Dynamics performance of carrier and code tracking loops in ultra-tight GPS/INS/PL integration

Ravindra Babu[1], Jinling Wang[1]
[1]School of Surveying and Spatial Information Systems, University of New South Wales,
Sydney, 2052, Australia
Email: s.ravi@unsw.edu.au

Abstract**:** *Integrating the correlator measurements, I (in-phase) and Q (quadrature), with position, velocity and attitude from INS in a Kalman filter characterizes the ultra-tight GPS/INS integrated system. The Doppler feedback derived from the corrected INS is fed back to the carrier-tracking loop to remove the dynamics from the GPS/PL ranging signals, thereby reducing the carrier tracking bandwidth. This reduction in bandwidth results in better code and carrier measurements accuracy. Therefore accurate estimation of the Doppler frequency from the INS becomes paramount in leveraging the benefits of ultra-tightly coupled systems. Although the code loops are not directly aided by the INS derived Doppler in ultra-tightly coupled system, nevertheless, an accurate knowledge of Doppler information from INS results in better code thresholds. This improvement in threshold further increases the accuracy of raw measurements and also jamming immunity. In unaided mode, the carrier and code tracking loop bandwidths are about 15 Hz and 3 Hz respectively, whereas in ultra-tight integration mode the bandwidths can be reduced to 3 Hz and 1 Hz respectively.*

In this paper, the performance of the carrier and code tracking loops are analyzed. A Software GPS receiver is used to perform the analysis. A Costas Loop is used for carrier tracking with an arctan discriminator function, while a narrowband DLL with a E-L/E+L discriminator is used for the code tracking loops. A dynamic trajectory was chosen to analyze the performance of both carrier and code tracking loops, and the results show substantial improvement in the performance of the loops in ultra-tight aided configuration.

I. INTRODUCTION

The integration of GPS (Global Positioning System) and INS (Inertial Navigation System) are increasingly used in modern navigation systems as their integrated performance outweighs the shortcomings of the individual systems. Though INS is autonomous and provides good short-term accuracy, its usage as a stand-alone navigation system is limited due to the time-dependent growth of the inertial sensor biases [4]. However, if these systematic biases are calibrated by GPS then the INS solution can be used for extended periods without degradation. This is the main justification for GPS and INS integration, and such integration has been successfully implemented in many applications.

Initially GPS and INS were integrated in the so-called loosely coupled mode where the position solutions from both systems are combined for optimality. This system level integration, though comparatively simple to implement, is limited in its applications. Therefore, the multisensor integration advanced to the next level, the so-called tightly coupled mode where the raw measurements from the GPS are combined with the INS measurements or positions [7]. This improved the overall system performance, however, with an improved insight into the individual systems, the level of integration moved deeper into the hardware level which improved the performance even further. This type of integration is often referred to as ‘ultra-tight integration’.

Ultra-tight integration, or integration at the signal tracking loop level, combines the I (in-phase) and Q (quadrature) measurements from the GPS tracking loop with the INS navigation parameters [10] [12]. This integration strategy is more complex compared to the other two modes, requiring knowledge on the hardware functioning of the tracking loops. However, the improved performance justifies the complexity, and due to its benefits, significant research in carried out in this area. Also, the emphasis is increasingly on the use a low cost IMU sensor, which can be utilized in many commercial applications. Unlike in conventional tracking loops where the feedback signal to the NCO (Numerically Controlled Oscillator) is generated within each channel, in ultra-tight integrated systems the feedback signal is derived from both the individual channel and the navigation filter. This improves the jamming immunity and also facilitates a reduction in the tracking loop bandwidth, hence improving the measurements accuracy.

In contrast to the other two configurations, ultra-tight systems have a stringent requirement on the quality of the aiding signal, i.e. Doppler measurements from the INS, to the tracking loop [11]. Any deviations from the actual Doppler results in correlations in the tracking loop measurements I and Q. As in any other system, if unaccounted for, these correlations introduce a bias in the navigation parameters. By appropriately modeling the bias, the correlations can be removed from within the tracking loop.

II. GPS/INS ULTRA-TIGHT INTEGRATION

The main idea behind the ultra-tight integration is that, if the integration of inertial measurements with GPS can reduce the tracking loop bandwidth, then the accuracy of the GPS receiver measurements and the anti-jam performance of the integrated system can be improved [10]. However, the quality of the aiding signal is very important in such an integration strategy, as any bias in the aiding signal degrades the tracking loop measurements. Therefore, for optimal performance of the tracking loop, the correlations induced due to the INS-derived Doppler offsets should be mitigated. The block diagram of the GPS/INS ultra-tight integration is shown in Fig. 1.

The conventional unaided GPS receiver uses a 2nd order carrier-tracking loop with a loop bandwidth of about 12 to 18Hz [7]. But, to receive a dynamically varying signal the order of the loop should be increased to 3 to reduce the dynamic stress error [1] [11]. However, the design of a 3rd order filter is complex, and furthermore it has stability problems [10]. In ultra-tight systems, as the dynamics from the GPS signal are removed by the INS aiding, the filter order can be reduced to 2 and the bandwidth can be maintained at about 3Hz. Further reduction in bandwidth is possible if an accurate receiver clock and a navigation-grade INS are used, but they are too expensive to be used in many commercial applications, forcing a limit on the bandwidth reduction.

Using an additional sensor such as an INS is attractive in that it is not only autonomous and a complementary system to GPS, but also it reduces the complexity of the tracking loop design for dynamic signals. The conventional carrier-tracking loop bandwidth and order are 18Hz and 2 respectively, whilst the code loop parameters are 3Hz and 1 respectively. The effect of dynamics on code signals is less due to its lower frequency. In order to receive dynamic signals, the carrier tracking bandwidth and order are increased to >20Hz and 3. This complicates the design and reduces the reliability. With INS aiding the tracking loops the bandwidth can be reduced to 3 to 5Hz and the order to 2, and still be able to receive a dynamically-varying signal.

III. DOPPLER ANALYSIS

The received carrier Doppler frequency on L1 is given as

$$f_{rx} = f_{tx}\left(1 - \frac{v_r \vec{a}}{c}\right) and \; f_{carr} = f_{tx} - f_{rx} \qquad (1)$$

where

$f_{tx} = 1575.42e6$
$v_r = relative \; velocity$
$c = velocity \; of \; light$
$\vec{a} = line \; of \; sight \; vector$

The total Doppler on f_{rx} can be factored into

$$f_{carr} = f_{rel\_vel} + f_{sat\_clk} + f_{rx\_clk} + f_{errors} \qquad (2)$$

where f_{rel_vel} represents the Doppler due to the relative velocity between the satellite and the receiver, f_{sat_clk} represent the Doppler due to Satellite clock errors, f_{rx_clk} is due to receiver clock errors, f_{errors} is due to atmospheric and other errors. Due to its lower frequency, the Doppler on the code is 1540 times less than the carrier.

$$f_{code} = f_{carr} / 1540 \qquad (3)$$

The INS measurements can rate-aid the carrier and code tracking loops to reduce the dynamic stress. The aiding will significantly reduce the loop bandwidths. As a result, the thermal noise and interferences are mitigated resulting in the improvement in the accuracy of the measurements; the tracking thresholds also can be improved. However, the factors that limit the bandwidth of the loops is determined by how accurately the IMU derived Doppler measurements can be obtained. Any errors in the calibration of inertial sensor errors by the integration Kalman filter translate to aiding Doppler errors which in turn limit the bandwidth reduction. The INS estimated Doppler frequency is given as

$$f_{INS} = f_{rel\_vel} + f_{sys\_errors} + f_{stoc\_errors} \qquad (4)$$

where f_{sys_errors} is due to residual inertial bias from the integration Kalman filter, and f_{stoc_errors} is due to the stochastic errors from the inertial sensors.

The INS aiding cancels the Doppler due to relative velocity leading to

$$\begin{aligned} f^{carr}_{ultra-tight} &= f_{carr} - f_{INS} \\ &= f_{sat\_clk} + f_{rx\_clk} + f_{errors} - f_{sys\_errors} - f_{stoc\_errors} \end{aligned} \qquad (5)$$

As the carrier frequency aids the code loop, the code Doppler is given as

$$f^{code}_{ultra-tight} = \frac{f^{carr}_{ultra-tight}}{1540} \qquad (6)$$

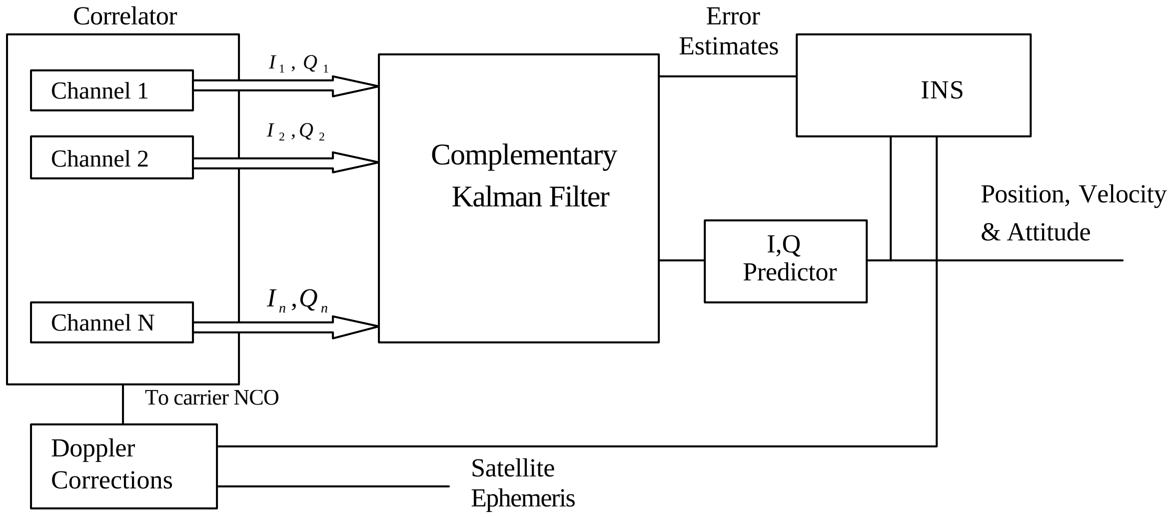

Fig. 1. Ultra-tight GPS/INS configuration

Therefore, the code tracking loop needs to track this Doppler for continuous tracking.

IV. SIMULATION & RESULTS

Simulation experiments performed for some of our previous studies [10] [11] [12] are summarized in this paper. A reference trajectory shown in Fig. 2 is generated using GPSoft^{TM}. The trajectory comprises the following segments: acceleration, pitch up, roll, 90 deg turns, straight leveling. Inertial sensor measurements are derived from this trajectory and added with 10.0 mg acc. bias and 1.0 deg/sec gyro bias. The performance of both the loops is shown in Fig. 5. In unaided configuration, the carrier tracking bandwidth is set at 13 Hz, whereas the code tracking bandwidth is set at 3 Hz with a 0.25 chips spacing, and the experiments are performed. The results in Figs. 3 and 4 shows that both the loops loose lock. Under ultra-aided configuration, with carrier and code bandwidths set at 3 Hz and 1 Hz respectively, the same experiments are again performed, and the results in Figs. 3 and 5 shows the loops maintain lock even in dynamic signal conditions.

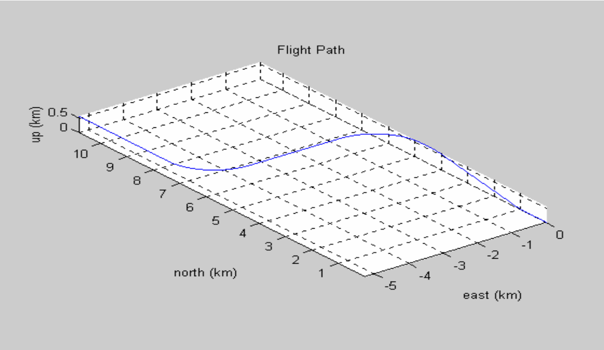

Fig. 2. Receiver Trajectory

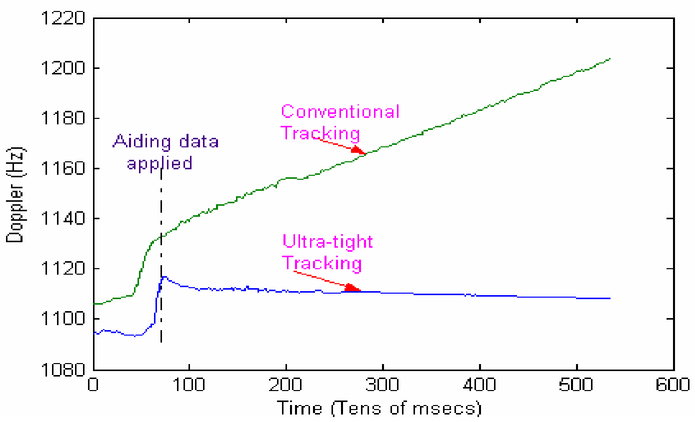

Fig. 3. Conventional vs. ultra-tight carrier tracking loop performance

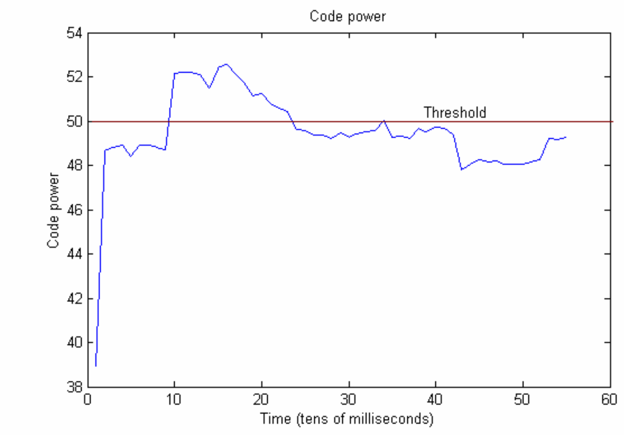

Fig. 4. Unaided code loop

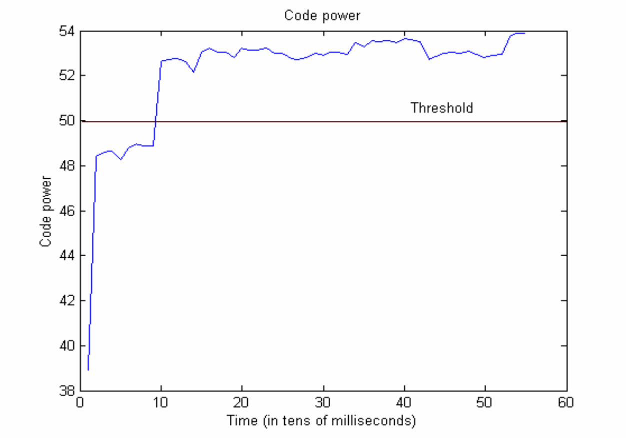

Fig. 5. Ultra-tight aided code loop

V. CONCLUDING REMARKS

Ultra-tight integration systems can provide a more robust performance than loosely and tightly coupled GPS/INS systems. However, the quality of the aiding Doppler signal derived from the inertial navigation system must be high if this configuration is to be effective. Consequently the performance can become sub-optimal if the correlation parameters due to Doppler estimation are inaccurate. There are two approaches to mitigate this effect: navigation Kalman filter and in-channel processing. The latter method, due to its simpler structure, has been implemented. A software GPS receiver is used to optimize the tracking loop.

Simulation experiments have demonstrated that the correlations in the tracking loop due to inaccurate Doppler estimation from the INS can be mitigated using the proposed tracking loop structure. The concepts of ultra-tight integration and the algorithms for the modified tracking loop structure have been described. The results of preliminary investigations are encouraging and this method may prove to be an attractive solution, especially when using low cost inertial sensors.

VI. ACKNOWLEDGEMENTS

This research is supported by an ARC (Australian Research Council) – Discovery Research Project on 'Robust Positioning on Ultra-tight integration of GPS, Pseudolites and inertial sensors'.

REFERENCES

[1]. Cox, D.B., "Integration of GPS with Inertial Navigation Systems", Navigation, Journal of the Institute of Navigation, 1, 1982, pp 144-153.

[2]. Kaplan, E.D., "Understanding GPS: Principles and Applications", Artech House, MA, 1996.

[3]. Brown, R.G., & Hwang, P.Y.C., "Introduction to Random Signals and Kalman Filtering", 3rd edition, John Wiley & Sons, NY, 1997.

[4]. Sennott, J., & Senffner, D., "Robustness of Tightly Coupled Integrations for Real-Time Centimeter GPS Positioning", 10th Int. Tech. Meeting of the Satellite Division of the U.S. Inst. Of Navigation, Kansas City, Missouri, 16-19 September 1997, pp 655-663.

[5]. Titterton, D.H., & Weston, J.L., "Strapdown Inertial Navigation Technology", Stevenage, U.K., Peregrinus, 1997.

[6]. Ward, P., "Performance Comparisons between FLL, PLL and a Novel FLL-Assisted PLL Carrier Tracking Loop Under RF Interference Conditions", 11th Int. Tech. Meeting of the Satellite Division of the U.S. Inst. Of Navigation, Nashville, Tennessee, 15-18 September 1998, pp 783-795.

[7]. Tsui, J.B.Y., "Fundamentals of Global Positioning Receivers – A Software Approach", John Wiley & Sons, 2000.

[8]. Jwo, D.-J., "Optimization and Sensitivity Analysis of GPS Receiver Tracking Loops in Dynamic Environments", IEE Proceedings of Radar, Sonar Navigation, 148, 2001, pp 241-250.

[9]. Beser, J., Alexander, S., Crane, R., Rounds, S., Wyman, J., Beader, B., "Trunav™ : A Low-Cost Guidance/Navigation Unit Integrating a SAASM-based GPS and MEMS IMU in a Deeply Coupled Mechanization", 15th Int. Tech. Meeting of the Satellite Division of the U.S. Inst. Of Navigation, Portland, Oregan, 24-27 September 2002, pp 545-555.

[10]. Babu, R., Wang, J., "Mitigating the correlations in INS aided Tracking Loop Measurements: A Kalman Filter Based Approach", 17th Int. Tech. Meeting of the Satellite Division of theU.S. Institute of Navigation, Long Beach, California, 21-24 September 2004.

[11]. Babu, R., Wang, J., "Improving the Quality of IMU-Derived Doppler Estimates of Ultra-Tight GPS/INS Integration", GNSS 2004, Rotterdam, The Netherlands, 16-19 May 2004.

[12]. Babu, R., Wang, J., "Performance of Code Tracking Loop in Ultra-Tight GPS/INS Integration", ENC-GNSS 2005, Munich, Germany, 19-22 July 2005.