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GROUND STATION SITING CONSIDERATIONS FOR DGPS

P-11

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BIOGRAPHY

James Waid is a student at Ohio University currently completing his M.S.E.E. under Dr. Frank van Graas. He has been working on developing a GPS landing system funded under a grant from NASA Langley Research Center. He received a B.S.E.E. degree form Ohio University in 1990.

ABSTRACT

Aircraft guidance and positioning in the final approach and landing phases of flight requires a high degree of accuracy. The Global Positioning System operating in differential mode (DGPS) is being considered for this application. Prior to implementation, all sources of error must be considered. Multipath has been shown to be the dominant source of error for DGPS and theoretical studies have verified that multipath is particularly severe within the final approach and landing regions. Because of aircraft dynamics, the ground station segment of DGPS is the part of the system where multipath can most effectively be reduced. Ground station siting will be a key element in reducing multipath errors for a DGPS system. This situation can also be improved by using P-code or narrow correlator C/A-code receivers along with a multipath rejecting antenna. This paper presents a study of GPS multipath errors for a stationary DGPS ground station. A discussion of GPS multipath error characteristics will be presented along with some actual multipath data. The data was collected for different ground station siting configurations using P-code, standard C/A-code and narrow correlator C/A-code receiver architectures and two separate antenna constructions.

INTRODUCTION

GPS soon will have the capability to provide position information to users anywhere in the world nearly 24-hours per day. For applications requiring precise positioning (better than 100 meters (95%)), a stand alone installation is not sufficient to provide adequate positioning accuracy for civilian users. However, differential GPS (DGPS) can provide users with sub-meter level accuracies. Aircraft guidance and positioning in the final approach and landing phases of flight is a prime example of an application for DGPS.

At Ohio University's Avionics Engineering Center, the use of DGPS for guidance and positioning of aircraft during final approach and landing is being investigated. GPS by itself has many sources of error including Selective Availability (SA), ionospheric delay, tropospheric delay, receiver hardware errors, receiver noise and multipath. DGPS eliminates those errors which are common to both receivers. The single largest source of error that remains is the error due to multipath [1]. If DGPS is to be used for final approach and landing, the effects that multipath has on the GPS range measurements must be characterized and controlled to meet the required error budgets. This paper will present a discussion of different characteristics and multipath errors observed for various antenna and receiver configurations. The siting configurations include: ground level and ground plane mounted hangar rooftop antenna placements using a standard microstrip GPS antenna and an experimental helix antenna. The above antenna placements will be combined with separate receiver architectures that include: P-code, standard C/A-code and narrow correlator C/A-code receivers.

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BACKGROUND

The accuracy of GPS positioning depends on the accuracy of the pseudorange measurements. There are many error sources which cause erroneous range measurements. The major error sources are as follows:

- signal delay due to propagation through the troposphere
- signal delay due to propagation through the ionosphere
- error due to satellite clock offset and orbit uncertainty
- Selective Availability (SA)
- receiver inter-channel biases
- receiver measurement errors
- dynamics
- thermal noise
- specular multipath
- diffuse multipath

Although integrated carrier phase measurement accuracies are typically on the order of two centimeters, the code phase measurements are still required for ambiguity resolution. Therefore, this paper focuses on the code phase measurement error. The signal at the antenna is a combination of different types of signals: direct and non-direct. The direct signal is the signal received that travels the geometric distance from the satellite to the receiver. The non-direct or multipath signal is a signal that has been reflected or diffracted off an object and arrives at the receiver after the direct signal. In general, multipath signals are weaker than the direct signals. When the direct and the multipath signals combine, the result is a signal with the same frequency but having a relative phase difference with respect to the original direct signal. This phase error affects both the code measurement and the carrier phase measurement.

DGPS eliminates the errors in the measurements that are common to both receivers, but multipath has a different effect on each receiver. This is because multipath depends on the GPS antenna environment. For a typical DGPS system, the receivers are not close enough to each other to possess the same multipath characteristics. Three categories of multipath for the final approach and landing environment are [2]:

- Obstacle-based at the airborne receiver.
- Airframe-based at the airborne receiver.
- Obstacle-based at the ground reference station receiver.

The air and ground system obstacle-based multipath originates from the ground itself as well as from buildings or other structures on or near the ground.

The obstacle-based multipath at the ground reference station often arrives at the antenna from a direction below the horizon. An effective method for eliminating this multipath is to limit the antenna's gain pattern so that the antenna is only capable of receiving signals from above the horizon. This can be achieved in two ways: placing the antenna on a large ground plane or electrically adjusting the antenna gain pattern to attenuate any signals below the horizon. Both of these methods will be discussed later in the results segment of the paper.

DATA COLLECTION

GPS multipath data collection was performed at the Ohio University Airport (UNI) located near Albany, Ohio. The area surrounding UNI is flat and free of clutter. There are also two large fixed structures (hangars) that are capable of generating significant multipath. Data was collected at two sites: site one was located on top of the larger of the two aircraft hangars, site two was located in a field approximately 500 meters away from the hangars and the antenna was placed at ground level. Site one represents a typical DGPS reference station siting with the hangars being the leading multipath contributor. Site two can be considered a benign multipath environment because the antenna is being placed on a large ground plane and the leading multipath contributor is the ground itself because there are no fixed obstacles above the horizon that are generating multipath signals.

Two GPS antennas were used during the data collection, a dual-frequency microstrip antenna and an experimental helix antenna. The experimental helix antenna was provided by Mr. Don Spitzmesser of the Jet Propulsion Laboratories. The antenna consists of a 20 cm parabolic reflector and a thin wire helix placed in the center of the reflector dish. The helix is configured to receive both L1 and L2 frequencies. Because of the parabolic dish, the helix antenna is more directive and better masks signals that may arrive from below the horizon. There were two GPS receivers used for the data collection: an Ashtech P-12 GPS receiver and a Novatel GPS CARD receiver. The P-12 is capable of continuous tracking of L1 C/A-code and both L1 and L2 P-code. The Novatel GPS CARD is an L1 frequency, narrow correlator C/A-code receiver.

The measurement data for the P-12 and the GPS CARD was collected and recorded in real time using a 386 notebook computer and a 286 desktop computer respectively. Data was collected over a 120 minute time period. Five sets of data were collected for this analysis:

Hangar Roof:
- P-12 with microstrip antenna
- GPS Card with microstrip antenna
- P-12 with Helix antenna
- GPS Card with Helix antenna

Field Location:
- P-12 with microstrip antenna on the ground

DATA PROCESSING TECHNIQUES

The combination of multipath, thermal noise, unknown bias and receiver error was extracted from the data using the standard code-minus-integrated Doppler technique [3,4]. Equation 1 shows the result:

$$\begin{aligned} d_{code} - d_{phase} &= 2d_{iono} + d_{code\text{-}meas} \\ &- d_{phase\text{-}meas} + d_{code\text{-}noise} \\ &- d_{phase\text{-}noise} + d_{code\text{-}mp} \\ &- d_{phase\text{-}mp} - \Delta + d_{other} \end{aligned} \tag{1}$$

where:
- d_{code} is the code measurement
- d_{phase} is the carrier-phase (integrated doppler) measurement
- d_{iono} is the signal delay due to propagation through the ionosphere
- $d_{code\text{-}noise}$ is a combination of thermal noise and diffuse multipath on the pseudorange
- $d_{phase\text{-}noise}$ is a combination of thermal noise and diffuse multipath on integrated carrier phase
- $d_{code\text{-}meas}$ & $d_{phase\text{-}meas}$ is receiver measurement noise for code and phase measurements
- $d_{code\text{-}mp}$ & $d_{phase\text{-}mp}$ is specular multipath on the code and phase
- Δ is an integer wavelength ambiguity
- d_{other} includes receiver measurement error

For situations where the strength of the multipath is less than the direct signal, the carrier-phase multipath term (d_{phase}) will not exceed 4.8 centimeters [5]. It has been shown that state-of-the-art receivers exhibit phase-noise ($d_{phase\text{-}noise}$) values on the order of 0.1 millimeter (1-sigma) [6] allowing this term to be neglected as well. The receiver phase measurement errors ($d_{phase\text{-}meas}$) **are** also negligible [7]. When compared to the code-multipath error ($d_{code\text{-}mp}$), which is usually on the order of meter, the carrier-phase multipath ($d_{phase\text{-}mp}$) and the noise ($d_{phase\text{-}noise}$) terms are very small. For this reason they can be dropped from equation (1). The integer ambiguity (Δ) is a constant bias for the duration of the data collection, which is not of interest for this study. Equation (1) is then approximated by:

$$\begin{aligned} (d_{code} - d_{phase})' &= 2d_{iono} + d_{code\text{-}meas} \\ &+ d_{code\text{-}noise} + d_{code\text{-}mp} + d_{other} \end{aligned} \tag{2}$$

The error due to the propagation delay through the ionosphere can be removed through the standard dual-frequency correction [8]:

$$d_{iono_{f1}} = \left(\frac{f_2^2}{f_2^2 - f_1^2}\right)\left(d_{code_{f1}} - d_{code_{f2}}\right) \tag{3}$$

Noise in the data is reduced by averaging (filtering) the code measurements against the stable carrier measurements. This is accomplished using a complementary Kalman filter [9]. After applying the ionospheric correction and the complementary Kalman filter, we arrive at the following:

$$\begin{aligned} (d_{code} - d_{phase})'' &= d_{code\text{-}meas} \\ &+ d_{code\text{-}mp} + d_{other} \end{aligned} \tag{4}$$

The next section presents the results of the data collection and data analysis.

DISCUSSION OF RESULTS

The results are presented in the following figures and table. The filtered code-minus-carrier for satellites 3, 17, and 23 is shown in figures 2 through 25 for all the receiver and antenna configurations being considered. The three satellites were selected because they include the elevation angles of interest: SV17 exhibits the characteristics of a high elevation satellite, SV23 represents a medium elevation satellite and SV3 is indicative of a lower elevation satellite that vanishes below the horizon during the data collection. Figure 1 shows the elevation angles for the satellites during the data collection. As anticipated, the error levels are correlated to the lower elevation angles for all the test cases. Table I shows the root mean squared (rms) of the multipath error in meters for C/A-code, narrow correlator C/A-code and P-code for each satellite for data collected on the hangar roof and C/A-code and P-code for data collected at the site away from the aircraft hangars. The last row in the table represents the average for the three satellites for the receiver and antenna configuration listed in that column.

The best case for all the scenarios run was the P-code receiver operating out in the field away from all structures. The worst case was observed on the hangar roof using the standard C/A-code with the microstrip antenna. The contrast between the two results indicates that the multipath does indeed enter the antenna from below the horizon. These results are as expected. From the data presented it is easy to see that the lowest levels of multipath were experienced for high elevation satellites using the P-code measurements. This result is also expected.

In general, the measurement taken away from the hangar showed lower rms levels of multipath for all satellites. This kind of multipath environment may not be available for a typical DGPS reference station location. The hangar roof can be considered a more typical example of a DGPS reference station site. For this site the helix antenna produced results that were significantly better than the microstrip antenna. The helix antenna has the limitation of only being able to track satellites down to an elevation angle of 10°. Another consideration for a DGPS landing system, P-code may not be available for all aircraft. In the case that P-code is not available, obviously C/A-code would have to be used. Looking at the comparison between C/A-code and narrow correlator C/A-code, the narrow correlator C/A-code exhibits multipath with less noise and having smaller magnitude than the standard C/A-code measurements.

Also it should be noted that the C/A-code errors measured in the field are mostly caused by high-frequency measurement noise, rather than by multipath. Integration over time of high-frequency noise gives rise to a random-walk error. It was found that the errors measured in the field exhibit insignificant correlations from one day to the next.

Although the helix antenna performed very well in a multipath environment, its gain at lower elevation angles is much less than that of the microstrip antenna. Another concern is the stability of the phase center of the helix antenna for carrier-phase tracking applications. For code-phase DGPS, however, this is not a significant problem.

Table I

	Field		Hangar Roof					
	Microstrip		Microstrip			Helix		
	C/A rms (meters)	P rms (meters)	C/A rms (meters)	N.C.C/A rms (meters)	P rms (meters)	C/A rms (meters)	N.C.C/A rms (meters)	P rms (meters)
SV3	0.4757	0.0802	1.2658	0.4516	0.3329	0.9232	0.2031	0.0996
SV17	0.4624	0.0456	0.8015	0.3115	0.3408	0.3504	0.0685	0.0417
SV23	0.4289	0.0397	0.6418	0.3463	0.2550	0.4438	0.1809	0.0445
average	0.4557	0.0552	0.9030	0.3698	0.3096	0.5725	0.1508	0.0619

Recommendations:

1.) Use a site out in the field for minimum multipath. A major draw back to this recommendation is that snow can cover the antenna and the area around the antenna when placed on the ground. This will seriously affect the performance of the antenna.
2.) The next best siting that was considered was the helix antenna placed at a location that provided visibility down to 5° (hangar roof). The same effect can be achieved by placing any antenna on a large ground plane.

For all siting options considered, the use of narrow correlator C/A-code or P-code significantly reduces the multipath error.

CONCLUSIONS

Multipath is the dominate error source for DGPS. A number of extreme siting scenarios were investigated with respect to multipath performance. It was found that a significant level of multipath enters the antenna pattern from below the horizon. Therefore it is recommended to either have a large ground plane or reduce the antenna pattern below the horizon.

ACKNOWLEGDEMENTS

This work was supported by NASA Langley Research Center (Grant NAG1-1423), and the FAA and NASA through the Joint University Program (Grant NGR 36-009-017). The P-12 GPS receivers were provided by Ashtech, Inc. The GPS Card receivers were provided by Novatel, Inc. The author would like to thank Dr. Frank van Graas for his helpful suggestions during the writing of the paper. The author would also like to thank Mr. Don Spitzmesser for providing the experimental helix antenna.

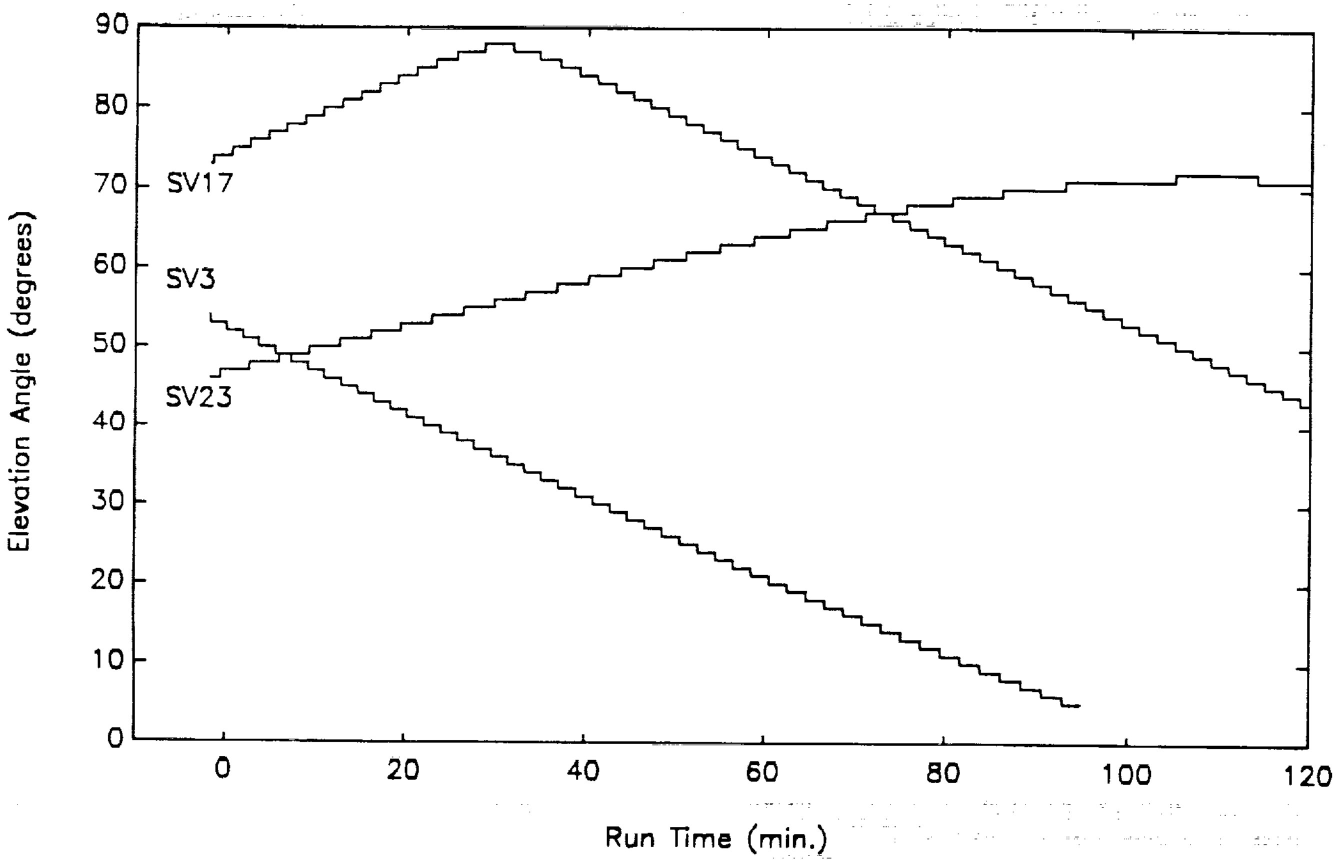


Figure 1. Satellite Elevation Angles

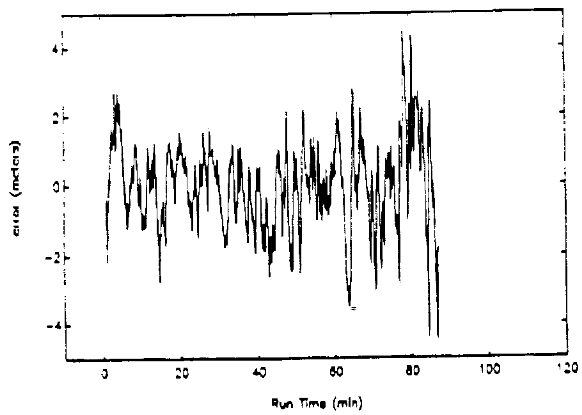


Figure 2. SV3: C/A-code

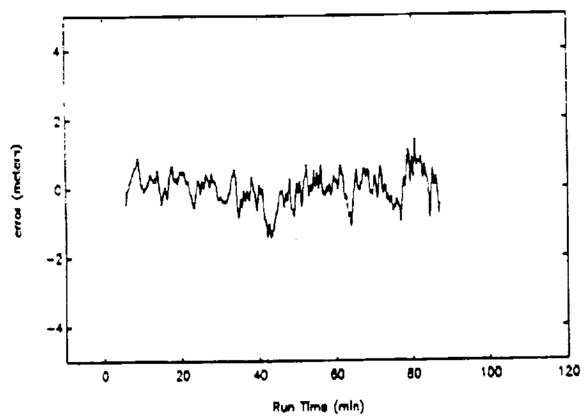


Figure 3. SV3: Narrow Correlator C/A-code

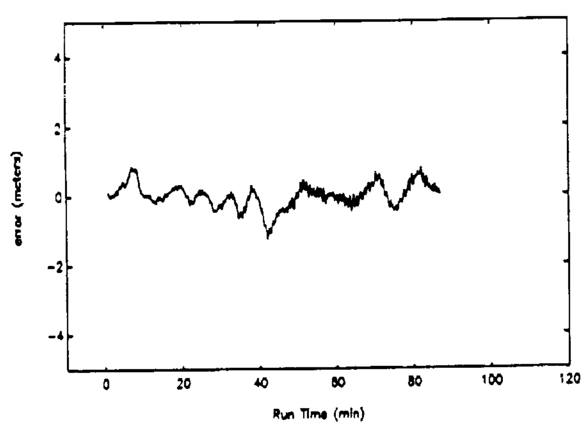


Figure 4. SV3: P-code

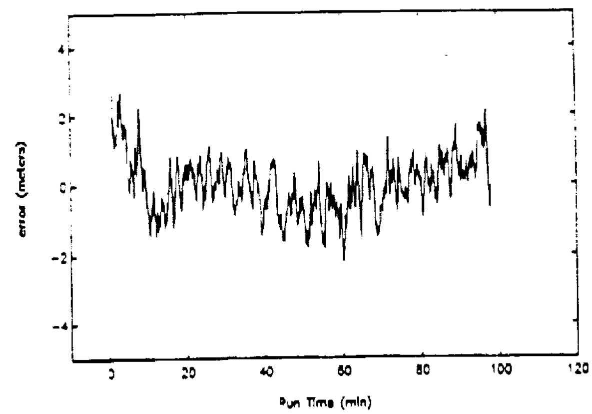


Figure 5. SV17: C/A-code

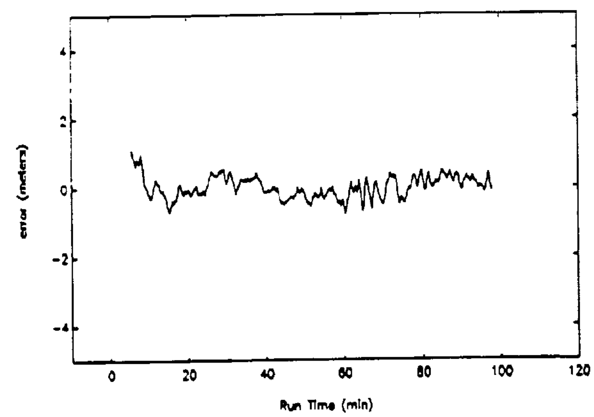


Figure 6. SV17: Narrow Correlator C/A-code

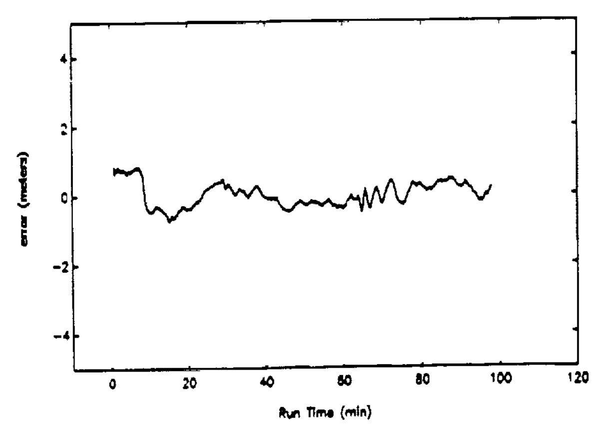


Figure 7. SV17: P-code

Figures 2-7: Hanger Roof with Microstrip Antenna - Multipath, Thermal Noise, Unknown Bias and Receiver Error

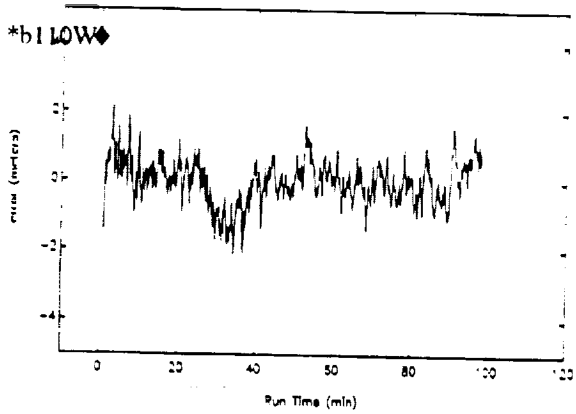


Figure 8. SV23: C/A-code

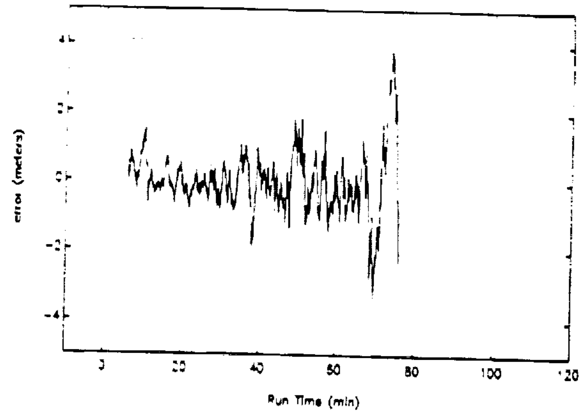


Figure 11. SV3: C/A-code

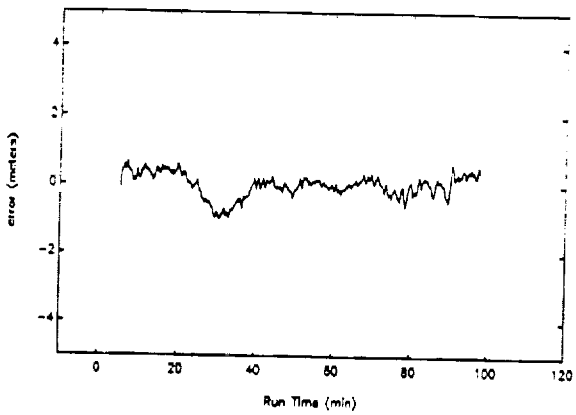


Figure 9. SV23: Narrow Correlator C/A-code

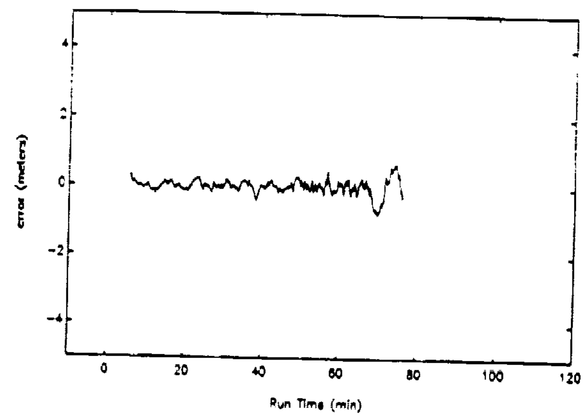


Figure 12. SV3: Narrow Correlator C/A-code

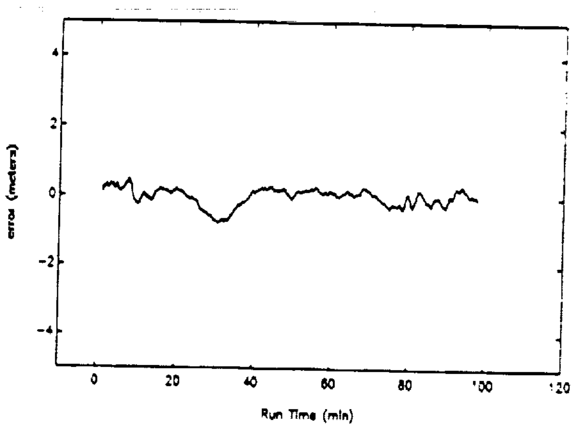


Figure 10. SV23: P-code

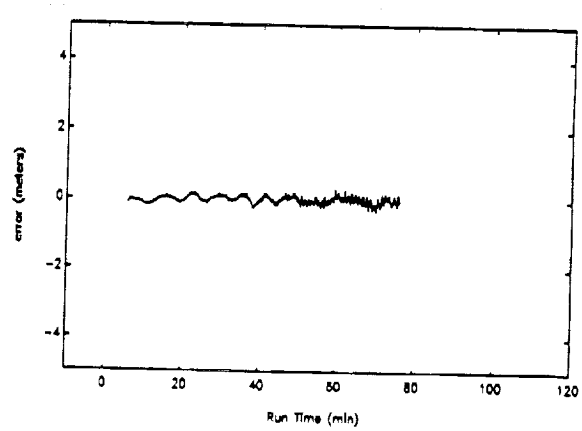


Figure 13. SV3: P-code

Figures 8-10: Hanger Roof with Microstrip Antenna - Multipath, Thermal Noise Unknown Bias and Receiver Error

Figures 11-13: Hanger Roof with Helix Antenna - Multipath, Thermal Noise, Unknown Bias and Receiver Error

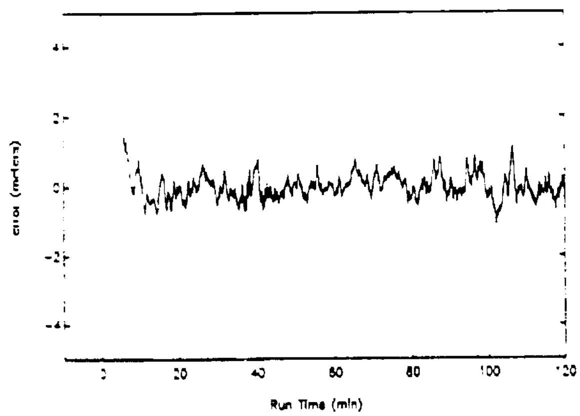


Figure 14. SV17: C/A-code

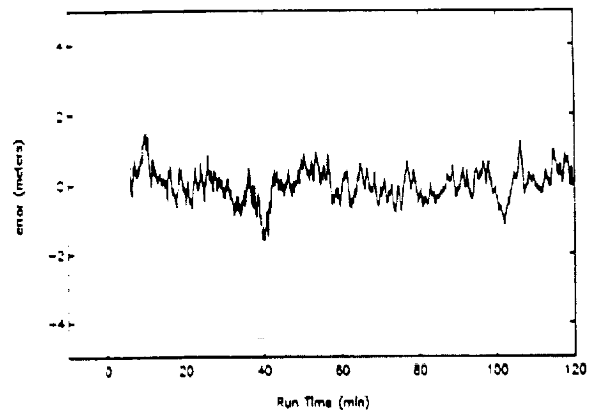


Figure 17. SV23: C/A-code

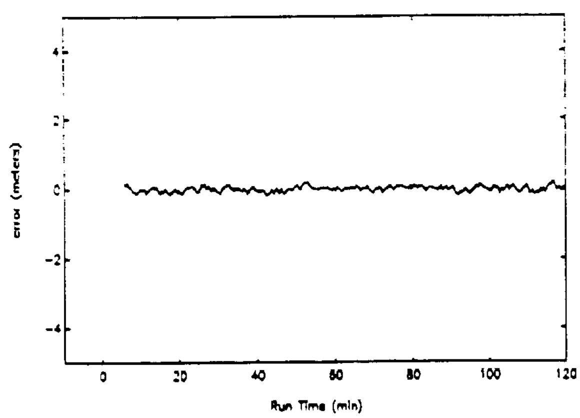


Figure 15. SV17: Narrow Correlator C/A-code

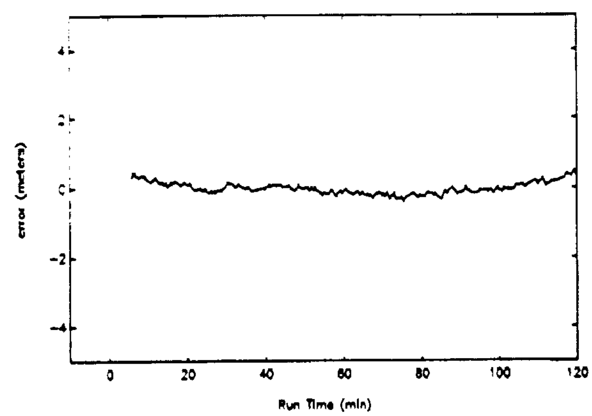


Figure 18. SV23: Narrow Correlator C/A-code

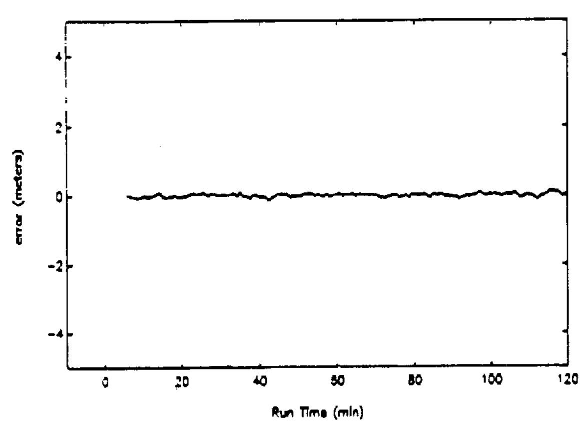


Figure 16. SV17: P-code

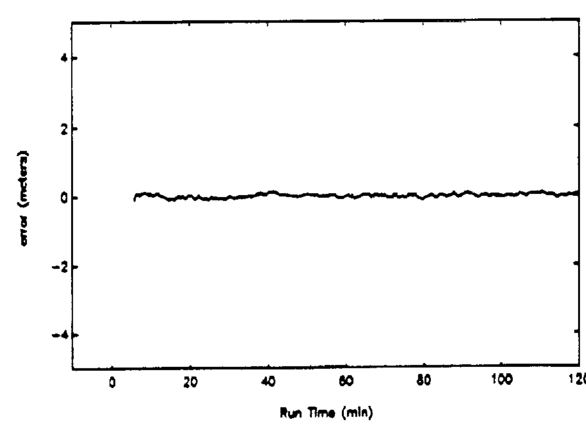


Figure 19. SV23: P-code

Figures 14-19: Hanger Roof with Helix Antenna - Multipath, Thermal Noise, Unknown Bias and Receiver Error

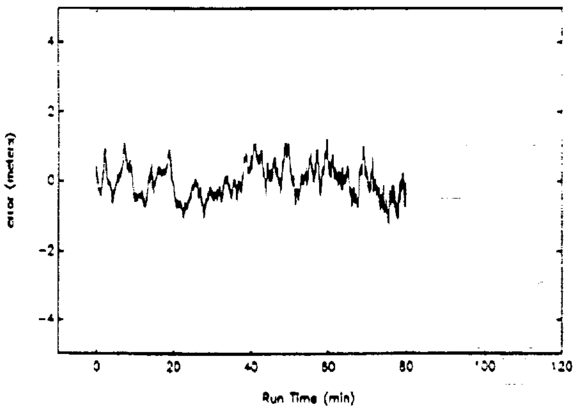


Figure 20. SV3:C/A-code

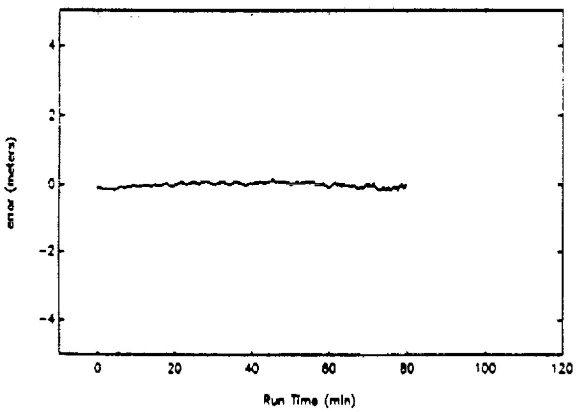


Figure 21. SV3:P-code

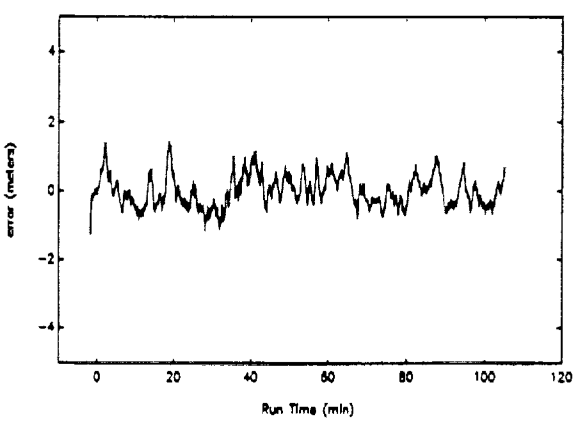
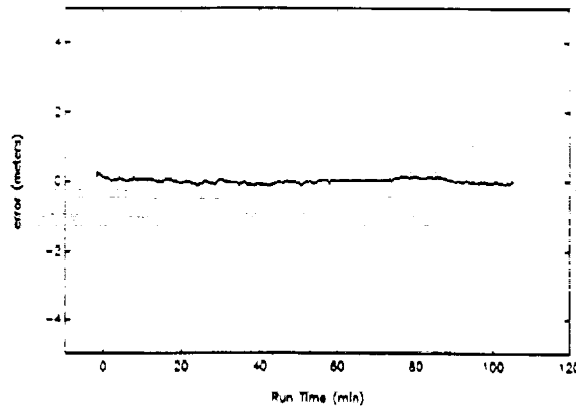


Figure 22. SV17:C/A-code



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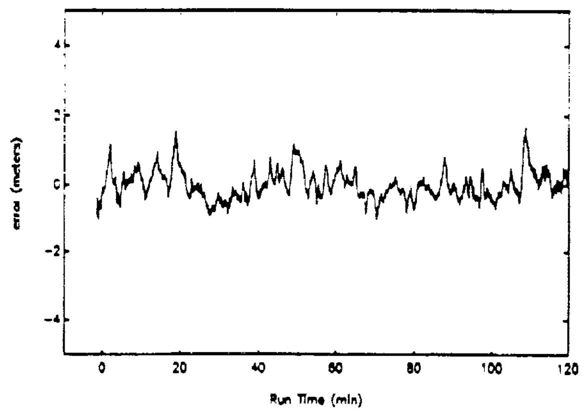

Figure 24. SV23:C/A-code

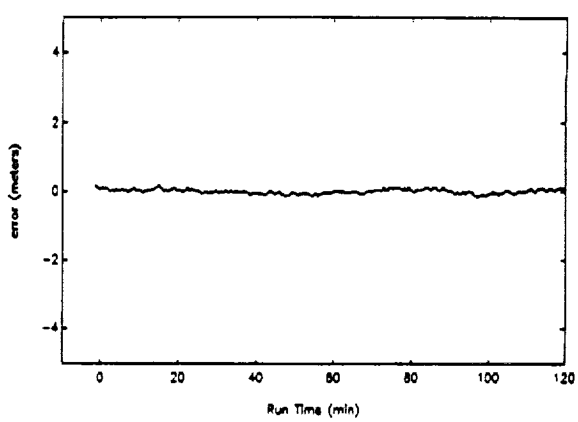

Figure 25. SV23:P-code

Figures 20-25: Field with Microstrip Antenna - Multipath, Thermal Noise, Unknown Bias and Receiver Error

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