

DigitalIF GPS Signal Simulator Design

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Abstract: In order to test the static and dynamic performance of a Global Positioning System (GPS) receiver, a GPS signal simulator is required to generate real satellite signals in various environments. The software simulator is widely used because of the advantages of being flexible and reprogrammable. Therefore, a digital intermediate frequency GPS signal software simulator which implemented using MATLAB software is proposed. It is a method to calculate the satellite ephemeris parameters by using the anchor point, satellite elevation angle and azimuth angle, and to achieve navigation information transmission delay by modifying the C/A code frequency based on analyzing the positional relationship between the satellite and the receiver. The simulation results show that the simulator is correct and effective. When the receiver is stationary and the satellite is moving, the receiver positioning error is less than 1 m.

Key words: GPS; Ephemeris Parameters; Satellite; C/A Code

1 Introduction

GPS signal simulator is used to provide a simulation environment for the receiver in the design stage, which is an important tool for measuring the performance of the receiver^[1]. The literature^[2-5] has studied the modeling process of digital intermediate frequency (IF) signals, which considering the whole process from satellite signal generation to IF sampling at the receiving end. The literature^[6-7] also considers the impact of receiver motion model on GPS simulator modeling. However, the above literature does not analyze the design method of ephemeris parameters in navigation messages.

The GPS signal software simulator proposed in this paper involves the ephemeris parameter design method and the delay of navigation information. In detail, the satellite ephemeris parameters are calculated using the positioning point, satellite elevation angle and azimuth angle. The simulated GPS signal takes into account all the satellites navigation signals and all the path delays from sending to receiving. In one frame time (30s) of ephemeris, due to the movement of satellite and receiver, the distance between satellites and receiver changes, which affects the transmission delay, that is, the Doppler shift^[8],

therefore, the method to modify the C/A code frequency to correct the transmission delay of one frame time is proposed. Finally, a GPS signal software simulator is implemented using MATLAB software. Experiment shows that the navigation signal generated by the simulator can reach a small positioning error.

2 Overall Design of Digital IF GPS Signal Simulator

The structure of the digitalIF GPS signal simulator designed in this paper is shown in Figure 1, including ephemeris parameter design and delay module. In this paper, positioning point, satellite elevation angle and azimuth angle are used to calculate ephemeris parameters, and the C/A code frequency is modified to correct the transmission delay of one frame time. The trajectory of satellites within 30s after transmission can be calculated from the ephemeris parameters, and the transmission delay between satellites and receiver can be obtained at any time, which includes the basic delay and the offset delay. According to the GPS positioning principle, at least four satellites are required for effective positioning. In this paper, the IF signals of multiple satellites can

be superimposed and transmitted.

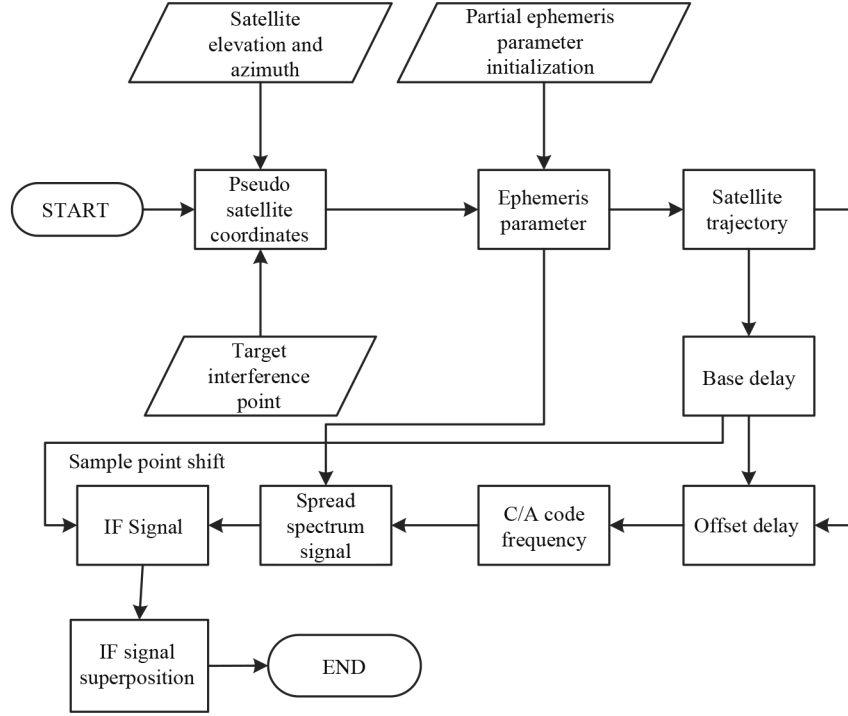


Fig. 1 Digital IF GPS Signal Simulator Structure

3 Ephemeris Parameter Design Method

3.1 Satellite Elevation and Azimuth Analysis

The positioning accuracy of the GPS navigation system is measured by PDOP (Position Dilution of precision). It is strongly related to the geometry between the satellite and the receiver. When the degree of satellite distribution is poor, its PDOP and the positioning error is large^[9]. In GPS signal simulator, the satellite navigation signal is also affected by noise. Especially when the available satellites are less, in order to improve the positioning accuracy, the simulator needs to refer to anchor point to establish the elevation angle and azimuth of the satellite. For the receiver, it does not know its true position, and the position is solved by positioning equation, so the elevation and azimuth are relative to the anchor point, not the true position of the receiver.

Let the receiver positioning point in the Earth-Centered, Earth-Fixed (ECEF) coordinate system be (x, y, z) , The corresponding Geodetic coordinates is (φ, λ, h) , satellite position is (x_s, y_s, z_s) , then

the observation vector is:

$$\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} = \begin{bmatrix} x_s \\ y_s \\ z_s \end{bmatrix} - \begin{bmatrix} x \\ y \\ z \end{bmatrix} \quad (1)$$

After the coordinate transformation, the position of the positioning point is taken as the coordinate origin, and the position of the satellite in local Cartesian coordinates coordinate system $(\Delta e, \Delta n, \Delta u)$ is:

$$\begin{bmatrix} \Delta e \\ \Delta n \\ \Delta u \end{bmatrix} = S \cdot \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} \quad (2)$$

where S is the coordinate transformation matrix:

$$S = \begin{bmatrix} -\sin\lambda & \cos\lambda & 0 \\ -\sin\varphi\cos\lambda & -\sin\varphi\sin\lambda & \cos\varphi \\ \cos\varphi\cos\lambda & \cos\varphi\sin\lambda & \sin\varphi \end{bmatrix} \quad (3)$$

The elevation angle of the satellite is:

$$\theta = \arcsin\left(\frac{\Delta u}{\sqrt{(\Delta e)^2 + (\Delta n)^2 + (\Delta u)^2}}\right) \quad (4)$$

Azimuth angle is:

$$\alpha = \arctan\left(\frac{\Delta e}{\Delta n}\right) \quad (5)$$

3.2 Ephemeris Parameter Calculation

The Kepler orbital parameter is used to describe the unobserved elliptical orbital motion of a GPS satellite and consists of 6 parameters: right ascension of ascending node Ω_0 , orbital inclination i_0 , argument of perigee ω , long radius $\sqrt{a_s}$, eccentricity e_s and true anomaly ν . Where (Ω_0, i_0, ω) defines the orbital plane of the satellite, $(\sqrt{a_s}, e_s)$ defines the specific elliptic equation or motion orbit of the satellite in the elliptical orbit plane, ν defines the specific location of the satellite. The calculation process of satellite ephemeris parameters is given below:

Calculate the ECEF (x, y, z) coordinates using the Geodetic coordinate (φ, λ, h) of the given anchor points:

$$\begin{cases} x = (N + h) \cos \varphi \cos \lambda \\ y = (N + h) \cos \varphi \sin \lambda \\ z = [N(1 - e^2) + h] \sin \varphi \end{cases} \quad (6)$$

$$N = \frac{a}{\sqrt{1 - e^2 \sin^2 \varphi}} \quad (7)$$

where e is the eccentricity, a is the reference ellipsoid long radius, e and a are constants, N is the radius of curvature of the reference ellipsoid. The average height of GPS satellites is 20,000km and the radius of the earth is 6400km. Then the observation vector satisfies the equation:

$$2\rho\Delta\rho\sin\theta + \Delta\rho^2 + \rho^2 = (26400 \times 10^3)^2 \quad (8)$$

where ρ and $\Delta\rho$ are:

$$\rho = \sqrt{x^2 + y^2 + z^2} \quad (9)$$

$$\Delta\rho^2 = (\Delta u^2 + \Delta e^2 + \Delta n^2) \quad (10)$$

Initialize the satellite elevation angle θ , solving Equation (8) to get $\Delta\rho$. Initialize satellite azimuth α , and combined with (2), (3), (4), (5), it can be solved to get $(\Delta x, \Delta y, \Delta z)$. The position of the satellite in ECEF coordinate (x_k, y_k, z_k) is obtained by the equation (1), where k is the time number. The position (x'_k, y'_k) in the orbital plane rectangular coordinate system is:

$$\begin{bmatrix} x_k \\ y_k \\ z_k \end{bmatrix} = \begin{bmatrix} \cos \Omega_k & -\cos i_k \sin \Omega_k \\ \sin \Omega_k & \cos i_k \cos \Omega_k \\ \sin i_k & 0 \end{bmatrix} \cdot \begin{bmatrix} x'_k \\ y'_k \\ y'_k \end{bmatrix} \quad (11)$$

where Ω_k and i_k are the ascending node right ascension and orbital inclination at time $(t_k + t_{oe})$, respectively. Initialize the orbital inclination i_k , solving the unknown gets:

$$\begin{cases} y'_k = \frac{z_k}{\sin i_k} \\ \Omega_k = -\arctan2\left(\frac{x'_k}{y'_k}\right) \pm \arccos\left(y'_k \cdot \frac{\cos(i_k)}{r_k}\right) \\ x'_k = \frac{(y_k - y'_k \cos i_k \cos \Omega_k)}{\sin \Omega_k} \end{cases} \quad (12)$$

where r_k is the satellite diameter length:

$$r_k = \sqrt{(x'_k)^2 + (y'_k)^2} \quad (13)$$

In equation (12), the operation $\arctan2$ is:

$$\arctan2\left(\frac{A}{B}\right) = \begin{cases} \arctan(A/B), \text{ when } B > 0 \\ \arctan(A/B) + \pi, \text{ when } B \leq 0 \end{cases} \quad (14)$$

Initialize $\dot{\Omega}$ and t_{oe} , find the right ascension of ascending node Ω_0 at the time t_{oe} , and the angle of intersection u_k at the time $(t_k + t_{oe})$ is:

$$\Omega_0 = \Omega_k - (\dot{\Omega} - \dot{\Omega}_e) t_k + \dot{\Omega}_e t_{oe} \quad (15)$$

$$u_k = \arctan2(y'_k / x'_k) \quad (16)$$

where $\dot{\Omega}_e$ is the angular velocity constant of the Earth's rotation. (r_k, u_k, Ω_k) is the polar coordinate representation of the position in the orbital plane Cartesian coordinate system. u_k is the correction value of φ_k .

$$u_k = \varphi_k + C_{us} \sin(2\varphi_k) + C_{uc} \cos(2\varphi_k) \quad (17)$$

In the formula, C_{us} and C_{uc} are the sine and cosine harmonic correction parameters of the ascending node angular distance, respectively. Initialize C_{us} and C_{uc} , and using an iterative algorithm to solve the pitch angle of the ascending node angular distance φ_k . Initialize the sine and cosine harmonic correction parameters C_{is} , C_{ic} of the orbital inclination, initialize the correction parameter i and the time difference

t_k , and calculate the orbital inclination at time t_{oe} :

$$\begin{cases} \delta i_k = C_{is} \sin(2 \varphi_k) + C_{ic} \cos(2 \varphi_k) \\ i_0 = i_k - i \cdot t_k - \delta i_k \end{cases} \quad (18)$$

The sine and cosine harmonic correction parameters C_{rs} and C_{rc} of the orbital radius are initialized to obtain the satellite radial correction length:

$$\delta r_k = C_{rs} \sin(2 \varphi_k) + C_{rc} \cos(2 \varphi_k) \quad (19)$$

Initialize the argument of perigee ω and solve the true anomaly:

$$v_k = \varphi_k - \omega \quad (20)$$

Initialize e_s , and iteratively solve the near point angle:

$$\tan(v_k) = \frac{\sqrt{1-e_s^2} \sin E_k}{\cos E_k - e_s} \quad (21)$$

Solving the orbit long radius a_s :

$$a_s = \frac{r_k - \delta r_k}{1 - e_s \cos E_k} \quad (22)$$

Solving the near point angle M_k :

$$M_k = E_k - e_s \sin E_k \quad (23)$$

Solving the average angular velocity:

$$\begin{cases} n_0 = \sqrt{\frac{\mu}{a_s^3}} \\ n = n_0 + \Delta n \end{cases} \quad (24)$$

where μ is the gravity constant of the Earth, and Δn is initialized to get n . Then at time t_{oe} :

$$M_0 = M_k - n t_k \quad (25)$$

The time difference t_k is used to define the satellite position at time $(t_{oe} + t_k)$ as (x_k, y_k, z_k) , and the satellite position in other frame time can be calculated by the simulator using the ephemeris parameters of the above design.

The parameters that need to be initialized during the ephemeris parameter calculation process include the geodetic coordinates of the anchor point (φ, λ, h) , satellite elevation angle θ , azimuth and other parameters, include α , t_{oe} , e_s , i_k , t_k , ω , Δn , \dot{i} , $\dot{\Omega}$, C_{us} , C_{uc} , C_{is} , C_{ic} , C_{rs} , C_{rc} . The parameters that need to be solved include $\sqrt{a_s}$, i_0 , Ω_0 , M_0 . Each satellite needs to separately design elevation, azimuth and ephemeris parameters. When the posi-

tioning point moves locally with respect to the satellite, its elevation angle and azimuth angle change slowly and continuously. Set the initial position of the satellite relative to the anchor point, and keep the navigation information of one frame unchanged. After adding the delay, the positioning point is dynamically changed locally without adjusting the satellite position and ephemeris parameters in real time. Due to the slow change of elevation angle and azimuth, the simulator must simultaneously detect the relative position of the receiver and the satellite. When the PDOP value is large, re-initialize the satellite elevation and azimuth, and calculate the satellite position and ephemeris parameters so that the receiver always has a small positioning error.

4 GPS Navigation Information Delay Method

4.1 Base Delay

Set the location at the time of satellite transmission frame header is (x_i, y_i, z_i) . And i is the satellite number, location is (x_A, y_A, z_A) , the pseudo-range of each satellite is:

$$d_i = \sqrt{(x_A - x_i)^2 + (y_A - y_i)^2 + (z_A - z_i)^2} + c \Delta t_i \quad (26)$$

where Δt_i is the clock difference between the satellite and the receiver, and the information transmission delay $\Delta \bar{t}_i$ is:

$$\Delta \bar{t}_i = d_i / c - \Delta t_i \quad (27)$$

The delay of the satellite navigation signal is relative and its value is greater than zero. When there is a delay less than zero, the correction values for all delays are obtained:

$$\Delta \hat{t}_i = \Delta \bar{t}_i + \left| \min_{1 \leq i \leq N} (\Delta \bar{t}_i) \right| + t_c \quad (28)$$

where t_c is the delay value constant greater than zero, and N is the number of satellites. After using this delay value, the clock error between the receiver and the satellite becomes:

$$\Delta \hat{t}_i = \Delta \bar{t}_i - \left| \min_{1 \leq i \leq N} (\Delta \bar{t}_i) \right| - t_c \quad (29)$$

In digital signals, this delay is converted to the delay of the IF sampling point of the GPS signal. The

sampling frequency of the IF signal is f_s , and the number of delayed sampling points is $n_i = \Delta t_i f_s$, and the sampling frequency f_s has an influence on the positioning error.

4.2 Offset Delay

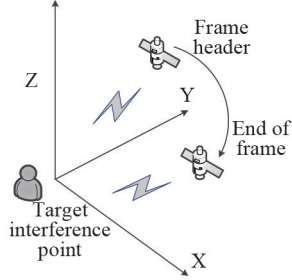


Fig. 2 Pseudo-Range Change from Frame Header to Frame End

Due to the dynamic changes of satellite position and positioning point, at both frame head and frame end of the navigation information, both transmission delay and distance between satellites and positioning point change. Therefore, this leads to the Doppler shift of the satellite signal. In fact, When the satellite moves at a higher speed relative to the receiver, and the positioning point is stationary, within one frame time, the distance between the satellite and the receiver changes at frame head and end, as shown in Fig. 2. Let the initial position of the satellite at the frame head be (x_i, y_i, z_i) , according to the above design ephemeris parameters, the simulator calculates the position of the satellite at the frame end is (x'_i, y'_i, z'_i) . And the pseudorange at frame end can be obtained, which is:

$$d'_i = \sqrt{(x_A - x'_i)^2 + (y_A - y'_i)^2 + (z_A - z'_i)^2} + c\Delta t'_i \quad (30)$$

Get the transmission delay difference as:

$$\Delta t''_i = (d'_i - d_i) / c \quad (31)$$

Then, when the ephemeris parameters of one frame time sent by the satellite arrives at the receiving end, its frame length becomes $(\Delta t''_i + 30)$. Assuming that the satellite and the positioning point delay are linear, and the 1500 bits information transmitted remains unchanged, the code frequency be-

comes:

$$f_i = 1023 \times 1500 \times 20 / (30 + \Delta t''_i) \quad (32)$$

It can be seen that the delay module of simulator includes two parts. One part is the relative delay of each satellite at the frame head, which is called base delay. The other part is the variation delay caused by Doppler shift in one frame time, called offset delay. Under the conditions of initializing the positioning point and part of the ephemeris parameters, the calculated values of the satellite ephemeris parameters, the base delay and the offset delay are determined only by the elevation and azimuth of the satellite. In this paper, the basic delay is achieved by the sampling point shift of the IF signal, and the offset delay is achieved by modifying the C/A code frequency.

5 Simulation Results

This paper takes one frame navigational message of four satellites as an example to test the positioning performance of the IF signal of the GPS simulator. All calculations should be accurate, otherwise, there will be large errors in calculation results. The average elevation of Beijing is 43.5m, and the average elevation of the Yellow Sea is 72.260m. The latitude and longitude range are from $39^\circ 26'$ to $41^\circ 03'$ north latitude, and $115^\circ 25'$ to $117^\circ 30'$ east longitude. Taking geodetic coordinates (40° , 116° , 115.76) as an example, the coordinates of ECEF are $(-2145883.837, 70315, 4399713.8760257, 4080005.26123138)$. Initialize the elevation angle, azimuth and other ephemeris parameters of the four satellites, and calculate the position and code frequency of the four satellite in frame head which are shown in Tables 1 and 2. Table 1 lists the private parameters of each satellite, and Table 2 lists the common parameters of the four satellites. The elevation and azimuth parameters designed in this paper are evenly distributed around the positioning point. After calculation, the corresponding PDOP value is 1.6330. In one frame time, the satellite S4 motion trajectory is shown in Figure 3, and its height is about 20,000 kilometers. The receiver positioning position coordinates are

shown in Figures 4 and 5. Compared with the anchor point, the longitude error in the geodetic coordinates is less than 0.0000001° , and the latitude error is less

than 0.00010° . In the WGS-84 coordinates, the X, Y, and Z axis coordinate errors are less than 1 m.

Table 1 Satellite Coordinates and Ephemeris Parameters (Private Parameters)

Parameter	Satellite S1	Satellite S2	Satellite S3	Satellite S4
Elevation Angle * ($^\circ$)	90	0	0	0
Azimuth * ($^\circ$)	0	120	240	0
i_k * (rad)	1.5263397448	1.525398163397448	1.52398163397448	1.525398163397448
ω * (rad)	-1.717457876	-1.717457876	-1.717457876	-1.817457876
e_s *	$0.0059120382 \times 10^{-6}$	$0.0089120382 \times 10^{-7}$	$0.00881203826 \times 10^{-6}$	$0.005962038265 \times 10^{-6}$
X(m)	-8871354.6426	-25696941.7431	14186164.4721	5073125.75785
Y(m)	18188972.5037	2074150.11187	21526440.7463	-10401449.2301
Z(m)	16953434.8044	-5732776.30914	-5732776.30914	23705568.4022
Delay (s)	0.0668045527467	0.0854569636351	0.0854569636351	0.0854569636351
Code Frequency (MHz)	1.022999980049	1.0230032375812957	1.02300136155623	1.0230031342104137
$\sqrt{a_s}$ (m)	5138.0842862001	5139.05653606577	5139.05653796536	5136.12362436012
i_0 (rad)	1.52633967130072	1.52539827722757	1.52398174780593	1.52539804130185
Ω_0 (rad)	2.00568174521019	3.08952976074568	1.01690645304428	5.09135789417098
M_0 (rad)	2.41620700813181	1.49900919199154	1.49899462569214	2.9368093544197

Table 2 Satellite Ephemeris Parameters (Shared Parameters)

Parameter	Value	Parameter	Value
C_{us} *	$2.237036824 \times 10^{-6}$	C_{uc} *	$3.054738045 \times 10^{-7}$
C_{is} *	$8.940696716 \times 10^{-8}$	C_{ic} *	$-8.381903172 \times 10^{-8}$
C_{rs} *	2.53125	C_{rc} *	350.53125
Δn * (rad/s)	$4.249105564 \times 10^{-20}$	\dot{i} * (rad)	$7.422851197 \times 10^{-51}$
$\dot{\Omega}$ * (rad/s)	$-8.151768125 \times 10^{-9}$	t_{oe} * (s)	256
t_k * (s)	-4		

Explanation: * indicates the simulator initialization parameter, otherwise the parameter is calculated.

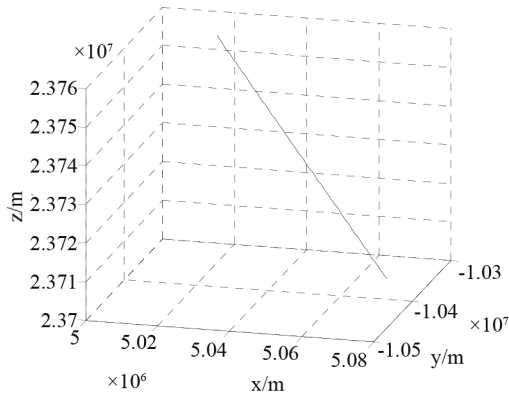


Fig. 3 Satellite S4 Motion Trajectory

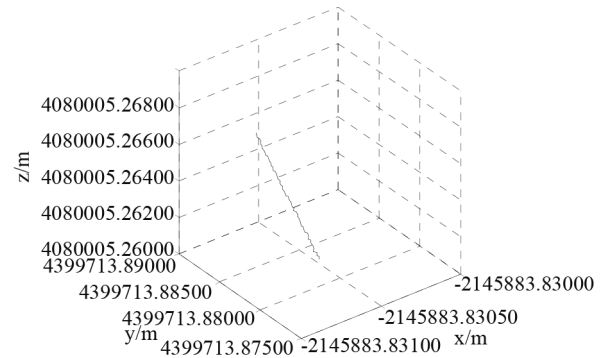


Fig. 4 Positioning Position in WGS-84 Coordinates

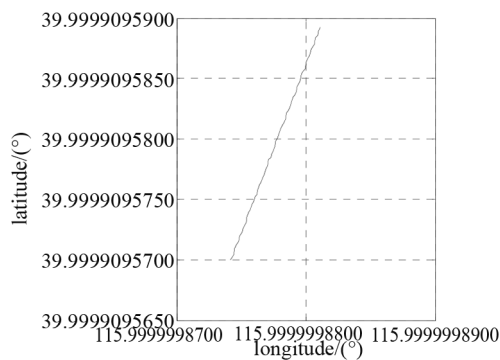


Fig. 5 Positioning Position in Geodetic Coordinates

6 Conclusion

In this paper, the positioning point, satellite elevation angle and azimuth angle are used to calculate the position of the satellite in the ECEF coordinate system, then calculate the navigation ephemeris parameters, the basic delay and the offset delay. The basic delay is achieved by using the frequency translation of the IF signal, and the offset delay is achieved by modifying the C/A code frequency. Since the elevation angle and azimuth angle of the satellite are established by the simulator, satellites with small DOP value can be selected to improve the positioning accuracy of the receiver, and thus has high efficiency. Finally, a software simulator is implemented using MATLAB software. The simulation results show that the ephemeris parameter design method and delay scheme of the simulator are correct. When the receiver is stationary and the satellite is moving, under theoretical conditions, the receiver positioning error is less than 20m. This error is mainly due to the linearization of the delay, that is, the C/A code frequency does not change within 30s. In practical applications, the C/A code frequency is changed, therefore the positioning error can theoretically be less than 1 m.

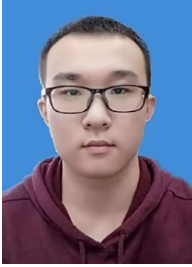
References

- [1] Liao, M., Liu, P. and Ying, R. (2012). Design and implementation of GPS IF digital signal generator. *Information Technology*, 36(05), pp. 47-51+54.
- [2] Wang, C., Wang, S., Li, W., Wang, M. and Luo, D. (2008). Design of a Software Simulator for Digitized IF GPS Signal. *Modern Defense Technology*, (04), pp. 128-135.
- [3] Ding, J., Zhao, L., Huang, W. and Liu, F. (2008). Schematic Design and Verification for IF GPS Signal Generator. *Journal of Data Acquisition & Processing*, (04), pp. 497-501.
- [4] Li, B., Zhang, Q. and Yang D. (2006) Research and Implementation of Carrier and Code NCO in GPS Signal Simulator. *Journal of Test and Measurement Technology*, (06), pp. 517-523.
- [5] Zhao, J., Zhang, Q., Chang, Q. and Li, J. (2003) The Key Technique Analysis and Applications of High Dynamic GPS Signal Simulator. *Telecommunication Engineering*, (04), pp. 49-54.
- [6] Zhang, B., Zhang, Q. and Chang, Q. (2008) Development on the High Dynamic GPS Signal Simulator Signal Model. *ACTA Electronica Sinica*, (06), pp. 1084-1087.
- [7] Liu, S. and Zeng, Y. (2011) Design and Application of GPS Simulator in the Simulation of UAV. *Computer Measurement & Control*, 19(10), pp. 2522-2524+2528.
- [8] Li, C., Lu, M. and Feng, Z. (2008) Mathematical model and realization for GPS IF signal simulator. *Journal of Tsinghua University (Science and Technology)*, (10), pp. 1582-1585.
- [9] Sun, H., Hao, X., Feng, W. and Yin, J. (2011) Inter-satellite links topology scenario based on minimum PDOP criterion. *Journal of Beijing University of Aeronautics and Astronautics*, 37(10), pp. 1245-1249.

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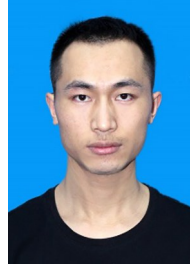


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