David Powell, Bradford Parkinson,

Stanford University

ABSTRACT

Recently there has been growing demand for a Category III precision landing system architecture which is completely contained on airport property. In response, Stanford is exploring different Local Area Augmentation System (LAAS) architectures and evaluating their performance. To maximize this performance, the architectures incorporate information from a variety of sources, including code-centered carrier techniques, satellite motion, and airport pseudolites (APLs). In addition to using APLs as additional ranging sources, a new concept was developed for positioning with pseudolites.

The new concept involves using the differential carrier phase between a pair of pseudolites. This differential carrier phase provides an additional observable that can improve the accuracy of GPS positioning. The surfaces of constant differential phase are hyperbolic. In the far field however, the system approximates an angular based system such as the Instrument Landing System (ILS). For example, if the two pseudolites are located at the top and bottom of a tower near the aim point, the phase difference measurement at the aircraft is analogous to the glideslope measurement for ILS. Although there is an integer cycle ambiguity associated with the differential carrier phase measurement, this ambiguity can be resolved when the aircraft is on long final approach. At this distance, the position difference between integer candidates is so large that differential code phase positioning can isolate the correct integer.

Several APL configurations have been explored through computer simulation. The effects of both additional ranging sources and APL differential carrier phase measurements are incorporated into the simulation. Also incorporated are the effects of satellite motion and code-centered carrier smoothing. The resulting performance is due to a combination of these effects. In addition to simulation, ground experiments and flight tests have been performed. The results of simulation and flight testing are presented, and the navigation performance of these architectures is assessed.

1 INTRODUCTION

Stringent Required Navigation Performance (RNP) parameters for Category III precision landing have been proposed in [ORD]. Simulations incorporating realistic satellite failure models show that the proposed availability and continuity may be unrealizable with the nominal GPS constellation [LA]. Methods to augment the constellation are therefore being researched. One such method uses ground-based GPS transmitters called pseudolites. This form of augmentation is desirable for early LAAS installations because it does not rely on additional satellites.

Initial studies of pseudolite augmentation located pseudolites to optimize ranging performance [KP]. This was achieved by minimizing Dilution of Precision (DOP). In some cases, this minimization was constrained to provide robustness to worst-case satellite failures. Later, work by Cohen [CC] suggested placing pseudolites under the glideslope to leverage the effect of geometry change. Although this technique provides centimeter-level accuracy, it might require the installation of equipment off the airport property. Current research focuses on developing an augmentation system completely contained on airport property. Augmentation pseudolites located on airport property have come to be called Airport PseudoLites (APLs).

Given that APLs may be required, there are two questions that must be addressed:

1. How does the carrier and code phase signal quality provided by APLs compare to that provided by space vehicles (SVs)?
2. Where should APLs be located to maximize the resulting performance?

This paper begins to answer both questions.

Presented at ION GPS-96
Kansas City, Missouri, September 17-20, 1996

2 STACKED APLs

Until recently, only the performance of a single APL has been assessed. Assuming the APL signal noise level and continuity are comparable to a satellite signal (recent flight trials indicate that this is so), a single APL provides the benefits of an additional ranging source:

1. Improved DOP
2. Improved Availability/Continuity
3. A small amount of geometry change for cycle ambiguity resolution.

At first thought it would seem that each additional APL would provide only these same benefits. However, the presence of multiple pseudolites provides additional information that can improve the accuracy performance beyond the level expected from an additional ranging source. Specifically, the difference between the APL carrier phase measurements can be interpreted as a new observable. One configuration that takes advantage of this observable to improve vertical accuracy is to place APLs at the top and bottom of a tower; the method has therefore come to be called the “stacked APL” method.

2.1 STACKED APL ANALYSIS

The measurement equation for the differential carrier phase between two APL’s is given by Equation (2.1). The derivation of this equation assumes the line biases are calibrated for the two APL antennas such that the fractional number of cycles in the difference between line biases is known. Although this calibration is not necessary, without it the bias will not be an integer. The following analysis assumes this calibration has been performed; Section 2.2 discusses the impact of not calibrating line biases.

$$\varphi = \left|\vec{x} - \vec{r}_{APL_2}\right| - \left|\vec{x} - \vec{r}_{APL_1}\right| + N + \delta\varphi \qquad \textbf{(2.1)}$$

where:

φ is the carrier phase difference between the two APL’s, corrected for any non-integral difference between the APL line biases.

$\vec{x}$ is the position of the aircraft relative to the reference station.

$\vec{r}_{APL_i}$ is the position of the i^{th} APL relative to the reference station.

N is the cycle ambiguity for the phase difference.

$\delta\varphi$ is the error in the measurement of φ.

The form of Equation (2.1) shows that the surfaces of constant phase difference are hyperbolic. Far away from the APL’s, the hyperbolic surfaces are well approximated by straight lines as shown in Figure 2.1. The figure shows two APL’s "stacked" with one at the base of a tower and one at the top. Hypothetical lines of constant phase are shown for different values of the integer cycle ambiguity. Note that when the aircraft is far from the APL’s the lines of constant phase are far apart. At this distance, a code phase DGPS position estimate has sufficient accuracy to determine which line of constant phase the aircraft is on, thereby resolving the cycle ambiguity. As the aircraft approaches the APL’s, the lines of constant phase converge, improving the positioning geometry of the differential APL observable.

The potential performance of a stacked APL system can be quantified by linearizing Equation (2.1) to find the sensitivity of φ to changes in $\vec{x}$ as calculated in Equation (2.2):

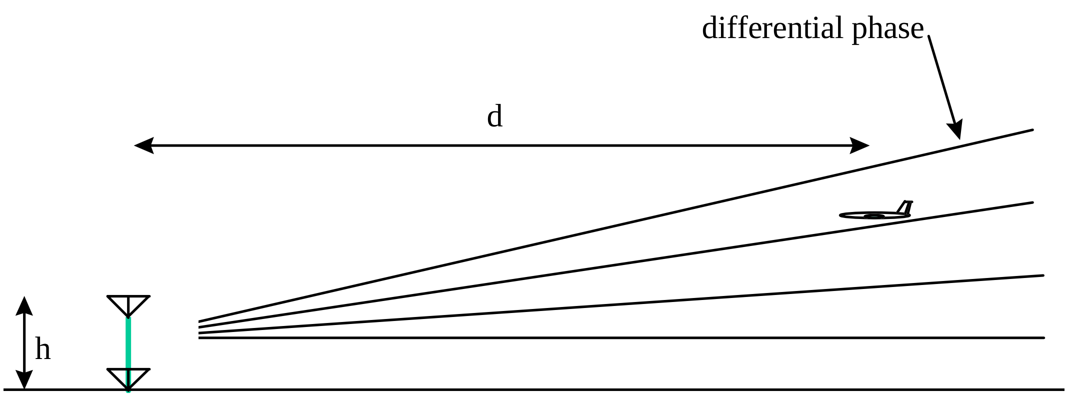

Figure 2.1: Stacked APL Geometry

$$\frac{d\varphi}{d\bar{x}} = \hat{e}_2 - \hat{e}_1 \equiv \Delta e \qquad (2.2)$$

where $\hat{e}_i$ is a unit vector from the aircraft toward the i^{th} APL.

The differential APL carrier phase observable therefore provides information parallel to Δe, the difference in the direction of the APLs seen from the aircraft. No information is provided normal to Δe. The dilution of precision (DOP) of the measurement, defined as the position error parallel to Δe for a unit error $\delta\varphi$, is $\frac{1}{|\Delta e|}$. For the configuration shown in Figure 2.1, $|\Delta e|$ can be approximated by:

$$|\Delta e| \cong \frac{h}{d} \qquad (2.3)$$

Far from the APL's, $|\Delta e|$ is small, so the lines representing different possible cycle ambiguities are far apart (the distance between these lines is $\frac{1}{|\Delta e|}$ cycles). For example, 10000 feet from a 50 foot APL tower, the ambiguity lines are about 40 meters apart, so the cycle can be easily resolved using code phase DGPS.

DGPS accuracy performance is typically the worst in the vertical direction; however, this direction is most critical for an aircraft approach guidance system above 100 feet. Between the altitudes of 100 and 50 feet, the on-board radar altimeter begins providing a supplemental source of vertical information. Therefore, the performance of the APL will be judged based on its vertical error at an altitude of 75 feet, about 1500 feet from touchdown. At a distance of 1500 feet from a 36 foot APL tower (the height of an ILS glide slope antenna), a 1.5 cm error in φ will result in a position error of about 60 cm. Note that Δe is approximately vertical for the tower configuration; so this new information provides a new source of vertical positioning information accurate to about 60 cm. When combined with the existing satellite DGPS position estimates and when filtered over the entire approach, the vertical position estimate will improve.

2.2 CYCLE AMBIGUITY UNCERTAINTY

If line biases in the pseudolite RF plumbing are uncalibrated, the cycle ambiguity term in Equation (2.1) will be a non-integral bias (in general). In this case, the bias cannot be calculated by simply rounding the bias estimated using code DGPS. Instead, the floating estimate can be continuously updated at a distance from the airport where it is highly observable. If initiated at a sufficient distance, this procedure will arrive at a very accurate (better than a centimeter) estimate of the bias; nevertheless, the uncertainty in the bias should be accounted for in an uncalibrated system. [PL] discusses uncalibrated systems in more detail. The analysis in this paper assumes calibrated biases.

3 INTRACK APLs

The analysis of Section 2.1 lends insight for the development of other configurations which take advantage of the differential carrier phase measurement between APL's. The important parameters in this development are the size and direction of Δe. At a distance, the magnitude of Δe should be small to allow for cycle ambiguity resolution. Near the airport, $|\Delta e|$ should increase to improve the DOP of the differential measurement. The direction of Δe near the airport should be nearly vertical to improve the vertical performance of the system. A configuration that meets these requirements is shown in Figure 3.1 where an APL is placed near each end of a runway. Although the APL's are spaced longitudinally, their appearance to an aircraft on final approach will be nearly identical to the stacked configuration. The longitudinal configuration has the advantage of servicing both runway ends without the need for a tower. The long baseline can provide DOP equivalent to a high tower.

With a longitudinal baseline, the horizontal component of Δe is not negligible. The following 2D analysis shows how the APL differential carrier phase measurement can combine with a single code DGPS position solution to provide improved vertical performance. Assume the code DGPS position covariance ($P_{\bar{x}_{code}}$) is given by:

$$P_{\bar{x}_{code}} = \begin{bmatrix} \sigma_h{}^2 & 0 \\ 0 & \sigma_v{}^2 \end{bmatrix} \qquad (3.1)$$

where $\sigma_h{}^2$ and $\sigma_v{}^2$ are the horizontal and vertical variances respectively. Assume also that the variance of the differential APL carrier phase measurement error is $\sigma_\varphi{}^2$. This information can be shown graphically by the covariance ellipses as in Figure 3.2. There is no position information provided by the differential APL measurement in the direction normal to Δe, so the corresponding covariance ellipse is infinitely long in that direction. In the direction parallel to Δe, the width of the ellipse scales with $\frac{1}{|\Delta e|}$.

Because Δe is not perfectly vertical, the APL measurement must be combined with the horizontal information provided by code DGPS to yield a vertical position estimate. The resulting variance ($\sigma^2_{v_{APL}}$) is approximated by:

$$\sigma^2_{v_{APL}} \cong \frac{\sigma_\varphi{}^2}{|\Delta e|^2} + \theta^2 \sigma_h{}^2 \qquad \textbf{(3.2)}$$

where θ is the angle between Δe and vertical.

The combined vertical variance ($\sigma^2_{v_{combined}}$) will be better than both $\sigma_v{}^2$ and $\sigma_{v_{APL}}{}^2$ as determined by Equation (3.3).

$$\sigma^2_{v_{combined}} \cong \frac{1}{\dfrac{1}{\sigma_v{}^2} + \dfrac{1}{\sigma_{v_{APL}}{}^2}} \qquad \textbf{(3.3)}$$

For the layout of Figure 3.1, when the aircraft is at a height of 75 feet, the geometry is such that:

$$\Delta e = \begin{pmatrix} 0.0043 \\ 0.0860 \end{pmatrix}$$

$$\frac{1}{|\Delta e|} = 11.6$$

$$\theta = 0.05 \text{ rad}$$

Assuming $\sigma_h = 1m$, $\sigma_v = 1.5m$, and $\sigma_\varphi = 0.02m$, the resulting combined vertical standard deviation ($\sigma_{v_{combined}}$) at 75 feet is 23 centimeters, a six times improvement over code DGPS alone. Therefore, this concept is promising, but further study is required.

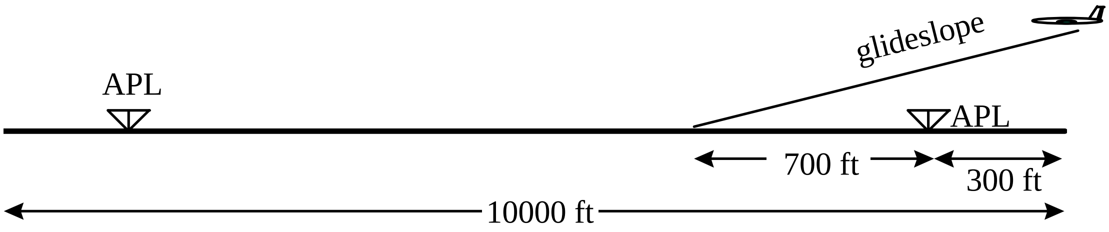

Figure 3.1: Longitudinal “Stacked” APL’s

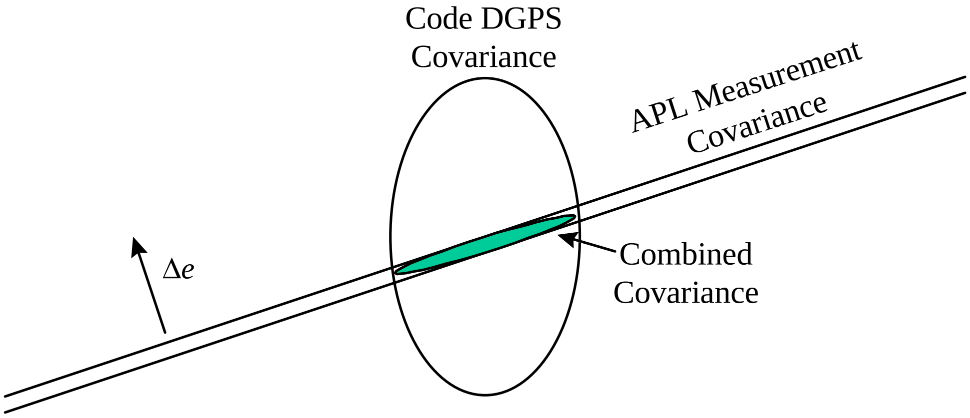

Figure 3.2: Simplified Stacked APL Covariance Analysis

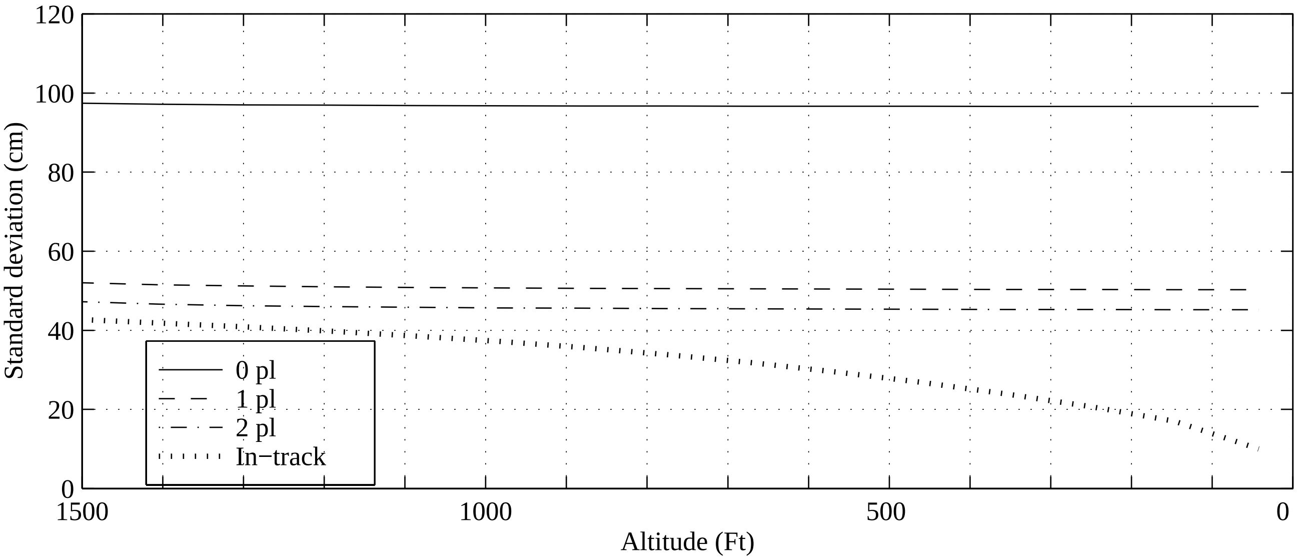

Figure 4.1: In-track APL Simulation Results

4 SIMULATION

A simulation-based covariance analysis was conducted to assess the performance of various levels of APL augmentation. Nominal approaches were simulated for San Francisco International Airport runway 28 (starting 10 km out). Figure 4.1 shows sample runs for different PL options for a representative five satellite geometry. In this case, the figure shows that augmenting the SVs with a single APL makes a considerable difference in the vertical accuracy of the system. Performance improves to a lesser extent as a second APL is added. However, when two APLs are oriented in the in-track configuration, a steady improvement in vertical accuracy with decreasing altitude is clearly observed. For this approach, vertical standard deviation was less than 15 cm at 100 feet. Further simulation is underway, particularly to study the robustness of the method to varying approach geometries. Initial results show some degradation with off-nominal approach trajectories, but still show a notable improvement over traditional methods.

5 FLIGHT TEST

To experimentally validate the in-track APL concept, a flight test was performed at Palo Alto Airport (PAO) in northern California. Although the performance of an in-track APL system is predicted to improve with runway length, the 2500 foot runway at PAO was sufficient for a proof-of-concept test. An antenna mounted atop the vertical tail of the Piper Dakota test aircraft (Figure 5.1) was used to track both the satellite and pseudolite signals. A direct line-of-sight to both pseudolites was available from this antenna above 100 feet.

Figure 5.1: Piper Dakota

To avoid interrupting the flow of air traffic, the pseudolites were not installed under the approach path. Instead they were offset to one side so they could be installed well clear of landing aircraft. Since the vertical positioning performance of a Category III system is typically evaluated at 100 feet altitude (below which, the laser altimeter is used to provide vertical guidance,) low approaches were performed down to an altitude of less than 75 feet in line with the offset in-track APLs. The APL's were separated by about 3000 feet and were pulsed to avoid the near-far problem [LA].

The differential reference station was located near the upwind end of the runway and received both pseudolites by line-of-sight through the same antenna used to track satellites. (In an operational setting, the pseudolites may have to be cabled to the reference station to prevent signal interruptions from ground traffic. Alternatively, autonomous pseudolites [SC], which do not require reception by a reference station would eliminate the need for these cables.) A NovAtel 3951 (GPS-Card) was used both at the reference station and in the aircraft. This receiver was chosen for its ability to track APLs without modification and to provide synchronous carrier and code phase measurements.

Before flight, the initial position of the aircraft was recorded to provide a kinematic reference trajectory to be used as truth. In post flight analysis, this centimeter-level truth trajectory was used to assess the ranging and positioning performance provided by the APLs.

Due to a combination hardware problems and time constraints, only three passes were flown with both the aircraft receiver and reference receiver tracking both APLs. Of the three, first pass had the best geometry to test the in-track APL concept.

5.1 RESULTS

Given the kinematic reference trajectory, the phases measured for the APLs could be used to generate phase profile plots. Figure 5.2 plots the differential code phase for the APLs corrected for known range and second-differenced with a satellite to remove receiver clock error. The result is an error profile dominated by the APL code phase error (the satellite code phase noise was found to be about half that of the APLs). The figure shows the profile during all three approaches. The missing points result from pseudolites signals being lost during turns at a distance from the airport. No outages were observed on final approach.

Figure 5.3 plots similar information to Figure 5.2, showing the carrier phase error profiles for the APLs

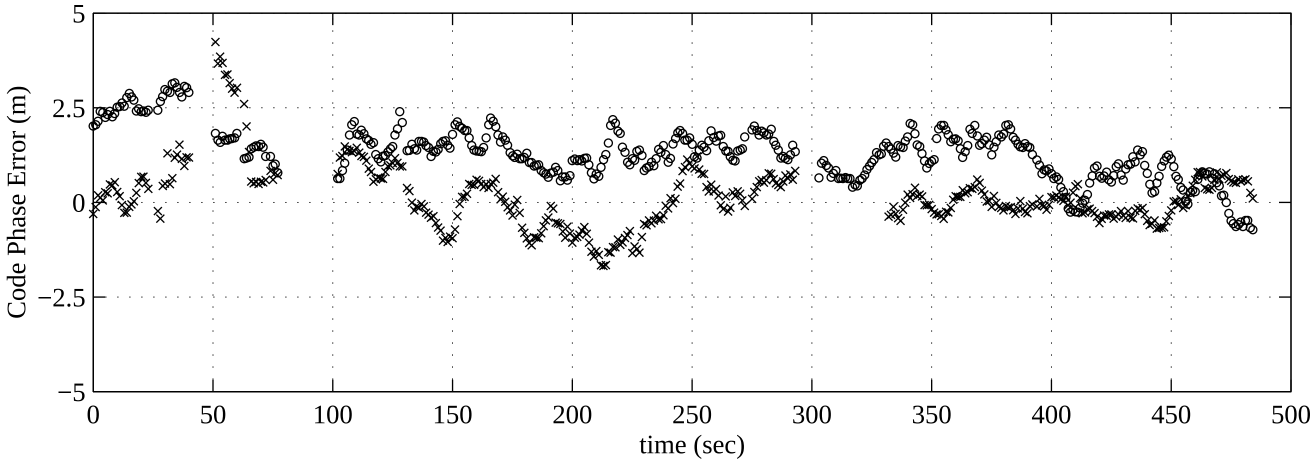

Figure 5.2: Code Phase Double Difference (APL-Spacecraft)
x=APL #1
o=APL #2

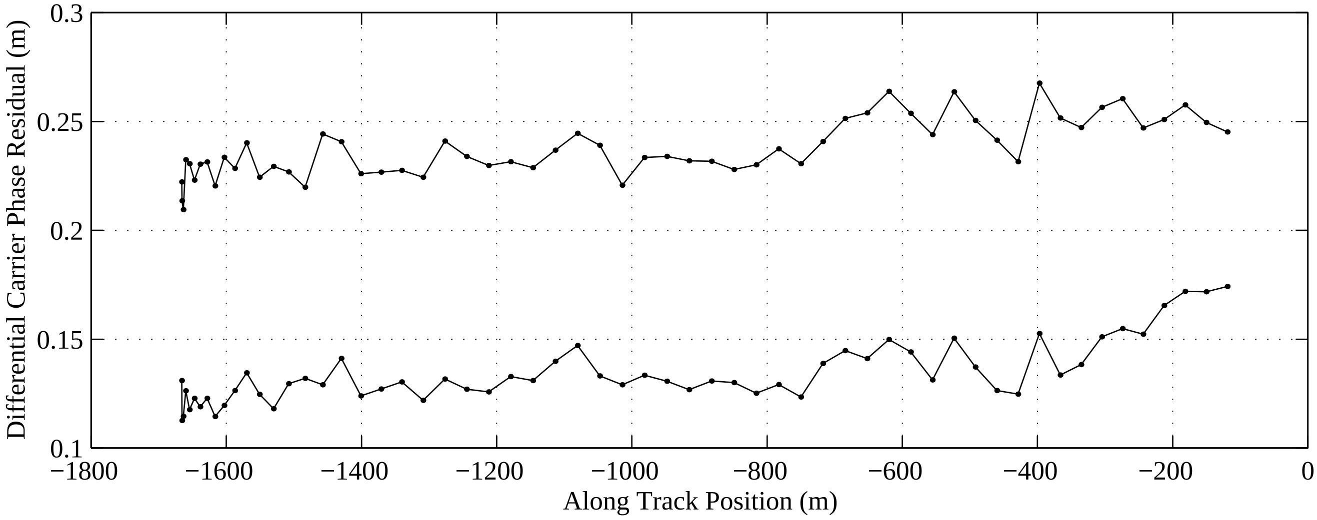

Figure 5.3: APL Carrier Phase Residual

during the first approach. The offset between the two curves is due to uncalibrated line biases (see Section 2.2); however, the noise level is what determines the performance of the system, not the absolute value of the phase profiles. The 1σ noise for the single-difference APL carrier phase was 9.4 mm during this approach, compared to 3.4 mm for satellites. Toward the end of the approach, the downwind pseudolite may have been blocked from the tail antenna by the fuselage as evidenced by the increased error toward the right of the lower curve.

Figure 5.4 shows the double difference APL carrier phase for the same approach. This quality of this measurement is the key to the performance of the stacked and in-track APL systems. As shown in the figure, the measurement noise is less than a few centimeters until the point where the near pseudolite is speculated to have been blocked by the fuselage. Table 5.1 summarizes the results of the APL signal quality analysis.

Table 5.1: Single Difference Ranging Error

1σ Phase Error	Spacecraft	APL
Carrier	3.4 mm	9.4 mm
Code	0.32 m	0.70 m

Figure 5.5 plots the vertical error with and without the pseudolites, along with the predicted 95% bound. For this approach, the relative performance improvements offered by APLs are clear from the figure. Further simulation and flight tests are planned to gather statistical data.

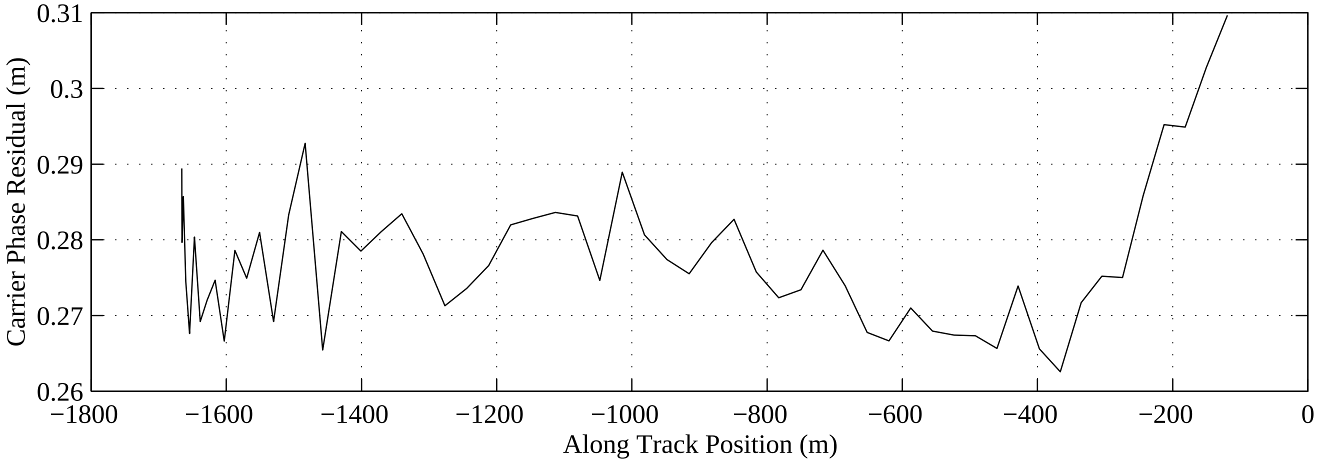

Figure 5.4: Double Difference APL Carrier Phase Residual

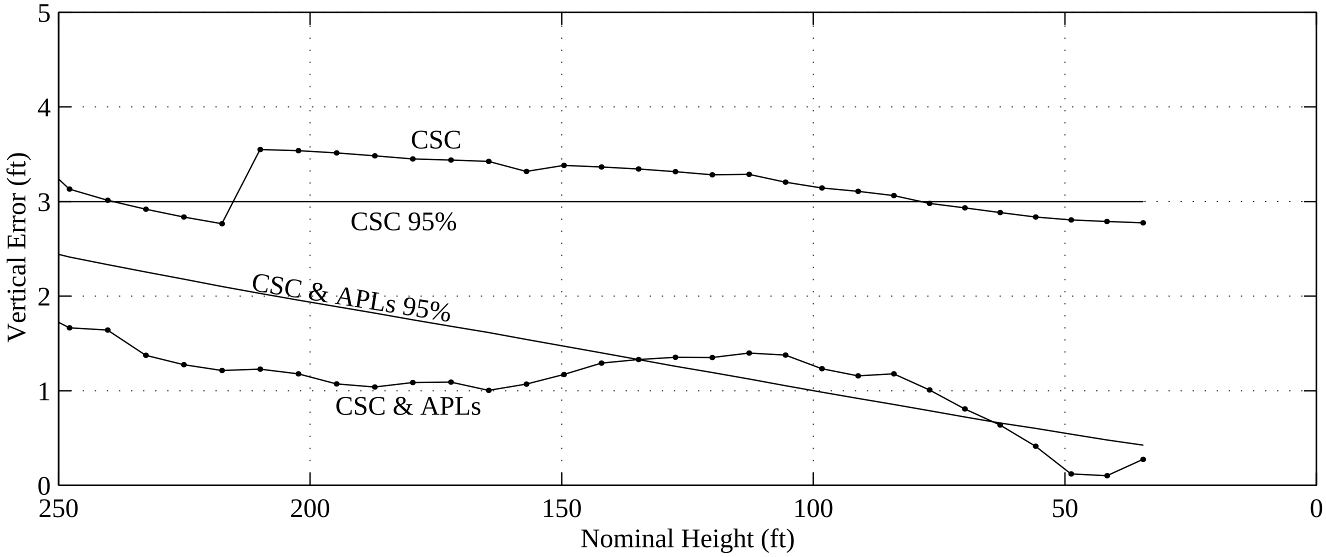

Figure 5.5: Vertical Position Error – Carrier Smooth Code with and without APLs

6 CONCLUSIONS

This paper continued to explore the signal quality of pulsed pseudolites received at an aircraft. Current results show better than 1 cm single difference carrier phase noise and 70 cm code phase noise from Airport PseudoLites (APLs). No APL signal continuity interruptions were observed on final approach during recent flight tests.

A new method of positioning using APLs was introduced. This method indicates that optimal pseudolite placement does not minimize ranging DOP as one might expect. Instead, performance improvements may be achieved by arranging pseudolites to make use of the differential APL carrier phase measurement. Preliminary flight test and simulation results of this concept are promising.

6.1 FUTURE WORK

The flight testing described in Section 5 will be continued with efforts to create more realistic conditions. Flight tests are planned for 11/96 at Moffet field in northern California with the following differences from the preliminary test:

- The longer runway (9200 feet versus 2500 feet at PAO) should provide improved in-track APL performance (just as a high tower improves stacked APL performance).
- Due to less air traffic, longer final approaches will be performed (6 miles versus ~1 mile at PAO). Again, this should improve stacked APL performance.
- An air transport class jet (an FAA Boeing 727) will be used.
- New pseudolites are being designed and built under contract from the FAA.
- A nose antenna will be used to track pseudolites, hopefully providing better signal quality.
- A reference station incorporating three GPS receivers will provide ground monitoring capability.

Results of this flight test campaign will be published in a future paper.

7 ACKNOWLEDGMENTS

The authors wish to thank several individuals and organizations who made this research possible. At Stanford, Konstantin Gromov, Jock Christie, Andy Barrows, Sam Pullen, Vicki Lu, and Jonathan Stone provided generous assistance. The assistance of Palo Alto airport terminal and tower personnel was instrumental in performing the flight tests. This research was sponsored by the FAA.

8 REFERENCES

[CC] C. Cohen, B. Pervan, H.S. Cobb, D. Lawrence, J.D. Powell, B. Parkinson, “Real-Time Cycle Ambiguity Resolution using a Pseudolite for Precision Landing of Aircraft with GPS,” DSNS ‘93, Amsterdam, The Netherlands, March 30 - April 2, 1993.

[KP] D. Klein, B. Parkinson, “The Use of Pseudo-Satellites for Improving GPS Performance,” NAVIGATION: *Journal of the Institute of Navigation*, Vol. 31, No. 4, Winter 1984-85.

[LA] D. Lawrence, H.S. Cobb, B. Pervan, C. Cohen, P. Enge, J.D. Powell, B. Parkinson, “Augmenting Kinematic GPS With a Pulsed Pseudolite to Improve Navigation Performance,” ION National Technical Meeting, January 1996, Santa Monica, CA.

[ORD] *Operational Requirements Document: Local Area Augmentation System*, Satellite Navigation Program Office, Federal Aviation Administration, February 28, 1995.

[PL] B. Pervan, *Presentation to the Local Area Augmentation System Architecture Review Committee*, October 1996.

[SC] H.S. Cobb, D. Lawrence, B. Pervan, C.E. Cohen, J.D. Powell, B. Parkinson, “Precision Landing Tests with Improved Integrity Beacon Pseudolites,” ION GPS-95, Palm Springs, CA, September, 1995.