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Analysis of the GNSS Code-Carrier Hardware Delay Difference in RTK Process: Effect, Measurement and Calibration

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ABSTRACT In satellite navigation receivers, the hardware delays of code and carrier are different because of their different tracking processes, which is called as the code-carrier hardware delay difference. This difference depends on the condition of receivers and varies from one to another. Therefore, in the carrier phase RTK (real-time kinematic) position process, the bias of code-carrier hardware delay difference between the base receiver and the moving receiver will cause the baseline resolution error. In this article, we analyze the code-carrier hardware delay difference, and the theoretical derivation shows that the baseline resolution error increases with the bias as well as the signal Doppler frequency. For a static RTK user on the ground, a microsecond level bias leads to a baseline resolution error in millimeter level, compared to a centimeter level error caused by the LEO satellite whose speed can reach several kilometers per second. In that case, the bias needs to be calibrated for those high precision RTK applications. However, there are few researches to calibrate the receiver carrier hardware delay because the carrier phase measurement integral ambiguity is difficult to be measured. In this article, we propose a method to measure and calibrate the bias of code-carrier hardware delay difference between different receivers. Real data test results show that the proposed method can effectively eliminate the RTK baseline resolution error caused by the bias of code-carrier hardware delay differences between the base receiver and the moving receiver.

INDEX TERMS Code tracking, carrier tracking, code hardware delay, carrier hardware delay, RTK, baseline resolution error, LEO satellite, hardware delay measurement and calibration.

I. INTRODUCTION

The performance of satellite navigation signal is highly sensitive to the time delay of its propagation process. However, several undesirable delays are introduced during the propagation, including the analog channel delays, the digital processing delays and the clock biases of both transmitting and receiving systems. These delays are known as the satellite and receiver hardware delays. As for the receiver hardware delay, the carrier hardware delay is different from that of code [1] because of their different tracking processes. The difference between the code hardware delay and the carrier hardware delay in the receiver can be called as the code-carrier hardware delay difference which also varies from one to another in different receivers.

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Unfortunately, the hardware delay in receivers will lead to a pseudo range and carrier phase measuring time bias, which causes pseudo-range and carrier phase measurement errors. If the carrier hardware delay is different from that of code, the pseudo-range measurement error caused by code hardware delay will be inconsistent with that caused by carrier hardware delay, which significantly influences those high precise applications simultaneously using the pseudo-range measurement and the carrier phase measurement, such as the conventional RTK process, the precise modeling of ionosphere, non-difference ambiguity fixing, time synchronization between satellite and ground stations, and so on. Specifically, the inter frequency bias of code hardware delay is the main error source of the precise modeling of ionosphere, which is called as DCB (differential code bias) [2]; in the PPP(precise point positioning) application which uses the non-difference observations, the carrier hardware delay is the main factor that influences the fixed of non-difference ambiguity, which is also known as the fractional cycle bais [3], [4]; in the time synchronization between satellite and ground station, the hardware delay directly influences the estimated satellite and receiver clock bias.

In this paper, we analyze the RTK baseline resolution error which is caused by the bias of code-carrier hardware delay differences between the base receiver and the moving receiver, and the theoretical deduction indicates that the baseline resolution error is related to the code-carrier hardware difference as well as the signal Doppler frequency. It can be proved that the baseline resolution error increases with the signal Doppler frequency, and for static RTK user on the ground, a microsecond level bias will lead to a millimeter level baseline resolution error, compared to a centimeter level error caused by the relative positioning of LEO satellite whose speed can reach several kilometers per second. Therefore, although the baseline resolution error caused by the code-carrier hardware difference is not significant for normal dynamic RTK users on the ground, a centimeter level error is non-negligible for the high precision application and needs to be calibrated for the high dynamic RTK user.

There are lots of researches about eliminating the receiver code hardware delay, for example, the zero pseudo-range method based on navigation signal generation is widely used [7], [8]. However, as the carrier phase measurement contains integral ambiguity, there are few researches to measure and calibrate the receiver carrier hardware delay.

In this paper, we propose a method to measure and calibrate the bias of code-carrier hardware delay differences between two receivers. The real data results show that this method can effectively eliminate the RTK baseline resolution error caused by the bias of code-carrier hardware delay differences between the base receiver and the moving receiver.

The rest of this article is organized as follows: In section II, the influences of the difference between code hardware delay and carrier hardware delay in RTK process are discussed. After that, in section III, measurement and calibration methods are proposed for the bias of code-carrier hardware delay differences between two receivers. Then in section IV, the real data tests are presented to show the effectiveness of the proposed method. Last, the conclusions are drawn in section V.

II. INFLUENCE OF THE CODE-CARRIER HARDWARE DELAY DIFFERENCE IN RTK PROCESS

A. THE PSEUDO-RANGE AND CARRIER PHASE MEASUREMENT MODEL

The basic observations of satellite navigation system is the measurement of pseudo-range and carrier phase, as both of them are used to calculate the distance between satellite and receiver based on the arrival time. Therefore, the distance between satellite and receiver can either be described by the phase of spread spectrum code or the phase of carrier. However, unlike the pseudo-range measured by code phase, the carrier phase measurement contains undetermined carrier integer cycle count, which makes it more difficult to determinate the distance by carrier phase.

The arrival time measurements of receiver, both of the pseudo-range and carrier phase measurements, contain many parts, including the real distance and a lot of errors, such as the ionosphere delay, the tropospheric delay, the clock bias, the hardware delay of satellite and receiver, the antenna phase center offset(PCO), the antenna center variation (PCV), the multipath error, and so on. The mathematic models of the pseudo-range measurement and the carrier phase measurement are given in follows.

We can take the note that the measuring time of receiver r is t_r, the propagation delay between satellite k and receiver r in frequency i is $\tau_{r,i}^{k}$, the code hardware delay of receiver r in frequency i is $d\tau_{\rho,i}^{k}$, the carrier hardware delay of receiver r in frequency i is $d\tau_{\varphi,i}^{r}$, the code hardware delay of satellite k in frequency i is $d\tau_{s\rho,i}^{k}$, and the carrier hardware delay of satellite k in frequency i is $d\tau_{s\varphi,i}^{k}$. For convenience, we suppose that the code and carrier hardware delays of satellite and receiver are constant in a short time. Therefore, we can obtain the transmission time of code signal and carrier signal as follows:

$$t_{\rho,i}^{k} = t_r - t_{r,i}^{k} - d\tau_{\rho,i}^{r} \tag{1}$$

$$t_{\varphi,i}^{k} = t_r - t_{r,i}^{k} - d\tau_{\varphi,i}^{r} \tag{2}$$

The corresponding pseudo-range measurement equation and carrier phase measurement equation are given as follows:

$$\begin{aligned} P_{r,i}^{k}(t_r) &= c\left(t_r - t_{\rho,i}^{k}\right) + cdt_r(t_r) \\ &\quad -c\left[dt_{s,k}(t_{\rho,i}^{k}) + d\tau_{s\rho,i}^{k}\right] + \varepsilon_p \\ &= \left\|X_{s,k}(t_{\rho,i}^{k}) - X_r\left(t_r\right)\right\| + I_{r,i}^{k} + T_r^{k} + cdt_r(t_r) \\ &\quad -c\left[dt_{s,k}(t_{\rho,i}^{k}) + d\tau_{s\rho,s}^{k}\right] + \varepsilon_p \\ &= R_{\rho,r,i}^{k}\left(t_r\right) + I_{r,i}^{k} + T_r^{k} + cdt_r(t_r) \\ &\quad -c\left[dt_{s,k}(t_{\rho,i}^{k}) + d\tau_{s\rho,s}^{k}\right] + \varepsilon_p \end{aligned} \tag{3}$$

$$\begin{aligned} L_{r,i}^{k}\left(t_r\right) &= c\left(t_r - t_{\phi,i}^{k}\right) - c\left[dt_{s,k}(t_{\phi,i}^{k}) + d\tau_{s\phi,i}^{k}\right] \\ &\quad +cdt_r(t_r) + \lambda_i^{k} N_{r,i}^{k} + d\varphi_{r,i}^{k} + \varepsilon_\phi \\ &= \left\|X_{s,k}(t_{\phi,i}^{k}) - X_r\left(t_r\right)\right\| - I_{r,i}^{k} + T_r^{k} \\ &\quad -c\left[dt_{s,k}(t_{\phi,s}^{k}) + d\tau_{s\phi,i}^{k}\right] + cdt_r(t_r) \\ &\quad +\lambda_i^{k} N_i^{k} + d\varphi_{r,i}^{k} + \varepsilon_\phi \\ &= R_{\phi,r,i}^{k} - I_{r,i}^{k} + T_r^{k} - c\left[dt_{s,k}(t_{\phi,s}^{k}) + d\tau_{s\phi,i}^{k}\right] \\ &\quad +cdt_r(t_r) + \lambda_i^{k} N_i^{k} + d\varphi_{r,i}^{k} + \varepsilon_\phi \end{aligned} \tag{4}$$

where $X_{s,k}$ is the three-dimensional coordinate of satellite k, X_r is the three-dimensional coordinate of receiver r, c is the speed of light, $dt_r(t)$ is the clock error of receiver r, $dt_{s,k}(t)$ is the clock error of satellite k, $I_{r,i}^{k}$ is the ionosphere delay, T_r^{k} is the tropospheric delay, λ_i^{k} is the carrier wavelength, and

N_i^k is the carrier integer ambiguity. Besides, ε_p contains the pseudo-rang multipath error and the pseudo-range measurement error, ε_ϕ contains the carrier multipath error and the carrier phase measurement error, and $d\varphi_{r,i}^k$ is the carrier phase correction terms which contains the initial carrier phase of satellite and receiver, and the PCO &PCV errors of antennas.

The distance between satellite k and receiver r that measured by pseudo-range is:

$$R_{\rho,i,r}^k\left(t_r\right) = \left\| X_{s,k}(t_{\rho,i}^k) - X_r\left(t_r\right) \right\| \tag{5}$$

The distance between satellite k and receiver r that measured by carrier phase is:

$$R_{\phi,i,r}^k\left(t_r\right) = \left\| X_{s,k}(t_{\phi,i}^k) - X_r\left(t_r\right) \right\| \tag{6}$$

Because of the code-carrier hardware delay difference, the transmission time of code signal $t_{\rho,i}^k$ is different from that of carrier signal $t_{\phi,i}^k$. Thus, the distance measured by pseudo-range $R_{\rho,i,r}^k\left(t_r\right)$ is different from $R_{\phi,i,r}^k\left(t_r\right)$ measured by carrier phase, as shown in FIGURE 1.

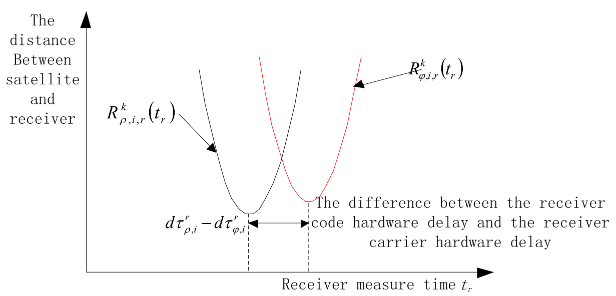

FIGURE 1. Satellite-receiver distances measured by pseudo-range and carrier phase.

If we note that the difference between the distance measured by pseudo-range and the distance measure by carrier phase is $dR_r^k(t_r)$, $dR_r^k(t_r)$ is related to the received signal Doppler frequency and the code-carrier hardware delay difference

$$d\tau_{\rho\phi,i}^r = d\tau_{\rho,i}^r - d\tau_{\phi,i}^r \tag{7}$$

as shown in the following equation.

$$dR_{r,i}^k(t_r) = R_{\phi,r,i}^k(t_r) - R_{\rho,r,i}^k(t_r) = \lambda_i^k f_{d,r,i}^k\left(t_r\right) d\tau_{\rho\phi,i}^r \tag{8}$$

where $f_{d,r,i}^k$ is the signal Doppler frequency between satellite k and receiver r in frequency i. Therefore, it can be noticed that $dR_{r,i}^k(t_r)$ is increased with $d\tau_{\rho\phi,i}^r$ and $f_{d,r,i}^k$. As the satellite speed is about 1000m/s, the receiver speed can be ignored for those are not in high dynamic, and a code-carrier hardware delay difference $d\tau_{\rho\phi,i}^r$ in microsecond level leads to a distance measure error $dR_{r,i}^k(t_r)$ in millimeter level.

B. THE MATHEMATIC MODEL OF RTK PROCESS

The RTK carrier phase differential position technology uses pseudo-range difference and carrier phase difference between two stations, namely, reference station and moving station, to eliminate lots of correction errors. The errors include ionosphere delay, tropospheric, clock error, orbit error, and so on. By using RTK technology, a high precise measurement of baseline can be realized between these two stations. The carrier phase RTK differential position technology usually adopts double differential observation model, as shown in FIGURE 2.

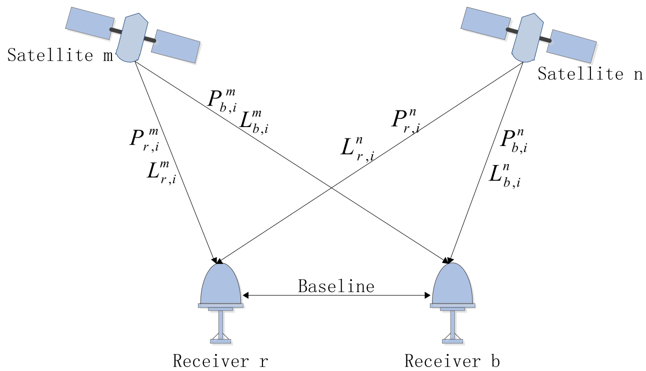

FIGURE 2. Sketching map of double differential observation model.

The equations of pseudo-range observation and carrier phase observation are:

$$\begin{aligned} P_{rb,i}^{mn} &= \left(P_{r,i}^m - P_{b,i}^m\right) - \left(P_{r,i}^n - P_{b,i}^n\right) \\ &= \left(R_{\rho,r,i}^m - R_{\rho,b,i}^m\right) - \left(R_{\rho,r,i}^n - R_{\rho,b,i}^n\right) + dP_{dd} + \varepsilon_p \\ &= R_{\rho,rb,i}^{mn} + dP_{dd} + \varepsilon_P \end{aligned} \tag{9}$$

$$\begin{aligned} L_{rb,i}^{mn} &= \left(L_{r,i}^m - L_{b,i}^m\right) - \left(L_{r,i}^n - L_{b,i}^n\right) \\ &= \left(R_{\phi,r,i}^m - R_{\phi,b,i}^m\right) - \left(R_{\phi,r,i}^n - R_{\phi,b,i}^n\right) + dP_{dd} + \varepsilon_\phi \\ &= R_{\phi,rb,i}^{mn} + \lambda_i^m N_{rb,i}^m - \lambda_i^n N_{rb,i}^n + dL_{dd} + \varepsilon_\phi \end{aligned} \tag{10}$$

where dP_{dd} and dL_{dd} are the pseudo-range and the carrier phase double differential residues apart from the real distance. When the baseline is short enough, for example less than 10 kilometers, the double differential operation will eliminate all kinds of correction errors, and $dP_{dd} \approx 0, dL_{dd} \approx 0$. Thus, in the short baseline, the double differential observation equations can be expressed as:

$$P_{rb,i}^{mn} = R_{\rho,rb,i}^{mn} + \varepsilon_P \tag{11}$$

$$L_{rb,i}^{mn} = R_{\phi,rb,i}^{mn} + \lambda_i^m N_{rb,i}^m - \lambda_i^n N_{rb,i}^n + \varepsilon_\phi \tag{12}$$

Supposing that:

$$R_{rb,i}^{mn} = R_{\rho,rb,i}^{mn} \tag{13}$$

$$dR_{rb,i}^{mn} = R_{\phi,rb,i}^{mn} - R_{\rho,rb,i}^{mn} \tag{14}$$

Then, the equations(11∼12) can be expressed asčž

$$P_{rb,i}^{mn} = R_{rb,i}^{mn} + \varepsilon_P \tag{15}$$

$$L_{rb,i}^{mn} = R_{rb,i}^{mn} + \lambda_i^m N_{rb,i}^m - \lambda_i^n N_{rb,i}^n + dR_{rb,i}^{mn} + \varepsilon_\phi \tag{16}$$

where $dR_{rb,i}^{mn}$ is the double differential error caused by the bias of code-carrier hardware delay differences between the reference receiver and the moving receiver, which can be regarded as a carrier phase double differential error that is similar to ε_ϕ. The effect of $dR^{mn}_{rb,i}$ in the RTK process will be discussed in next section.

In this paper, we will take the single frequency RTK process as an example to describe the mathematic model of RTK process briefly, and more details can be referenced to T. Takasu [9]. The single frequency observation equations are given as follow:

$$y = h(x) \tag{17}$$

where the observation vector is:

$$y = \left[L^{m1}_{rb,1}\ldots L^{mj(j\neq m)}_{rb,1}\ldots L^{mN}_{rb,1}, P^{m1}_{rb,1}\ldots P^{mj(j\neq m)}_{rb,1}\ldots P^{mN}_{rb,1}\right]^T_{2N-2} \tag{18}$$

where m is the reference satellite. N is the number of satellite and the estimation vector is:

$$x = \left[x_r, v_r, a_r, N^1_{rb,1}, N^2_{rb,1}, \ldots, N^N_{rb,1}\right]^T_{9+N} \tag{19}$$

where x_r,v_r,a_r are the coordinate, the speed and the accelerated speed of the moving station.

Therefore, the observation model is:

$$h(x) = \left[h_{\phi,1}(x), h_{\rho,1}(x)\right]^T \tag{20}$$

$$h_{\phi,1}(x) = \begin{bmatrix} R^{m1}_{rb,1} + \lambda^m_1 N^m_{rb,1} - \lambda^1_1 N^1_{rb,1} \\ R^{m2}_{rb,1} + \lambda^m_1 N^m_{rb,1} - \lambda^1_1 N^1_{rb,1} \\ \cdots \\ R^{mn}_{rb,1} + \lambda^m_1 N^m_{rb,1} - \lambda^n_1 N^n_{rb,1} \end{bmatrix}_{(N-1)} \tag{21}$$

$$h_{\rho,1}(x) = \begin{bmatrix} R^{m1}_{rb,1} \\ R^{m2}_{rb,1} \\ \cdots \\ R^{mn}_{rb,1} \end{bmatrix}_{(N-1)} \tag{22}$$

Then we can get the observation matrix as follows:

$$H(\hat{x}) = \left.\frac{\partial h(x)}{\partial x}\right|_{x=\hat{x}_0} \tag{23}$$

where $\hat{x}_0$ is the single point positioning estimation results of the estimation vector x.

The extended Kalman filter(EKF) [10] is used to estimate the estimation vector x. The estimation results $\hat{x}_k$ and the corresponding covariance matrix $\hat{P}_k$ usually adopt the float resolution, so $\hat{x}_k$ contains the float resolution of single differential integer ambiguities $\hat{N}_0$. Then, $\hat{N}_0$ are transformed to a double differential forms $\hat{N}$. The fixed resolution of carrier phase double differential integer ambiguities $\check{N}$ can be obtained by solving an ILS (integer least square) problem expressed as:

$$\check{N} = \arg\min_{N\in Z}\left[\left(N-\hat{N}\right)^T Q_N^{-1}\left(N-\hat{N}\right)\right] \tag{24}$$

And the lambda algorithm is adopted to solve the ILS problem [11], [12]. When the carrier phase double differential integer ambiguities are resolved, the fixed solution $\check{x}$ with higher accuracy than the float solution can be obtained.

C. EFFECT OF THE CODE-CARRIER HARDWARE DELAY DIFFERENCE IN THE RTK PROCESS

According to the mathematic model of RTK process in the above section, the code-carrier hardware delay difference brings in double differential error as

$$dR^{mn}_{rb,i} = R^{mn}_{\phi,rb,i} - R^{mn}_{\rho,rb,i} \tag{25}$$

with the equation (8), $dR^{mn}_{rb,i}$ can be expressed as:

$$\begin{aligned} dR^{mn}_{rb,i} &= R^{mn}_{\phi,rb,i} - R^{mn}_{\rho,rb,i} \\ &= \left[dR^m_{r,i}(t_r) - dR^n_{r,i}(t_r)\right] \\ &\quad - \left[dR^m_{b,i}(t_r) - dR^n_{b,i}(t_r)\right] \\ &= d\tau^r_{\rho\phi,i}\left[\lambda^m_i f^m_{d,r,i}(t_r) - \lambda^n_i f^n_{d,r,i}(t_r)\right] \\ &\quad - d\tau^b_{\rho\phi,i}\left[\lambda^m_i f^m_{d,b,i}(t_r) - \lambda^n_i f^n_{d,b,i}(t_r)\right] \end{aligned} \tag{26}$$

when the receiver r and the receiver b are the same type, which means $d\tau^r_{\rho\phi,i} = d\tau^b_{\rho\phi,i}$, the double differential of Doppler frequency is close to 0 and $dR^{mn}_{rb,i} = 0$, under the short baseline assumption,.

When $d\tau^r_{\rho\phi,i} \neq d\tau^b_{\rho\phi,i}$ and $dR^{mn}_{rb,i} \neq 0$, $dR^{mn}_{rb,i}$ will cause a baseline resolution error directly, which is related to the received signal Doppler frequency of the reference receiver and the moving receiver, and the baseline resolution error is increased with the Doppler frequency. Although it is difficult to get a specific equation which can directly describe the relationship between the baseline error and the different code-carrier hardware differences $d\tau^r_{\rho\phi,i}$,$d\tau^b_{\rho\phi,i}$, section IV presents a real data test result to show the effect of code-carrier hardware delay on the RTK baseline resolution.

III. MEASUREMENT AND CALIBRATION FOR THE DIFFERENT CODE-CARRIER HARDWARE DELAY DIFFERENCES BETWEEN RECEIVERS

In recent researches, the zero pseudo-range method based on navigation signal simulator is widely used to calibrate the receiver code hardware delay, which can be described as follows:

1) A navigation signal simulator and a receiver compose a homologous signal receiving testing scene;

2) The navigation signal simulator transmits signal with zero pseudo-range: a high speed oscilloscope is adopt to monitor the reversal point of signal and the 1pps output of simulator, and then the upper computer software for simulator adapts the signal delay to ensure the reversal point of signal align with the 1pps output of simulator;

3) The receiver measures the pseudo-range of received signal, and a time difference measuring equipment is used to measure the clock error between the 1pps output of receiver and the 1pps output of simulator;

4) The pseudo-range that measured by receiver subtracts the clock error that measured by time difference measuring equipment, getting the code hardware delay of receiver.

The method above is an effective way to measure the code hardware delay. However, for the carrier hardware delay, as the carrier phase measurement contains integral ambiguity, there is no such an effective way to measure it currently.

According to the analysis in section II, the code-carrier hardware delay difference brings in inconsistency between the measurements of them, which increases with the signal Doppler frequency, as shown in (8). Therefore, we can use a signal with constant acceleration that generated by the navigation signal simulator to measure the code-carrier hardware delay difference, and the measuring theory is given as follows.

The navigation signal simulator transmits a signal of one satellite with a constant acceleration speed a, and the initial Doppler frequency is 0Hz. Supposing the code-carrier hardware delay difference of simulator is:

$$d\tau_0 = d\tau_{\rho,0} - d\tau_{\phi,0} \tag{27}$$

the code-carrier hardware delay differences of two receivers (receiver a and receiver b) are:

$$d\tau_a = d\tau_{\rho,a} - d\tau_{\phi,a} \tag{28}$$
$$d\tau_b = d\tau_{\rho,b} - d\tau_{\phi,b} \tag{29}$$

and the clock errors between the receivers and the simulator are dt_a and dt_b respectively.

The pseudo-range and the carrier phase measured by two receivers can be expressed as follows:

$$\rho_a(t) = 0.5a\left(t - dt_a - d_{\rho,0} - d_{\rho,a}\right)^2 + \varepsilon_{a\rho} \tag{30}$$
$$\varphi_a(t) = 0.5a\left(t - dt_a - d_{\phi,0} - d_{\phi,a}\right)^2 + cN_a/f_l + \varepsilon_{a\varphi} \tag{31}$$
$$\rho_b(t) = 0.5a\left(t - dt_b - d_{\rho,0} - d_{\rho,b}\right)^2 + \varepsilon_{b\rho} \tag{32}$$
$$\varphi_a(t) = 0.5a\left(t - dt_b - d_{\phi,0} - d_{\phi,b}\right)^2 + cN_b/f_l + \varepsilon_{b\varphi} \tag{33}$$

where c is the speed of light, f_l is the carrier frequency, $\varepsilon_{a\rho}$ is the pseudo-range measuring noise of receiver a, $\varepsilon_{a\varphi}$ is the carrier phase measuring noise of receiver a, $\varepsilon_{b\rho}$ is the pseudo-range measuring noise of receiver b, $\varepsilon_{b\varphi}$ is the carrier phase measuring noise of receiver b.

Subtracting the pseudo-range measurements with the carrier phase measurements of two receivers, we get:

$$d_a(t) = \rho_a(t) - \phi_a(t) = -a\left(d\tau_0 + d\tau_a\right)t + \varepsilon_a \tag{34}$$
$$d_b(t) = \rho_b(t) - \phi_b(t) = -a\left(d\tau_0 + d\tau_b\right)t + \varepsilon_b \tag{35}$$

where ε_a and ε_b contain the measuring noise and constant residues.

Doing linear fitting for $d_a(t)$ and $d_b(t)$, we get:

$$d_a(t)' = l_a t \tag{36}$$
$$d_b(t)' = l_b t \tag{37}$$

Then the bias of code-carrier hardware delay difference of two receivers can be expressed as:

$$d\tau_{ab} = \left(d\tau_a + d\tau_0\right) - \left(d\tau_b + d\tau_0\right) = \left(l_a - l_b\right)/a \tag{38}$$

(30) ~ (38) is the measuring principle, and a computing example is given below in detail.

Supposing the frequency of measurement for two receivers is 1Hz, the pseudo-range and the carrier phase measured by the two receivers are $\rho_a(k)$, $\phi_a(k)$, $\rho_b(k)$, $\phi_b(k)$, $(1 \le k < N)$, and the values that the pseudo-range measurement subtracts the carrier phase measurement of two receivers are:

$$d_a(k) = \left[\rho_a(k) - \phi_a(k)\right], \quad 1 \le k < N \tag{39}$$
$$d_b(k) = \left[\rho_b(k) - \phi_b(k)\right], \quad 1 \le k < N \tag{40}$$

Doing linear fitting for the two equations above:

$$d_a(k)' = l_a k \tag{41}$$
$$d_b(k)' = l_b k \tag{42}$$

Then the bias of code-carrier hardware delay difference of two receivers can be expressed as:

$$d\tau_{ab} = \left(l_a - l_b\right)/a \tag{43}$$

Real data test of this method will be presented in section IV.

IV. REAL DATA ANALYSIS

To show the effect of code-carrier hardware delay on the RTK baseline resolution, two experiments are fulfilled.

Experiment 1: a self-developed GNSS receiver and a Trimble NetR9 GNSS receiver are used to compose a zero baseline test scene, as shown in FIGURE 3, and the baseline resolution accuracy of the G1 signal of GLONASS system is analyzed.

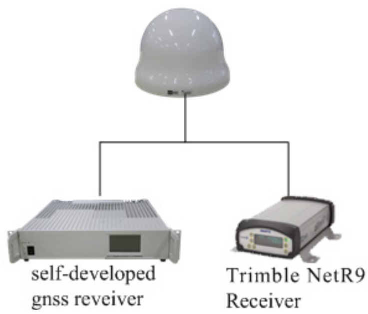

FIGURE 3. Zero baseline test scene with a self-developed GNSS reveiver and a Trimber NetR9 GNSS reveiver.

Experiment 2: two self-developed GNSS receiver are used to compose a zero baseline test scene, as shown in FIGURE 4. The observation of receiver 1 is added correction value according to the equation below, which is equal to add an extra code-carrier hardware delay difference to the receiver,

$$\hat{L}_{r,i}^{k}(t_r) = L_{r,i}^{k}(t_r) + \lambda_i^k f_{d,r,i}^k(t_r)d\tau_{\rho\phi} \tag{44}$$

where $d\tau_{\rho\phi}$ is the extra code-carrier hardware delay difference that added to receiver 1, and $\hat{L}_{r,i}^{k}(t_r)$ is the carrier phase observation modified. And then the baseline resolution accuracy of G1 signal is analyzed.

The baseline resolution of experiment 1 is shown in FIGURE 5. It can be noticed that there is a considerable error margin up to 20 mm existing in the baseline resolution. Analysis in section II indicates that the error is caused by the bias between the two receivers' code-carrier hardware delay differences.

The baseline resolution of experiment 2 is shown in FIGURE 6. It can be known from the figure that the bias of

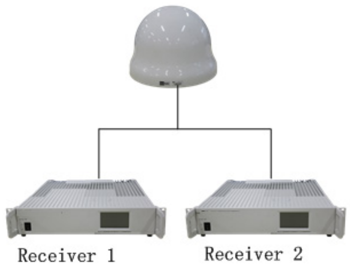

FIGURE 4. Zero baseline test scene with two self-developed GNSS reveiver.

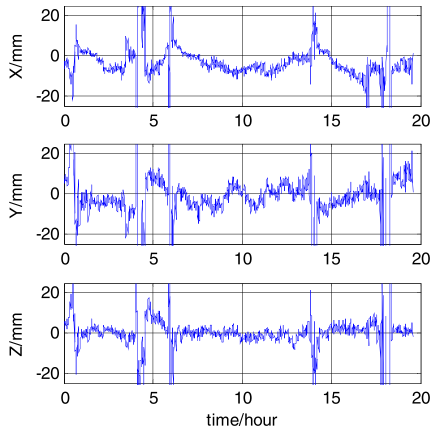

FIGURE 5. Baseline resolution of experiment 1.

the two receivers' code-carrier hardware delay differences causes a baseline resolution error, and the baseline resolution error increases with the bias. When the bias is 6us, the amplitude of error is up to 10mm.

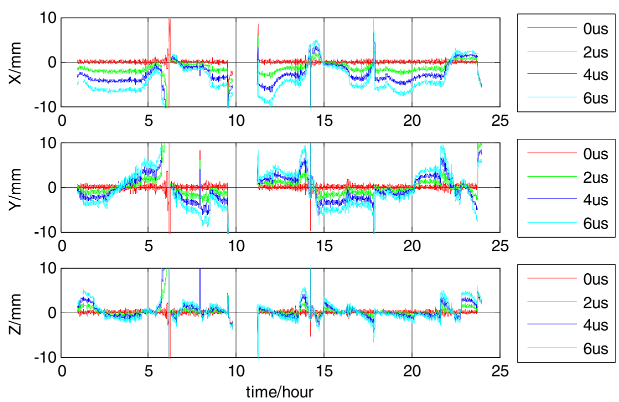

FIGURE 6. Baseline resolution of experiment 2.

In the above experiments, the receiver is static, and the signal Doppler frequency is mainly caused by the movement of satellite, which is at a speed of 1000m/s or so. In the navigation application using LEO satellite, the orbit height is lower than the GNSS MEO satellite, which means a much higher speed. Therefore, a more significant baseline error will be introduced because of the bias of code-carrier delay differences of two receivers. Supposing the LEO satellite moves at a speed of 5000m/s, a 1us bias can bring in a baseline resolution error up to 10 mm.

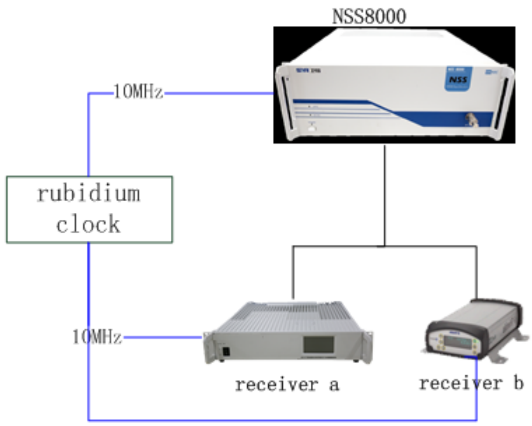

FIGURE 7. Test scene for the bias of code-carrier hardware delay difference between the two receivers.

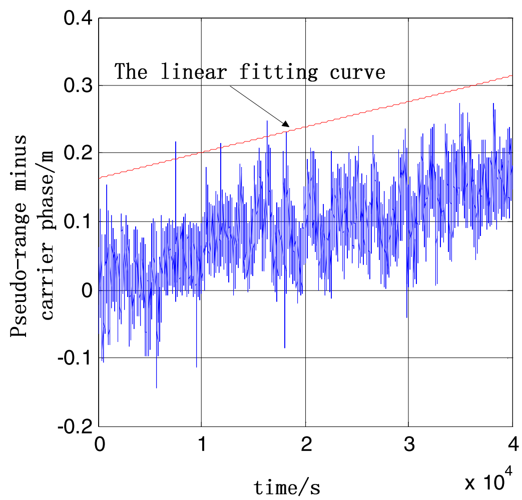

FIGURE 8. pseudo-range measurement subtracting carrier phase measurement of self-developed GNSS receiver.

In section III, we propose a method to measure and calibrate the bias of code-carrier hardware delay differences between two receivers, and a real data test is analyzed to prove the effectiveness of this method.

Firstly, we use NSS8000 navigation signal simulator produced by Hunan Weidao Information Technology Corporation to measure the bias of code-carrier hardware delay difference between two receivers. Then, we choose a self-developed receiver as receiver *a*, and a Trimble NetR9 GNSS receiver as receiver *b*. The test scene is shown in FIGURE 7. In the test, the NSS8000 transmits the signal of one satellite (GLONASS system, satellite 3, G1 signal) with a constant acceleration speed, whose initial Doppler frequency is 0Hz, and acceleration is $0.5m/s^2$.

FIGURE 8 and FIGURE 9 are the outcomes of pseudo-range measurement subtracting the carrier phase measurement of two receivers, and the red lines are their linear

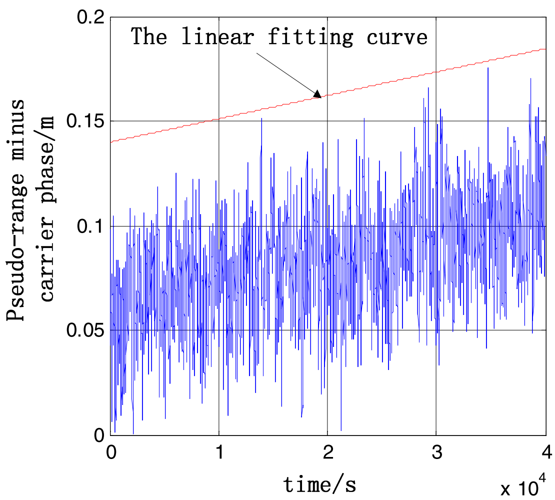

FIGURE 9. pseudo-range measurement subtracting carrier phase measurement of Trimble netR9 GNSS receiver.

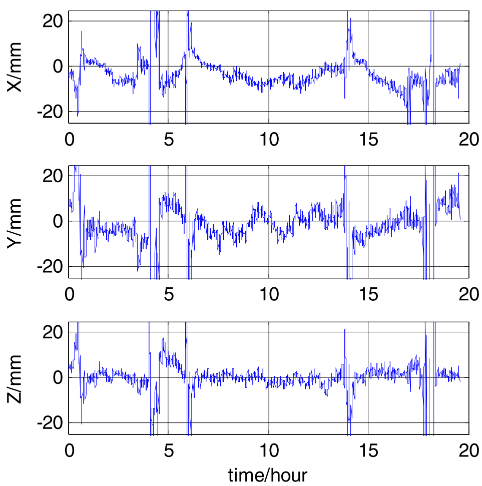

FIGURE 10. Baseline resolution of set2.

fitting curves. The slops of the two linear fitting curves are $3.75e^{-6}$m/s and $1.12e^{-6}$ m/s respectively, then the bias of code-carrier hardware delay between the two receivers is ($3.75e^{-6}$m/s- $1.12e^{-6}$ m/s)/ (0.5m/s^2) = 5.26 us.

Next, we take the self-developed GNSS receiver and the Trimber NetR9 GNSS receiver to set up a zero baseline test scene, as shown in FIGURE 3. We record 20-hours data, and then do two sets of RTK resolution using the same data as follows (G1 signal of GLONASS system):

Set1: modifying the carrier phase of self-developed GNSS receiver according to the equation below:

$$\hat{L}_a^k(t_a) = L_a^k(t_a) - \lambda^k f_{d,a}^k(t_a) d\tau_{ab} \tag{45}$$

where $d\tau_{ab} = 5.26$ us is the bias of code-carrier hardware delay between the self-developed GNSS receiver and the Trimble NetR9 GNSS receiver, $\hat{L}_a^k(t_a)$ is the modified carrier phase measurement, $f_{d,a}^k(t_a)$ is the signal Doppler frequency measurement of self-developed receiver, and λ^k is the carrier wavelength.

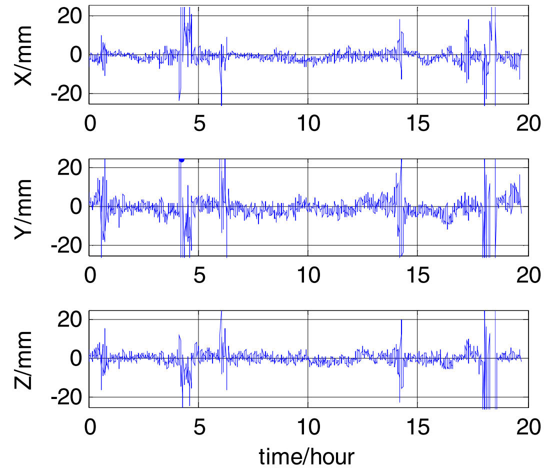

FIGURE 11. Baseline resolution of set1.

Set2: without modification.

FIGURE 10 and FIGURE 11 are results of the two sets of RTK resolution. It can be known from the figures that there is a considerable error up to 20 mm in the baseline resolution without modification. On the other hand, after modifying the influence of bias of code-carrier hardware delay differences between two receivers, the baseline resolution error is significantly eliminated, and the accuracy of baseline resolution is greatly improved. Therefore, it can be proved that the proposed method can be used effectively to measure and calibrate the bias of code-carrier hardware delay differences between different receivers.

V. CONCLUSION

In satellite navigation receivers, the carrier hardware delay is different from the code hardware delay because of their different tracking processes. In this paper, we analyses the influence of code-carrier hardware delay difference in RTK process by theoretical derivation and real data test. It can be known from the derivation that if the bias of code-carrier hardware delay differences of two receivers is not zero, there will be an error in the baseline resolution, and the error increases with the bias as well as the signal Doppler frequency. The real data test results confirm the derivation, and indicate that for the low dynamic RTK user on the ground, the bias in microsecond level leads to a baseline resolution error in millimeter level, while for the positioning applications using high speed LEO satellite, the baseline resolution error will rise to centimeter level.

Aiming at this baseline error problem, we also propose a method to measure and calibrate the bias of code-carrier hardware delay differences between two receivers. By using a simulator generated signal with constant acceleration speed, the bias can be measured and finally eliminated. Real data test has been carried out and the result proves the effectiveness of the proposed method.

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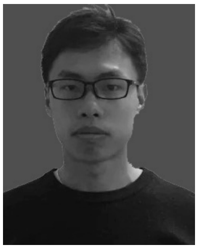

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