Study on an effective algorithm of acquiring and tracking BD2 medium-frequency signals

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Abstract: According to the modulation characteristics of NH code in MEO/IGSO satellites, a simple and effective serial-parallel combined method of capturing the BD2 satellite signals was presented and a complete software receiver of the B1 frequency point was realized. Based on Kalman filter, a new kind of vector tracking loop structure of pseudo code and carrier wave to adapt to the high dynamic situation was put forward, and the half-vector deeply-coupled structure based on CKF pre-filter was further studied. Simulation and practical test results showed that the new acquisition algorithm had high sensitivity, stronger adaptability for weak signal, and less computation, and that nonlinear filtering methods could not only be applied to KFPLL, but also track high dynamic signal of 100g.

1. Introduction
Nowadays, as the construction of the Beidou Navigation Satellite System (BDS)[1] has been primarily accomplished and begun to serve China and its circumjacent regions[2], further and deeper studies on satellite signal acquisition and tracking algorithms of the 2nd generation of Beidou Navigation Satellite System (BD2) will be conducted.

BDS satellites are different from GPS/GEO satellites [3], as MEO/IGSO satellite signal modulation has Neumann-Hoffman Codes (NH codes). Therefore, only when the four-dimensional search of satellite serial number, pseudo-code phase, carrier frequency and NH code phase is executed, can the acquisition of such satellite signals be performed and to obtain complete navigation messages in the tracking process, the influence of NH codes must be removed. Many papers on BD2 Baseband algorithm failed to fully discuss the acquisition of NH codes. Due to the phase flip, the adopted coherent integral length in the NH code acquisition process cannot exceed 1ms [4]. Because the length is too short, the integrated energy amplitude of useful signals is not significant, and then it will be very difficult to acquire the weak signals. Xie F and Liu J [5] proposed the dichotomy to check the flipping position of data bits, which was not practical as it required tedious calculation.

Based on the analysis of original acquisition algorithm and combined with the features of second modulation, we propose a novel serial-parallel combined acquisition method of MEO/LGSO satellite signals, which realizes the complete BD2 software receiver based on traditional tracking loops. In the light of the nonlinearity of system model in high dynamic environment, combined with the requirements of the software receiver for PLL performance, Cubature Kalman Filter (CKF), Unscented Kalman Filter (UKF) and Extended Kalman Filter are imbedded into the PLL, then more accurate observation equation is determined and new vector tracking loop structure is designed. Through EKF, the combined tracking structure of carrier waves and code loops is realized, the realization means of the semi-vector deep composite structure based on CKF pre-filtering is given and algorithm design is verified through simulation.

2. Analysis and Verification of BD2 Acquisition Algorithm
After NH code modulation, the BD2 input signals can be expressed as:
\[ x(n) = D(n)C(n)h(n)\cos\left(\frac{2\pi(f_i + f_d)n}{f_s} + \varphi\right) \]  

In which, \( f_i \) denotes the intermediate frequency, \( f_d \) the Doppler frequency shift and \( f_s \) the sampling frequency. Through the traditional code phase acquisition process, obvious peak values can be obtained in the situation of code phase alignment. But because of the frequency spectrum shifting effects of NH codes, several peak values may appear, which makes it difficult to obtain correct Doppler frequency shift estimation.

3. Overall Design of BD2 Receiver

As to the BD2 software receiver designed in this paper, its corresponding frequency point is B1I frequency point, the intermediate frequency is 4.092MHz, the sampling frequency is 16.368MHz and the digitalizing bit is 2bit. The latest universal serial bus USB3.0 is adopted to apply the collection of intermediate-frequency data, and in Qt creator of Linux operating system, C/C++ is utilized to accomplish the functions of BD2 acquisition and tracking, as well as positioning resolution.

In the tracking phase [6], set the preliminary testing integral time length as 1ms, adopt third-order phase locked loop (PLL) in carrier wave cracking, utilize the arctangent phase discriminator with a noise bandwidth of 18Hz and set the loop gain 0.15. In code tracking, use a second-order delay locked loop (DLL), adopt a unitized early minus late power discriminator with a noise bandwidth of 5Hz and set the loop gain as 1. And then the tracking results are shown in Fig. 1. As for the navigation solution phase, refer to [7], and need not be repeated here.

4. Design and Simulation of High Dynamic Signal Tracking Loop

In practical application, high dynamic environment may result in strong nonlinear characteristics. In addition, as an indispensable part of the tracking loops of the receiver, code tracking loop will be relatively less influenced under specific conditions. Therefore, referring to [8] and [9], VDLL is designed and EKF is adopted, but the acceleration must be taken into consideration as a state quantity and the actual realization processes need to be repeated here.
4.1. Principle of Nonlinear Filtering
When either the dynamic process or the measurement process of the system presents nonlinear characteristics, it will be difficult to apply standard Kalman filter and it is necessary to adopt other nonlinear filters to solve the problem of nonlinear optimal filtering. Assume the following nonlinear state equation and measurement equation. In which, \( w_{k-1} \) and \( v_k \) are additive white Gaussian noises.

\[
\begin{align*}
    x_k &= f(x_{k-1}, k-1) + w_{k-1} \\
    z_k &= h(x_k, k) + v_k
\end{align*}
\]  

(2)

\( Q \) and \( R \) are the system noise matrix and measurement noise matrix. In this paper, based on EKF, UKF and CKF, high dynamic signal tracking loops are designed. After the instruction of nonlinear filtering, the loop structure is shown in Fig. 2:

![Figure 2. The overall structure of vector tracking loops](image)

4.2. Modeling and Algorithm Design
In high dynamic environment, select the low order derivatives of the carrier wave phase error, frequency error and the low order derivatives of the frequency order as states, i.e. \( \mathbf{x}(k) = [\Delta \phi, \Delta \dot{\phi}, \Delta \Omega, \dot{\Delta} \Omega] \), select the in-phase accumulated value of the instant branch and the related accumulated value of the orthogonal branch as the observation value, and then the model of the PLL in a certain channel of the receiver may be expressed as:

\[
\begin{align*}
    X(k) &= F X(k-1) + \xi(k) \\
    Z(k) &= \begin{bmatrix} AR(\Delta \tau) \sin(\frac{T \omega_c}{2}) \sin(LX(k)) \\
                 AR(\Delta \tau) \sin(\frac{T \omega_c}{2}) \cos(LX(k)) \end{bmatrix} + \eta(k)
\end{align*}
\]  

(3)

From the discussion above, it can be seen that the PLL model has strong characteristics of nonlinearity. In this paper, CKF and UKF are utilized to perform optimal estimation to the states [10].

4.3. KFPLL Simulation Verification
The high dynamic intermediate frequency data are obtained through simulation. From the 4th second, the receiver begins to execute the high dynamic process, the maximum acceleration on the X-axis can reach 100 times of g per second, and along other directions, the dynamic characteristics are not significant. The carrier-to-noise ratio of satellite signals is set as 40dB-Hz, and the refreshing cycle of the carrier wave loops is set as 1ms. Figure 3 and figure 4 are the Doppler frequency shift results of traditional carrier wave loops and KFPLL in tracking Satellite No. 23.
From the simulation results, it can be seen that when the high dynamic environment is serious, the traditional carrier wave loops may lose lock, but the carrier wave loops based on EKF, UKF and CKF nonlinear Kalman filtering don’t lose lock. This indicates that the designed BD2 intermediate signal processing algorithm reaches the purpose to realize stable tracking of high dynamic signals.

5. The Design and Simulation of Semi-Vector Deep Composite Structure

As the full-vector deep composite structure [11] requires GNSS receiver to provide high-accuracy initial positioning results as the filtering initial value of the deep composite main filter in order to realize good carrier wave phase tracking, therefore, a semi-vector deep composite structure, i.e. all the channels tracking the carrier wave phase individually, can avoid the limitations of the full-vector deep composite structure.

The dramatic change of the receiver’s motion state may result in the loss-of-lock of the traditional carrier tracking loops, which have fixed parameters. In order to adapt to the high-variability, CKF [12], a nonlinearity-adaptive filter, is introduced in the semi-vector deep composite to realize the stable tracking of carrier phases. The dynamic modeling of carrier tracking loops and the actual realization method of CKF-based carrier tracking are discussed above. The semi-vector deep composite structure of the CKF-based pre-filtering is shown in Fig. 5.
5.1. Establishment of Semi-Vector Deep Composite Model
The semi-vector deep composite structure of CKF-based pre-filtering composes of INS navigation computation, the computation of local NCO controlling quantity, pre-filter, navigation filter and the basic tracking loops. Navigation filter has the functions of estimating the error parameters of GNSS and INS, and the state quantity consists of user carrier position, errors of velocity and attitude angle, random drift of INS sensor, and the clock bias and clock drift of receiver.

\[
X_f = \begin{bmatrix}
\delta v_x & \delta v_y & \delta v_z & \phi_x & \phi_y & \phi_z & \delta L & \delta \lambda & \delta h \\
\varepsilon_{xb} & \varepsilon_{yb} & \nabla_{xb} & \nabla_{yb} & \nabla_{zb}
\end{bmatrix}^T
\]

\[
X_G = \begin{bmatrix}
\delta u_x & \delta f_u
\end{bmatrix}^T
\]

Where, the state quantities in \(X_f\) respectively denote the velocity errors along three axial directions (East, North, Sky) of the navigation coordinate system (i.e. Geographic Coordinate System), 3-D attitude error, latitude error, longitude error, altitude error, and the random drift of gyroscopes and accelerometers along the three axial directions of carrier coordinate system. \(X_G\) are the equivalent distance and distance rate, which are caused by the clock bias and clock drift of receiver.

The error state equation of GNSS/INS deep composite system is:

\[
\dot{X}(t) = F(t)X(t) + W(t)
\]

\[
W(t) = \begin{bmatrix}
w_v & w_u & w_{xv} & w_{yx} & w_{yg} & w_{yg} & w_g & 0 & 0 \\
w_u & w_v & w_{ux} & w_{xy} & w_{yv} & w_{yv} & w_u & w_f & 0
\end{bmatrix}^T
\]

\[
X(t) = \begin{bmatrix}
X_f(t) \\
X_G(t)
\end{bmatrix}
\]

\[
F(t) = \begin{bmatrix}
F_f(t) \\
0 \\
F_G(t)
\end{bmatrix}
\]

Select the estimated the Pseudorange and pseudorange rate error of the channels as the observation values of the navigation filter, and the observation equation value is:

\[
Z(t) = H(t)X(t) + V(t)
\]

Assume there are n channels and the observation value is denoted as:

\[
Z = \begin{bmatrix}
\delta \rho_1 & \delta \rho_N & \delta \dot{\rho}_1 & \delta \dot{\rho}_N
\end{bmatrix}^T
\]
5.2. Simulation Verification

Through setting such motor states as velocity, position and angular velocity of the carrier, calculate the motor tracks of the carrier first, and calculate the nominal outputs of the gyroscope and accelerometer. Finally, add different-grade noises as necessary to simulate IMU outputs with different accuracy grades. In the uniform motion state, as to the INS devices with different accuracy grades, the velocity errors by means of navigation solution are shown in Fig. 6.

High-dynamic medium-frequency signals still follow the high-dynamic scene mentioned above, and in this scene, add the output signal simulation module. As to the gyroscope, the random drift is $0.1^\circ/h$, and the constant drift is $10^\circ/h$; and as to the accelerometer, the constant drift and the random drift are 1mg and 0.01mg respectively. The simulation results are shown in Fig.7, which indicates that deep composite navigation can restrain the accumulated errors of INS satisfactorily.

Figure 6. Velocity error of INS with different accuracy grades

Figure 7. The velocity error of the East direction of deep composite navigation
6. Conclusion
In this paper, the influences of NH-code modulation on the acquisition of MEO/IGSO satellites are discussed in depth, and a simple but effective acquisition approach is proposed, which improves the ability to acquire weak signals [13-14]. Also, the processing algorithms of BD2 medium-frequency signals and baseband singles, and complete programs of BD2 software receiver are developed. In addition, based on EKF, UKF and CKF, the basic structure and the actual realization steps of KFPLL are developed. The simulation results verify that non-linear filtering method-based carrier tracking loops have higher adaptability to the high-dynamic conditions. The semi-vector deep composite structure, which is based on the CKF pre-filtering, can provide relatively high-accuracy navigation solution.

7. References
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