A scheme for weak GPS signal acquisition aided by SINS information

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Abstract In order to enhance the acquisition performance of global positioning system (GPS) receivers in weak signal conditions, a high-sensitivity acquisition scheme aided by strapdown inertial navigation system (SINS) information is proposed. The carrier Doppler shift and Doppler rate are pre-estimated with SINS aiding and GPS ephemeris, so that the frequency search space is reduced, and the dynamic effect on the acquisition sensitivity is mitigated effectively. Meanwhile, to eliminate the signal-to-noise ratio gain attenuation caused by data bit transitions, an optimal estimation of the unknown data bits is implemented with the Viterbi algorithm. A differential correction method is then utilized to improve the acquisition accuracy of Doppler shift and therefore to meet the requirement of carrier-tracking loop initialization. Finally, the reacquisition experiments of weak GPS signals are implemented in short signal blockage situations. The simulation results show that the proposed scheme can significantly improve the acquisition accuracy and sensitivity and shorten the reacquisition time.

Introduction

The design of high-sensitivity receivers in harsh environment such as urban canyon, dense foliage canopies, and tunnels has become an important issue in current research (Ziedan 2006; O'Drisoll 2007; Jin 2012). The sensitivity of global positioning system (GPS) receiver mainly depends on the performance of the front-end and the acquisition scheme. In general, the extension of coherent integration time is a typical strategy for improving the acquisition sensitivity. Such extension, however, is limited by several factors including data bit transitions, increased power loss due to frequency errors (O'Drisoll 2007; Jin 2012), and a sharp increase in signal acquisition time.

In order to eliminate the negative effect of data bit transitions, the noncoherent combination (NC) method and the differential combination (DC) method are introduced to the acquisition of weak GPS signals (Zarrabizadeh and Sousa 1997; Choi et al. 2002). New algorithms, such as half-bit alternation and block addition can be treated as variations of the NC or DC methods (Tsui 2004; Ma et al. 2009; Chuang and Feng 2006). In noncoherent processing, the bit transitions are eliminated through the squaring operation. However, the noise is also squared and averaged toward a nonzero value. This value is referred as the squaring loss which attenuates the signal-to-noise ratio (SNR) processing gain of NC method significantly (Strässle 2007). Unlike NC method, the DC method, in which the present coherent integration result multiplies with the delay conjugate of the last result, can utilize the noise independence property at different sampling times to eliminate squaring loss. The differential approach in DC method can also lessen the bit transition effect and provide an overall sensitivity improvement with respect to that of the NC method (Borio et al. 2009; Yu et al. 2007). However, without external aiding, the DC method is still unable to eliminate the power loss due to frequency errors. Especially in the presence of Doppler variation, this power loss increases rapidly with the extension of integration time.

Ultra-tight GPS/SINS integration has been proven to be a feasible way to improve the performance of GPS receivers in high dynamic and/or weak signal conditions (Yang 2008; Yu et al. 2010; Wang and Li 2012). Utilizing SINS-aiding information, GPS tracking loops can extend the dynamic tracking range and narrow the tracking bandwidth. Subsequently, the noise-resistance capability is also enhanced. However, in many environmental situations, the line-of-sight (LOS) obstruction is inevitable. This leads an excessive attenuation or even blockage of GPS signals resulting in the loss-of-lock in tracking loops. It is crucial to recover the signal tracking as soon as possible after signal blockages. Therefore, a fast reacquisition capability of a GPS receiver is necessary to enhance the availability of positioning.

We propose a new SINS-aided acquisition scheme in weak signal conditions. Based on the SINS aiding, an optimal estimation of unknown data bits and a differential correction method are utilized to perform a fast, high sensitive and precise acquisition for weak GPS signals. Section "Problem description" describes the GPS received signal model and the problems in weak signal acquisition. Section "A signal acquisition scheme based on SINS aiding" gives detailed descriptions of the proposed acquisition scheme. Section "Simulation test" presents the simulation results followed by "Conclusions".

Problem description

In order to derive positioning and timing solutions, a conventional GPS receiver must have two fundamental functions: signal demodulation and parameter extraction. The initial acquisition and subsequent tracking ensures a continuous demodulation to allow the parameter extraction. Because of limited prior information, the acquisition is one of the most challenging processes in receiver design. Its performance is highly correlated with the strength and dynamic characteristics of the received GPS signals.

Received signal representation

The signal at the input of a receiver acquisition module is generally an intermediate frequency (IF) signal, obtained by down converting the received radio-frequency signal. For the purposes of the scheme proposed, the IF signal can be written as (Zhuang and Tranquilla 1989):

$$r_{\mathrm{IF}}(t_{\mathrm{n}}) = AD(t_{\mathrm{n}})c[(1+\eta)t_{\mathrm{n}} - \tau]\cos\left[2\pi\left(f_{\mathrm{IF}} + f_{\mathrm{d,0}} + \dot{f}_{\mathrm{d}} \cdot \mathrm{t_n}/2\right) t_{\mathrm{n}} + \phi_0\right] \tag{1}$$

where A is the carrier amplitude, D is the navigation data modulation, $c[\cdot]$ is the C/A code sequence, τ is code propagation delay, and f_{IF} is the carrier IF. The Doppler shift caused by the LOS motion between the receiver platform and satellite consists of two components: the initial Doppler shift $f_{\mathrm{d,0}}$ and the Doppler rate $\dot{f}_{\mathrm{d}}$. The symbol ϕ_0 denotes the initial carrier phase, $\eta = f_{\mathrm{d}}/f_{\mathrm{L1}}$ denotes the code rate shift due to Doppler effect, and f_{L1} is the carrier transmission frequency of L1.

In a digital receiver, the IF signal is sampled to generate a sequence of samples $r_{\mathrm{IF}}(nT_{\mathrm{s}})$, obtained by sampling $r_{\mathrm{IF}}(t_{\mathrm{n}})$ at the sampling frequency $f_{\mathrm{s}} = 1/T_{\mathrm{s}}$. The notation $r_{\mathrm{IF}}(n)$ is adopted here to indicate a generic sequence $r_{\mathrm{IF}}(nT_{\mathrm{s}})$. A realistic model of the signal $s_{\mathrm{IF}}(n)$ at the acquisition input is:

$$s_{\mathrm{IF}}(n) = r_{\mathrm{IF}}(n) + n_{\mathrm{w}}(n) \tag{2}$$

where $n_{\mathrm{w}}(n)$ is a Gaussian noise with flat power spectral density $N_0/2$ over the front-end band B_{r} and with the power $\sigma_{\mathrm{n}}^2 = N_0 B_{\mathrm{r}}$.

Analysis of weak signal acquisition

The purpose of acquisition is to determine the visible satellites and coarse values of carrier frequency and code phase of the satellite signals. The basic acquisition is a correlation operation between the locally generated signals and the input signals. For one visible satellite, the local signal sequence is:

$$s_{\mathrm{L}}(n) = c[(1+\hat{\eta}_{\mathrm{L}})nT_{\mathrm{s}} - \hat{\tau}_{\mathrm{L}}]\exp\left[-j \cdot 2\pi\left(f_{\mathrm{IF}} + \hat{f}_{\mathrm{d,L}}\right)nT_{\mathrm{s}}\right] \tag{3}$$

where $\hat{\tau}_{\mathrm{L}}$ and $\hat{f}_{\mathrm{d,L}}$ are the local code phase and Doppler shift estimations, respectively, and $\hat{\eta}_{\mathrm{L}} = \hat{f}_{\mathrm{d,L}}/f_{\mathrm{L1}}$ is the local code rate shift estimation.

Assuming the coherent integration time is T_{c}, the output of the kth coherent integration is (Jin 2012):

$$\begin{aligned} Y_{\mathrm{k}} &= \sum_{n=kN_{\mathrm{c}}}^{(k+1)N_{\mathrm{c}}-1} s_{\mathrm{IF}}(n) \cdot s_{\mathrm{L}}(n) \\ &= 0.5AN_{\mathrm{c}}D_{\mathrm{k}}R(\delta\tau_{\mathrm{L}})\sin c[\pi\delta f_{\mathrm{d}}(k)T_{\mathrm{c}}]\exp[j \cdot \phi_{\mathrm{k}} \\ &\quad + j \cdot \pi\delta f_{\mathrm{d}}(k)T_{\mathrm{c}}] + n_{\mathrm{k}} \end{aligned} \tag{4}$$

where, k denotes the index of the coherent integration interval, $N_{\mathrm{c}} = T_{\mathrm{c}}/T_{\mathrm{s}}$ is the number of samples in the coherent integration time T_{c}. $D_{\mathrm{k}} = \pm 1$ is navigation data, $\delta\tau_{\mathrm{L}}$ is the error of code delay estimation, and $R(\cdot)$ is the autocorrelation function of the C/A code. The Doppler shift error $\delta f_{\mathrm{d}}(k) = \delta f_{\mathrm{d,L}} + (k+1/2)\dot{f}_{\mathrm{d}}T_{\mathrm{c}}$ and $\delta f_{\mathrm{d,L}}$ is the initial

Doppler shift error. Furthermore, ϕ_k is the initial carrier phase error in the kth coherent integration interval, and n_k is the noise term.

In a typical urban environment, the power of received GPS signals is generally lower than that in normal conditions by 20–33 dB (Shanmugam et al. 2007; Ma et al. 2009). Thus, in order to reach the necessary SNR level for weak signal detection, a further combination needs to be implemented on the coherent integration output Y_k. There are two typical post-correlation methods, namely NC and DC methods. Compared with NC method, the DC method can suppress squaring loss and obtain a superior SNR gain (Yu et al. 2007; Borio et al. 2009). The mathematical representation of the conventional DC method is:

$$z_K = \sum_{k=1}^{K} Y_k \cdot Y_{k-1}^{*} = [0.5AN_cR(\delta\tau_L)]^2 \exp\left(j \cdot 2\pi\delta f_{d,L}T_c\right) \times \sum_{k=1}^{K} D_k D_{k-1} \sin c[\pi\delta f_d(k)T_c] \sin c[\pi\delta f_d(k-1)T_c] \exp\left(j \cdot 2\pi\dot{f}_d k T_c^2\right) + n_z \tag{5}$$

where n_z is the accumulated noise term, K is the accumulation time, and $(\cdot)^*$ denotes the conjugate operation. In the equation of differential accumulation result z_K, the factors related with the accumulation time K include Doppler rate $\dot{f}_d$ and navigation data D_k. As a result, the DC method might suffer from the accumulation gain loss due to $\dot{f}_d$ and the unknown D_k transitions.

Figure 1 shows the magnitude attenuation of z_K in relation to the accumulation time T_I ($T_I = KT_c$). Doppler rate $\dot{f}_d$ is the only consideration. The LOS accelerations are assumed to 1, 2, and 10 g, respectively. As shown in this figure, with the increase in the accumulation time T_I, a sharp attenuation occurs in the magnitude of z_K. Meanwhile, the larger the LOS acceleration, the more rapid the magnitude attenuation.

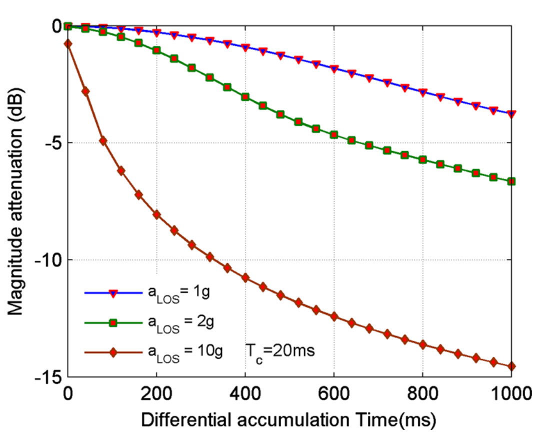

Fig. 1 The attenuation curves of differential accumulation result

For the effect of navigation data D_k, assuming that the number of bit boundaries within the accumulation time T_I is B in total, and ignoring Doppler rate $\dot{f}_d$, then the attenuation of z_K magnitude due to bit transitions can be expressed as:

$$\alpha_D = \frac{1}{K}\sum_{k=1}^{K} D_k D_{k-1} = \frac{1}{K} \cdot (K - 2\eta B)|_{\eta=\frac{1}{2}} = 1 - T_c/T_D \tag{6}$$

where, $T_D = 20$ ms is the data bit period and $\eta = 1/2$ is the probability of a transition occurring at each bit boundary.

As presented in (6), the attenuation factor α_D only depends on the coherent integration time T_c. With a short T_c, the DC method can suppress the attenuation due to unknown bit transitions. However, if T_c is long (compared with T_D), the attenuation will increase rapidly. The extreme case is $T_c = 20$ ms, and the z_K magnitude is attenuated to zero in the statistical sense.

From the above analysis, it follows that the DC method applies only to the static and low dynamic acquisition applications and requires the coherent integration time not be too long. These facts limit the sensitivity, reliability, and application field of the DC-based acquisition.

A signal acquisition scheme based on SINS aiding

In order to resolve the issue that the DC performance is vulnerable to the dynamics of the receiver platform and the data bit transitions, a new signal acquisition scheme is proposed. The block diagram of the proposed scheme is shown in Fig. 2.

The proposed acquisition scheme consists of two components: coarse acquisition and fine acquisition. On the one hand, the Doppler shift and Doppler rate, caused by the LOS motion between the receiver platform and satellite, are computed by SINS measurements and GPS ephemeris. This aiding information is used to mitigate the dynamic effect on the acquisition time and sensitivity. On the other hand, in fine acquisition, an optimal estimation of unknown data bits is performed. As a result, the SNR gain attenuation caused by bit transitions can be eliminated. In addition, the acquisition accuracy of Doppler shift is improved through a differential correction method to meet the requirement of carrier-tracking loop initialization.

Carrier Doppler shift estimation

The carrier Doppler shift of the received GPS signals can be written as (Yang 2008; Wang and Li 2012):

$$f_d = f_{rec} - f_s + \Delta f_{rec} + \Delta f_s \tag{7}$$

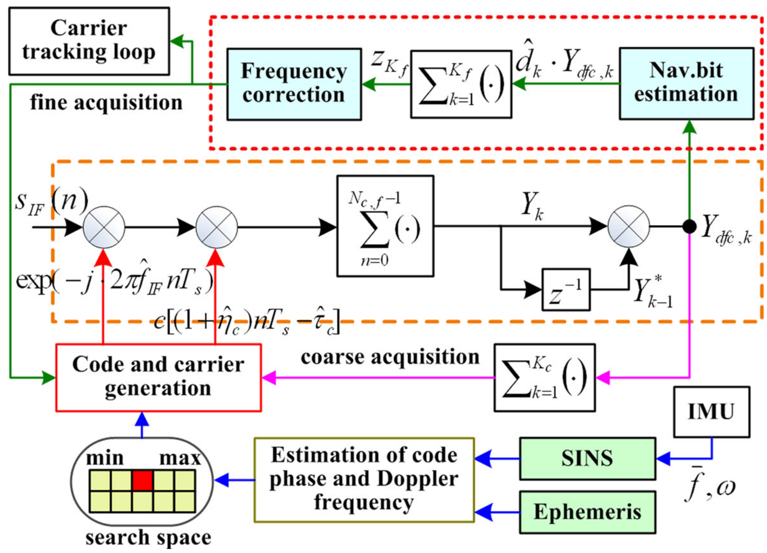

Fig. 2 The block diagram of the proposed GPS signal acquisition scheme

where, f_{rec} is the Doppler shift caused by the motion of receiver platform, f_s is the Doppler shift caused by the motion of satellite, Δf_{rec} is the frequency error caused by the receiver oscillator drift, and Δf_s is the satellite oscillator drift.

However, most of Δf_{rec} can be mitigated by pre-calibrating the receiver oscillator drift error and pre-estimating the aging speed of oscillator. The satellite oscillator drift is very small, and Δf_s is ignored. Therefore, the carrier Doppler shift can be expressed simply as the LOS velocity between the receiver platform and satellite:

$$\hat{f}_{\mathrm{d}} = \vec{E} \cdot \left(\vec{V}_{\mathrm{rec}} - \vec{V}_{\mathrm{s}}\right) / \lambda_{\mathrm{L1}} \tag{8}$$

where, λ_{L1} is the wavelength of carrier at L1 frequency, $\vec{V}_{rec}$ is the receiver velocity measured by SINS, $\vec{V}_s$ is the satellite velocity calculated from GPS ephemeris, and $\vec{E}$ is the unit LOS vector from the receiver platform to satellite.

For the estimation of Doppler rate $\dot{f}_d$, the same approach as f_d is performed. The result is:

$$\hat{\dot{f}}_{\mathrm{d}} = \vec{E} \cdot (\vec{a}_{\mathrm{rec}} - \vec{a}_{\mathrm{s}}) / \lambda_{\mathrm{L1}} \tag{9}$$

where, $\vec{a}_{rec}$ and $\vec{a}_s$ are the accelerations of receiver and satellite, respectively.

The frequency search space of coarse acquisition mainly depends on the accuracy of Doppler shift estimated by SINS. In short signal blockage situations, the satellite velocity error in (8) can be ignored. Therefore, the error variance in Doppler shift estimation can be expressed as:

$$\sigma^2_{\mathrm{dopp}} = \vec{E} \cdot \left(\delta\vec{V}_{\mathrm{rec}} \cdot \delta\vec{V}^T_{\mathrm{rec}}\right) \cdot \vec{E}^T \Big/ \lambda^2_{\mathrm{L1}} \tag{10}$$

where, $\delta\vec{V}_{rec}$ is the receiver velocity error measured by SINS. In the Earth-centered-Earth-fixed (ECEF) frame, this velocity error can be computed as:

$$\delta\vec{V}^e_{\mathrm{rec}} = \delta\vec{V}^e_{\mathrm{rec},0} - \int_{\mathrm{T}} F^e \left(\int_{\mathrm{T}} C^{\mathrm{e}}_{\mathrm{b}} \delta\omega \mathrm{d}t \right) \mathrm{d}t + \int_{\mathrm{T}} C^{\mathrm{e}}_{\mathrm{b}} \delta a \mathrm{d}t \tag{11}$$

where $\delta\vec{V}^e_{rec,0}$ is the initial velocity error, T is the signal blockage time, F^e is the acceleration vector, $\delta\omega$, and δa are the errors of gyro and accelerometer, respectively, and C^e_b defines the direction cosine matrix from the body frame to the ECEF frame.

Therefore, the standard deviation in Doppler shift estimation is:

$$\sigma_{\mathrm{dopp}} = \mathrm{norm}\left[\delta\vec{V}^e_{\mathrm{rec},0} - \int_{\mathrm{T}} F^e \left(\int_{\mathrm{T}} C^{\mathrm{e}}_{\mathrm{b}} \delta\omega \mathrm{d}t \right) \mathrm{d}t + \int_{\mathrm{T}} C^{\mathrm{e}}_{\mathrm{b}} \delta a \mathrm{d}t \right] \Big/ \lambda_{\mathrm{L1}} \tag{12}$$

In theory, the $\delta\vec{V}^e_{rec}$ can be estimated and calibrated according to the SINS error function in real time. However, if the receiver platform is in high dynamic conditions, it is hard to model the SINS error precisely due to the strong nonlinearities. Meanwhile, with the increase in signal blockage time, the estimation accuracy of $\delta\vec{V}^e_{rec}$ degrades rapidly. Therefore, in order to enhance the reliability of signal acquisition, the search space of Doppler shift has been set as the maximum σ_{dopp}.

Table 1 compares the frequency search with and without SINS aiding. The LOS acceleration is 6 g, the signal blockage time T is 200 s, and the frequency search step is 200 Hz. As shown in the table, considering a low-grade inertial measurement unit (IMU) with the gyro bias $\varepsilon = 10°/\mathrm{h}$ and the accelerometer bias $\nabla = 1$ mg, the Doppler shift search bins can be reduced to 6.93 % of that without aiding. This percent will become 0.99 % if the gyro bias is improved to 1°/h. With the same dwell time,

Table 1 Comparison of the frequency search with and without SINS aiding

Aiding condition	Search space	Search bins	Percent
No aiding	±10 kHz	101	1
$\varepsilon = 10°/h$	±588.5 Hz	7	6.93 %
$\varepsilon = 1°/h$	±49.6 Hz	1	0.99 %

the reduction of frequency search bins means the shortened acquisition time. Hereby, the SINS aiding can significantly shorten the reacquisition time in the presence of short signal blockage and enhance the reacquisition capability of GPS receivers.

Code phase estimation

All GPS signals are synchronous in time, which means that, except for the relative drift between satellite clocks, the first PRN chip and the first navigation data bit are transmitted from each satellite at precisely midnight of Saturday in GPS time (Kaplan and Hegarty 2005). Therefore, the code phase and data bit can be estimated according to the transmission time of the received signal. That is:

$$\begin{cases} \tau = \mathrm{Mod}(2{,}046 \times t_{sv} \times 1000, 2046) \\ D = 1 + \mathrm{Mod}(t_{sv}, 0.020) \end{cases} \tag{13}$$

where, t_{sv} is the signal transmission time, which can be calculated with the received time t_r and the propagation time d_t. Considering the satellite clock correction t_c, the transmission time is:

$$\hat{t}_{sv} = t_r - d_t + t_c \tag{14}$$

The estimation of received code phase can be then written as:

$$\hat{\tau} = \mathrm{Mod}[2{,}046 \times (t_r - d_t + t_c) \times 1000, 2046] \tag{15}$$

where, t_c can be obtained from GPS ephemeris. The propagation time $d_t = \mathrm{norm}\left(\vec{P}_{rec} - \vec{P}_s\right)/c$, where $\vec{P}_{rec}$ and $\vec{P}_s$ are the positions of receiver platform and satellite, respectively, and c is the speed of light.

The code phase uncertainty consists of two main terms, that is, the position uncertainty and the time uncertainty. Thus,

$$\sigma_\tau^2 = 4\sigma_{pos}^2 \cos^2(\varphi_{el}) + \sigma_{time}^2 \tag{16}$$

where, σ_τ is the standard deviation in code phase estimation in units of half-chips, φ_{el} is the satellite elevation angle, σ_{pos} is the standard deviation in SINS position measurement, and σ_{time} is time uncertainty term.

The code phase uncertainty computed in (16) is then used to judge the coarse acquisition state. If the code phase $\hat{\tau}_c$ estimated by coarse acquisition is in the range of $\hat{\tau} \pm \sigma_\tau$, the coarse acquisition is considered to be accomplished.

An acquisition algorithm for weak GPS signals

The Fast Fourier Transform (FFT)-based parallel code phase search is utilized in coarse acquisition. First, the input signal multiplies with the local carrier wave $\exp\left[-j \cdot 2\pi\left(\bar{f}_{IF} + \hat{f}_{d,c}\right)nT_s\right]$. A sequence $y(n) = s_{IF}(n)\exp\left[-j \cdot 2\pi\left(\bar{f}_{IF} + \hat{f}_{d,c}\right)nT_s\right]$ for each frequency search bin $\hat{f}_{d,c}$ is obtained. Subsequently, a circular cross-correlation between the sequence $y(n)$ and the local code is implemented through the FFT/IFFT algorithm. The computing process can be expressed as:

$$Y_{k,c}\left(\hat{\tau}_c, \hat{f}_{d,c}\right) = \mathrm{IFFT}(\mathrm{FFT}[y(n)] \times \mathrm{FFT}\{c[(1 + \hat{\eta}_c)nT_s]\}^*) \tag{17}$$

where, $\bar{f}_{IF} = f_{IF} + \hat{f}_d + \hat{\dot{f}}_d nT_s/2$ is the carrier IF compensated by SINS aiding and $\hat{\eta}_c = \left(\hat{f}_d + \hat{f}_{d,c}\right)/f_{L1}$ is the local estimation of code rate shift.

In DC-based coarse acquisition, a search for the maximum differential accumulation result is implemented to detect the code phase and Doppler shift of the input signal. That is:

$$\left[\hat{\tau}_c, \hat{f}_{d,c}\right] = \arg \max_{\left[\tau_c, f_{d,c}\right]} \left| \sum_{k=1}^{K_c} Y_{k,c} \cdot Y_{k-1,c}^* \right| \tag{18}$$

where K_c is the accumulation time. If the maximum result exceeds the preassigned threshold (Tsui 2004; Mao and Chen 2009), the coarse acquisition parameter $\left[\hat{\tau}_c, \hat{f}_{d,c}\right]$ can then be determined.

For the fine acquisition, the data bit boundaries are determined with (13), so that the coherent integration time can be expanded to the whole data period to further improve the SNR gain. In addition, the search step of code phase in coarse acquisition is one sampling interval. This can meet the requirement of code-loop initialization. Therefore, the fine acquisition only performs a fine search on the coarse estimation of Doppler shift $\hat{f}_{d,c}$. The output of coherent integration at the frequency search bin $\hat{f}_{d,l}$ is:

$$\begin{aligned} Y_{k,l} = {} & 0.5AN_D D_k R(\delta\tau_c)\,\mathrm{sinc}\left(\pi\delta f_{d,l}T_D\right) \\ & \exp\left(j \cdot \phi_k + j \cdot \pi\delta f_{d,l}T_D\right) + n_k \end{aligned} \tag{19}$$

where $N_D = T_D/T_s$, $\delta\tau_c$ is the residual error of code phase, $\delta f_{d,l}$ is the residual error of Doppler shift, and $l = 1, \ldots, L_f$ is the index of frequency search bins in fine acquisition. Compared with (4), the SINS aiding has removed the Doppler rate $\dot{f}_d$ from $\delta f_{d,l}$. The differential product Y_{dfc} can be expressed as:

$$
\begin{aligned}
Y_{\mathrm{dfc}}(k,l) &= Y_{\mathrm{k,l}}Y^{*}_{\mathrm{k-1,l}} \\
&= d_{\mathrm{k}}\cdot \bar{A}^2 D_{\mathrm{k}}D_{\mathrm{k-1}}\exp\big(j\cdot 2\pi\delta f_{\mathrm{d,l}}T_{\mathrm{D}}\big)+n_{\mathrm{dfc}}(k)
\end{aligned}
\tag{20}
$$

where $\bar{A}^2 = 0.25A^2N_{\mathrm{D}}^2R^2(\delta\tau_{\mathrm{c}})\operatorname{sin}c^2\left(\pi\delta f_{\mathrm{d,l}}T_{\mathrm{D}}\right)$. The parameter d_{k} is introduced to compensate the navigation bit transitions. When a bit transition occurs, then $d_{\mathrm{k}} = -1$, otherwise $d_{\mathrm{k}} = 1$. This bit transition parameter can ensure the sign of differential product Y_{dfc} is always positive. However, a wrong parameter d_{k} would cause two problems. One is that the accumulation of Y_{dfc} is counteract, and the SNR gain is then attenuated. The other is for the differential frequency error correction using the phase information of Y_{dfc}, a $1/(2T_{\mathrm{D}})$ bias will occur in the correction value. Therefore, a pre-estimate operation on the parameter d_{k} needs to be implemented before differential accumulation. The concrete steps of the proposed estimation scheme are as follows.

Step 1. Define the objective function $f\left(\vec{d}_{\mathrm{K_f}}\right)$ to estimate d_{k}

The objective function is:

$$
f\left(\vec{d}_{\mathrm{K_f}}\right) = \sum_{\mathrm{k=1}}^{\mathrm{K_f}}\left|d_{\mathrm{k}}\cdot Y_{\mathrm{dfc}}(k,l)-\bar{A}^2\right|^2 \tag{21}
$$

where $\vec{d}_{\mathrm{K_f}} = [d_1, d_2, \ldots, d_{\mathrm{K_f}}]^T$ is the parameter sequence to be estimated, K_{f} is the differential accumulation time in fine acquisition, and $\bar{A}^2$ is the expected signal level which can be obtained by coarse acquisition.

Step 2. Map the objective function to geometrical distance

Map the function $f\left(\vec{d}_{\mathrm{K_f}}\right)$ to the geometrical distance from $d_{\mathrm{k}}\cdot Y_{\mathrm{dfc}}(k, l)$ to $\bar{A}^2$.

As shown in Fig. 3, the angle of the product $d_{\mathrm{k}}\cdot Y_{\mathrm{dfc}}(k, l)$ with a right d_{k} is $2\pi\cdot\delta f_{\mathrm{d,l}}T_{\mathrm{D}}$. If $|2\pi\cdot\delta f_{\mathrm{d,l}}T_{\mathrm{D}}| < \pi/2$, the product $d_{\mathrm{k}}\cdot Y_{\mathrm{dfc}}(k, l)$ is corresponding to the short distance. However, a wrong d_{k} will introduce a 180° phase shift and make the distance increase. Therefore, the optimal solution of $\vec{d}_{\mathrm{K_f}}$ is equivalent to the sequence which can make the summation of the distance from $d_{\mathrm{k}}\cdot Y_{\mathrm{dfc}}(k, l)$ to $\bar{A}^2$ minimum. That is:

$$
\begin{aligned}
\hat{\vec{d}}_{\mathrm{K_f}} &= \arg\min_{\vec{d}_{\mathrm{K_f}}}\left[f\left(\hat{\vec{d}}_{\mathrm{K_f}}\right)\right] \\
&= \arg\min_{\vec{d}_{\mathrm{K_f}}}\left[\sum_{\mathrm{k=1}}^{\mathrm{K_f}}\left|\hat{d}_{\mathrm{k}}\cdot Y_{\mathrm{dfc}}(k,l)-\bar{A}^2\right|^2\right]
\end{aligned}
\tag{22}
$$

Step 3. An optimal estimation of $\vec{d}_{\mathrm{K_f}}$

$\hat{\vec{d}}$

The normal method to solve $_{\mathrm{K_f}}$ needs to search all of the $2^{\mathrm{K_f}}$ possible states. This large calculation burden will seriously degrade the signal acquisition speed. In order to

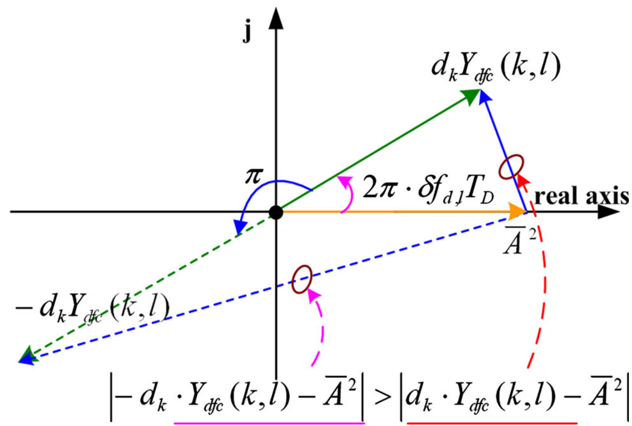

Fig. 3 The geometrical distance form of the objective function

improve the computing efficiency, the Viterbi algorithm (VA) (Viterbi 1967) is used here. The idea behind VA is that the optimal solution to the original problem consists of the optimal solutions to its similar subproblems. Then, convert (21) to its recursion form:

$$
f\left(\hat{\vec{d}}_{\mathrm{K_1}}\right) = f\left(\hat{\vec{d}}_{\mathrm{K_1-1}}\right)+\left|\hat{d}_{\mathrm{K_1}}\cdot Y_{\mathrm{dfc}}(\mathrm{K_1},l)-\bar{A}^2\right|^2 \tag{23}
$$

where $K_1 = 2, 3, \ldots, K_{\mathrm{f}}$ represents the dimension of the subsequence.

Figure 4 shows the flow of VA. Each arrow represents a possible transition from step k to step $k+1$. For the K_1th step observation, there are two values $d_{\mathrm{K_1}} = \pm 1$ and only one can generate the minimum $f\left(\hat{\vec{d}}_{\mathrm{K_1}}\right)$. This value is then kept as the optimal solution of the subsequence $\vec{d}_{\mathrm{K_1}}$. By inference, when all of the K_{f} observations have been completed, the $\hat{\vec{d}}_{\mathrm{K_f}} = \left[\hat{d}_1, \ldots, \hat{d}_{\mathrm{K_1}}, \ldots, \hat{d}_{\mathrm{K_f}}\right]^T$ will represent the optimal solution of $\vec{d}_{\mathrm{K_f}}$.

On the basis of the optimal solution of $\vec{d}_{\mathrm{K_f}}$, a K_{f}-time accumulation is performed on the product $\hat{d}_{\mathrm{k}}\cdot Y_{\mathrm{dfc}}(k,l)$. The differential accumulation result is:

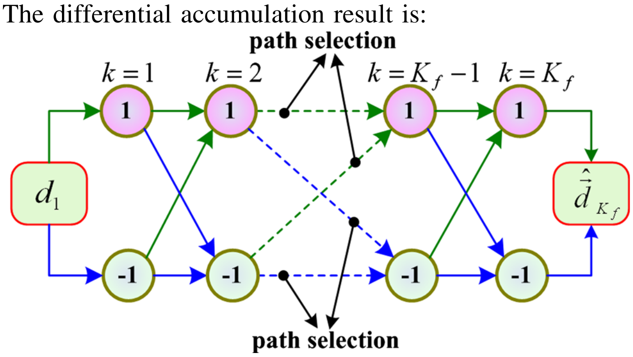

Fig. 4 The flow of Viterbi algorithm

$$z_{\mathrm{K_f},l} = \sum_{k=1}^{\mathrm{K_f}} \hat{d}_k \cdot Y_{\mathrm{dfc}}(k,l) = \mathrm{K_f}\bar{A}^2 \exp\left(j \cdot 2\pi\delta f_{\mathrm{d},l} T_{\mathrm{D}}\right) + n_z \tag{24}$$

Step 4. Differential frequency error correction

Performing the processing mentioned above at all of the frequency search bins of fine acquisition, the differential accumulation results $z_{\mathrm{K_f},l}$ can be obtained. Due to the presence of the attenuation factor $\sin c^2\left(\pi\delta f_{\mathrm{d},l} T_{\mathrm{D}}\right)$ in Y_{dfc}, the peak value of $z_{\mathrm{K_f},l}$ will be corresponding to the search bin with least frequency error. Then, the error of Doppler shift in fine acquisition can be computed as:

$$\delta\hat{f}_{\mathrm{d},l} = \mathrm{angle}\left[\max\left(z_{\mathrm{K_f},l}\right)\right] / 2\pi T_{\mathrm{D}} \tag{25}$$

where the operator angle[·] returns the phase angle between $\pm\pi/2$. Therefore, the final Doppler shift estimation $\bar{f}_{\mathrm{d}}$ is:

$$\bar{f}_{\mathrm{d}} = \hat{f}_{\mathrm{d}} + \hat{f}_{\mathrm{d,c}} + \hat{f}_{\mathrm{d,f}} + \delta\hat{f}_{\mathrm{d},l} \tag{26}$$

where $\hat{f}_{\mathrm{d}}$ is the Doppler shift derived by SINS, $\hat{f}_{\mathrm{d,c}}$ is the value estimated by coarse acquisition, $\hat{f}_{\mathrm{d,f}}$ is the value estimated by fine acquisition, and $\delta\hat{f}_{\mathrm{d},l}$ is the differential correction value.

Simulation test

To validate the performance of the proposed signal acquisition scheme, simulation tests were carried out in a signal blockage situation under high dynamic conditions. A dedicated simulation platform was designed, and the signal blockage situation could be achieved by adjusting the amplitude of IF signals. The high-level configuration of the platform is shown in Fig. 5.

Simulation conditions

The test GPS signal was generated by an IF signal simulator. The sampling frequency was set to 5 MHz. The IF carrier frequency was set to 1.25 MHz. The input signal C/N_0 was set to 19–28 dB Hz. A low-grade IMU was utilized to provide the measurement information for SINS solution. The specification of the IMU is listed as follows. The gyro rate bias is 10°/h, and the scale factor rate error is 100 ppm. The accelerometer bias is 1 mg, and the scale factor error is 100 ppm. The white noise standard variations of gyros and accelerometers are 0.3°/h and 50 μg, respectively.

For the simulated signal blockage situation, the initial LOS acceleration was 6 g, and the blockage time was 200 s. According to (12), the frequency search space of coarse acquisition was set to ±600 Hz. The frequency search space of fine acquisition was set to ±100 Hz. The search steps of coarse and fine acquisition were 200 and 20 Hz, respectively. The coherent integration intervals were 1 and 20 ms. The differential accumulation times were chosen as $K_c = 400$ and $K_f = 20$.

Simulation results and analyses

Figures 6, 7, and 8 show the acquisition results of code phase, Doppler shift, and bit transition parameter, respectively, for satellite 10. The input C/N_0 is 21 dB Hz. As shown in Fig. 6, the code phase corresponding to the coarse acquisition peak is 147.7 chip. It is consistent to the value set in the simulation. In Fig. 7, the Doppler shift derived from the coarse acquisition aided by SINS is 7.3 kHz. The fine acquisition is −60 Hz, and the differential correction value is −4.08 Hz. As a result, the final acquisition result of the Doppler shift is 7,235.92 Hz. The residual error is 0.96 Hz. Figure 8 shows that there is only one error

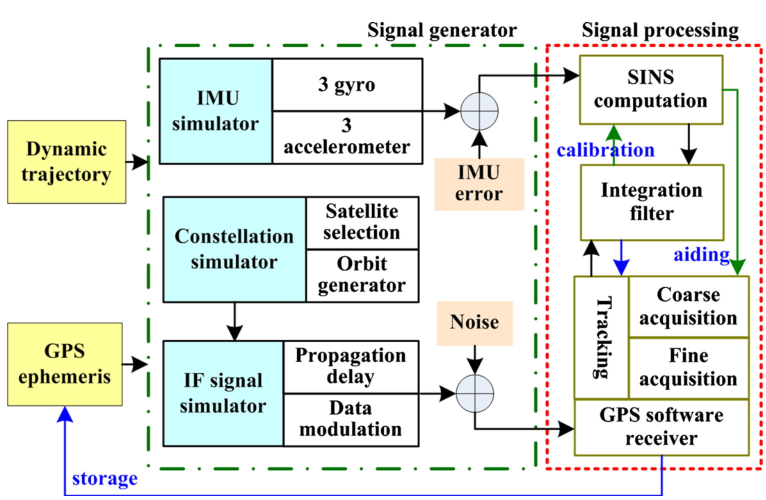

Fig. 5 The high-level configuration of the simulation platform

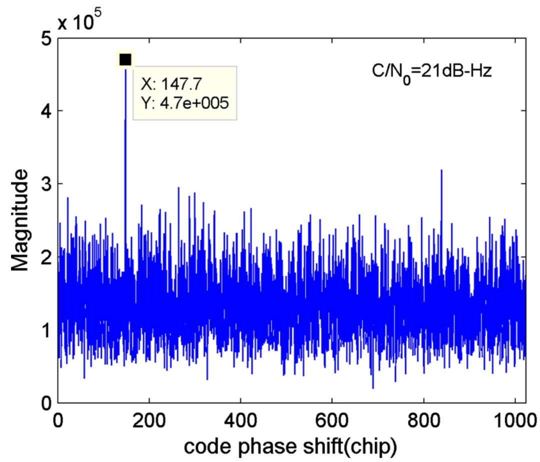

Fig. 6 Code phase acquisition

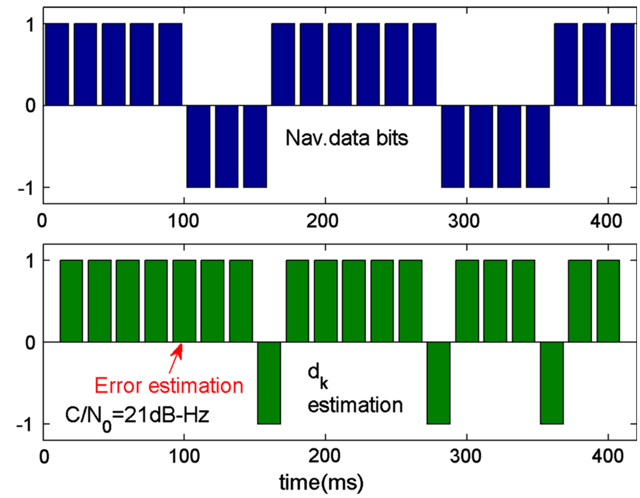

Fig. 8 The estimation of bit transition parameter

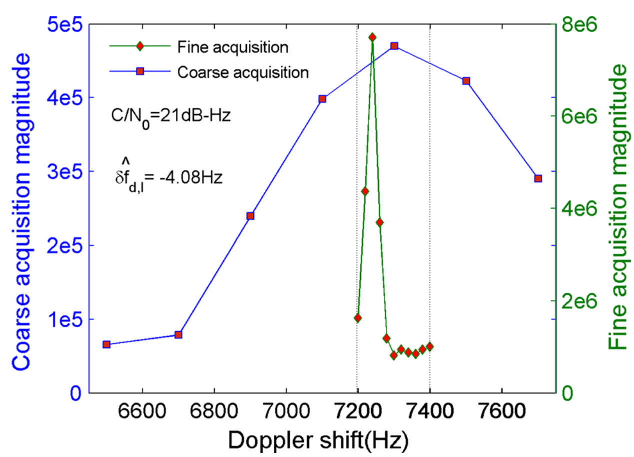

Fig. 7 Doppler shift acquisition

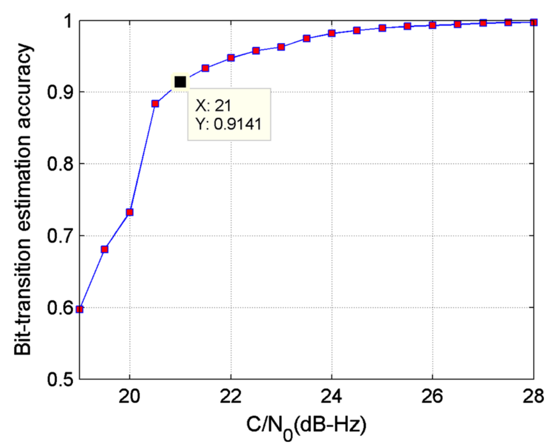

Fig. 9 Bit transition parameter estimation accuracy

estimation which appears at 100 ms in the estimations of bit transition parameters.

Figure 9 shows the accuracy curve of bit transition parameter estimation against C/N_0. It can be seen that the accuracy of bit transition parameters estimated by fine acquisition is 91.41 % at C/N_0 of 21 dB Hz. These parameters can improve the SNR of the peak value $\max\left(z_{K_f,l}\right)$ significantly. Subsequently, a differential correction value with high precision is acquired for the reduction of acquisition errors in Doppler shift.

Figure 10 compares the Doppler shift acquisition errors of the conventional DC method and the proposed algorithm against C/N_0. The Doppler shift error of conventional DC method mainly depends on the relative relationship between the real Doppler shift and the nearest search bin. In this experiment, the real Doppler shift was 7,234.96 Hz, and the nearest search bin was 7,240 Hz. Therefore, the frequency acquisition root mean square error (RMSE) converges to about 5 Hz. However, for the proposed algorithm, the differential correction was utilized to eliminate the accuracy limitation due to frequency search step. The RMSE can converge to 0 Hz. The figure also shows that the RMSE of the proposed algorithm is significantly reduced comparing with the conventional DC method.

Figure 11 compares the acquisition sensitivity of the conventional DC method and the proposed algorithm, with and without SINS aiding. The virtual signal lengths of acquisition processing are 400 ms. For the 90 % detection possibility, the acquisition sensitivity of the proposed algorithm with SINS aiding has improved about 3.75 dB Hz compared to that without SINS aiding. Meanwhile, on the basis of the estimated bit transition parameters, the proposed algorithm can obtain a higher SNR gain through extending the coherent integration time ($T_c = 20$ ms) and increase the acquisition sensitivity by 2.4 dB Hz compared with the conventional DC method ($T_c = 1$ ms).

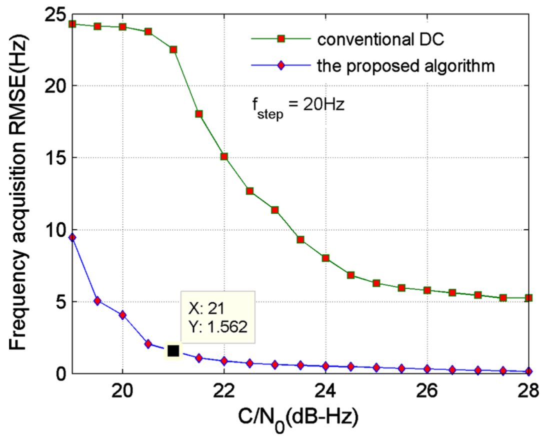

Fig. 10 Frequency acquisition errors of the conventional DC method and the proposed algorithm

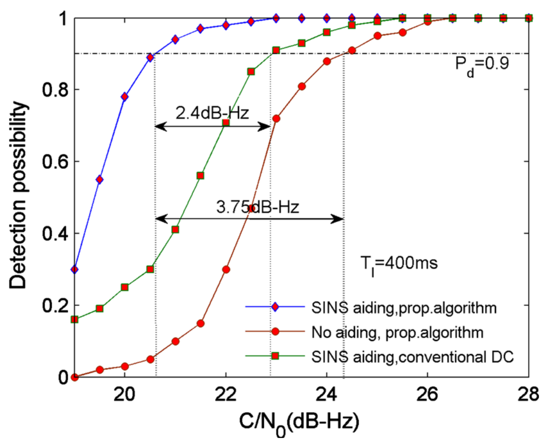

Fig. 11 Acquisition sensitivity of the conventional DC method and the proposed algorithm, with and without SINS aiding

Conclusions

We propose a new scheme for weak GPS signal acquisition in high dynamic conditions. Three approaches including SINS aiding, optimal estimation of unknown data bits, and differential frequency error correction are used to enhance the acquisition performance. The SINS aiding information is utilized to improve the acquisition speed and reduce the sensitivity attenuation due to Doppler rate. A data bit estimation is performed to mitigate the impact of bit transitions, and then the acquisition sensitivity can be increased with a long coherent integration time. The accuracy limitation of frequency search step is eliminated effectively with a differential correction operation.

Simulation results demonstrate that the proposed acquisition scheme can acquire GPS signal as low as 21 dB Hz effectively within 400 ms. The acquisition accuracy is higher than 1.6 Hz. The high sensitivity and fast acquisition capability has the potential to be used in challenging environments especially in severe jamming and high dynamic situations. The proposed scheme is planned to be implemented in a receiver firmware in the near future.

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References

Borio D, O'Drisoll C, Lachapelle G (2009) Coherent, non-coherent and differentially coherent combining techniques for the acquisition of new composite GNSS signals. IEEE Trans Aerosp Electron Syst 45:1227–1240

Choi H, Cho DJ, Yun SJ, Kim YB, Lee SJ (2002) A novel weak signal acquisition scheme for assisted GPS. Proceedings of ION GPS 2002. Portland, pp 177–183

Chuang MY, Feng KT (2006) Adaptive GPS acquisition technique in weak signal environment. Proceedings of IEEE vehicular technology conference 2006. Melbourne, pp 2612–2616

Jin SG (2012) Global navigation satellite systems: signal, theory and applications. InTech, Shanghai

Kaplan ED, Hegarty CJ (2005) Understanding GPS: principles and applications, 2nd edn. Artech House Inc., Boston

Ma YK, Zhang Y, Zhang ZZ, Ma GF (2009) Modified method of high dynamic & high sensitivity GPS signal acquisition. Syst Eng Electron 31:265–269

Mao WL, Chen AB (2009) New code delay compensation algorithm for weak GPS signal acquisition. AEU Int J Electron Commun 63:665–677

O'Drisoll C (2007) Performance analysis of the parallel acquisition of weak GPS signals. Ph.D. thesis, National University of Ireland, Ireland

Shanmugam SK, Nielsen J, Lachapelle G (2007) Enhanced differential detection scheme for weak GPS signal acquisition. Proceedings of ION GNSS 2007. Fort Worth, pp 189–202

Strässle C (2007) The squaring-loss paradox. Proceeding of ION GNSS 2007. Fort Worth, pp 2715–2722

Tsui JBY (2004) Fundamentals of global positioning system receivers: a software approach, 2nd edn. Wiley, New York

Viterbi AJ (1967) Error bounds for convolutional codes and an asymptotically optimum decoding algorithm. IEEE Trans Inf Theory 13:260–269

Wang XL, Li YF (2012) An innovative scheme for SINS/GPS ultra-tight integration system with low-grade IMU. Aerosp Sci Technol 23:452–460

Yang Y (2008) Tightly coupled MEMS INS/GPS integration with INS aided receiver tracking loops. Ph.D. thesis, The University of Calgary, Canada

Yu W, Zheng B, Watson R, Lachapelle G (2007) Differential combining for acquiring weak GPS signals. Signal Process 87:824–840

Yu J, Wang XL, Ji JX (2010) Design and analysis for an innovative scheme of SINS/GPS ultra-tight integration. Aircr Eng Aerosp Technol 82:4–14

Zarrabizadeh MH, Sousa ES (1997) A differentially coherent PN code acquisition receiver for CDMA systems. IEEE Trans COM 45:1456–1465

Zhuang WH, Tranquilla J (1989) Digital baseband processor for the GPS receiver modeling and simulations. IEEE Trans Aerosp Electron Syst 25:749–760

Ziedan NI (2006) GNSS receivers for weak signals. Artech House Inc., Boston

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