Enhanced Tracking Performance Using Ultra-Tightly-Coupled GPS/INS Techniques

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ABSTRACT

The need to provide for robust GPS navigation in challenging environments such as urban or dense vegetation is established. The use of ultra-tightly coupled techniques can significantly extend the tracking threshold of GPS receivers in these environments providing for robust navigation using code and carrier measurements at C/N_o levels previously unobtainable. The use of conventional tracking loops which employ fixed gains do not adapt well to time varying signal conditions in these environments. Under low C/N_o conditions typical of signal shadowing in the urbane or dense vegetation environments, carrier tracking loops break down at typically 18 dB Hz C/N_o. The fundamental reason for the loop break down is that at a low signal to noise ratio (SINR) into the loop there is virtually no restoring force to any loop perturbation. The only way to recover signal to noise ratio is to integrate longer and use narrow bandwidths which results in correlated measurement problems. Using techniques which operate on the I and Q data to directly produce residuals that are input to a Kalman filter eliminates the need for conventional tracking loops. These techniques provide optimal processing gain while retaining the Kalman Filter optimality requirements of uncorrelated measurement errors. These techniques have been successfully implemented into a miniaturized GPS receiver and demonstrated in handheld and weapon system applications providing enhanced tracking performance. When coupled with low cost inertial sensors, these techniques can provide reliable tracking at levels down to 2 dB Hz C/N_o. This paper provides an overview of the techniques used and the implementation of these techniques into a miniaturized GPS receiver developed for weapon system applications. This paper also addresses the results from a high fidelity GPS receiver simulation and actual laboratory and field testing of this GPS receiver.

1.0 INTRODUCTION

Unaided GPS receivers used in the ground and urban environment for mobile and handheld applications typically use conventional code and carrier tracking loops. Delay lock loops (DLLs) are used for tracking code phase and phase lock loops (PLLs) are used to track carrier phase. These tracking loops must have the bandwidth and stability to reliably track the GPS signal through platform dynamics and clock instabilities and varying C/N_o conditions caused by signal shadowing and foliage density.

Tightly coupling the GPS receiver to an Inertial Measurement Unit (IMU) using conventional code and carrier tracking loops have demonstrated good code and carrier phase tracking performance under high vehicle dynamic by aiding these loops with delta velocity and phase measurements from the IMU. Tightly-coupled GPS receivers use the IMU data to remove most of the vehicle dynamics so the receiver only has to track through the residual motion. **Weiss (1995)** This allows the receiver tracking loops to have lower bandwidth, resulting in improved tracking performance. However, the use of conventional

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tracking loops which employ fixed gains do not adapt well to time varying signal conditions in these environments. Under low C/N_o conditions typical of signal shadowing in the urbane or dense vegetation environments or in the presence of interference, carrier tracking loops break down at typically 18 dB Hz C/N_o.

Applications using an IMU when Ultra-Tightly Coupled (UTC) to the GPS receiver have demonstrated significantly improved tracking performance through further reduction of the receiver tracking loop bandwidths. Jaffe and Rechtin (1955) These Ultra-Tightly Coupled techniques when employed in applications without the use of an IMU have also shown improvements in the receiver's tracking performance under low C/N_o conditions .

1.1 Loosely Coupled and Tightly-Coupled GPS Architectures

Loosely coupled GPS/INS systems work reasonably well in fixed or static environments. These systems used conventional phase and frequency tracking loops and increasing the tracking performance of these systems could be obtained by narrowing the tracking bandwidths and lengthening the integration times to improve the receiver's carrier to noise (C/N_o). However, in a more dynamic C/N_o environment cause by signal shadowing in an urbane environment or due to heavy foliage other techniques may be more effective. It may also become necessary to "aid" the tracking loops due to platform dynamics to maintain performance giving rise to "tightly coupled" GPS/INS systems. Under high C/N_o conditions, both loosely-coupled and tightly-coupled GPS receivers perform well.

Under low C/N_o conditions narrow tracking loop bandwidths need to be employed, resulting in temporally correlated noise which is a sub-optimal solution when viewed from the point of view of the Kalman filter. Narrow bandwidths also produce a correlation effect between measurements and process noise which tends to have a destabilizing effect on system performance. As noise increases the carrier tracking loop breaks down at approximately a C/N_o of 18 dB-Hz. The reason for the loop break down is the low signal to noise ratio (SINR) into the Costas loop (product of C/N_o and the coherent integration time $[C/N_o) \cdot T_i = \text{SINR}]$ which is the signal to noise ratio prior to the squaring operation). When this happens, the information loss through traditional non-linear loop error discriminates, such as the arc tangent function, becomes prohibitive, resulting in virtually no restoring force to loop perturbation. The only way to recover signal to noise ratio is to integrate longer and use narrower bandwidths. Conventional tracking loops employ fixed gains which do not "adapt" well to time varying signal conditions. Data wipe off techniques is one method being employed to improve signal to noise ratio. Since I and Q data input to the baseband algorithm is bi-phase shift keyed (BPSK) modulated at a 50 Hz rate, the signal polarity can change at a 50 Hz rate. Coherently adding I or Q signal samples over beyond the 50 Hz rate can result in signal cancellation. Data wipe off techniques use a priori estimates of the 50 Hz data stream to remove this effect, thus allowing coherent integration which results in improved tracking performance. GPS receiver tracking loops maintain carrier phase lock and code lock at C/N_o levels of approximately 18 and 13 dB respectively. The outputs of these tracking loops produce range and delta (Δ) range measurements to a Kalman filter. Below these C/N_o levels, complete loss of GPS measurements occurs, resulting in an inertial only system drifting in a divergent fashion.

Figure 1 depicts the architecture for a tightly coupled GPS/INS system. The functions to the left of the dotted line are performed typically in hardware and the functions to the right are performed in software. The GPS satellite signal is received by an antenna, is down converted to baseband and digitized by an analog to digital (A/D) converter prior to the functions shown in Figure 1. The digitized signal is then provided to a digital GPS receiver. The digital GPS receiver function provides the replica code generation and correlators. LOS geometry to the satellites is computed using the Earth Centered Earth Fixed (ECEF) Position and velocity of the receiver, GPS time, ephemerides and known satellite position and velocity information. The LOS Geometry outputs aiding information in the form of range and range rate to the replica code generator, the tracking loops, and the residual form functions to remove the effects of receiver motion. The replica code generator uses the aiding information to adjust the time position of the replica code such that it aligns with the satellite generated code. The hardware then generates the I and Q phase outputs that are fed to the tracking loops to adjust the replica based on the observed error. The tracking loop software then determines whether the replica is early, late or prompt based on the I and Q information. This is then used to adjust the time position of the replica. The range measurements are then formed by the tracking loop, and residuals are created and fed to the Kalman filter. The Navigation function uses the output of the Kalman Filter and the IMU to update the receiver's current location and velocity.

The performance of a Tightly-Coupled GPS/INS is susceptible to a number of error sources including receiver clock instabilities, IMU instabilities, IMU interface errors, and lever arm compensation. Receiver clock and IMU data are used directly by the receiver without any filtering or compensation, and therefore receiver track loop bandwidth must be wide enough to encompass these errors in order for the receiver to provide accurate and reliable position data.

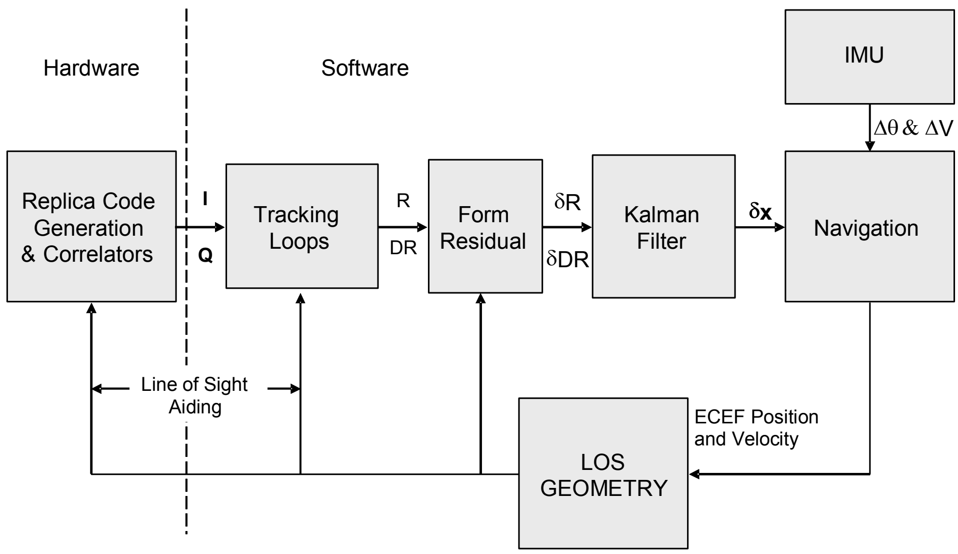

Figure 1. Tightly-Coupled GPS/INS System

1.2 Ultra-Tightly Coupled Architecture

Ultra-Tightly Coupled GPS/INS techniques provide improvements in the tracking performance of the GPS receiver under low C/N_o conditions. As shown in Figure 2, the Ultra-Tightly Coupled GPS/INS architecture eliminates the traditional tracking loop function and instead processes I and Q data directly into the Kalman filter.

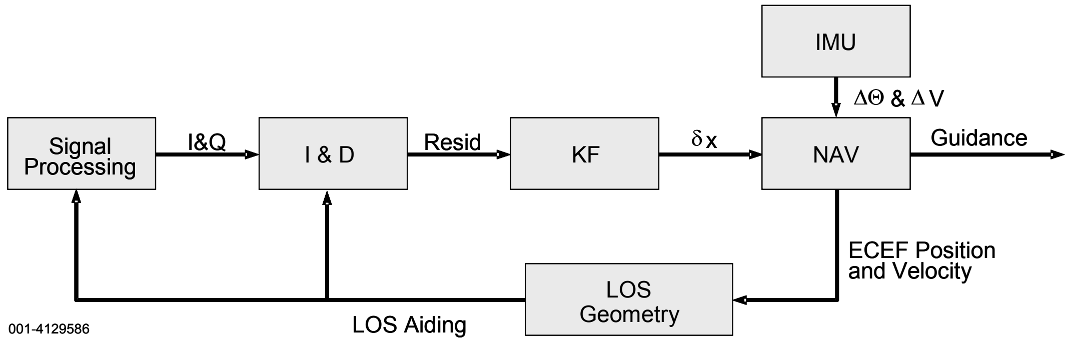

Figure 2. Ultra-Tightly Coupled GPS/INS Architecture

In the Ultra-Tightly Coupled Architectures, the intermediate tracking loops are replaced by an integrate and dump (I & D) operation which then provides residuals directly into the Kalman filter. Greenspan (1996) Using this method, each measurement is independent from sample to sample and loop closure is accomplished by the Kalman filter (and navigation function) as opposed to the tracking loops which are also closed loop systems. This process takes advantage of certain mathematical/statistical properties of the residual estimates used to enhance SINR and thus provides a more stable system at lower C/N_o levels. The integrate and dump algorithm, as shown in Figure 3, inputs the I and Q signals from the GPS signal processor at a predetermined rate. These signals are added up coherently (in phase) over a designated time frame (T_i). This time frame is determined as a function of LOS range rate covariance calculated from Kalman filter covariance in order to determine the optimum pre-detection integration time T_i. The outputs from each coherent summation Σ( ), cross and dot products are formed at the T_i rate and the cross and dot products are then summed over a different time interval of length T_k. This time, T_k, is chosen to a targeted or desired signal to noise ratio and is determined by SINR estimates computed by the GPS receiver to provide a pair of second summations or integrals, one for the dot product signal and one for the cross product signal. Then an arc tangent function of the summed cross products and dot products is taken and divided by the integration time (T_i) to obtain the range rate residual directly. This residual is then input to a Kalman filter.

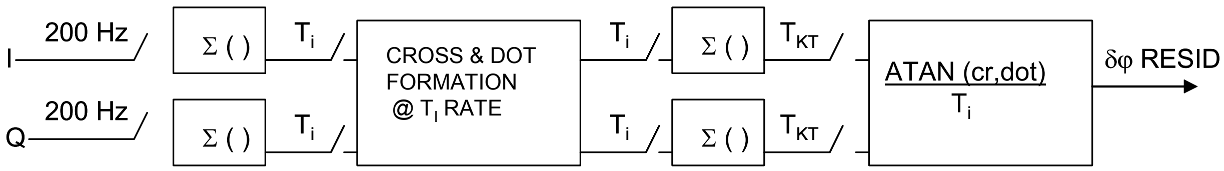

Figure 3. Integrate and Dump Function

The algorithm which computes range residuals, receives the I and Q signals from the GPS signal processor at a predetermined rate. These signals are added up coherently over a designated time frame (T_i) for each of the I and Q signals individually to provide summations or integrals for each of the I and Q signals. This approach is used for both an early channel and a late channel as shown in Figure 4. In each channel, the I signals and Q signals are squared, this being an envelope detect type of operational. The squared signals are summed for the time period T_k.

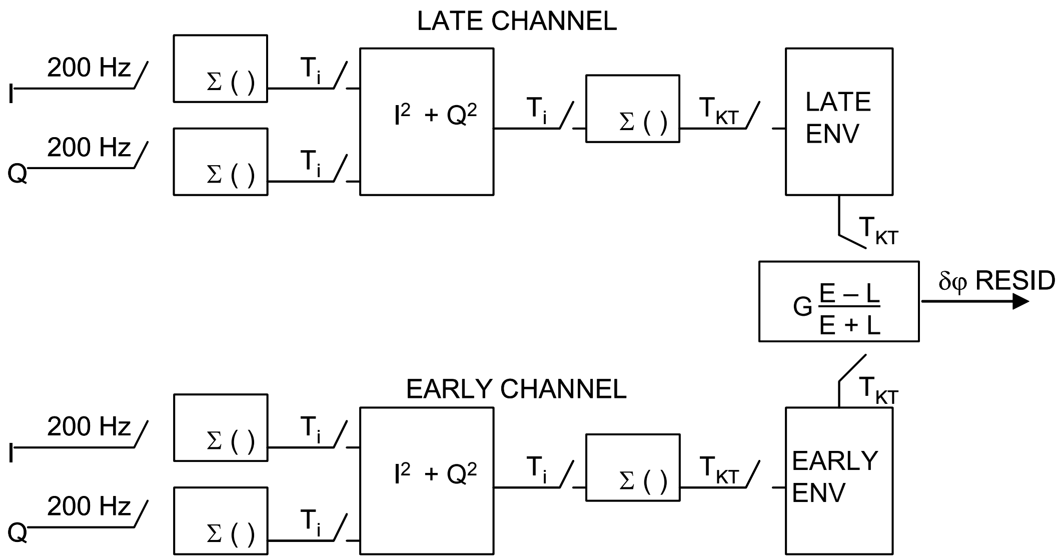

Figure 4. Early/Late Channel Processing

The algorithm which computes a phase lock loop (PLL) range residual is a biased estimate in contrast to the range residual described above which provides an unbiased estimate of the range to the satellite but is quite noisy and is shown in Figure 5. The Kalman filter separates the noise from the signal optimally as long as it is advised of the amount of noise present in the total signal sent thereto. The more noise present, the slower the filter operates. Here, the Kalman filter is used to close a phase lock loop PLL by maintaining all of the energy in the I (cosine) channel and providing no energy in the Q (sine) channel or keeping that signal at zero. Although the PLL provides a measurement with two orders of magnitude less noise, a problem with the PLL is 2π looks like 4π which looks like 6π, etc. and has ambiguity. Each 2π represents a 0.2 meter bias. Accordingly, the system is allowed to converge using the unbiased estimate and then, when the error is low, the PLL mode is used.

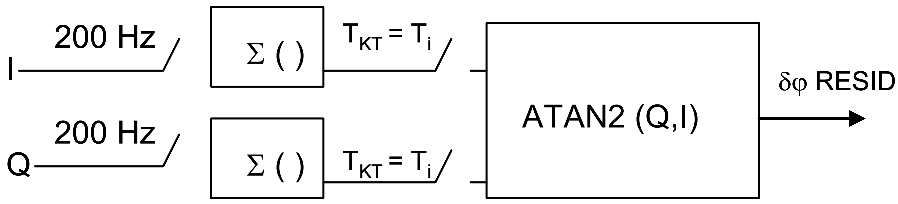

Figure 5. Phase Lock Loop Residual Processing

In order to estimate pseudo range and range rate residuals input to the navigation Kalman filter, the following calculations are made. For the first residual, the I and Q values are coherently integrated for a specified period of time which depends upon the range rate uncertainty (LOS covariance) calculated by the Kalman filter according to:

$$\overline{I} = \sum_{i=1}^{N} I_i \tag{1}$$

$$\overline{Q} = \sum_{i=1}^{N} Q_i \tag{2}$$

The bars over the I and Q data indicate that they are average orthogonal components of a phasor. Using the above coherently derived I and Q values, three different residual are formed to drive the eighteen state extended Kalman filter. By coherently integrating I and Q values for both early and late code states, the unbiased pseudo-range residual is formed as follows from coherent samples as follows:

$$E = \left[\left(\sum \left(\bar{I}_E \right)^2 + \left(\bar{Q}_E \right)^2 \right)_i \right]^{1/2} \tag{3}$$

$$L = \left[\left(\sum \left(\bar{I}_L \right)^2 + \left(\overline{QL} \right)^2 \right)_i \right]^{1/2} \tag{4}$$

The range residual is then formed as:

$$\delta R = \tau_e = G \frac{E - L}{E + L} \tag{5}$$

G is a gain factor derived from C/N_o estimates to compensate for gain depression effects.

The residual δR, scaled to meters, then drives the extended Kalman filter every t_k seconds. This residual is an unbiased range error measurement from which the navigation ECEF position and clock states are directly observable. The Kalman filter takes the place of traditional tracking loop filters in order to close a delay lock loop. The action of this closed loop system is to estimate navigation states that directly drive the pseudo-range residual to zero. The second residual estimated to directly drive the Kalman filter is an unbiased estimate of pseudo range rate. This residual has as inputs coherently generated I and δQ data sampled from the prompt code correlator. The pseudo range rate residual is calculated as follows:

$$\delta R = \frac{\delta \overline{\theta_e}}{\partial t} = ATan2(cross, dot) / \partial t \tag{6}$$

whereas

$$cross = \sum_{i=1}^{K} \left(\overline{I_n Q_{n-1} - Q_n I_{n-1}} \right)_i \tag{7}$$

and

$$dot = \sum_{i=1}^{K} \left(\overline{I_n I_{n-1} - Q_n Q_{n-1}} \right)_i \tag{8}$$

where I and Q data are coherently averaged over adjacent time steps (n and n-1), separated in time by dt. In this case the Kalman filter is used in place of traditional tracking loop filters in order to close a frequency lock loop. This measurement directly couples to the velocity and time bias rate state variable of the Kalman filter.

The third residual for direct use into the Kalman filter is treated as a range residual and provides a locally stable but biased range residual. This residual is calculated as follows:

$$\delta R = \theta_e(\tau_{mid}) = \sum_{i=1}^{K} \left(ARCTAN2\left(\overline{Q}, \overline{I}\right)\right)_i \tag{9}$$

and

$$\delta R = \theta_e(\tau_{mid}) = \sum_{i=1}^{K} \left(ARCTAN2\left(\frac{\overline{Q}}{\overline{I}}\right)\right)_i \tag{10}$$

1.3 Hardware Configuration

A Raytheon (*RAPToR^{TM}*) GPS receiver/navigator shown in Figure 6 was used in the performance of the study and configured with candidate IMU and oscillator technologies. The *RAPToR^{TM}* GPS receiver is approximately 3.5 inches in diameter and operates simultaneously on L1 and L2. The IMUs selected for the study included a Kearfott Ring Laser Gyro (RLG) and a Honeywell MEMS HG1900 and are representative of IMU technology available today. The RLG IMU has a gyro bias of 0.7 degree per hour 1 sigma and an angle random walk of 0.03 degrees per root hour. The MEMS IMU has a gyro bias of 30 degrees per hour 1 sigma and an angle random walk of 0.2 degrees per root hour. The GPS receiver clock references were an OCXO and a good quality TCXO. The OCXO has an Allan variance of 1 x 10^{-11} for a one second average and a g-sensitivity of 0.3 parts per billion per g. The TCXO has an Allan variance of 0.5 x 10^{-6} for a one second average and a g-sensitivity of 2 parts per billion per g.

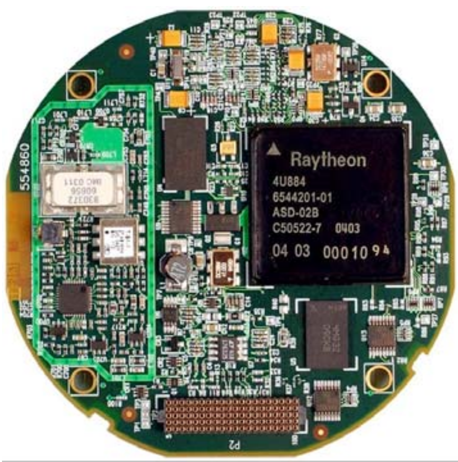

Figure 6. RAPToR ^{TM} GPS Receiver

1.4 6-DOF Simulation

A high fidelity 6-Degree of Freedom (DOF) simulation tool was used in developing and testing both the Tightly-Coupled and Ultra-Tightly-Coupled navigation software prior to hardware integration. The 6-DOF simulation is capable of modelling a variety of user dynamic profiles and accurately models satellite dynamics for a full GPS constellation. The relative dynamics between user and each satellite is calculated and input to a high fidelity software model of the GPS receiver. The receiver model outputs I and Q data at the software sample rate. This sample rate effectively drives the software algorithms very much the same as they are driven in the actual GPS receiver. The oscillators and IMUs with Monte Carlo error parameters, were also modelled in the 6-DOF environment. The high fidelity IMU and oscillator models include Allan variance noise statistics as well as the bias instabilities which are the critical parameters that drive the ability of the GPS receiver to track the GPS signal at low signal to noise ratios. In addition, interference models are part of the simulation environment. The model assumes an omni directional antenna for both noise interference and signal, and effectively produces I and Q data with the appropriate signal-to-noise ratio (SINR) for a given interference level at each sample point.

1.4.1 Tightly-Coupled Navigation 6-DOF Results

The GPS receiver is allowed to track and converge to a navigation solution in an high C/N_o environment. The C/N_o levels are gradually decreased with time until the system navigation solution degrades. Figure 7 contains the ensemble navigation statistics for a Monte Carlo set of 25 runs using a RLG and OCXO. Plotted are the RMS statistics for the Root-Sum-Square (RSS) position, velocity, and attitude errors (tilt and yaw are shown separately) for the Tightly-Coupled navigator. As can be seen from Figure 5 the C/N_o was initially high for system acquisition and navigation convergence and then gradually decreased until at 220 seconds the was just above loss of track (approx 18 dB- Hz). Figure 8 contains a histogram of the terminal Spherical Error Probability (SEP) errors for each of the 25 cases.

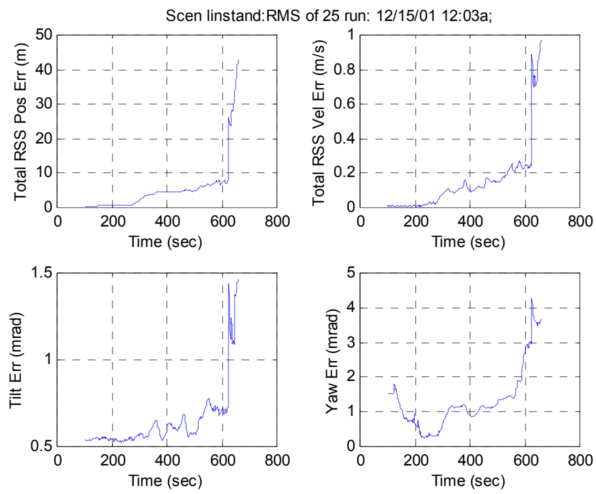

Figure 7. Standard Navigation 6-DOF Statistics (RLG, OCXO)

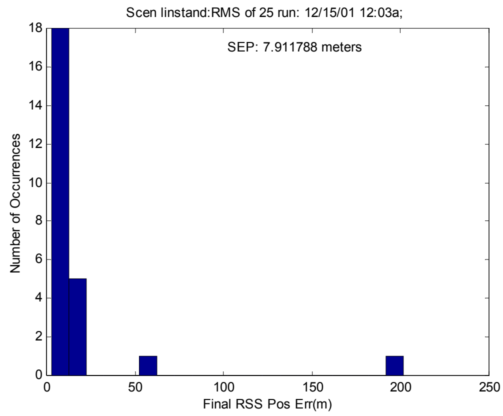

Figure 8. Standard Navigation SEP Histogram (RLG,OCXO)

1.4.2 Ultra-Tightly-Coupled Navigation 6-DOF Results

For the Ultra-Tightly Coupled test cases, once the navigator has converged to an initial solution, the system is allowed to transition to the Ultra-tightly Coupled mode when the C/N_o is approximately 25 dB-Hz. At approximately 220 seconds, the C/N_o was just above the 18 dB-Hz carrier tracking threshold. The C/N_o decreased was continued to a level significantly lower than that used for the standard navigation case and maintained just below loss of track for the rest of the scenario, a period of almost 450 seconds. Figure 9 contains the Ensemble navigation statistics for a Monte Carlo set of 25 runs. As can be seen from the plot, the variance of the navigation errors grow as a function of time after the C/N_o was decreased but the system never lost carrier track. The terminal RMS position and velocity error are about 5.0 and 0.1 m/s respectively at a C/N_o of approximately 5 to 7 dB-Hz . Note that the scale in Figure 9 for the total RSS velocity error is an order of magnitude lower than in Figure 7 representing the improvement in velocity accuracy measurement that this architecture can provide. Figure 10 contains a histogram of the terminal SEP errors for each of the 25 cases.

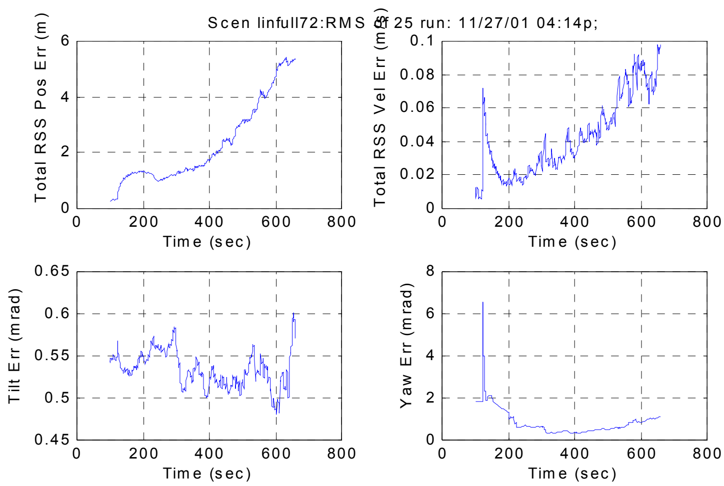

Figure 9. Ultra-Tight Coupling 6-DOF Statistics (RLG, OCXO)

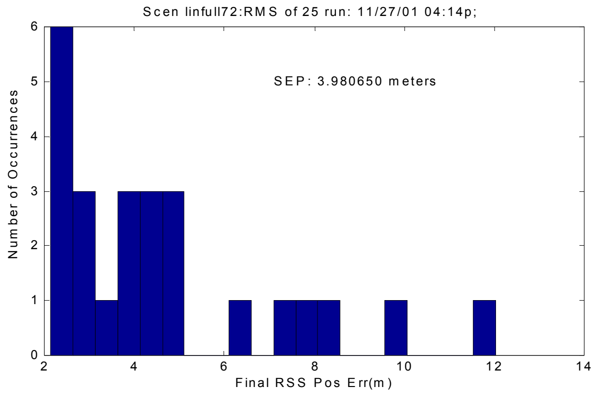

Figure 10. Ultra Tight Coupling SEP Histogram (RLG,OCXO)

1.4.2 6-DOF Performance Summary

The simulation was changed from using a RLG IMU to a MEMS IMU and from a OCXO to a TCXO and the test case runs repeated. Using a MEMS IMU and TXCO resulted in a 5 to 6 dB overall tracking performance loss for the Ultra-Tightly-Coupled system. However, is all cases, the performance of the Ultra-Tightly Coupled Architecture exceeded the performance of the Tightly Coupled Architecture. This was also the case when no IMU was used. In stationary or very low velocity cases, zero velocity aiding data input to the Kalman filter produced improved performance at a lower C/No than standard unaided GPS receiver performance.

1.5 Laboratory Testing Environment

The laboratory test environment used the GPS receiver, IMU, and reference clock previously described but satellite signals and IMU signals were generated from a simulator. The scenarios ran in the Laboratory environment closely matched the 6-DOF simulations for a particular set of IMU parameters and reference clock performance.

1.5.1 Tightly-Coupled Navigator Laboratory Test Results

In Figure 11, ECEF position, velocity, and attitude errors are plotted as a function of interference scenario time for the Tightly-Coupled Navigator test scenario. Initially the C/N_o started at 38 dB-Hz and was gradually decreased to loss of GPS receiver track. Both position and velocity errors begin to diverge from the truth at around 4.39 x 10^4 seconds at a C/N_o 19 dB-Hz from the start of the scenario. which the system no longer performs delta range measurements.

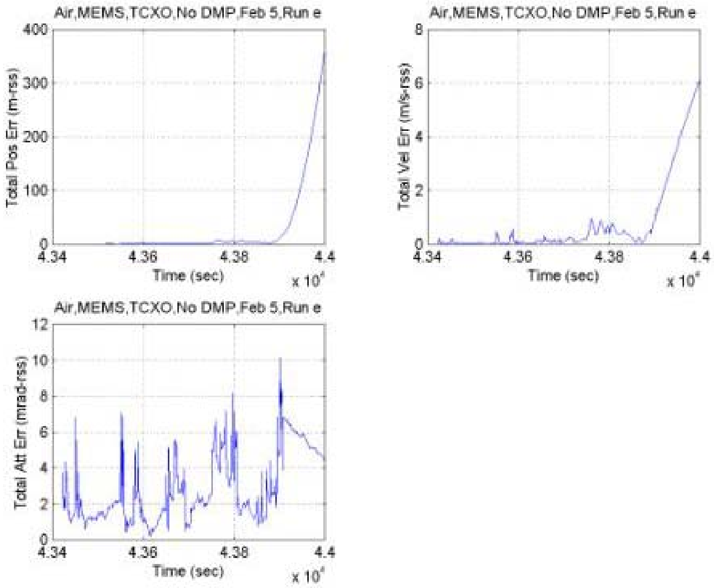

Figure 11. Tightly CoupledLaboratory Test Results (MEMS, TCXO)

1.5.2 Ultra-Tightly-Coupled Navigator Laboratory Test Results

Plots of ECEF position, velocity and attitude errors are shown in the Figure 12 and 13 for the Ultra-Tightly-Coupled test scenarios using a RLG and OCXO versus a MEMS and TCXO respectively. At the end of the scenarios, the RSS position and velocity errors have risen to about 5 meters and 0.1 m/s for the RLG/OCXO configuration at a C/N_o of approximately 6 dB-Hz versus 8 meters and 0.3 m/s for the MEMS/TCXO at a C/N_o of approximately 11 dB-Hz. These results compare favourably to the 6-DOF simulation runs which predicted a 5 dB to 6 dB improvements when using a RLG and OCXO versus a MEMs and TCXO.

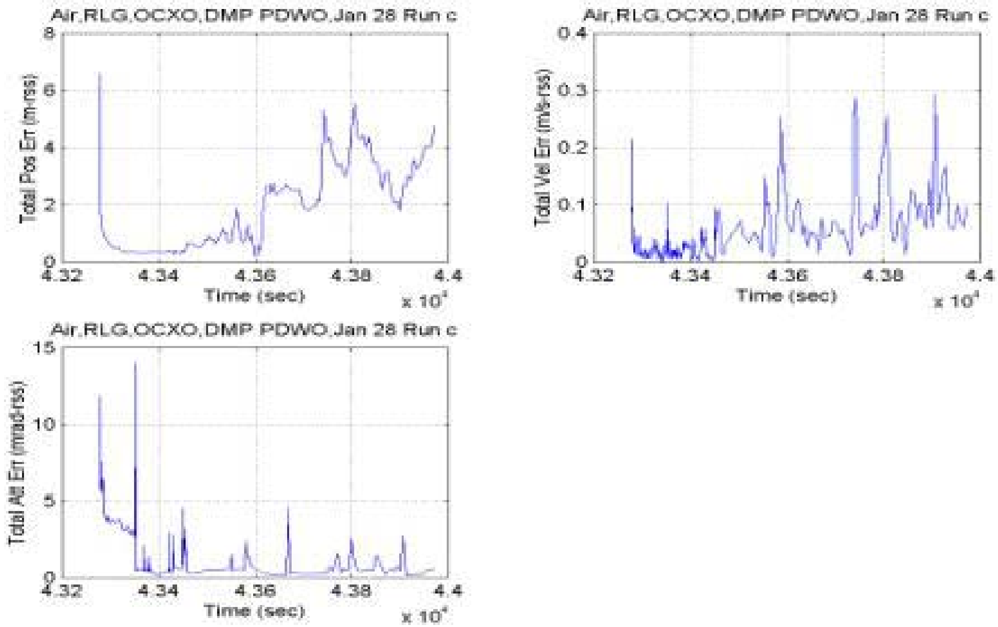

Figure 12 Ultra-Tightly-Coupled with RLG and OCXO

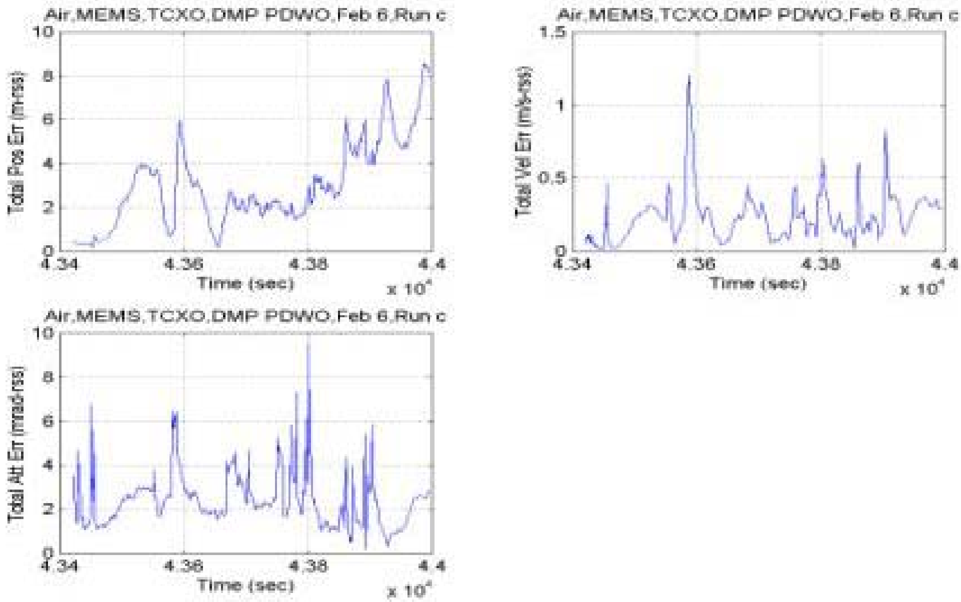

Figure 13 Ultra-Tightly-Coupled with MEMS and TCXO

2.0 CONCLUSIONS

The simulation and laboratory results discussed in this paper validated the possible tracking threshold improvements obtainable using Ultra-Tightly Coupled techniques versus the conventional tracking loops approach used in current GPS receivers. These results also demonstrated the sensitivity of the Ultra-Tightly-Coupled GPS/INS architecture to the quality of IMU and clock technology. Ultra-Tightly-

Coupled GPS/INS provides significant improvement in GPS tracking performance over Tightly-Coupled systems and that IMU and oscillator quality have a noticeable effect on Ultra-tightly Coupled performance.

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ATTACHMENT 1

AUTHOR INFORMATION FORM
FOR

AUTHOR SUBMITTING AN ABSTRACT FOR THE
SENSORS & ELECTRONICS TECHNOLOGY PANEL SYMPOSIUM
on

ADVANCED NAVIGATION SENSORS and SYSTEMS for URBAN, INDOOR and SUBTERRANEAN ENVIRONMENTS

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Satellite Navigation In Indoor/Urban Environments or Integration Techniques

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