A DBZP Acquisition Method for High-Dynamic and Weak GPS Signal Aided by SINS

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Abstract. In order to enhance the acquisition performance in high-dynamic and weak GPS signal conditions, a Double Block Zero Padding (DBZP) acquisition method based on SINS is presented. In the method, the GPS doppler frequency estimated by SINS decreases the range of frequency uncertainty; the doppler rate and code doppler aided from SINS overcomes the energy diffusion caused by the receiver's dynamic, and the energy based navigation data bits estimation method expands coherent integration time. All of them make the acquisition faster and higher sensitivity in high-dynamic and weak conditions. At last, the re-acquisition experiments of weak signal in high-dynamic environment are conducted, and the simulation results show that the proposed method can acquire high-dynamic and weak signal effectively.

Keywords: High-dynamic and weak signal · SINS · Signal acquisition · DBZP · Navigation bits estimation

1 Introduction

With the development of satellite navigation techniques, Global Positioning System (GPS) has been widely applied in civil and military fields. Therefore, it is very important to research the GPS receiver for high-dynamic and weak signal applications such as high earth orbit satellite, ballistic missile and cruise missile, etc. [1, 2]. In these applications, the acquisition performance is limited by many factors, such as serious signal energy attenuation, large Doppler search range, frequent signal blockage caused by Line-Of-Sight (LOS) obstructions, and so on.

Acquisition of weak GPS signals requires long coherent integration time to boost the post signal-to-noise ratio (SNR). As the increase of coherent integration time, the complexity of dealing with data bits and the computational cost of signal acquisition grow rapidly [3, 4]. Double block zero padding (DBZP) is an effective acquisition approach to process long data coherently with fewer operations [5]. At present, as an advanced weak signal acquisition algorithm, the DBZP algorithm has been used to enhance the receiver acquisition performance for weak signals by many researchers [6, 7]. But the studies of its application in high-dynamic and weak signal conditions are relatively few.

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When acquiring weak signals in high-dynamic conditions, the coherent integration time need to be short so as to reduce the attenuation of coherently integrated energy; however, the time should be long to acquire weak signal reliably [7]. Obviously, the requirements of acquisition weak signals and high-dynamic signals are contradictory, and it's difficult to balance them when the stand-alone DBZP method is applied [8, 9]. In addition, once the coherent integration time of DBZP method beyond one data bit period, the effect of unknown navigation date bit transition should be taken into account.

Many researches have indicated that the information from other navigation systems [10–12] such as SINS can improve the performance of signal acquisition at the same time overcoming dynamics and noise/interference. With SINS aiding, the dynamic effect on GPS signal acquisition could be mitigated effectively. Then, the acquisition algorithm only needs to deal with the issues from weak signals.

Thereby, a DBZP acquisition method for high-dynamic and weak signal aided by SINS is proposed. This method can not only make full use of the DBZP advantages in acquiring weak signals but also improve the receiver acquisition speed and capability in high-dynamic environments.

2 Performance Analysis of DBZP Algorithm in High-Dynamic Environments

The principles of DBZP acquisition algorithm have been introduced by many researchers in detail. It can be seen from the DBZP algorithm, the coherent integration is calculated at all the Doppler bins and all the code delays in the same processing step. Thus, DBZP requires less process compared to long data circular correlation. And it has advantages in dealing with long coherent integration, which is suitable to acquisition for weak signals. However, its acquisition performance will be greatly influenced by Doppler effect and Doppler rate when applied to acquiring high-dynamic and weak signals. Furthermore, when the DBZP algorithm is applied to acquisition of weak signal, the bit transition will seriously affect the coherent integration result once the coherent integration beyond the 20 ms date bit period. So the data wipe off technique must be considered to extend coherent integration time.

Assuming there is no navigation bit sign changes during integration time, the n-th coherent integration result [5] is

$$Y_n = 0.54 A_{sat} N_c R_c(\tau - \tau_u) \mathrm{sinc}(\pi \delta f_d T) \exp\left[j \cdot (\pi \delta f_d T + \theta)\right] + n \tag{2.1}$$

where: T is the coherent integration time. $N_c = T \cdot f_s$ is the number of sampled points in coherent integration time. $R_c(\tau - \tau_u)$ is C/A code autocorrelation function and τ_u is the code delay of the local signal. θ is the carrier phase error. $\delta f_d = f_{d.0} + \alpha\left(n + 1/2\right)$ denotes the Doppler frequency difference.

For the sake of analyzing how the Doppler rate affects coherent integration, code phase, Doppler error and noise are ignored. Then, the n-th coherent integration result can be simplified as

$$Y_n = 0.5 A_{sat} N_c \mathrm{sinc}\left\{\pi\left[f_{d,0} + \alpha\left(n + 1/2\right)T\right]\right\} \exp\left\{j \cdot \pi\left[f_{d,0} + \alpha\left(n + 1/2\right)T\right]\right\} \tag{2.2}$$

The above coherent integration results are accumulated during the whole integration time, and then FFT is performed on the accumulation. Figure 1 shows the effects on the integration results with different Doppler rates, where the coherent integration time is 80 ms and the number of incoherent accumulations is 10.

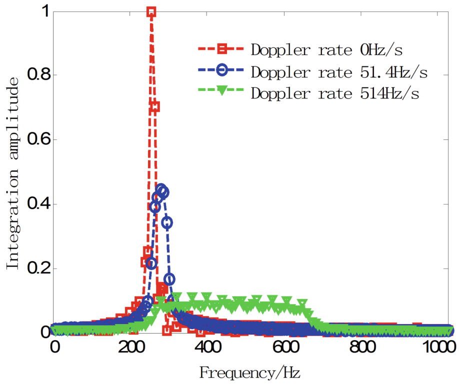


Fig. 1. The effects on the integration results with different Doppler rates

It can be seen in this figure, when the Doppler rate is 0 Hz/s, a peak value appears at the frequency bin which corresponds to the true Doppler shift. However, when there is a nonzero Doppler rate, the accumulated peak energy will diffuse to adjacent frequency bins. As the Doppler rate increases, the diffusion range becomes larger and the peak value weaker. And longer the coherent integration time is more serious the effect, which will have a bad impact on the valid SNR gain. As mentioned before, it is crucial to increase the coherent time for weak signal acquisition, so it will be very difficult to acquire high-dynamic and weak signals by DBZP without external aiding.

Moreover, the acquisition time is an important variable to evaluate the receiver performance. The mean acquisition time [11] is given by,

$$\overline{T}_{acq} = \left(\frac{2 - P_d}{2P_d}\right)\left(\frac{t_v}{T}P_{fa} + 1\right)LTN_s \tag{2.3}$$

$$N_s = \frac{f_{\text{cov}} \times L_c \times f_s}{f_{res}} \tag{2.4}$$

where: P_d is the probability of detection. P_{fa} is the probability of false alarm. t_v is the false alarm search time. L is the incoherent integration time. N_s is the total search cell number. f_{cov} is the Doppler shift search range. L_c is the length of C/A code chip.

As can be inferred from Eq. (2.3), in high-dynamic environments the Doppler search range for stand-alone DBZP acquisition grows severely, which will greatly increase acquisition time.

3 A DBZP Acquisition Method for High-Dynamic and Weak GPS Signal Aided by SINS Information

To overcome the problem that the performance of DBZP acquisition method is vulnerable to the vehicle dynamics and data bit transitions, a DBZP acquisition scheme for high-dynamic and weak signal aided by SINS is designed. And its structure is presented in Fig. 2.

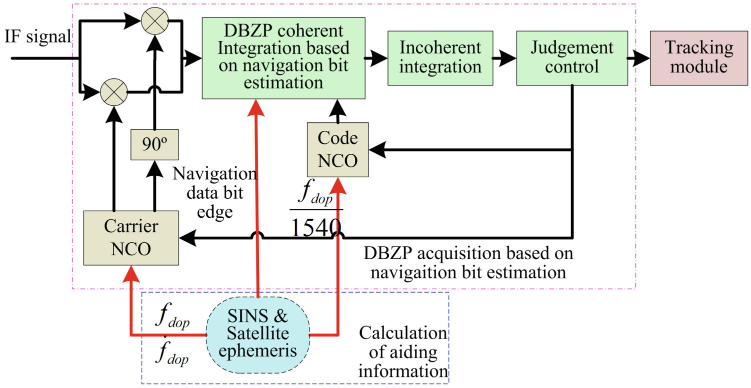


Fig. 2. The structure of the DBZP acquisition scheme for high-dynamic and weak signal aided by SINS

In this scheme, the local Doppler frequency aided by the LOS velocity and acceleration derived from SINS and satellite ephemeris mitigate the dynamic of received signals and reduce the search frequency range, which will improve the acquisition sensitivity and speed. With the data bit edge aided by SINS, an energy-based method is utilized to estimate the unknown data bits during the DBZP coherent integration time, which will enhance the acquisition reliability for weak signals.

3.1 Calculation of Aiding Information

(1) Estimation of Doppler Shift and Doppler Rate

Based on the velocity and position from SINS and satellite ephemeris, the estimated Doppler shift $\hat{f}_{aid}$, which is caused by the relative movement between satellite and receiver, can be calculated as,

$$\hat{f}_{aid} = \frac{1}{\lambda_{L1}}\left(\hat{\boldsymbol{V}}_r - \hat{\boldsymbol{V}}_s\right)\boldsymbol{e}_j \tag{3.1}$$

where: λ_{L1} is the wavelength of L1 carrier. $\hat{\boldsymbol{V}}_r$ is the SINS aiding velocity. $\hat{\boldsymbol{V}}_s$ is the satellite velocity provided by satellite ephemeris. $\boldsymbol{e}_i$ denotes the LOS unit vector from the satellite to receiver.

Similarly, the Doppler rate aided by SINS and satellite ephemeris can be given as,

$$f_{dop} = \frac{1}{\lambda_{L1}}(\hat{\boldsymbol{a}}_r - \hat{\boldsymbol{a}}_s)\boldsymbol{e}_j \tag{3.2}$$

where $\hat{\mathbf{a}}_r$ and $\hat{\mathbf{a}}_s$ are the acceleration measurement of receiver and the satellite, respectively.

The search range of Doppler shift mainly depends on the velocity error of SINS information, and the influence of the satellite ephemeris error can be ignored. As the frequency aiding error reduces, the search range will be smaller and the acquisition speed faster. The estimation error variance of Doppler shift can be expressed as,

$$\sigma_{dop}^2 = \frac{1}{\lambda_{L1}^2}\boldsymbol{e}_j^T \delta \boldsymbol{V}_r^T \delta \boldsymbol{V}_r \boldsymbol{e}_j \tag{3.3}$$

where $\delta \mathbf{V}_r$ can be expressed as,

$$\delta \boldsymbol{V}_r = \delta \boldsymbol{V}_{r0} + \int_T \delta \boldsymbol{a} dt \tag{3.4}$$

where: $\delta \mathbf{V}_{r0}$ is the initial velocity error. $\delta \mathbf{a}$ represents the acceleration error of the SINS with respect to the earth-centered earth-fixed (ECEF) frame. $\delta \mathbf{a}$ can be described as [12],

$$\delta a = \boldsymbol{R}_b^e \cdot \left[diag\left(k_{ax}, k_{ay}, k_{az}\right) \cdot \boldsymbol{f}_b + \boldsymbol{\Delta}_b\right] - \boldsymbol{a}^e \cdot \int_T \boldsymbol{R}_b^e \cdot \left(diag\left(k_{wx}, k_{wy}, k_{wz}\right) \cdot \omega_b + \varepsilon_b\right) dt \tag{3.5}$$

where: $\boldsymbol{R}_b^e$ is the transformation matrix from the body frame to the ECEF frame. $\boldsymbol{f}_b$ is the specific force measured by the accelerometer. k_{ax}, k_{ay}, k_{az} are the accelerometer scale factors errors. $\boldsymbol{a}^e$ denotes the acceleration vector with respect to the ECEF frame. k_{wx}, k_{wy}, k_{wz} are gyro's scale factor errors. $\boldsymbol{\omega}_b$ is the angular rate measured by gyro. $\boldsymbol{\varepsilon}_b$ is the gyro's bias. Substituting Eq. (3.4) to Eq. (3.3), the expression of velocity error can be got.

Theoretically, the velocity error $\delta \boldsymbol{V}_r$ can be forecasted by error state equations of SINS. But in practical use, when the vehicle is under high-dynamic scenarios, it is difficult to accurately model the error function of SINS. Moreover, as the signal blockage time longer, the forecasting precision of $\delta \boldsymbol{V}_r$ will be worse. Hence, the search range of Doppler shift is set as the maximum of Doppler error estimated by SINS, and enough margin is provided to ensure the reliability of acquisition.

The Doppler shift search comparison of No aiding and SINS aiding acquisition is presented in Table 1. The vehicle LOS acceleration with respect to the satellite is 7g, and the reacquisition is performed after 150 s signal blockage. Without external aiding, the total Doppler search range is set to be ±8 KHz in high-dynamic environments. While using the aiding from SINS and satellite ephemeris, the Doppler search range is sharply reduced. This range is relative to the signal blockage time and the performance of SINS inertial components. Deduced from the compared results in the table, the Doppler shift search range is greatly reduced owing to the SINS aiding. Hence the acquisition speed after signal blockage is obviously improved, that is to say, the re-acquisition capability are enhanced.

Table 1. The search comparison between no aiding and SINS aiding acquisition.

Aiding condition	Search range	Search number	Search time
Non	±8 kHz	1280	1000 ms
SINS aiding (ε = 50°/h)	±1 kHz	160	12.5 ms

(2) Determining Data Bit Edge

When ignoring the relative drift among satellites clocks, the GPS signals are transmitted simultaneously. Therefore, according to GPS signal transmitted time, the data bit edge can be calculated as,

$$D = 1 + \mathrm{mod}(t_s, 0.02) \tag{3.8}$$

where t_s is the transmitted time of GPS signal. It can be calculated with the GPS time t_r when the signal is received, the delay of signal transmitting from the satellite to the receiver t_D and the satellite clock correction T_{corr} as,

$$t_s = t_r = t_D + T_{corr} \tag{3.9}$$

where

$$T_{corr} = a_1 + a_2 \times (t_r - t_{oc}) + a_3 \times (t_r - t_{oc})^2$$

$$t_D = |\boldsymbol{P}_r - \boldsymbol{P}_s| \big/ c$$

a_1, a_2 and a_3 are the zeroth through second-order satellite clock correction terms from navigation data message subframe 1. t_{oc} is the reference GPS time for the satellite clock correction terms. c is the velocity of light. $\boldsymbol{P}_r$ and $\boldsymbol{P}_s$ represent the receiver's position aided by SINS and the satellite's position aided by satellite ephemeris respectively.

3.2 A DBZP Acquisition Method Based on Navigation Bit Estimation

A longer coherent integration time is essential to increase accumulated SNR for the weak signal acquisition. But when the coherent integration time beyond one data bit period, bit transitions must be considered. To solve this problem, with the SINS aided data bit edge, an energy-based estimation method is taken to wipe off data bits during the DBZP coherent integration time. Its specific implementation steps are given as follows:

(1) DBZP Coherent Integration Based on Navigation Bit Estimation

Align the start position of DBZP acquisition with the navigation data bit edge aided by SINS. Before performing column-wise FFT on the DBZP matrix $\boldsymbol{M}_c$, $2^{N_{db-1}}$ navigation bit combinations need to be taken into account. Thus, we will obtain coherent integration matrixes $\boldsymbol{M}_{cc}$ for a DBZP coherent integration.

The number of rows in $\boldsymbol{M}_c$ is $20N_{db}N_{step}$. According to the principle of DBZP acquisition, $\boldsymbol{M}_c$ can be written into N_{db} sub-matrixes as,

$$\boldsymbol{M}_c = \left[\boldsymbol{M}_c^1 \ \ldots \ \boldsymbol{M}_c^i \ \ldots \ \boldsymbol{M}_c^{Ndb}\right]^T \tag{3.10}$$

where $\boldsymbol{M}_c^i$ is a matrix of size $20N_{step} \times \left(S_{block} \times N_{step}\right)$, $i = 1, 2, \ldots,\ N_{db}$. Each $\boldsymbol{M}_c^i$ is produced by coherent integration operation with one navigation data bit. In this paper, the coherent integration time is set to 80 ms (i.e. N_{db} equals to 4).

When N_{db} equals to 4, the total number of navigation bit combinations are $2^{N_{db-1}} = 8$. And all these combinations can be written into a matrix $\boldsymbol{H}$ as,

$$\boldsymbol{H} = [\boldsymbol{H}_1 \quad \boldsymbol{H}_2 \quad \boldsymbol{H}_3 \quad \ldots \quad \boldsymbol{H}_8]\begin{bmatrix} \boldsymbol{I}\,\boldsymbol{I} & \boldsymbol{I} & \ldots \boldsymbol{I} \\ \boldsymbol{I} - \boldsymbol{I} & -\boldsymbol{I} & \ldots -\boldsymbol{I} \\ \boldsymbol{I}\,\boldsymbol{I} & -\boldsymbol{I} & \ldots -\boldsymbol{I} \\ \boldsymbol{I}\,\boldsymbol{I} & \boldsymbol{I} & \ldots -\boldsymbol{I} \end{bmatrix}_{20N_{step} \times (S_{block} \times N_{step} \times 8)} \tag{3.11}$$

where: $\boldsymbol{I}$ is a matrix of size $20N_{step} \times \left(S_{block} \times N_{step}\right)$ whose elements are 1, $\boldsymbol{H}_i$ corresponds to one navigation bit combination. Then eight coherent integration matrixes $\boldsymbol{M}_{c,i}$, $i = 1, 2, \ldots, 2^{N_{db}-1}$ can be obtained as,

$$\boldsymbol{M}_{c,i} = \text{columnwise} \ \ \text{FFT}(\boldsymbol{H}_i \cdot \boldsymbol{M}_c), i = 1, 2, \ldots, 8 \tag{3.12}$$

where "·" denotes dot-multiply operation.

(2) Incoherently Integrating the Resulting Coherent Integration

It is hardly possible to determine the reliable navigation bit combination through only one coherent integration matrix for acquisition in high-dynamic and weak signal conditions. Thus, some coherent integration matrixes must be integrated incoherently. In the following method, the incoherent integration matrix can be got meanwhile the most reliable navigation bit combination determined.

Assuming $\boldsymbol{I}_{c,i}$ and $Q_{c,i}$ are real part and image part of $\boldsymbol{M}_c^i$, and the incoherent integration matrix of the former $c-1$ coherent integration matrixes is $\boldsymbol{P}_{\text{nc,c}-1}$, the $2^{N_{db-1}}$ incoherent integration matrixes $\mathbf{P}_{nc,i}$, $i = 1, 2, \ldots, 2^{N_{db}-1}$ of the c-th coherent integration will be got by the following equation,

$$\boldsymbol{P}_{nc,i}(\tau_u,f_d) = \boldsymbol{P}_{nc,c-1}(\tau_u,f_d) + [\boldsymbol{I}_{c,i}(\tau_u,f_d)^2 + \boldsymbol{Q}_{c,i}(\tau_u,f_d)^2], \quad i = 1, 2, \ldots, 2^{N_{db}-1} \tag{3.13}$$

Then $\boldsymbol{P}_{nc,i}$, $i = 1, 2, \ldots\ \ , 2^{N^{db}-1}$ are compared cell wise. The maximum from each index forms the new incoherent integration $\boldsymbol{M}_{\text{nc,c}}$ at that index. Thus $\boldsymbol{M}_{\text{nc,c}}$ is the c-th incoherent integration matrix.

$$\boldsymbol{M}_{\text{nc,c}}(\tau_u,f_d) = \max\left\{\boldsymbol{P}_{nc,1}(\tau_u,f_d), \boldsymbol{P}_{nc,2}(\tau_u,f_d), \ldots, \boldsymbol{P}_{nc,2^{N_{db}-1}}(\tau_u,f_d)\right\} \tag{3.14}$$

where m, n are index of each matrix.

(3) Making judgment control according to acquisition threshold

In the module of judgment control, judge whether the maximum power of $\boldsymbol{M}_{\mathrm{nc,c}}$ exceeds the acquisition threshold or not. If exceed, the acquisition is success, and the Doppler shift f_{dop} and code phase $\hat{\tau}_u$ can be got from the following equation,

$$\left(\hat{\tau}_u, \hat{f}_{dop}\right) = \arg \max_{(\tau_u, f_d)} M_{nc,c}(\tau_u, f_d) \tag{3.15}$$

The final estimation of Doppler shift is

$$\bar{\hat{f}}_{dop} = \hat{f}_{aid} + \hat{f}_{dop} \tag{3.16}$$

where: f_{aid} is the Doppler shift aided by SINS. f_{dop} is the residual Doppler shift estimated by acquisition method. Then the acquisition results are delivered to tracking module.

4 Simulation Verification

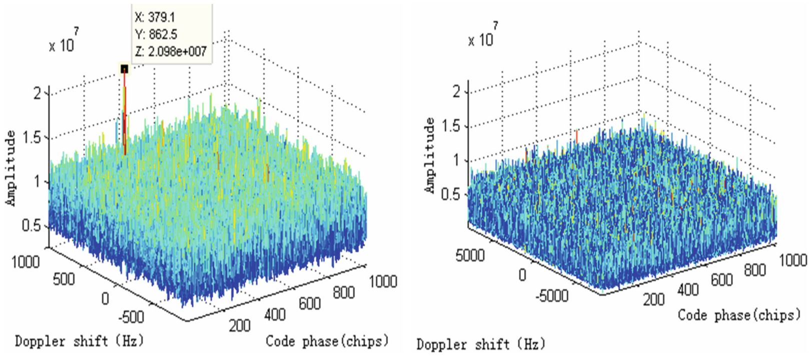
4.1 Simulation Conditions

The GPS IF signals in the simulation are generated by GPS signal simulator. Their parameters are set as follows. The sampling rate is 4.096 MHz. IF frequency is 1.25 MHz. The carrier to noise ratio is from 15 to 44 dB-Hz and 100 Monte Carlo simulations are performed for each C/N0. For DBZP acquisition, the coherent integration time is set to be 80 ms, and the number of incoherent integration times is 10.

A low-grade IMU is adopted. The gyro bias is $50^\circ/\mathrm{h}$ and its scale factor is 1000 ppm. The accelerometer bias is 1mg and its scale factor is 1000 ppm. The white noise standard variations of gyros and accelerations are $1^\circ/\sqrt{\mathrm{h}}$ and $0.1\ \mathrm{mg}/\sqrt{\mathrm{Hz}}$ respectively. Simulate a reacquisition scenario after GPS signal blockage in high-dynamic and weak signal conditions. In that scenario, the receiver LOS acceleration with respect to the satellite is 7g and the signal blockage time is 150 s. When the GPS signal is recovered, the initial Doppler shift is set to be 7365 Hz and the code phase is 379.1 chips. The Doppler shift error aided by SINS is 960 Hz, which is derived from Eq. (3.3). So the Doppler shift search range of SINS aiding DBZP acquisition algorithm is set ±1 KHz, i.e. $N_{step} = 2$. For the no aiding DBZP, the search rang is ±8 KHz ($N_{step} = 16$).

4.2 Simulation Results and Analysis

It can be seen from Fig. 3(a) that the final acquired code phase is 379.1 chips which is in accordance with the preinstalled code phase, the residual Doppler shift acquired by SINS aiding DBZP acquisition algorithm is 862.5 Hz. the Doppler shift aided by SINS $\hat{f}_{aid}$ is 6.5 kHz. So the total Doppler shift is 7362.5 Hz and the Doppler shift error estimated by the new algorithm is 2.5 Hz. Figure 3 shows that proposed SINS aiding DBZP algorithm gives the correct result and the no aiding DBZP algorithm can not acquire the signal.



(a) **(b)**

Fig. 3. (a) the final incoherent integration result using SINS aiding algorithm (b) the final incoherent integration result using no aiding algorithm

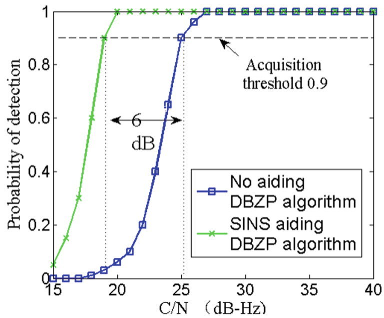


Fig. 4. The probability of detection of different acquisition algorithms.

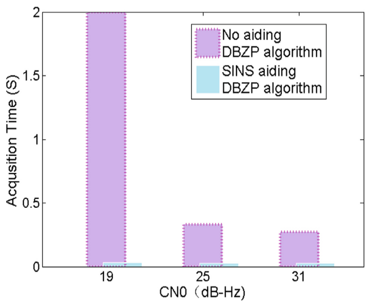


Fig. 5. The reacquisition speed of different acquisition algorithms

Figure 4 presents a comparison of the detection probability between different acquisition algorithms under high-dynamic environments. The algorithms are SINS aiding DBZP algorithm and no aiding DBZP algorithm. And the total integration time for all the two acquisition algorithm is 800 ms. It can be seen in this figure that the acquisition capability of SINS aiding DBZP algorithm is higher than the no aiding DBZP algorithm by 6 dB. The main reason is that the Doppler rate aided by SINS restrains the attenuation of integrated energy due to high-dynamic condition.

Figure 5 shows the normalized reacquisition time comparison of the above two acquisition algorithms. These acquisition times are calculated according to Eq. (2.3). The acquisition time which is infinite denotes the algorithm cannot acquire signals in the C/N0. It can be seen from this figure that the acquisition speed of SINS aiding DBZP algorithm is faster 9 times than no aiding DBZP algorithm due to the Doppler shift aided by SINS.

5 Conclusions

In order to improve the acquisition sensitivity and speed of GPS receiver in high-dynamic and weak signal conditions, a SINS aided DBZP acquisition method is proposed. The following conclusions are drawn by theoretical analysis and simulation verification.

(1) Under high-dynamic and weak signal environments, for traditional DBZP acquisition method, the integration gain will be seriously attenuated due to the effect of Doppler rate and the acquisition speed is largely limited due to seriously increased Doppler shift search range.
(2) Utilizing navigation data bit edge aided by SINS, the energy-based DBZP navigation bit estimation method extends coherent integration time, which enhances and capability for high-dynamic and weak signals.
(3) Using the information (such as positions, velocities, accelerations, etc.) aided by SINS and satellite ephemeris, Doppler rate and Doppler can be given to aid the acquisition in high-dynamic and weak signal conditions. The aiding Doppler rate effectively reduces the gain attenuation caused by vehicle dynamics and improves acquisition sensitivity. And the aiding Doppler not only improves acquisition speed through greatly reducing the Doppler shift search range, but also enhances acquisition sensitivity by transformed to code Doppler and compensating to code Doppler effect.

The acquisition method proposed in this paper can effectively improve the acquisition performance in high dynamic and weak signal environments such as ballistic missile, hypersonic cruise missile and high earth orbit satellite. This method has a wide application foreground.

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