

# Robustness of Tightly Coupled Integrations for Real-Time Centimeter GPS Positioning

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## BIOGRAPHY

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Dave Senffner is a Senior Systems Engineer with Tracking and Imaging Systems Inc. Previously, he was an instructor at Bradley University. He received his BSEE and MSEE from Bradley. His area of interest is high accuracy GPS navigation.

## ABSTRACT

A significant impediment to real-time centimeter survey and vehicle guidance is navigation outage from signal interruptions. The goals of this study were two-fold: first to measure and characterize signal amplitude fluctuations which induced positioning outages in representative single and dual-frequency RTK receivers and, secondly, to reproduce similar conditions in the laboratory and ascertain the benefits of more highly integrated tracking loop structures, with and without inertial aiding.

Off-the-shelf single and dual-frequency receivers, and a specially modified GPS receiver capable of 50 Hz recording of raw correlator and signal-to-noise data, were assembled and used to collect mobile observations in the suburbs of Washington DC. Double-difference solutions were generated, and intervals with high residuals and/or receiver tracking flags were analyzed for duration and onset rate of signal blockages. Signal amplitude recordings were then processed and prepared for input to receiver simulations.

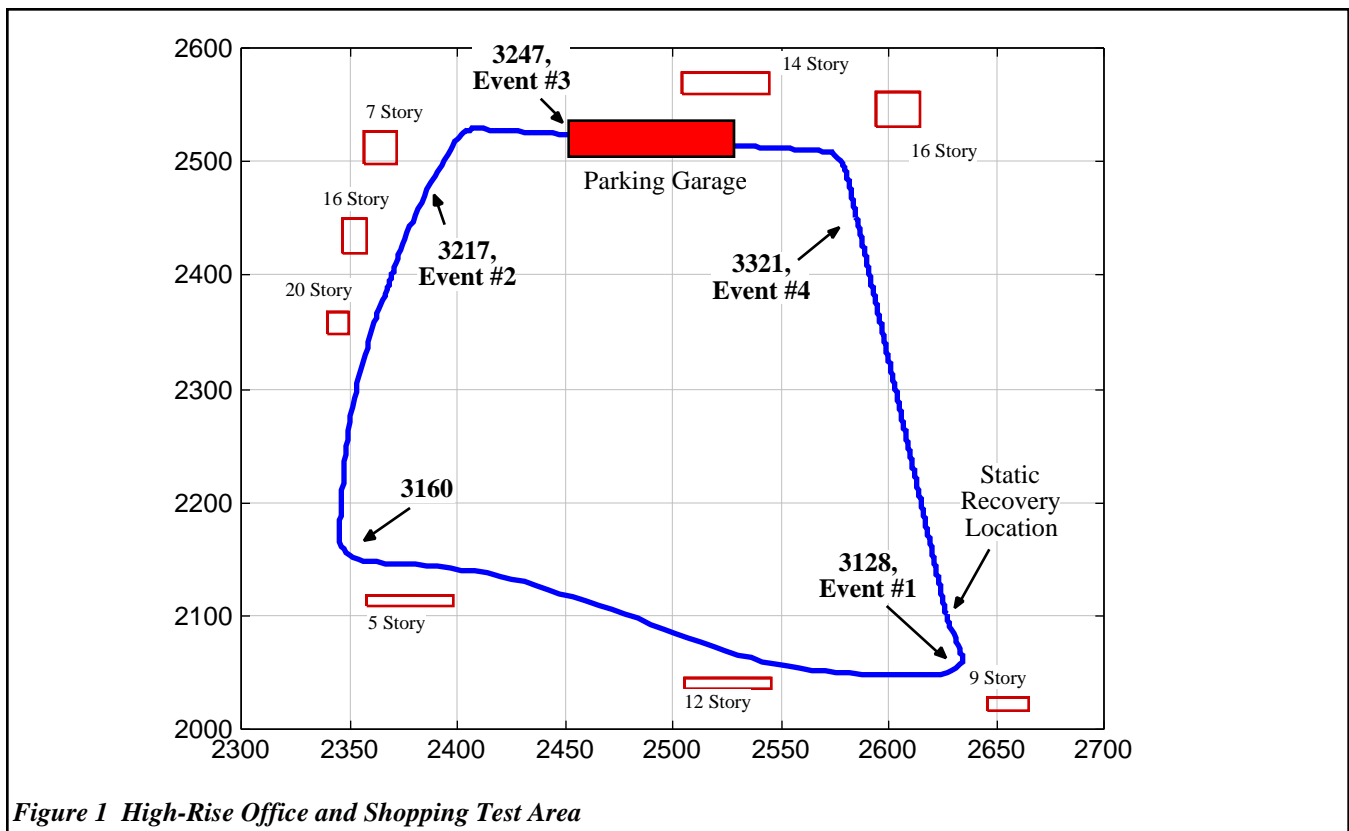
A correlator-level software simulation of aided and unaided receiver variants in the mobile environment was then carried out. A new aided configuration employing an extended

Kalman filter for direct incorporation of correlator data and update of IMU bias states was developed. In this structure filter gains adapted in real time to the signal amplitude variations, and problems of unmodeled loop dynamics and instabilities were eliminated. Substantial improvement in RTK continuity was observed in the troublesome reception intervals. RTK improvements were also obtained with an unaided receiver variant of this same structure.

## INTRODUCTION

Centimeter accuracies in land mobile applications such as real-time survey and vehicle guidance and control have proven very challenging for GPS and IMU-augmented GPS systems. The central problem is to provide the needed level of robustness in the face of multiple signal attenuations, and in strong and intermittent multipath. After these events the real-time navigation solution may take from tens to hundreds of seconds to recover full accuracy, depending upon the number of damaged tracking channels and overall constellation geometry. These problems are further compounded by vehicle control requirements, which demand independent estimates of vehicle position states at rates of 10 Hz, and higher. The work reported in this paper addresses these challenges with a signal tracking technique capable of adapting rapidly to the changing conditions of the land mobile environment. This technique is known as integrated demodulation/navigation, or IDN [1,2].

This paper is companion to the work presented recently for the high dynamics military test range application [3-5]. The demands of land-mobile and test range users are similar with respect to accuracies and, to some extent, the reception environment. The levels of acceleration and jerk are high in the test range application, and signal blockages are primarily vehicle-maneuver induced, while in the land mobile application the dynamics are milder, and dropouts are terrain induced.



**Figure 1 High-Rise Office and Shopping Test Area**

Prior to adapting the signal processing strategy to the land-mobile application, extensive data collection activities were carried out. These are discussed in the next section of the paper. The following section then addresses the responses of representative commercial receivers and positioning software packages, and correlates these responses to the measured signal environment. This sets the stage for discussion of signal processing options which could afford a maximum degree of improvement under these difficult reception regimes. Two variants of the IDN technique are then explored in a correlator-level signal tracking simulation, utilizing signal amplitude recordings from the data collection experiment. The paper then addresses velocity accuracies for aided and unaided versions of the signal processor, and concludes with simulations of all-in-view attenuations, as might be encountered with dense tree canopy blockage.

**RECEPTION ENVIRONMENT**

In cooperation with NAVTECH, a reference station was established at their location in North Shirlinton VA during March 1996. A total of six GPS receivers were utilized, three at the reference location and three aboard the test van. An active geodetic antenna, with low loss cables and splitters, was used to feed the receiver groups at mobile and reference sites. The receivers are identified generically as:

RCVR I: Dual frequency codeless, recorded at 2 Hz,

RCVR II: Narrow correlator C/A code, recorded at 20 Hz, and

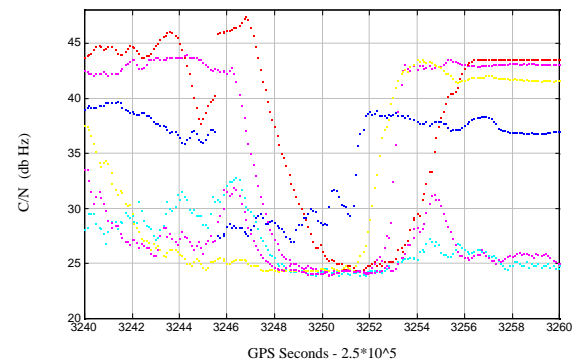
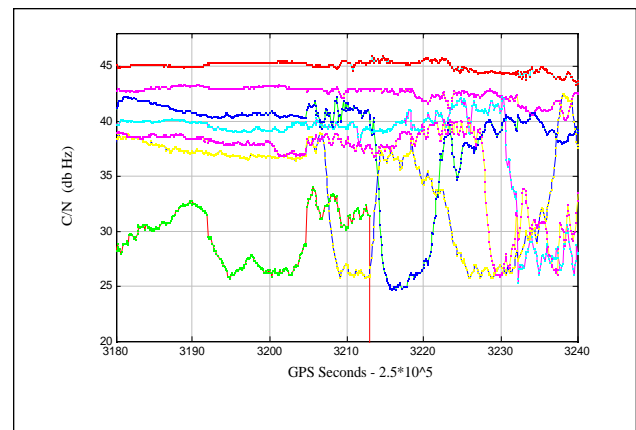
RCVR III. Half-chip correlator C/A code, recorded at 10 Hz, with raw I and Q correlator data recorded at 50 Hz

The outputs of the three receivers were post-processed with a variety of position fixing software, as discussed below. The internal software of RCVR III was modified to enable 10Hz recordings of the internally generated estimates of CNR, as well as 50 Hz recordings of the raw I and Q punctual correlator outputs on each channel, affording an opportunity to examine in detail signal amplitude fluctuation rates and depths.

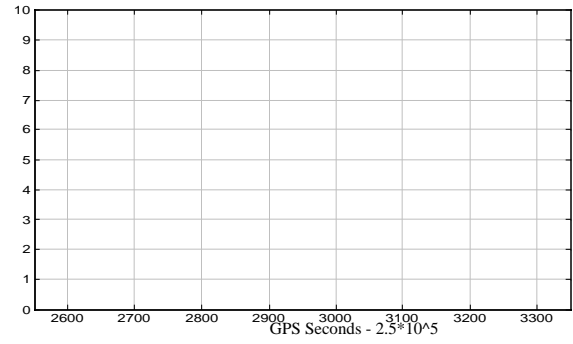
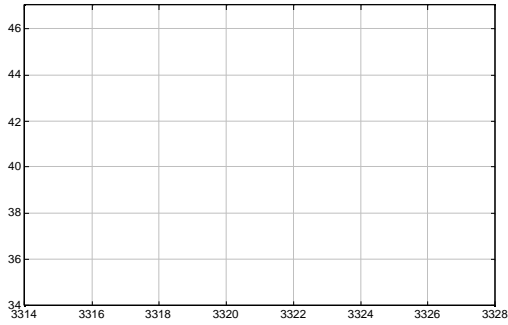
Data recordings were collected in five areas in Northern Virginia and Annapolis, during March 18,19,20,21, and 23, 1996. **Figure 1** depicts one of the five test areas. While not as challenging as a deep urban canyon, there were numerous high rise office buildings immediately adjacent to the roadway and, not shown, a high density of 2-3 story buildings along most of the route. A typical loop-around took approximately 250 seconds, with an additional 60 seconds at the indicated static recovery location. Truncated GPS second time tags shown in the figure indicate key events on the third loop of the test. Particularly challenging were the regions

entered near times 3217 and 3247. At time 3217 multiple satellite blockages from high-rise buildings were encountered and, a short time later, a partially enclosed parking deck one floor below street level was entered.

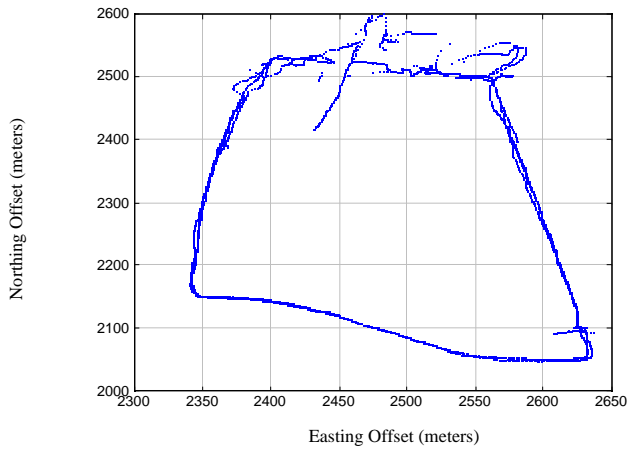
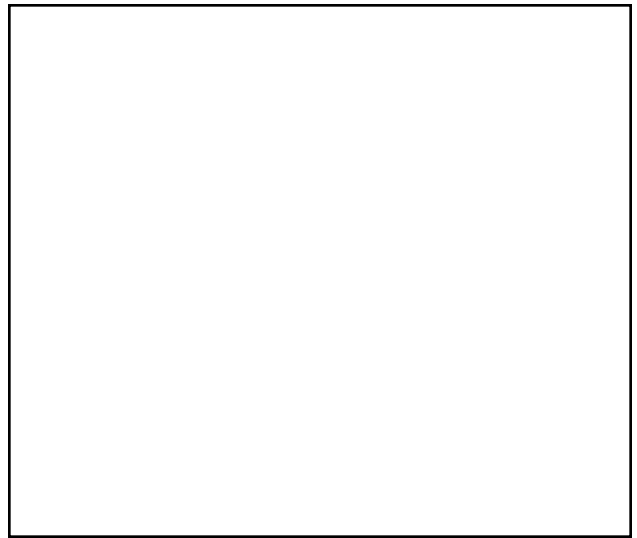
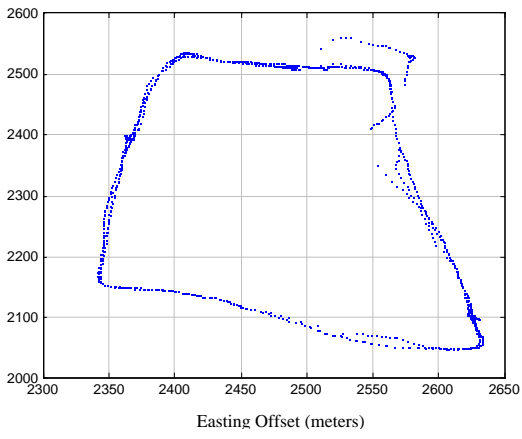
**Figure 2** is an on/off plot summarizing signal CNR status for the seven satellites generally available in the area at the time of the test. The on-threshold for the plot is a CNR of 35 dB-Hz. Four events of particular interest are depicted at 3128, 3217, 3247, and 3320, referred to respectively as Event 1 through Event 4. In each of these areas blockage patterns detrimental to carrier phase double difference and carrier-smoothed code solutions were encountered. **Figure 3** shows in detail the CNR traces captured in the region called Event 2. Just prior to this interval, as can be seen, six of the seven satellites were available with satisfactory CNR. Starting at 3210 amplitude fluctuations were encountered on SV-15, and SV-14. Shortly thereafter SV-27 and SV-4 were impacted, and periods with four satellites below threshold were encountered. At time 3240 a brief period with four satellites above threshold was encountered. As confirmed by a review of carrier lock flags on each channel of RCVR II, brief blockages of a given satellite resulted in tracking loop damage and cycle slippage on the assigned channel. This interval culminated in the complete loss of all satellites as the vehicle descended into the covered below-street parking

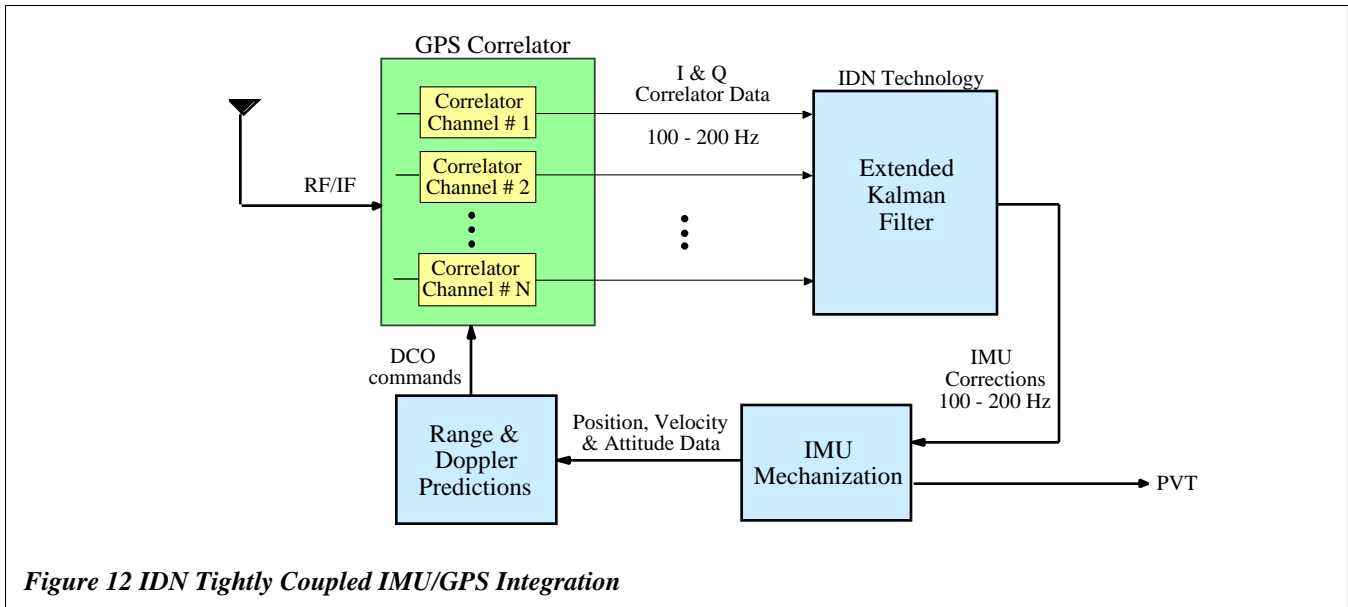
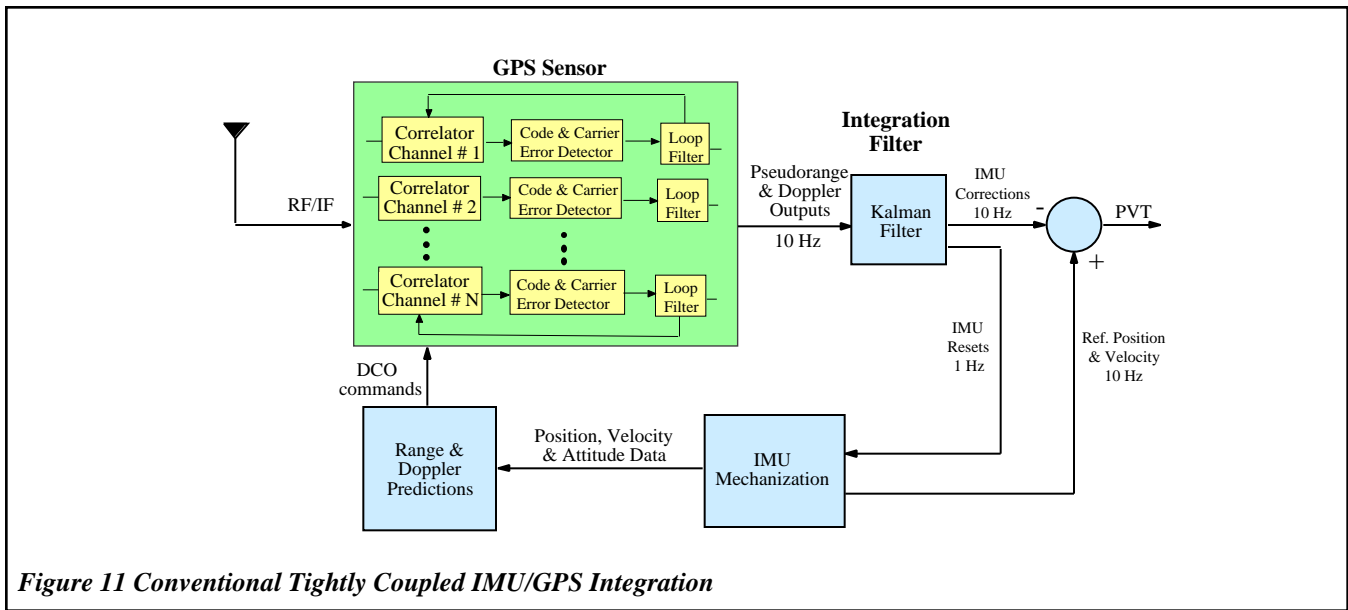


**Figure 4** Signal Amplitudes, Event Region 3



garage, Event 3. CNR's during this parking garage passage are shown in **Figure 4**. Note that one of the signals was able to penetrate a distance down the parking ramp and into the garage. The remainder of the signals fell to below the noise floor of the CNR estimator, 25 dB-Hz. Upon exit from the garage four SV's quickly recovered, but GDOP remained above six for most of the loop, due to sustained structural blockage of three SV's. During this period, there were occasional instants of blockage sufficient to cause tracking damage on the remaining satellites. Event 4, shown on a magnified time scale in **Figure 5**, is one such attenuation.



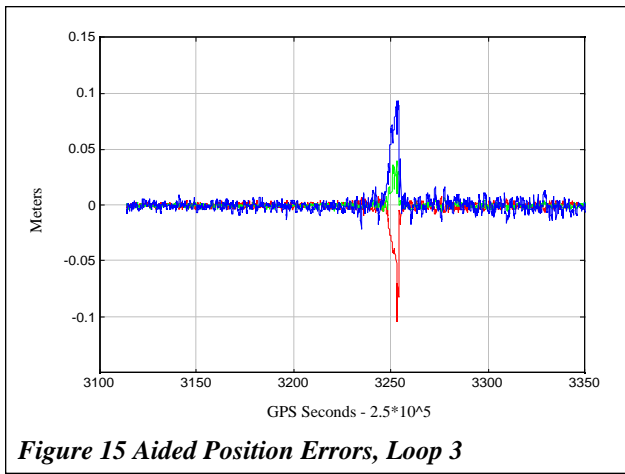
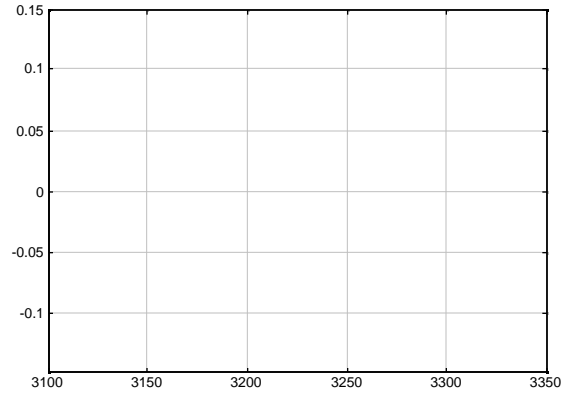
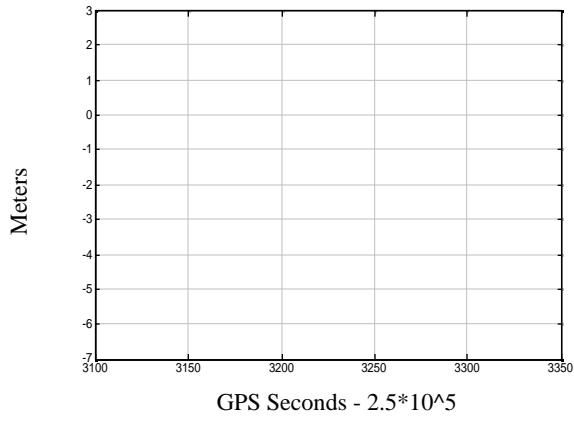


**VALIDATION OF THE AIDED RECEIVER STRUCTURE**

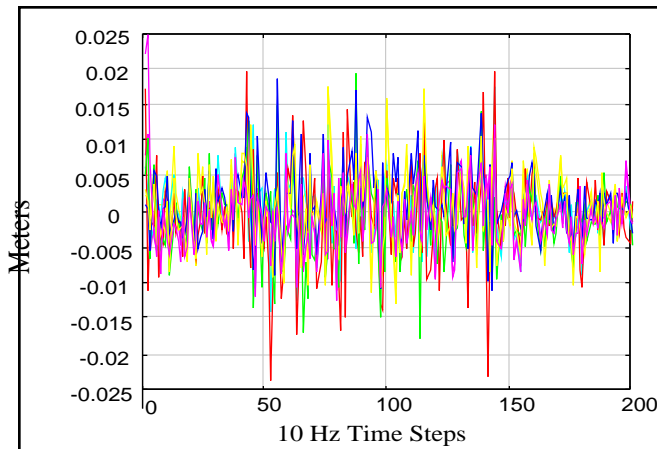
In exploring amplitude estimator tracking and overall aided system performance it is desirable to replicate as closely as possible the actual reception conditions encountered in the field. The first option considered, digital recording of the RF signal environment and full regeneration of the broadband signal in the laboratory, has been pioneered by the Johns Hopkins Applied Physics Lab. While this technique may be pursued in the future, at the time field measurements were collected the recording equipment was unavailable. The second approach uses an GPS RF signal generator driven with amplitude files derived from those recorded in the actual field experiment. In addition to these “pure” GPS signals, for a perfectly known nominal vehicle trajectory, multipath can be introduced to get an indication of the

algorithm’s ability to reject, or de-weight, multipath contaminated satellites. This method will be utilized in future studies. The final method is a correlator-level simulation. As developed in previous work [5], a mathematical model of the receiver’s correlator bank is employed. This model responds to DCO aiding commands from the prototype receiver’s software, and returns to the software inphase and quadrature correlator data, just as in the real-time environment. Correlator amplitude model parameters can be derived from signal CNR’s recorded in the actual field experiments, and synchronized with a nominal vehicle truth trajectory. As explored in previous studies [5], discrete multipath reflections are easily introduced into these test scenarios.

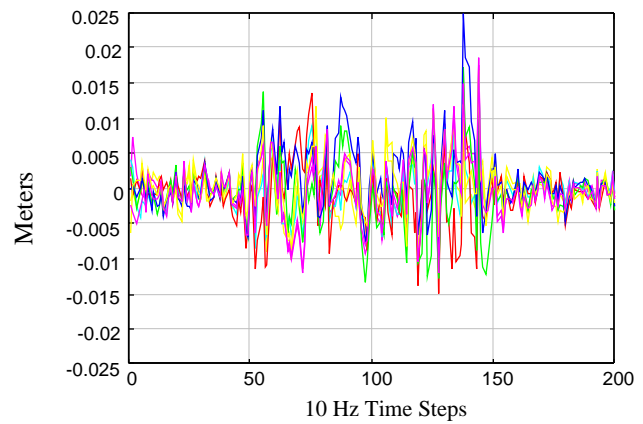




**Figure 15 Aided Position Errors, Loop 3**



**Figure 17a Unaided Position Errors in Foilage**



**Figure 17b Aided Position Errors in Foilage**

neous attenuations on all satellites with errors well below a centimeter. The improvement of the aided processor over the unaided processor is approximately 15 dB.

### SUMMARY AND CONCLUSIONS

Achievement of high accuracies in the land mobile environment calls for improved means for tracking attenuated and multipath corrupted signals. Auxiliary information from IMU sensors can be integrated in a variety of ways. It appears that the most robust technique is to monitor and track fluctuations in raw correlator data quality prior to loop filtering elements and bias state updates. In this paper such a scheme was explored, using the signal amplitude fluctuations and satellite geometries recorded in field experiments. An unaided version of the IDN processor was shown to prevent carrier phase mistracking during complex outage events. When fed with IMU data the processor was capable of providing decimeter accuracies during complete satellite blockage, with full recovery after reception was restored. With this approach corrupted signals were blocked prior to IMU bias state updates. The paper concluded with simulations of aided and unaided processors with multiple satellite attenuations, demonstrating a 15 dB advantage for the aided configuration, and a capability for millimeters/second velocity accuracies with multiple satellite outages.

### ACKNOWLEDGMENTS

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