A New GPS Receiver Correlator for the Deeply Coupled GPS/INS Integration System

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Abstract

A new GPS receiver correlator for the deeply-coupled GPS/INS integration system is proposed in order to the computation time problem of the Kalman filter. The proposed correlator consists of two early, prompt and late arm pairs. One pair is for detecting data bit transition boundary and another is for the correlator value calculation between input and replica signal. By detecting the data bit transition boundary, the measurement calculation time can be made longer than data bit period. As a result of this, the computational time problem of the integrated Kalman filter can be resolved. The validity of the proposed method is given through computer simulations.

Keywords: Deeply coupled GPS/INS integration system, Data Wipe-Off (DWO), Correlator, Kalman filter

1. Introduction

The GPS/INS integration systems have been used for many applications in the navigation and geodesy. It can be classified into the loosely coupled method, the tightly-coupled method and the deeply-coupled method. The deeply coupled method is known to gives best performance and have robust tracking and anti-jamming capability against external interference [1][2][3].

In the deeply coupled integration system, integration Kalman filter utilize in-phase(I) and quadrature-phase(Q) correlator outputs as measurement in order to estimate INS navigation error and sensor errors. In GPS receiver, the predetection integration time(PIT) should be less than the navigation data bit period. Since the correlator outputs are measurements of the Kalman filter, the Kalman filter should be updated in the same rate as correlator output. The correlator output rate is at least 50Hz and this is about 50times higher than the loosely or tightly coupled GPS/INS integration Kalman filter measurement update rate can give rise to a heavy computational problem

Some approaches have been proposed in order to resolve the heavy computational time problem of the deeply coupled-coupled method[3][4][5]. Jorvancevic et al. adopted the federated filter in which pre-filters were used in processing the I and Q correlator output at a higher rate approach and the outputs of the pre-filters were processed in a composite Kalman filter at a lower rate[3]. Zeidan and Garrison[4] and Psiaki and Jung[5] have utilized the data wipe-off(DWO) in order to extended the PIT of the correlator.

In this paper, a new correlator is proposed in order to computational time problem of the deeply coupled GPS/INS integration system. The proposed correlator consists of two pairs of correlators arm. One pairs is for detection data bit transition and another is for calculating correlation value between input and replica signal. When the data bit is detected, the sign of the correlator output is reversed.

2. Deeply Coupled GPS/INS Integration System

The structure of the deeply coupled GPS/INS integration system with proposed correlator is given in figure 1. In the deeply integration method, the integration with inertial measurement is carried out at the correlator output stage of the GPS receiver. The incoming signal is mixed with replica carrier and code. The replica carrier is generated using estimated Doppler frequency from position and velocity of SDINS. The replica code is generated using estimated propagation delay. The correlator consists of two early, prompt and late arm pairs. One is for detection data bit transition and another is for calculating correlation value between input and replica signal. When the data bit is detected, the sign of the correlator output is reversed. The data wiped correlator output can be accumulated longer than data bit period. The accumulated vaule used to compute range residual and range rate residual. The integration Kalman filter estimates navigation error and sensor errors using these residuals. Estimated errors are used to compensate the strapdown inertial navigation system error.

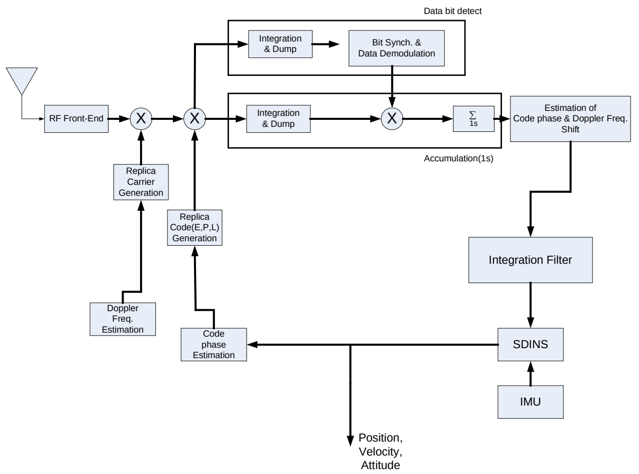


Figure 1. Structure of deeply coupled GPS/INS integration system

2.1 Precorrelation Signal Processing

The received GPS L1 signal from a single satellite at time t can be represented as

$$S_i(t) = \sqrt{2P}D(t-\tau)C(t-\tau)\cos\left(2\pi(f_{L1}+f_D)t+\theta\right)+n(t) \quad (1)$$

where subscript i is number of satellite. P denotes signal power, D navigation data, C pseudo-random coarse/acquisition code, f_{L1} frequency of L1 carrier. τ represents propagation delay due to line of sight range and atmospheric propagation effects. The received signal is processed by RF front end electronics. The front end converts the signal to a lower intermediate frequency. The downconverted signal can be expressed as

$$S_i(t) = \sqrt{2P}D(t-\tau)C(t-\tau)\cos\left(2\pi(f_{IF}+f_D)t+\theta_{IF}\right)+n(t) \quad (2)$$

where subscript IF denotes intermediate frequency. The downconverted signal is multiplied by the in-phase replica carrier and quadrature-phase replica carrier given by

$$R_I(t) = \sqrt{2}\cos\left(2\pi(f_{IF}+\hat{f}_D)t+\hat{\theta}\right) \quad (3\text{-a})$$

$$R_Q(t) = \sqrt{2}\sin\left(2\pi(f_{IF}+\hat{f}_D)t+\hat{\theta}\right) \quad (3\text{-a})$$

where $\hat{f}_D$ and $\hat{\theta}$ is estimated Doppler frequency, carrier phase respectively. The estimated Doppler frequency is

$$\hat{f}_D = \frac{1}{\lambda}\frac{r_i-\hat{r}_u}{|r_i-\hat{r}_u|}(v_i-\hat{v}_u) \quad (4)$$

where λ is wave length of L1 carrier. $\hat{r}_u$ is estimated user position and $\hat{v}_u$ is estimated user velocity from SDINS.
When the downconverted input signal and replica signal are multiplied and low-pass filtered, the output of the inphase and quadrature channel are given by equation (5).

$$\sqrt{P}D(t-\tau)C(t-\tau)\cos\left(2\pi(f_D-\hat{f}_D)t+\theta_{IF}-\hat{\theta}\right)+n_I(t) \quad (5\text{-a})$$

$$\sqrt{P}D(t-\tau)C(t-\tau)\sin\left(2\pi(f_D-\hat{f}_D)t+\theta_{IF}-\hat{\theta}\right)+n_Q(t) \quad (5\text{-b})$$

The code of the incoming signal is stripped using the replica code given equation (6).

$$C(t-\hat{\tau}) = C\left(t-\frac{|r_i-\hat{r}_u|}{c_{light}}\right) \quad (6)$$

where c_{light} is speed of light. $\hat{\tau}$ is estimated propagation delay using position of user and satellite. Figure 2 shows precorrelation processing. As shown in figure 2, multiplied signal is integrated by integration and dump function.

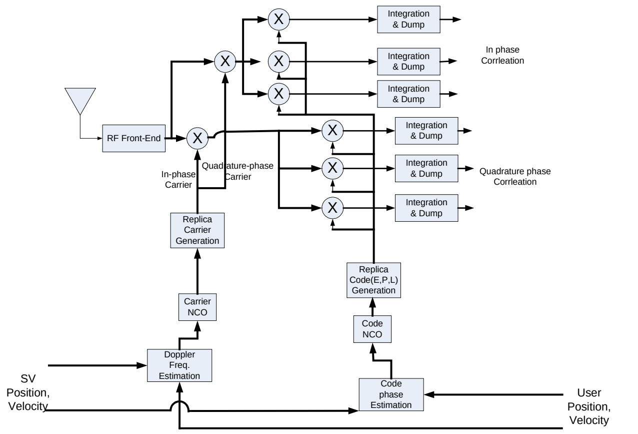


Figure 2. Precorrelation signal processing block

2.2 Correlation Processing with a Pair of Correlator for Data Wipe Off

The outputs of the integration and dump function are given by

$$S_I = \frac{\sqrt{P}D(t-\tau)}{T}\int_0^T C(t-\tau)C(t-\hat{\tau})\cos\left(2\pi\delta f_D t+\delta\theta\right)dt+\frac{1}{T}\int_o^T n_I(t) \quad (7\text{-a})$$

$$S_Q = \frac{\sqrt{P}D(t-\tau)}{T}\int_0^T C(t-\tau)C(t-\hat{\tau})\sin\left(2\pi\delta f_D t+\delta\theta\right)dt+\frac{1}{T}\int_o^T n_I(t) \quad (7\text{-b})$$

Equation (7) can be re-written as

$$S_I(k) = \frac{\sqrt{P}D(k)}{T}\frac{\sin(\pi\delta f_D(k)T)}{(\pi\delta f_D(k)T)}R(\delta\tau(k))\cos(\delta\theta(k))+\bar{n}_I(k) \quad (8\text{-a})$$

$$S_Q(k) = \frac{\sqrt{P}D(k)}{T}\frac{\sin(\pi\delta f_D(k)T)}{(\pi\delta f_D(k)T)}R(\delta\tau(k))\sin(\delta\theta(k))+\bar{n}_Q(k) \quad (8\text{-b})$$

where δf_D and $\delta\theta$ is frequency and phase error between incoming and replica carrier. $\delta\tau$ is code phase error between incoming and replica code. The navigation data bit D need to be wiped-off to increase predetection integration time.

Some approaches have been proposed in order to wipe off data. Zeidan and Garrison adopted Viterbi algorithm for the navigation data bit transition detection[4]. Since the method process the data in a block unit, there may be a delay time to compute the block of data. Psiaki and Jung introduced the bit transition detection approach using Kalman filter[5]. This method increases computational load. This paper utilizes a pair of correlator to detect bit transition and wipe off data bit. Figure 3 shows correlators for data wipe off processing.

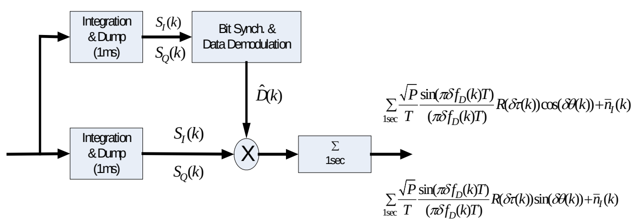


Figure 3. Correlators for data wipe off processing.

In order to wipe off data, detection of bit transition is carried out . The data bit transitions are detected by testing the sign of the dot-product between correlation value of in-phase and quadrature-phase.

$$sign\left(S_I(k-1)S_I(k)+S_Q(k-1)S_Q(k)\right) \quad (9)$$

Output of equation (9) is shown in table 1.

Table 1. Output of detector of bit transition

$D(k)$	$D(k-1)$	output
+1	+1	+1
+1	-1	-1
-1	+1	-1
-1	-1	+1

If an output of detector of bit transition is negative then a data bit transition is assumed to have occurred. Data bit estimation can be carried out using equation (10).

$$\begin{aligned}\hat{D}(k) &= sign\left(S_I(k-1)S_I(k)+S_Q(k-1)S_Q(k)\right) \\ &= sign\left(\frac{\sqrt{P}}{T}D(k-1)D(k)\left[\frac{\sin(\pi\delta f_D T)}{(\pi\delta f_D T)}\right]^2 R^2(\delta\tau)\right)\hat{D}(k-1)\end{aligned} \quad (10)$$

The data bit of correlator output is stripped by estimated data bit and can be written as

$$\begin{aligned}\hat{S}_I(k) &= S_I(k)\cdot\hat{D}(k) \\ &= \frac{\sqrt{P}}{T}\frac{\sin(\pi\delta f_D(k)T)}{(\pi\delta f_D(k)T)}R(\delta\tau(k))\cos(\delta\theta(k))+\overline{n}_I(k)\end{aligned} \quad (11\text{-a})$$

$$\begin{aligned}\hat{S}_Q(k) &= S_Q(k)\cdot\hat{D}(k) \\ &= \frac{\sqrt{P}}{T}\frac{\sin(\pi\delta f_D(k)T)}{(\pi\delta f_D(k)T)}R(\delta\tau(k))\sin(\delta\theta(k))+\overline{n}_Q(k)\end{aligned} \quad (11\text{-b})$$

These signals can be accumulated during 1 sec without energy loss. The accumulated signal is follow as

$$\hat{S}_I(j)=\sum_{k=1}^{N}\frac{\sqrt{P}}{T}\frac{\sin(\pi\delta f_D(k)T)}{(\pi\delta f_D(k)T)}R(\delta\tau(k))\cos(\delta\theta(k))+\overline{n}_I(k) \quad (12\text{-b})$$

$$\hat{S}_Q(j)=\sum_{k=1}^{N}\frac{\sqrt{P}}{T}\frac{\sin(\pi\delta f_D(k)T)}{(\pi\delta f_D(k)T)}R(\delta\tau(k))\sin(\delta\theta(k))+\overline{n}_Q(k) \quad (12\text{-b})$$

2.3. Integration Kalman Filter and Residual Calculation and

The error model of integration Kalman filter[9] is described by

$$\mathbf{x}(k+1)=\Phi(k)\mathbf{x}(k)+\mathbf{w}(k) \sim N(0,Q) \quad (13)$$

where Φ is system matrix. $\mathbf{x}$ is navigation error and sensor error vector.
The measurement model is described by

$$\mathbf{y}(k)=\mathbf{H}(k)\mathbf{x}(k)+\mathbf{v}(k) \sim N(0,R) \quad (14)$$

where measurement matrix H is related range and rage rate. The measurement matrix can be written as

$$H=\begin{bmatrix} l_j^i & 0 & 0 & 0 \\ 0 & l_j^i & 0 & 0 \end{bmatrix} \quad (15)$$

where l_j^i is line of sight vector between satellite i and user j.

The range residual is calculated from equation (16) to update Kalman filter.

$$\begin{aligned}&\frac{\sqrt{\hat{S}_{I_E}^2(j)+\hat{S}_{Q_E}^2(j)}-\sqrt{\hat{S}_{I_L}^2(j)+\hat{S}_{Q_L}^2(j)}}{\sqrt{\hat{S}_{I_E}^2(j)+\hat{S}_{Q_E}^2(j)}+\sqrt{\hat{S}_{I_L}^2(j)+\hat{S}_{Q_L}^2(j)}} \\ &=\frac{R(\delta\tau(j)-d)-R(\delta\tau(j)+d)}{R(\delta\tau(j)-d)+R(\delta\tau(j)+d)}=2\delta\tau(j)\end{aligned} \quad (16)$$

The range rate residual is calculated as follow

$$ATAN2(cross,\, dot)=\delta f_D \quad (17\text{-a})$$

$$cross=\hat{S}_{I_P}(j)\hat{S}_{I_P}(j-1)+\hat{S}_{I_P}(j)\hat{S}_{I_P}(j-1) \quad (17\text{-b})$$

$$dot=\hat{S}_{I_P}(j)\hat{S}_{Q_P}(j-1)+\hat{S}_{Q_P}(j)\hat{S}_{I_P}(j-1) \quad (17\text{-c})$$

These residuals, scaled to meter and meter/second, then drives the Kalman filter every 1second. As a result of this, the computational time problem of the integrated Kalman filter can be resolved

3. Validation of Proposed Method

3.1 Simulation Setup

To verify the proposed method, computer simulations have been carried out. The IMU and GPS IF signal were generated from GPS satellite and vehicle trajectory using Visual C++ and MATALB. Figure 4 shows simulation environment.

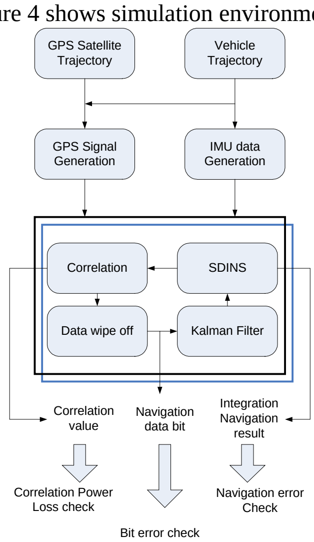


Figure 4. Simulation environment

The functional block diagram of the digitized IF GPS signal generation is shown in Figure 5.

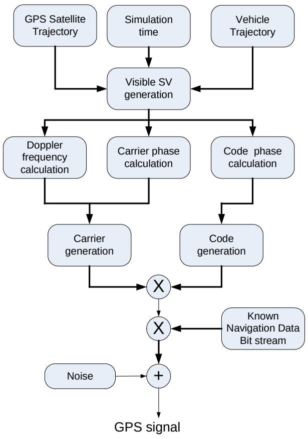


Figure 5. Block of GPS signal generation

A tactical grade inertial measurement unit (IMU) model is used in Figure 6 which shows the block diagram of IMU output generation.

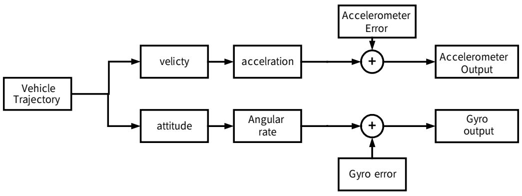


Figure 6. Block of IMU data generation

The vehicle goes toward the north for 50sec. Figure 7 shows the trajectory of the vehicle in the simulation.

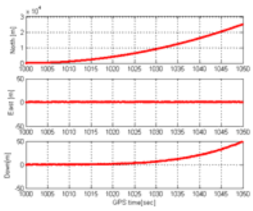


Figure 7. Vehicle trajectory

Figure 8 shows visible satellites and elevation angles. 6 visible satellites can be observed in figure 8.

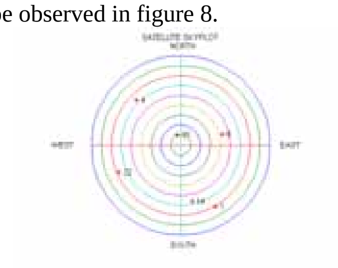


Figure 8. Visible satellite

3.2 Simulation result

In order to validate data bit estimation function, known data bit stream is applied to generated GPS signal. The test bit stream is [1 -1 1 -1 1 -1……]. Figure 9 shows result of data bit estimation. As shown in figure 9, data bit is estimated without error.

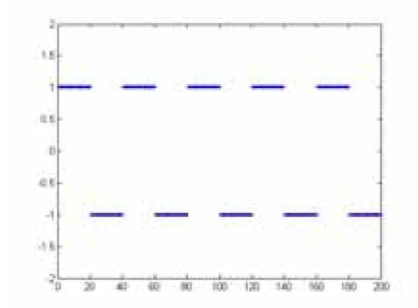


Figure 9. Estimated data bit

After data wipe off, correlation output is accumulated during 1 second. Figure 10, 11 show correlation power of 1msecond period and 1 second period. In figures, it is verified that proposed method do not induce correlation power loss.

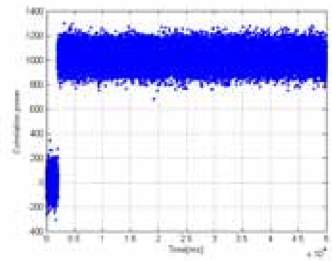


Figure 10. Correlation power of 1msec period

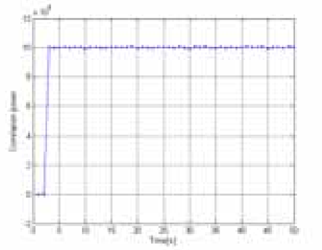
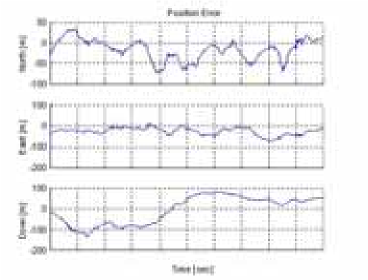
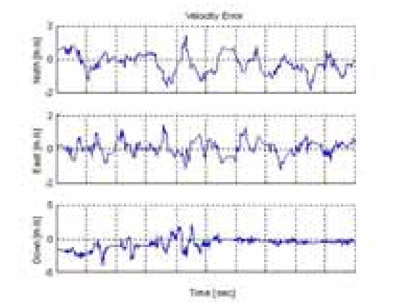


Figure 11. Correlation power of 1sec period

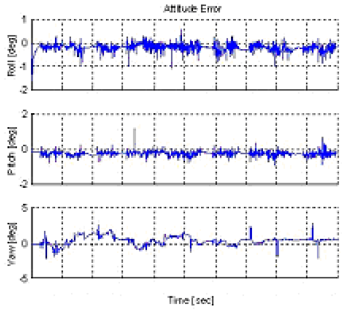
Figure 13 shows integration navigation result. The integration Kalman filter operate at 1Hz



(a) Position error



(b) Velocity error



(c) Attitude error

Fig. 12. Navigation result

Even though initial value has large error, navigation result converges to the true value. In order to verify computational load, simulation time of loosely, tightly and proposed method are compared. Table 2 shows the simulation time.

Table 2. Comparison of Simulation time

	loosely	Tightly	Proposed
Data length	50 sec	50 sec	50 sec
Simulation Time	9 sec	9.7 sec	12.3 sec

Table 2 shows that proposed method reduce computational load

4. Concluding Remarks and Further Study

In this paper, data wipe off method for deeply coupled GPS/INS integration system is adopted to extend the measurement update time of the integration Kalman filter. In order to wipe off data effectively, a pairs of correlator is proposed. One is used to detect data bit transition. The computational time problem is resolved by detecting the data bit transition. Through the simulation, the validity of the proposed method has been shown.

As a further work, a deeply coupled GPS/INS system using the proposed method should be implemented for the real GPS signal and jamming performance will be evaluated.

Reference

1. C. Kreye, B. Eissfeller and J. O. Winkler, "Improvement of GNSS Receiver Performance Using Deeply Coupled INS Measurement," *Proceedings of ION GPS 2000*. pp. 844-854, Sep. 2000.
2. Soloviev, A., van Graas, F. and Gunawardena, S., " Implementation of Deeply Integrated GPS IMU for Acquisition and Tracking of Low CNR GPS Signals," *Proceedings of ION NTM 03*, pp. 234-241, January 2003.
3. A. Jorvancevic, A. Brown, S. Ganguly, J. Noroha and B. Sirpatil," Ultra Tightly Coupling Implementation Using Real Time Software Receiver," *Proceeding of ION GNSS 17th*, pp. 1575-1586, Jul. 2003.
4. Zeidan, N. I. and Garrison, J. L., "Bit Synchronization and Doppler Frequency Removal at Very Low Carrier to Noise Ratio Using a Combination of the Viterbi Algorithm with an Extended Kalman Filter," *Proceedings of 16th ION ITM 16th*, pp. 651-663, September 2003.
5. Psiaki M. L., and Jung, H., "Extended Kalman Filter Methods for Tracking Weak GPS Signals," *Proceedings of the ION ITM 15th*, pp. 295-303, September 2002.
6. Bradford W. Parkinson and James J. Spilker Jr. *Global Positioning System : Theory and Application, Vol. I and II*, AIAA, Washington, 1996.
7. E. D. Kaplan, *Understanding GPS : Principle and Applications*, Artech House, Boston, 1996.
8. P. Misra, P. Enge, *Global Position System : Signals, Measurement, and Performance*, Ganga-Jamuna Press, 2001.
9. D. O Benson, JR. "A Comparison of Two Approach to pure-inertial and Doppler-inertial Error Analysis," *IEEE Trans. on AES Vol. 11*, No. 4, pp. 447-455, 1975.