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Design and Implementation of GPS/BDS Dual-mode Satellite Navigation Receiver Based on ZYNQ-7020

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***Abstract*— With the development and perfection of the satellite navigation system, the development of multimode satellite navigation receiver has become one of the important research directions in the field of satellite navigation. This paper introduces a design method of GPS/BDS dual mode receiver based on ZYNQ-7020 architecture. The overall architecture design, joint location algorithm and carrier smoothed pseudo range of the dual mode receiver are introduced in detail. Finally, the feasibility of the design scheme and the positioning performance of the satellite receiver is verified through vehicle field test and simulation on low-orbit satellite orbit.**

***Index Terms*— Satellite navigation, GPS/BDS, ZYNQ-7020, Vehicle field test, low-orbit satellite**

I. INTRODUCTION

With the rapid development of the global satellite navigation system, the development of dual-mode satellite navigation receiver has become an important research direction in the field of satellite navigation. The current global satellite navigation systems include GPS, GLONASS, GALILEO, and BDS. The Beidou satellite navigation system (BDS) is a self-constructed and independently operated satellite navigation system in China. With the completion of the Beidou-II system, it has now provided positioning, navigation, and timing services to the Asia-Pacific region. The Beidou III system is also rapidly constructing. The joint location of BDS and GPS can improve positioning accuracy when the number of available satellites is small [1-2].

At present, low-orbit satellites have been widely used in marine surveys, atmospheric surveys, and mobile communications. This paper presents a GPS/BDS dual-mode receiver design scheme based on ZYNQ-7020 platform. Its peripheral interface is rich, with good versatility and standard, while meeting the needs of navigation performance, with the advantages of small size, strong portability. This paper mainly studies the hardware architecture design and software algorithm of GPS/BDS dual-mode receiver. The GPS/BDS dual-mode receiver based on ZYNQ-7020 can work normally and output a higher-accuracy performance index in vehicle filed test and low-orbit satellite (European QB50 satellite orbit) orbit [3].

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II. HARDWARE DESIGN OF GPS/BDS DUAL-MODE RECEIVER BASED ON ZYNQ-7020

The ZYNQ-7020 is fully programmable SoC from Xilinx, a highly integrated device that includes the ARM Cortex-A9 Multi-Processor Core processor resources (Processing System, PS) and the Artix-7 family of FPGA logic cells (Programmable Logic, PL). The data interaction between processor ARM and logic cell FPGA is through AXI interface. The internal throughput of ZYNQ is very large, and resources are also very rich. The overall hardware framework of the GPS/BDS dual-mode receiver is shown in Figure 1.

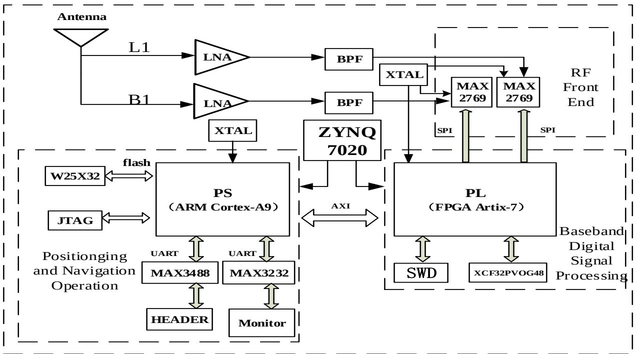

Figure 1. The overall hardware frame diagram of the GPS/BDS dual mode receiver

Radio frequency front-end module: the RF module receives signals from all the visible satellites through a satellite signal antenna. The weak GPS/BDS signal is filtered and amplified, and enters the mixer the down for down-conversion processing to generate the intermediate frequency signal. Then, use A/D chip to carry on the conversion and sampling, and the digital intermediate frequency signal is generated after discretizing the analog intermediate frequency signal which is convenient for subsequent processing into the PL. The flow chart of the internal signal of the RF module is shown in Figure 2.

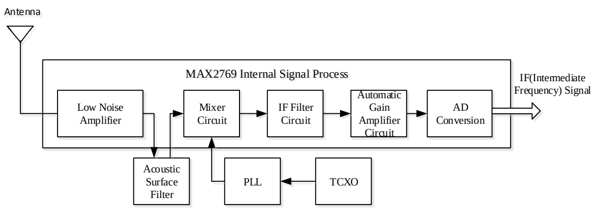

Figure 2. The flow chart of the signal of the RF module

Baseband signal processing module: the digital intermediate frequency signal generated by MAX2769 is received through the I/O port and provided to the channel correlator. Accumulator latches the I/Q signal and triggers accumulative interruption. The TIC latch latches the correlation quantity and triggers the TIC interrupt, simultaneously outputs the 1PPS . The whole structure design is divided into clock time base generator module, data sampling and accessing module, digital matched filter module, independent tracking channel module, register group module and so on. Functions implemented by FPGA: generation of local carrier, local pseudo code and intermediate frequency signal, correlation of local pseudo code and carrier [4].

Positioning and navigation module: obtain satellite ephemeris and almanac information, perform carrier tracking loop and code tracking loop control, and execute carrier phase smoothing pseudo range processing. Finally, calculate the position, velocity, and time information of the current carrier.

III. Research On Joint Location Algorithm Of GPS/BDS

A. Pseudo range measurement and carrier phase measurement

Pseudo range measurement is based on the principle that the time of signal propagation multiplied by the speed of light is equal to the distance. The local time of receiving signal time can be obtained from the receiver. To know the signal propagation time, it is also necessary to know the transmission time of the satellite signal. The formula for calculating the signal transmission time $t^{(s)}$ is as follows:

$$t^{(s)}=\begin{cases} TOW+(30w+b)\times 0.02+\left(c+\dfrac{CP}{1023}\right)\times 0.001, GPS \\ SOW+(30w+b)\times 0.02+\left(c+\dfrac{CP}{2046}\right)\times 0.001, BDS\ D1 \\ SOW+(30w+b)\times 0.002+\left(c+\dfrac{CP}{2046}\right)\times 0.001, BDS\ D2 \end{cases} \quad (1)$$

Where TOW and SOW respectively represent the GPS and BDS satellite seconds count; GPS obtains its value from the second word of the sub-frame; BDS obtains its value from the first word and the second word of the sub-frame; w is the word count value in the current sub-frame; b is the bit count value in the current word; c is the current bit pseudo-code cycle count value; CP is the code phase offset.

In combination with local time t_u , then the satellite pseudo range measurement can be expressed as:

$$\rho = c(t_u - t^{(s)}) \quad (2)$$

The pseudo range measurement equation can be further written as:

$$\rho = r + c\delta t_u - c\delta t^{(s)} + I + T + \varepsilon_\rho \quad (3)$$

Where r indicates the geometric distance between the satellite and receiver; c indicates the speed of light; δt_u indicates the receiver clock bias; $\delta t^{(s)}$ indicates the satellite clock bias; I indicates the ionosphere delay distance; T indicates the troposphere delay distance; ε_ρ indicates the pseudo range measurement noise converted to the distance.

The carrier phase measurement equation is as follows:

$$\phi = r + c\delta t_u - c\delta t^{(s)} - I + T + \lambda N + \varepsilon_\phi \quad (4)$$

Where ϕ is the carrier phase value that has been converted to distance, N indicates a random whole week number; λ indicates the carrier wave length; ε_ϕ is the carrier phase measurement noise that has been converted into distance.

B. Clock bias model of satellite receiver

In the joint location, the two system time must be unified. In order to maintain system compatibility, the time datum is generally selected as GPS. δt_{GB} indicates the system deviation between BDS and GPS. The definition is as follows:

$$\delta t_{GB} = t_{GPS} - t_{BDS} \quad (5)$$

Receiver local time relative to the GPS time of the clock bias is defined as:

$$\delta t_{u,GPS} = t_u - t_{GPS} \quad (6)$$

Receiver local time relative to the BDS time of the clock bias is defined as:

$$\delta t_{u,BDS} = t_u - t_{BDS} \quad (7)$$

From equations (5) to (7):

$$\delta t_{u,BDS} = \delta t_{u,GPS} + \delta t_{GB} \quad (8)$$

As shown in Figure 3, because of the existence of BDS and GPS time difference, the GPS pseudo range measurement value $\rho_c^{(i_{GPS})}$ and the BDS pseudo range measurement value $\rho_c^{(i_{BDS})}$ are different in physics, after correcting the pseudo range error of GPS and BDS. The difference between them is the difference between GPS and BDS time.

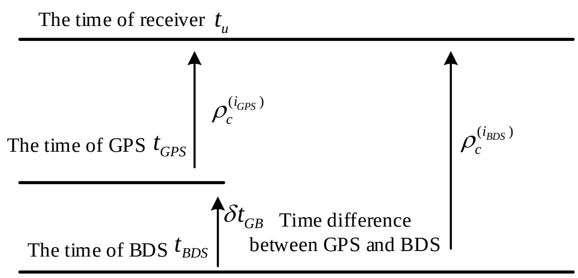

Figure 3. Pseudo range difference between BDS and GPS

C. Joint Location method

The measured value of BDS pseudo range can not be simply regarded as the measured value of GPS pseudo range. Otherwise, the difference between BDS and GPS time will introduce deviations in their joint location results. Using the receiver to measure the time difference of the system. Assuming that the system time difference value is regarded as an unknown state amount, GPS and BDS pseudo range measurement equations after error correction are:

$$r^{(i_{GPS})} + \delta t_{u,GPS} = \rho_c^{(i_{GPS})} - \varepsilon_\rho^{(i_{GPS})} \quad (9)$$

$$r^{(i_{BDS})} + \delta t_{u,GPS} + \delta t_{GB} = \rho_c^{(i_{BDS})} - \varepsilon_\rho^{(i_{BDS})} \quad (10)$$

Where:

$$\rho_c^{(i_{GPS})} = \rho^{(i_{GPS})} + \delta t^{(i_{GPS})} - I^{(i_{GPS})} - T^{(i_{GPS})} \quad (11)$$

$$\rho_c^{(i_{BDS})} = \rho^{(i_{BDS})} + \delta t^{(i_{BDS})} - I^{(i_{BDS})} - T^{(i_{BDS})} \quad (12)$$

Then, a linearized joint location matrix equation can be established:

$$\begin{bmatrix} M & M & M & M & M \\ -\mathbf{1}_x^{(i_{GPS})} & -\mathbf{1}_y^{(i_{GPS})} & -\mathbf{1}_z^{(i_{GPS})} & 1 & 0 \\ M & M & M & M & M \\ -\mathbf{1}_x^{(i_{BDS})} & -\mathbf{1}_y^{(i_{BDS})} & -\mathbf{1}_z^{(i_{BDS})} & 1 & 1 \\ M & M & M & M & M \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ \Delta\delta t_{u,GPS} \\ \Delta\delta t_{GB} \end{bmatrix} = \begin{bmatrix} M \\ b^{(i_{GPS})} \\ M \\ b^{(i_{BDS})} \\ M \end{bmatrix} \tag{13}$$

The formula (13) is also equivalent to another common joint location matrix equation. Substituting equation (8) into equation (10) :

$$r^{(i_{BDS})} + \delta t_{u,BDS} = \rho_c^{(i_{BDS})} - \varepsilon_\rho^{(i_{BDS})} \tag{14}$$

In this way, we can establish a linearized joint location matrix equation that is equivalent to the formula (13):

$$\begin{bmatrix} M & M & M & M & M \\ -\mathbf{1}_x^{(i_{GPS})} & -\mathbf{1}_y^{(i_{GPS})} & -\mathbf{1}_z^{(i_{GPS})} & 1 & 0 \\ M & M & M & M & M \\ -\mathbf{1}_x^{(i_{BDS})} & -\mathbf{1}_y^{(i_{BDS})} & -\mathbf{1}_z^{(i_{BDS})} & 0 & 1 \\ M & M & M & M & M \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ \Delta\delta t_{u,GPS} \\ \Delta\delta t_{u,BDS} \end{bmatrix} = \begin{bmatrix} M \\ b^{(i_{GPS})} \\ M \\ b^{(i_{BDS})} \\ M \end{bmatrix} \tag{15}$$

By adding the fifth unknown parameter in the GPS/BDS dual-mode joint location equation, the receiver avoids the use of potentially incorrect system time difference broadcast values. Allows the receiver to freely and flexibly compute the difference in time of the system that change over time [5].

IV. CARRIER SMOOTHING PSEUDO RANGE

A. Principle of carrier smoothing pseudo range

The pseudo range error of the satellite navigation system is large, which is susceptible to multi-path effect, and the measurement error can reach 1~3m [6-7]. The measurement error of carrier phase is only millimeter, and the error of random measurement is less than 1 cm when multipath effect is available. However, the carrier phase observation generally contains the ambiguity of the week, which limits the direct use of the carrier phase for positioning. The pseudo range is smoothed by the carrier phase difference value of the front and back, which can effectively reduce the noise of receiver measurement and multipath, and improve the location accuracy of pseudo range.

Assuming that there are no jump between adjacent epochs. Combining (3) and formula (4), the pseudo range and carrier phase measurement are calculated separately between the epochs:

$$\rho_k - \rho_{k-1} = r_k - r_{k-1} + I_k - I_{k-1} + \varepsilon_{\rho,k} - \varepsilon_{\rho,k-1} \tag{16}$$

$$\phi_k - \phi_{k-1} = r_k - r_{k-1} - I_k + I_{k-1} + \varepsilon_{\phi,k} - \varepsilon_{\phi,k-1} \tag{17}$$

It is assumed that the error caused by ionospheric delay at the adjacent moment is very small. Get the following formula:

$$I_k = I_{k-1} \tag{18}$$

Theoretically, the amount of pseudo range change and the amount of carrier phase change in units of distance should be equal.So:

$$\rho_k - \rho_{k-1} = \phi_k - \phi_{k-1} \tag{19}$$

According to the carrier phase difference, the pseudo range can be reconstructed by the formula (19):

$$\rho_k = \rho_{k-1} + (\phi_k - \phi_{k-1}) \tag{20}$$

As a result of $\varepsilon_\phi = \varepsilon_\rho$, the smoothed pseudo range error will be greatly compressed.

B. Carrier smoothing pseudo range based on ionospheric delay compensation

The divergent problem of carrier phase smoothing pseudo range is caused by ionospheric delay. This paper designs a carrier smoothing pseudo range method based on ionosphere delay compensation. Klobuchar's model is a commonly used model of ionospheric delay. The ionospheric delay error is calculated by using this model, and then use this error to compensate for pseudo range and carrier phase values. In the GPS system, the Klobuchar's model uses a constant to express the night's ionospheric delay and superimposes half a cosine function on the constant to indicate the daytime ionospheric delay. Using Klobuchar's model, the mathematical expression for estimating ionospheric time delay is:

$$I_{klo} = \begin{cases} F \times \left[5 \times 10^{-9} + A\left(1 - \dfrac{x^2}{2} + \dfrac{x^4}{24}\right)\right], & |x| < 1.57 \\ F \times 5 \times 10^{-9}, & |x| \geq 1.57 \end{cases} \tag{21}$$

where F is the tilt factor, and A is the amplitude. In the equation above,

$$x = 2\pi(t - 50400)/PER,$$

$$A = \max\left[\sum_0^3 \alpha_i (\phi_m)^i,\ 0\right],$$

$$PER = \max\left[\sum_0^3 \beta_i (\phi_m)^i,\ 72000\right]$$

ϕ_m indicates the geomagnetic latitude of the ionospheric penetrating point, which can be calculated by reference [8]. α_i and β_i (i=0,1,2,3) are the model parameters of the navigation message which is broadcasted to the user.

The Beidou positioning and navigation system also uses the Klobuchar's model to estimate the ionospheric time delay of the B1 signal. The formula is as follows:

$$I_{klo} = \begin{cases} 5 \times 10^{-9} + A_1 \cos\left[\dfrac{2\pi(t-50400)}{A_2}\right], & |t - 50400| < A_2/4 \\ 5 \times 10^{-9}, & |t - 50400| \geq A_2/4 \end{cases} \tag{22}$$

t is the location time at the intersection of receiver to satellite connection and the ionosphere. A_1 is amplitude and A_2 is the cycle.

According to the Klobuchar's model, the ionospheric delay variation of the k epoch and k-1 epoch is estimated as:

$$\delta I_{klo}(k) = I_{klo}(k) - I_{klo}(k-1) \tag{23}$$

$\delta I_{klo}(k)$ is used to compensate for pseudo range and carrier phase values. The smoothing of the k epoch can be improved to:

$$\rho'_{s,k}=\begin{cases}\frac{1}{k}\rho_k+(1-\frac{1}{k})[\rho'_{s,k-1}+(\phi_k-\phi_{k-1})+2\delta I_{klo}(k)], & 1\le k\le M\\ \frac{1}{M}\rho_k+(1-\frac{1}{M})[\rho'_{s,k-1}+(\phi_k-\phi_{k-1})+2\delta I_{klo}(k)], & k>M\end{cases} \quad (24)$$

Where $\rho'_{s,k}$ is the pseudo range value smoothed at time k, ρ_k is the pseudo range measurement at time k, and M is the smoothing time constant.

By using the method of carrier smoothing pseudo range based on ionospheric change, the error caused by ionospheric divergence can be suppressed to a certain extent and the smoothing precision is improved.

V. The Experiments And Results

In order to verify the feasibility of the GPS/BDS dual-mode receiver, the vehicle filed test and the high dynamic test are carried out.

The vehicle filed test was conducted in Nanjing. In the test, the starting point of latitude for 32.0273659°, longitude for 118.8957342°, height of 15.347m. The High precision integrated navigation system is used as the comparison datum. The system position and velocity errors are shown in Figures 4 and 5 below.

From figures 4 and 5, position error can converge to within 4.5m (1σ), velocity error can converge to 0.1m/s (1σ).The experimental results show that the performance index of the dual-mode receiver is good and meets the design requirements.

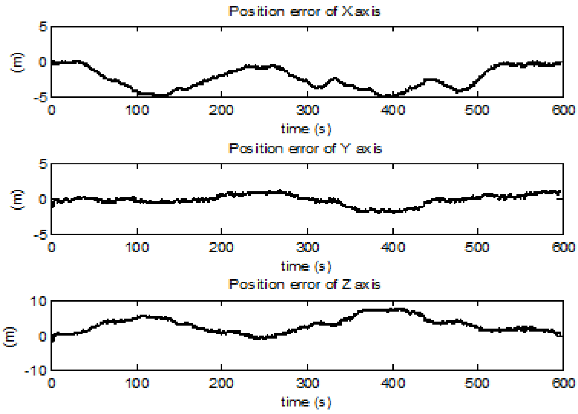

Figure 4. The position error

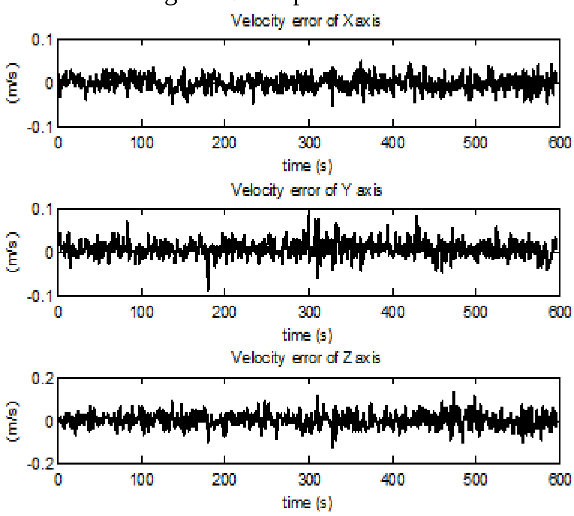

Figure 5. The velocity error

The high dynamic test uses satellite navigation signal simulator to simulate the high dynamic flight path of the carrier. The trajectory is set to: Low-orbit satellites (orbit data of the QB50 satellites in the European Union) with an orbital altitude of 360 km and a speed of approximately 7.6 km/s, making an approximate circular motion around the Earth. Figure 6 shows the trajectory of the simulation.

The experimental results are shown in Figures 7 and 8, compared with the original trajectory. position error can converge to within 5.1m (1σ), velocity error can converge to 0.2m/s (1σ). The experimental results show that the dual-mode receiver has good performance in high dynamic environment and meets the design requirements.

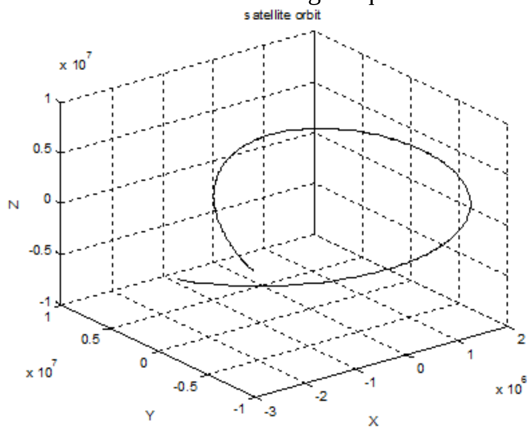

Figure 6. The trajectory of the satellite

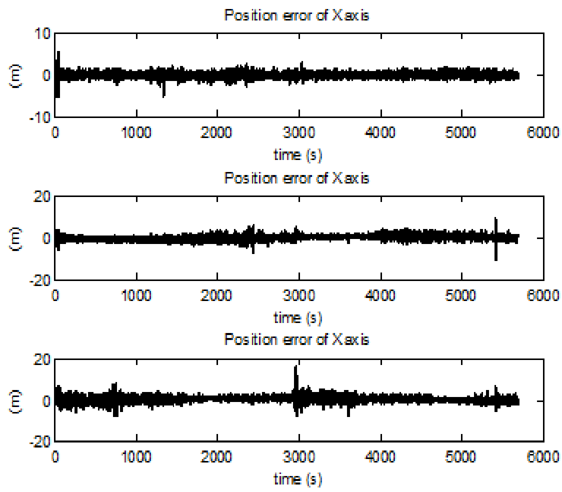

Figure 7. The position error

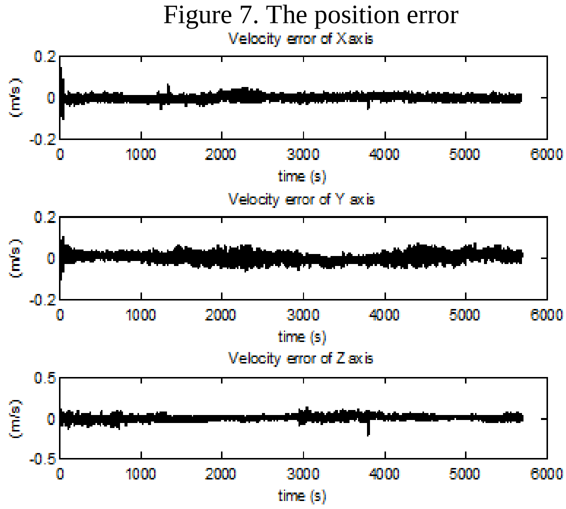

Figure 8. The velocity error

VI. CONCLUSIONS

This paper designs a GPS/BDS dual-mode satellite receiver based on ZYNQ-7020 platform, and introduces the hardware architecture and software algorithm in detail. Finally, the function and performance of the dual-mode satellite receiver were verified by vehicle filed test and high dynamic simulation data. The results show that the designed dual-mode satellite receiver satisfies the positioning requirements. The satellite receiver designed in this paper has a wide range of applications and has good development prospects in unmanned aerial vehicles, unmanned vehicles, and low-orbit satellites.

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