Stability Analysis of Tracking Weak GPS Signals through Non-coherent Ultra-tight GPS/INS Integration

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Abstract—**In comparison to the coherent ultra-tight GPS/INS integration, the non-coherent ultra-tight integration is more preferable for tracking weak signals because the code discriminator used in the non-coherent integration is independent of the carrier phase, which makes it to be computed regardless of whether the SNR being strong enough or not to track the carrier phase. This paper proposes a specific non-coherent ultra-tight integration approach to the weak signal tracking problems. Stability of this integration system is investigated under weak signal conditions using hardware-in-the-loop simulation. The experimental data including GPS IF(intermediate frequency) signal and INS true data are collected in the same simulation scenario with different levels of SNR by using Spirent GPS signal simulator and Nordnav Rxx-2 receiver. The performance of the system under weak signal condition is analysed in comparison to a stand-alone GPS receiver. The analysis results lead to the following conclusions. First, in comparison to the classical scalar tracking loops used in the stand-alone receiver, the non-coherent ultra-tight integration system can enhance continuous positioning when the GPS signal is severely attenuated. Second, outliers in one loop may severely corrupt the results of integration Kalman filter, which shows importance of quality control to the non-coherent ultra-tight GPS/INS integration system.**

Keywords-ultra-tight integration, GPS/INS, weak signal tracking, hardware-in-the-loop

I. INTRODUCTION

Ultra-tight GPS/INS integration combines GPS and INS on data processing level, which distinguishes itself from loosely- and tightly- coupled GPS/INS integration. The concept "ultra-tight integration" comes from vector tracking technique, which details can be found in [1]. Several ultra-tight integration architectures have been proposed over the past decade[2-8]. All these architectures can be categorised into two kinds - coherent and non-coherent [9]. However, both of them using navigation states estimator, instead of Phase Lock Loop (PLL) and Delay Lock Loop (DLL) in the individual channel, to generate the code and carrier NCOs (Numerically Controlled Oscillator) commands. For non- coherent integration, code and frequency discriminators are still used as the traditional scalar tracking. As the code discriminator is independent of the carrier phase, so it can be computed regardless of whether there is sufficient SNR to track carrier phase. This enables non-coherent integration to maintain tracking in weak SNR environments resulting from signal attenuation, jamming or interference [9].

This paper addresses on the performance of the non-coherent ultra-tight GPS/INS integration system. The system is introduced first, including the system architecture; the integration Kalman filter model; the code and frequency discriminators in use; and code and carrier NCO commands generating mechanism. Then experiments are set up to test the system under weak signal conditions. Outliers are further added to the measurements to test the stability of the system.

II. NON-COHERENT ULTRA-TIGHT INTEGRATION SYSTEM MODEL

A. System architecture

The system mainly divided into 3 parts, including integration Kalman filter, generation and conversion of the code and carrier frequency discriminators, and the calculation of corrected code and carrier NCOs. The code and carrier NCOs first generate the local replica signals, which are used to correlate with the coming satellite signals to form Is and Qs, which are sent to code and carrier discriminators to form measurements of the code and carrier frequency errors that further are converted into range residuals of the code phase and carrier frequency errors. These measurements are used by the integration Kalman filter to estimate the errors of INS. The estimated states, along with satellite ephemeris and clock corrections, to form the feedback of the NCOs, which means an integration Kalman filter is used instead of individual DLL and PLL in each channel to track all the satellite signals and the navigation solution.

B. Integration Kalman Filter Model

The following 17 states vector is estimated using the integration Kalman filter:

$$\begin{bmatrix}\delta R^e & \delta V^e & \delta\phi^e & \delta g^b & \delta a^b & \delta b & \delta d\end{bmatrix} \tag{1}$$

Where δR^e = position error vector; δV^e = velocity error vector; $\delta\phi^e$ = attitude error vector; δg^e = gyro bias error vector; δa^b = accelerometer bias error vector; δb = receiver clock bias; δd = receiver clock drift;

The navigation filter model in [8] is used as the integration Kalman filter model, and pseudorange and delta pseudorange residuals in each channel are chose as the measurements of the integration Kalman filter.

$$\begin{bmatrix} \delta \dot{R}^e \\ \delta \dot{V}^e \\ \delta \dot{\phi}^e \\ \delta \dot{g}^b \\ \delta \dot{a}^b \\ \delta \dot{b} \\ \delta \dot{d} \end{bmatrix} = \begin{bmatrix} 0 & I & 0 & 0 & 0 & 0 & 0 \\ G+\Delta G-\Omega^e\Omega^e & -2\Omega^e & a^e & 0 & C_b^e & 0 & 0 \\ 0 & 0 & -\Omega^e & -C_b^e & 0 & 0 & 0 \\ 0 & 0 & 0 & -\beta_g & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\beta_a & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\beta_d \end{bmatrix} \begin{bmatrix} \delta R^e \\ \delta V^e \\ \delta\phi^e \\ \delta g^b \\ \delta a^b \\ \delta b \\ \delta d \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} Z_1 \\ Z_2 \end{bmatrix} = \begin{bmatrix} -U & 0 & 0 & 0 & 0 & 1 & 0 \\ -\Delta U & -\Delta t U_f & 0.5\Delta t^2 U_f a^e & 0 & 0.5\Delta t^2 U_f C_b^e & 0 & \Delta t \end{bmatrix} \begin{bmatrix} \delta R^e \\ \delta V^e \\ \delta\phi^e \\ \delta g^b \\ \delta a^b \\ \delta b \\ \delta d \end{bmatrix} \quad (3)$$

Where: $G+\Delta G$ is gravity gradient matrices; Ω_e and a^e are skew symmetric matrix of the earth rate vector and specific force vector; C_b^e is the body-to-earth direction cosine matrix; Δt is the update interval of the filter; U and U_f are current and previous unit line of sight vectors from receiver to satellites. $\Delta U = U - U_f$.

β_g is gyro's time constant of first-order Gauss-Markov processes; β_a is accelerometer's time constant of first-order Gauss-Markov processes; β_d is receiver clock drift's time constant of first-order Gauss-Markov processes.

C. Code and carrier frequency discriminators

The measurements of pseudorange and delta pseudorange residuals in each channel are generated first by using the following code and carrier frequency discriminators [10]:

$$D_{code} = \frac{1}{2}\frac{\sqrt{I_E^2+Q_E^2}-\sqrt{I_L^2+Q_L^2}}{\sqrt{I_E^2+Q_E^2}+\sqrt{I_L^2+Q_L^2}} \quad (4)$$

$$D_{carrier} = \arctan\left(\frac{I_P(k-1)\cdot I_P(k)+Q_p(k-1)Q_p(k)}{I_P(k-1)\cdot Q_P(k)-I_p(k)Q_p(k-1)}\right) \quad (5)$$

Then turn the measurements of code and carrier frequency discriminators by multiplying a constant, shown in equation:

$$Z_1 = L_{code}\cdot D_{code} \quad (6)$$

$$Z_2 = \frac{\lambda}{2\pi}\cdot D_{carrier} \quad (7)$$

Where; $I_{E.P.Q}/Q_{E.P.Q}$ are early, prompt and late value of I & Q signals. L_{code} is code chip length(m), λ is GPS carrier wavelength(m).

III. Code and Carrier NCO Commands For Local Replica Signal Corrections

The code and carrier NCO commands mechanism is the key feature of the ultra-tight integration system. As the single tracking loop in each channel is emitted, the code and carrier NCO commands, which are used to control the receiver's replica signal, are generated using inertial navigation solution, updated by the integration Kalman filter. The code and carrier NCO value are updated every 20 ms:

$$f_{carr\ \ NCOi} = f_{IF} + f_{Di} + f_{\delta clk} \quad (8)$$

$$f_{code\ \ NCOi} = f_{code} + f_{\Delta code} + f_{Di/code} + f_{\delta clk/code} \quad (9)$$

Where, i is channel index ; Δt =20 ms ; $t_{\delta clk}$ is receiver clock drift (m/s)

f_{IF} is intermediate frequency of the receiver, which is 4.1304MHz in this paper.

f_{code} is code frequency, which is 1.023MHz for the GPS L1 signal. f_{Di} is Doppler shift on the carrier, $f_{Di/code}$ is code Doppler frequency

f_T is satellite's transmitted carrier frequency, for GPS L1 signal, which is 1575.42MHz.

$$f_{Di} = f_T\frac{(V_{user}-V_{sati})\cdot a}{c} \quad (10)$$

$$f_{Di/code} = f_{code}\frac{(V_{user}-V_{sati})\cdot a}{c} \quad (11)$$

V_{user} is vector of user's velocity; V_{sati} is vector of *i*th channel's satellite velocity; a is the direction cosines of the unit vector pointing from the approximate user's position to the *i*th satellite.

$f_{\delta clk}$ is the receiver clock error, $f_{\delta clk/code}$ is the code frequency error derived from receiver clock drift.

$$f_{\delta clk} = \frac{t_{\delta clk}}{\lambda} \quad (12)$$

$$f_{\delta clk/code} = \frac{t_{\delta clk}}{\lambda_{code}} \quad (13)$$

f_{code} is the code frequency correction value after the Kalman filter's update. $\rho^{-}_{i,k}$ is predicted pseudorange and $\rho^{+}_{i,k}$ is the estimated pseudorange after the Kalman filter's update at time k.

IV. EXPERIMENT SETUP

The capability of the ultra-tight integration system to track weak GPS signals has been demonstrated using data collected from hardware-in-the-loop simulation, in which a Spirent GPS signal simulator and Nordnav Rxx-2 receivers are used. The RF signals from the Spirent are down-converted, sampled by using Nordnav Rxx-2 receiver which can output the IF data at 4.1304 MHz. A 4-bit sample are used in the IF data collection and the sampling frequency is 16.3676MHz.

V. TEST RESULTS

The test has two steps, first, validation test of the ultra-tight integration system under weak signal conditions, then the stability test of the system when outliers are added in one of the channels. The receiver's initial position (latitude, longitude, and height) is (-33deg, 117deg, 500m).

A. Weak signal conditions

The simulated satellite signal has a slightly decrement by approximately -5dB-Hz per step with respect to 43 dB-Hz as shown in Table 1. There are 6 GPS satellites, which are SV4, SV20, SV13, SV7, SV23, SV8, in view at the time the data was recorded. All the satellites in the six channels are used in the ultra-tight integration system.

Table 1 Carrier to noise Ratio versus Time

Time(s)	**0**	**10**	**20**	**30**	**40**	**60**
Carrier to noise Ratio (dB-Hz)	**43**	**37.4**	**32.2**	**27.2**	**22.3**	**13.9**

Figure 1 and Figure 2 show both position and velocity errors, which are estimated by the integration Kalman filter.

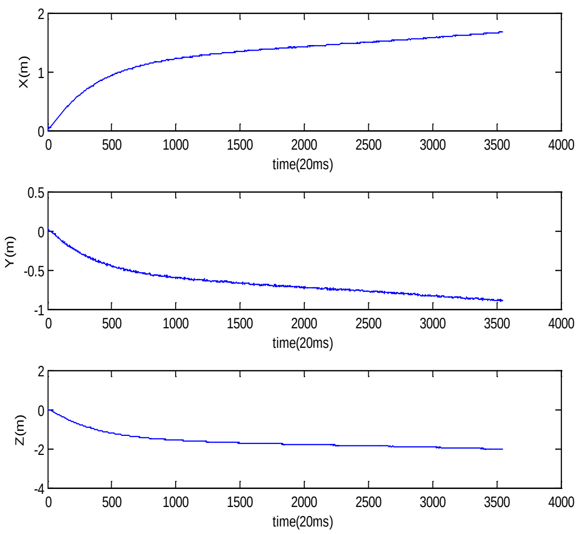

Figure 1 positions errors (X Y Z components in ECEF-frame)

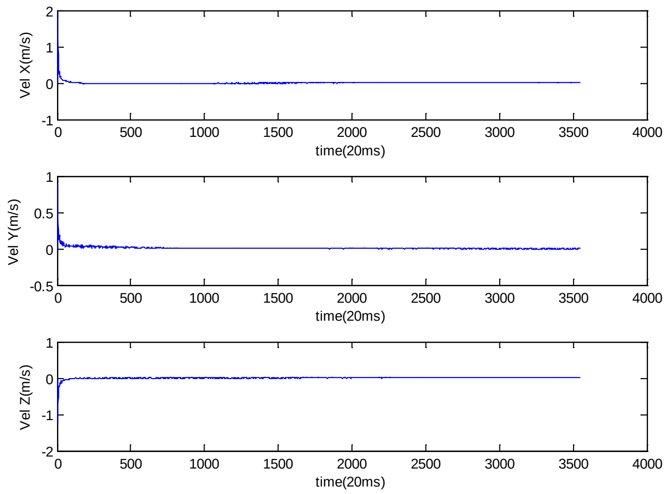

Figure 2 velocity errors (X Y Z components in ECEF-frame)

Receiver clock bias and drift are illustrated in Figure 3:

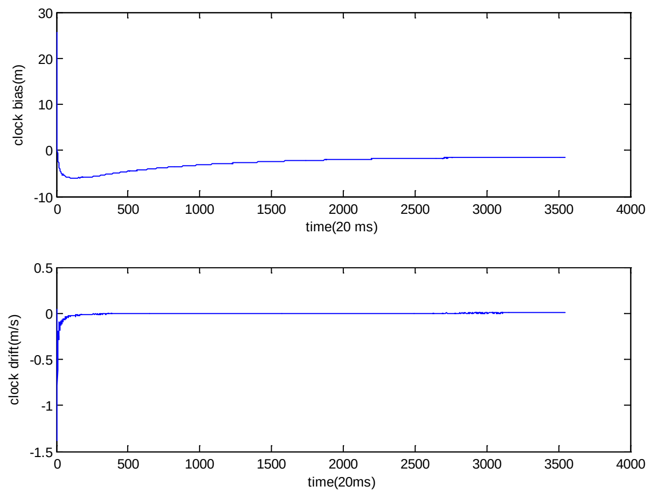

Figure 3 receiver clock bias and drift (m, m/s)

Figure 4 and Figure 5 show the calculation results of the procedure as described in Part III. This is the most important part because the calculated values are used to control NCOs to generate the replica signals. As can be seen from the figure 4 & 5, both the calculated code NCO and the carrier NCO value are stable due to the fact that the simulation data is static, hence vibration of Doppler shift is not observable.

During the test, the Nordnav Rxx-2 loss of lock at approximately 42s (2100 x 20 ms) since the data recording started. This is mainly because the carrier to noise ratio is insufficient for the normal tracking loops to track the GPS signal in the individual channel. However, as can be seen in the figures above, the ultra-tight integration system can track the signal continuously during the whole simulation period.

This is due to fact that the individual channels are eliminated; all the signals are tracked by the integration Kalman filter along with satellite ephemeris and clock corrections; The usage of INS to form the line of sight from satellites to user.

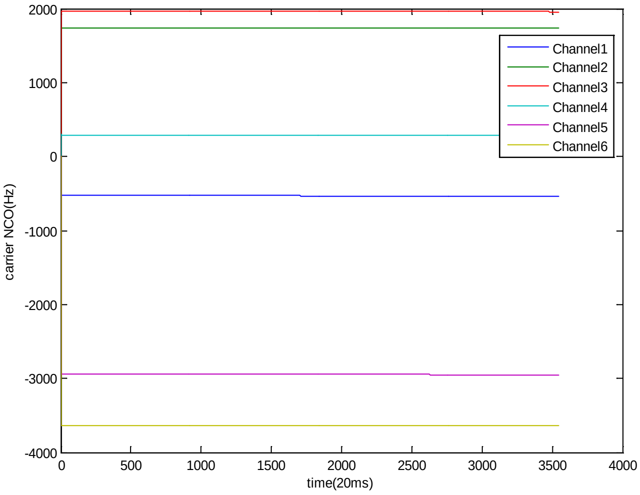

Figure 4 carrier frequency NCO commands (six channels)

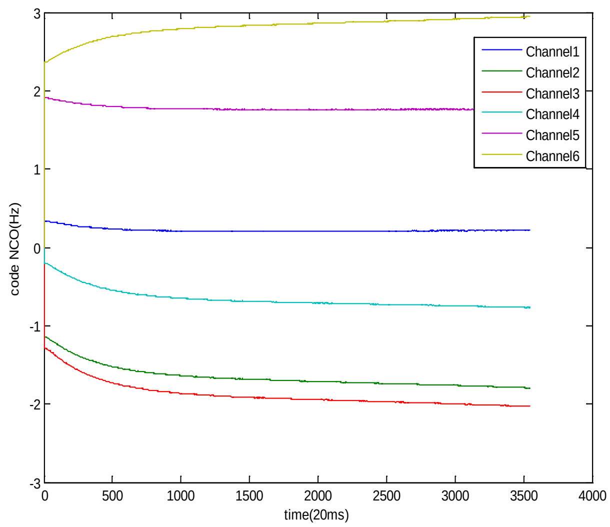

Figure 5 code frequency NCO commands (six channels)

B. Outliers in one of the tracking channels

Outliers (twenty times larger than the normal values) are added to the measurements of the code phase discriminator in channel 1 at epoch of 10s (500 x 20 ms) to demonstrate the propagation of errors from one of the channels to others.

Figure 6 shows the clock bias and drift. Figure 7 depicts code NCO results of the ultra-tight integration system suffering a 0.002s period of outliers.

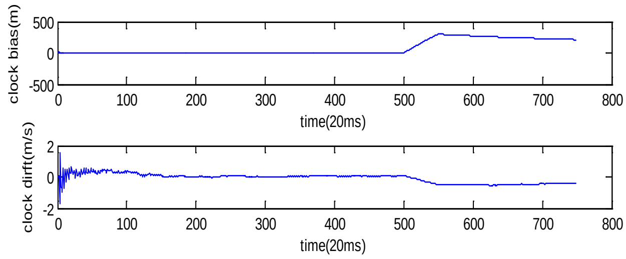

Figure 6 receiver clock bias and drift (m, m/s)

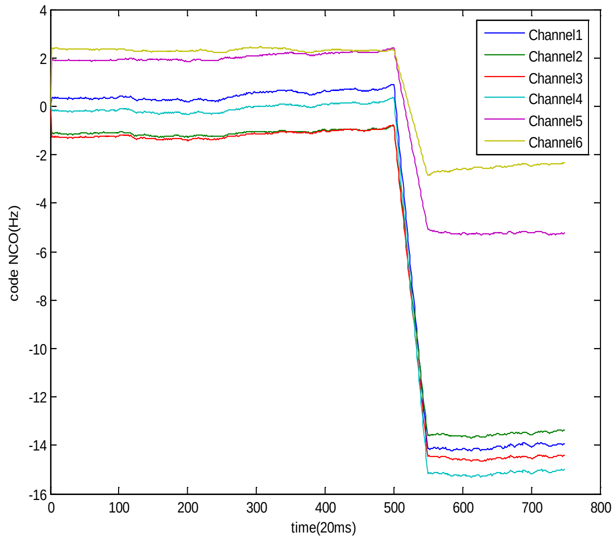

Figure 7 code frequency NCO commands (six channels)

As it can be seen from the figures above, the estimation of receiver's clock bias and drift, along with calculated code NCO values are relatively smooth and the system works well during the first 10 seconds, however, huge changes are occurred at epoch of 10s, when the outliers are added. The value of Code NCO in every channel has a dramatic change which leads to the loss of lock in the code tracking loop.

CONCLUSION

Due to the featured non-coherent ultra-tight integration structure, it can maintain tracking under weak SNR conditions, Hence, in comparison to the classical scalar tracking loops used in the traditional stand-alone receivers, the non-coherent ultra-tight integration system can enhance continuous positioning when the GPS signal is attenuated. Furthermore, outliers in one channel can propagate to others and severely corrupt the integration Kalman filter's results, which shows importance of quality control to the measurement data of the integration Kalman filter in the ultra-tight GPS/INS integration system.

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