A Pseudo-satellite Implementation Method Using High Precision Time Synchronization

Ruifeng Zheng(✉)

Beidou Navigation Technology Co., Ltd., Beijing, China

Abstract. In this paper, a GNSS-based multi-frequency pseudo-satellite implementation method is proposed. The analysis results show that the GNSS multi-frequency pseudo-satellite system (including Beidou and GPS) can be applied to the general receiver. The pseudo-satellite system can improve the positioning accuracy of the general receiver and improve the usability of the navigation system. Simulation analysis and test are carried out for the method. The experimental results show that the pseudo-satellite method is achievable and can significantly improve the availability and accuracy of the GNSS system.

Keywords: Pseudo-satellite · Time-synchronous · Ephemeris · General receiver

1 Introduction

With the application and popularization of GNSS satellite navigation system, pseudo-satellite system has gradually become a research contents to enhance the positioning accuracy of GNSS system. In recent years, many people have carried out a lot of research on pseudo-satellites. Among them, reference [1] verified the indoor pseudo-satellite system; reference [2, 3] established a four-dimensional model with altitude angle, azimuth angle and observation time as independent variables and double difference relative precision factor as dependent variables for mine application, and carried out optimization design verification; reference [4] proposed the concept of generalized pseudo-satellite and a new generation of GNSS enhancement system framework based on generalized pseudo-satellite.This is the most challenging task, as land, sea, space, air, underwater, indoor, and underground should all be connected to the "5G + BDS/GNSS" indoor/outdoor integrated network [5].

Based on the above analysis and application, further work is carried out in this paper. The purpose of this paper is to design a pseudo-satellite system and test the accuracy of the pseudo-satellite positioning system. The signal transmitted by the pseudo-satellite system designed in this paper can be received by the general receiver, which can supplement and improve the accuracy of the satellite system under special conditions. In this paper, the multi frequency pseudo-satellite enhancement system is implemented, and the design of the internal signal generation part of the pseudo-satellite signal generator is realized.

In the development process of pseudo-satellite receiver, the problem that needs to be solved is to use general Beidou/GPS receiver to obtain the original navigation

C. Yang and J. Xie (Eds.): *China Satellite Navigation Conference (CSNC 2021) Proceedings*, LNEE 773, pp. 280–288, 2021.
https://doi.org/10.1007/978-981-16-3142-9_25

observation, including pseudo-satellite information, doppler information, carrier phase and message information, etc. Through the design of a set of post-processing pseudo-satellite positioning algorithm to post process the above information, the positioning solution of the pseudo-satellite enhancement system can be realized, and the output of the positioning results can be obtained, the positioning results are analysed.

2 Principle Analysis

In the conventional pseudo-satellite system, time synchronization technology is usually used to broadcast pseudo-satellite signal. Like satellite positioning, the positioning accuracy of Pseudo-satellite system is directly related to the clock accuracy. Therefore, obtaining accurate clock accuracy is the basis of improving the positioning accuracy of Pseudo-satellite system. This paper analyses and experiments to improve the clock accuracy of the system.

In the pseudo satellite system, the pseudo range observation equation is as follows:

$$\rho^{(sGPS)} = r^{(sGPS)} + \delta t_{u,GPS} - \delta t^{(sGPS)} + I^{(sGPS)} + T^{(sGPS)} + \varepsilon_{\rho}^{(sGPS)} \tag{1.1}$$

Among them, s represents different satellites; u represents user receiver; $\delta t_{u,GPS}$ represents receiver clock error; $\delta t^{(sGPS)}$ represents satellite clock error; I represents ionosphere delay; T represents tropospheric delay; and $\varepsilon_{\rho}^{(sGPS)}$ is pseudo range measurement noise. In the pseudo-satellite system, the influence of ionosphere can be ignored because there is no influence of ionosphere, and the factor that can improve the ranging error $r^{(sGPS)}$ is the clock error of the pseudo-satellite system $\delta t^{(sGPS)}$ because the tropospheric delay and pseudo range measurement noise depend on the actual environment and receiver.

According to reference [6], the clock error can be expressed by Allan variance. In the conventional crystal oscillator indexes, the relative frequency accuracy is less than $\pm 5 \times 10^{-9}$/day, the relative time accuracy is less than ±50 ns/day, and the Allan variance of short-term stability can reach $\pm 5 \times 10^{-9}$/s. In the high precision cesium clock, the relative frequency accuracy is less than $\pm 5 \times 10^{-14}$/day, the relative time accuracy is less than ±10 ns/day, and the Allan variance of short-term stability is less than or equal to 5×10^{-14}/s. Therefore, the system pseudo range error is raised to ns level by improving the clock index. Therefore, the pseudo range measurement errors introduced by the system clock are 10 ns * c ≈ 3 m, which can improve the positioning accuracy of the pseudo-satellite system to within 5 m.

3 Function Composition and Working Process of Pseudo-satellite System

3.1 Composition and Function

In the pseudo-satellite system, the main problems include the accuracy of clock synchronization and the problem of improving the network layout of the pseudo-satellite system. In this paper, a pseudo-satellite system based on high-precision cesium clock

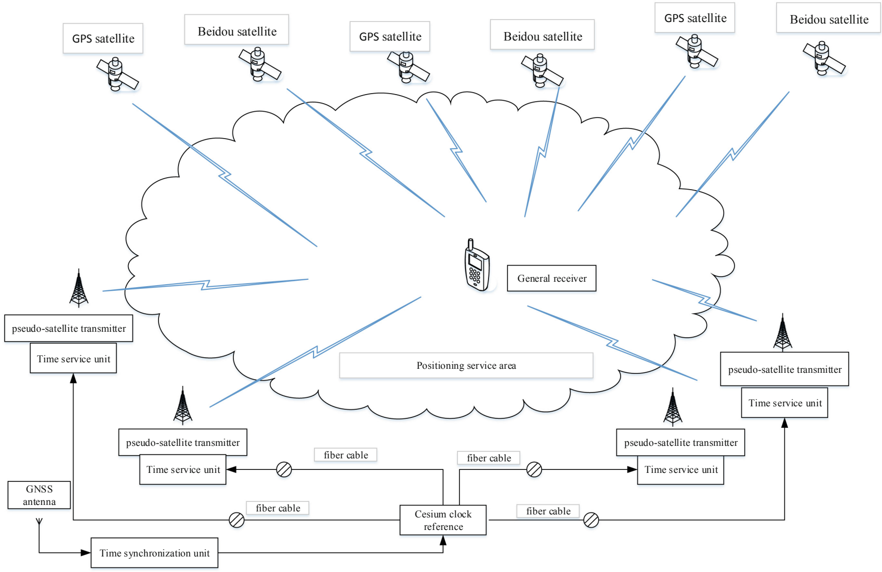

Fig. 1. Pseudo-satellite system composition block diagram

time synchronization is proposed. The composition of this pseudo-satellite system is shown in Fig. 1:

The main characteristics of this pseudo satellite positioning system are as follows:

(1) The time synchronization between pseudo-satellite system and GNSS satellite can realize the joint service of Pseudo-satellite system and GNSS system, and the user can realize positioning by using general receiver;
(2) Pseudo-satellite system can locate independently when GNSS signal cannot locate;
(3) The time synchronization of pseudo satellite signal generator can be realized through cesium clock networking, which can realize long-distance pseudo satellite signal networking;
(4) The synchronous time network generated by high-precision cesium clock is used to improve the positioning accuracy of Pseudo-satellite system; the high-precision cesium clock uses clock source regeneration technology to realize the traceability of high-precision time-frequency reference source; the high-precision clock transfer technology is used to complete the clock transfer of optical fiber cascade network.

The main components and functions of this pseudo satellite positioning system are as follows:

(1) Pseudo satellite signal generator: the system needs multiple pseudo satellites as signal sources to transmit GNSS signal in standard format. The modulation mode signal format is basically consistent with that of Beidou signal, and can be received by ordinary Beidou receiver. This scheme is realized through development;

(2) Cesium clock reference: it is the clock reference of the whole system, providing a clock with accuracy better than $1e^{-14}$;
(3) Time synchronization unit: the cesium clock is aligned with the GNSS system to ensure the long-term stability of the pseudo-satellite system. In this system, it is actually aligned with the GPS clock to realize the time base maintenance function. In this paper, tft3001 is used to realize the function. Part of the time is purified by the local cesium clock to generate stable second pulse signal, and the phase aging of 1PPS signal is less than 8 ns/day;
(4) Time service unit: receiving cesium clock reference clock through optical fiber, providing standard clock and 1PPS signal for each pseudo satellite signal generator, ensuring that the error between local clock and reference clock of pseudo satellite signal generator is less than 3 ns; optical fiber distance can reach 80 km, realizing clock transmission function; in this scheme, TFT 3001 equipment is used to trace to cesium clock and communicate with TFT 3001 Model 1002 equipment forms a star "clock transfer" system covering 80 km range; time synchronization and transfer are completed by TF protocol, so that cesium clock 1PPS signal can be stably and reliably transmitted to pseudo-satellite equipment, TF_ The relative phase accuracy of 1PPS signal is less than $5e^{-14}$/day, and the relative phase error is less than ± 10 ns/day.
(5) General receiver: receiving pseudo satellite signal, pseudo range measurement, navigation message calculation and positioning; this scheme is implemented by the general receiver.

3.2 Working Process

The main working process of the pseudo satellite positioning system is as follows:

(1) When the system works, first run the cesium atomic clock, and the cesium atomic clock runs stably, and achieves time synchronization with GPS through the time synchronization unit. Then, the reference clock signal of cesium atomic clock is transmitted to the clock input of pseudo satellite signal generator through the time service unit. In this system design, the system clock is 10 MHz, and the system synchronization signal is 1PPS, which ensures the accuracy of pseudo satellite signal generator Time synchronization between pseudo satellite navigation signal and GPS system;
(2) The receiver in the pseudo satellite signal generator receives the GNSS signal and calculates the current satellite information. At the same time, the pseudo satellite number that should be output and the pseudo range information of the pseudo satellite are calculated according to the satellite distribution;
(3) After the preparation of the internal signal generation of the pseudo satellite signal generator is completed, the pseudo satellite signal is output when the rising edge of the next 1PPS arrives; the pseudo satellite signal power output by the pseudo satellite signal generator is adjustable to ensure that the signal power received by the pseudo satellite user receiver is within the normal power range;
(4) The system control software can control all kinds of equipment, including pseudo-satellite signal generator and clock equipment. The operation control software can

flexibly control the transmitting state of Pseudo-satellite signal, modify the ranging code and message of Pseudo-satellite;

(5) Pseudo range measurement, navigation message calculation and positioning are carried out by using general user receiver.

4 Design and Implementation of Internal Algorithm

4.1 Design and Implementation of Pseudo-satellite Signal Generator

In order to carry out the pseudo satellite experiment, the pseudo satellite signal generator is specially designed. The pseudo-satellite signal generator includes ephemeris receiving module, clock module, baseband module, RF module and antenna part. It can generate customized pseudo-satellite ephemeris parameters by receiving GNSS signals, and generate pseudo-satellite RF signals of Beidou and GPS, and realize the power control and adjustment function of Pseudo-satellite. The block diagram of Pseudo-satellite signal generator is shown in Fig. 2.

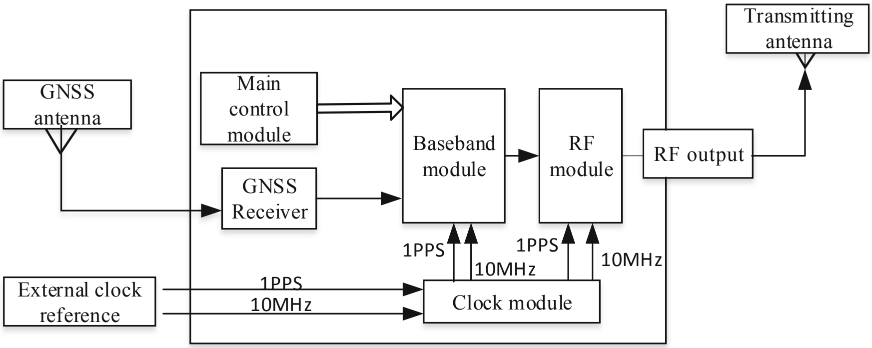

Fig. 2. Pseudo-satellite signal generator block diagram

The main functions of each part are as follows:

(1) The receiving antenna receives the actual satellite signal and transmits the signal to the base station navigation receiver;

(2) The GNSS receiver receives the ephemeris and almanac of the actual satellite, outputs the pseudo range parameters of the satellite, and sends them to the main control module through the serial port;

(3) The clock module receives the second pulse signal and 10 MHz signal from cesium clock, and outputs the two signals to baseband module and RF module respectively;

(4) The main control module runs related software, which is responsible for the parameter extraction of receiver, pseudo-satellite parameter simulation and pseudo-satellite baseband module control;

(5) The baseband module generates the baseband signal corresponding to the asterisk according to the command of the control computer and the second pulse synchronization of the clock taming module; calculates the parameters required by the digital signal processing algorithm according to the data transmitted by the control computer, generates the spread spectrum code, completes the signal spread spectrum, and generates the baseband digital signal; modulates the baseband signal to the digital intermediate frequency, and uses the DAC to convert the digital signal into the digital intermediate frequency In this paper, we design a special hardware circuit, the main chips are DSP, FPGA and DAC.
(6) RF module modulates IF signal of Pseudo-satellite baseband module into RF signal, outputs RF signal after filtering and amplification, receives clock of clock taming module, generates clock signal and local frequency signal required by baseband module, and finally connects RF output signal to transmitting antenna after combining; this paper realizes it through professional design.
(7) The transmitting antenna transmits the satellite signal to the presupposed service area.

4.2 Time Synchronization Algorithm and Synchronization Process

The system time generated by the pseudo satellite signal generator itself can be synchronized with 1PPS. The time synchronization accuracy depends on the internal sampling clock frequency and the time deviation of navigation observation message calculation. The time deviation of navigation observation and message calculation adopts mathematical calculation method, and the internal word length is 64 bits' floating-point calculation, so the error can be ignored The sampling time and frequency inside the block is 327.36 MHz, and the conversion time is 3 ns, which can meet the requirements of the system.

In order to realize the function of clock synchronization, the baseband module in this paper receives the time signal from cesium clock system, and reads the GNSS system time GPS time. When the pseudo satellite signal generator reads UTC in software, it uses 1PPS signal and 10 MHz to align in hardware synchronization. After the pseudo satellite signal generator reads the UTC time of the time service and obtains the stable 1PPS signal, it decides whether it has the condition to align with the actual time from the next second. After the judgment condition is established, it starts the signal simulation calculation and sends the time service instruction to the baseband module to calculate and generate the pseudo satellite signal of the next second. The 10 MHz clock signal output by the time service receiver is used as the pseudo satellite mode. The next 1PPS signal is used as the start signal of pseudo satellite signal generator. This mechanism ensures that the clock synchronization accuracy of multiple pseudo-satellite generators is consistent with that of cesium clock system.

4.3 Ephemeris Parameter Calculation Process

In this paper, we design a set of algorithms for generating Beidou and GPS pseudo-satellite signals, and transplant the algorithms to the pseudo-satellite baseband hardware platform, through which the pseudo-satellite baseband signals can be generated in real time; at the same time, in order to ensure that the existing receiving equipment can receive GPS and pseudo-satellite signals at the same time, the navigation message of Pseudo-satellite refers to the navigation message structure specified by GPS and Beidou standards. In addition, the pseudo-satellite coordinate position is confirmed after positioning by the receiver, and the pseudo-satellite information is written into the navigation message after real-time dynamic calculation and adding the error between the transmitting antenna and the receiving antenna.

According to the different positions of pseudo-satellites, the ephemeris calculation process of the selected pseudo-satellites is as follows: as shown in Fig. 3, taking the position of the receiving antenna of the user equipment as the origin, the measurement coordinate system is established, in which the altitude angle and azimuth angle of the satellite are calculated.

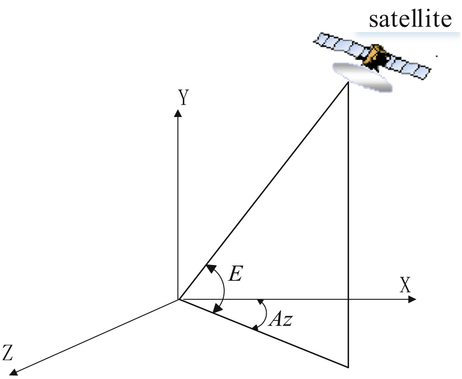

Fig. 3. Altitude and azimuth of satellite.

(1) Calculate the position of the satellite $\vec{r}_c^s$ in the measurement coordinate system, as shown in Eq. 4.1.

$$\vec{r}_c^s = R_Y(-90^\circ)R_X(B)R_Z(-90^\circ + L)(\vec{r}_D^s - \vec{r}_D^u) \tag{4.1}$$

In Eq. 4.1, $\vec{r}_D^s$ and $\vec{r}_D^u$ are the satellite coordinates and the user coordinates in the ECEF coordinate system respectively; and (L, B) are the longitude and latitude of the user.

(2) Calculate the altitude and azimuth of the satellite, as shown in Eq. 4.2.

$$\begin{cases} E = arctg(y_{sc}/D) \\ Az = \arccos(x_{sc}/D) + \begin{cases} 0, & \mathrm{z} \geq 0 \\ \pi & \mathrm{z} < 0 \end{cases} \end{cases} \tag{4.2}$$

In Eq. 4.2, $D = \sqrt{x_{sc}^2 + z_{sc}^s}$.

5 Test and Result Analysis

According to the scheme designed in this paper, the author has completed the development and actual test of the system. The experiment is an analysis of the positioning after the pseudo-satellites are combined with the actual GNSS System. The block diagram of the experiments is shown in Fig. 4

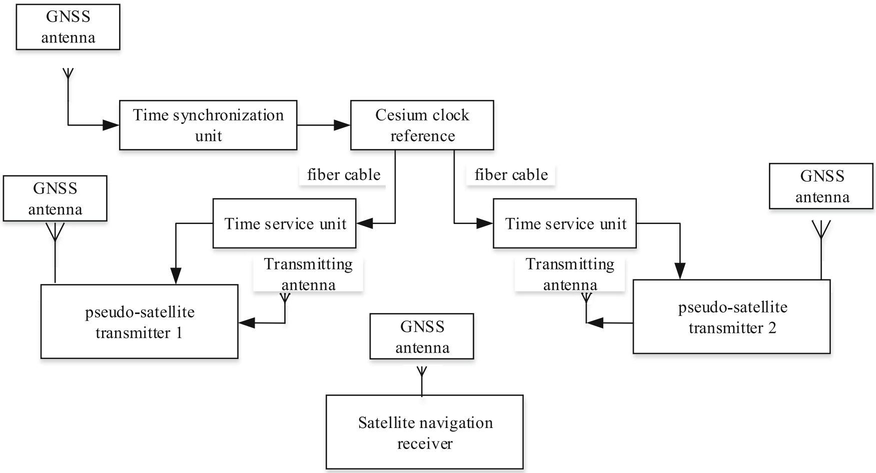

Fig. 4. Block diagram of joint working between pseudo-satellite and GNSS.

The experimental process is following the steps:

(1) The satellite navigation receiver receives the pseudo satellite signal and GNSS signal at the same time;
(2) The pseudo satellite signal generator adopts antenna transmission mode;
(3) The pseudo satellite signal generator simultaneously transmits GPS signals of G31 and Beidou signals of B12 and B13;
(4) The receiver receives real satellite signal and pseudo satellite signal at the same time.

The positioning data of the receiver is plotted, and the positioning accuracy results are shown in Fig. 5. The statistical analysis of the receiver data shows that the average positioning error is less than 5 m.

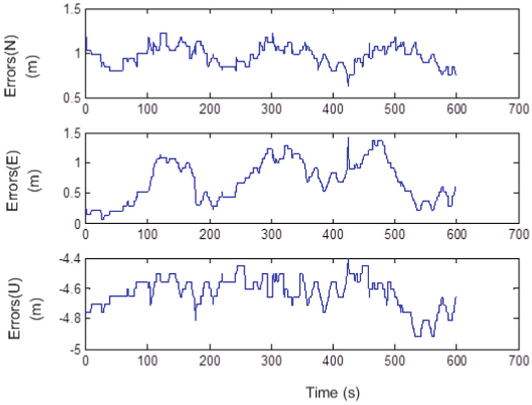

Fig. 5. Positioning errors of joint working between pseudo-satellite and GNSS.

6 Conclusion

The actual test results show that the positioning accuracy of the pseudo-satellite system designed in this paper can reach 5 m under the condition of joint positioning of Pseudo-satellite and GNSS.

The method proposed in this paper can achieve joint positioning without changing the existing receiver, and can effectively improve the positioning accuracy of the system.

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