TIME SYNCHRONIZATION AND FREQUENCY PRECISION CONTROL AMONG MULTIPLE BASE STATIONS IN GPS

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ABSTRACT

In this paper, we develop a method for achieving high precision of time and frequency synchronization among multiple base stations in GPS system. We first describe the basic theory of timing and frequency checking, and then analyze several error sources which influence the precision of time and frequency synchronization. Furthermore, we derive explicit formula for calculating the precision of time and frequency. Tested results have indicated that our method can indeed achieve very high time and frequency precision.

KEYWORDS

GPS, Precision, Time Synchronization, Frequency Control

Ⅰ. INTRODUCTION

In a single-direction multiple base station distance-determining system, the error of the sample time taken to calculate distance parameter by each base station will be multiplied by light speed and then directly brought into the distance calculation, becoming the major error affecting the final results. Therefore, to keep high precision of time synchronization is demanded to allow each base station to be able to describe the target's moving characters on the same time standard, in order to compare or jointly process the data to improve the precision and reliability (ref.[1][2]). There are several methods in application to synchronize time in us grade, as long-wave, short wave, satellite time checking system, etc. New methods are required to improve the precision of the system to *ns* grade.

In application, in order to realize the time synchronization between two base stations, the well applied method is to regularly check the local clock and then let it keep the correct time. Errors of time synchronization appear in two phases: time checking and time keeping. Time checking is the process to keep the local clock synchronizing with a received standard time signal by continuously compensating the local clock through a control circuit. The time checking process is actually a time measuring process. Errors in time checking come mainly from the receiving noise in the transit of the standard time signal and the remaining time difference by controlling compensation. There are a few ways to realize ns-grade time synchronization of the system, like the atom clock transport time checking, microwave bothway transmit time checking, optical fiber bothway transmit time checking and GPS, etc. Another problem is to keep the frequency synchronization. The major errors appearing in single-direction time measurement are the aircraft carried frequency error and the ground base frequency coordinate error. In this paper, we first explain how to use GPS to realize high precision time and frequency control, and then analyze the achievable time and frequency precision through calculation.

Ⅱ. HIGH PRECISION TIMING AND FREQUENCY CHECKING METHOD WITH GPS

In this paper, we hypothesize a composition of four base stations that form a ca. 30x30km square. The measurement target passes by the center point of the square. In each base station a GPS timing and frequency checking receiver is set up to receive signals from the same high elevation GPS satellite in order to measure the distance between the GPS satellite and the receiver at the moment of the sample time, to make sample time coordinate through calculating the time parameter in the GPS system at that moment and to calculate the relative difference between local frequency coordinate and the GPS signal frequency (ref.[3][4]). Less the Doppler frequency, this difference will be the after modification to modify the target frequency amplifier receiver's Doppler value to measurement target, thus to achieve time and frequency synchronization among different base stations. The relation between the GPS receiver and the other facilities in the system is shown in fig. 1.

In fig.1, the time encoder is used to produce sample time-sequenced pulse sequences and gather pseudocode tracking data and carrier Doppler data received by GPS receiver and multiple targets receiver. Sample pulses of time encoder are generated by independent clock. Calculating the difference between local time and GPS system time and correcting it in the later data process, sample data from each base station can correspond to the unified GPS system time. Meanwhile, we calculate the difference between downlink signal frequency received by GPS receiver and its nominal frequency to get a frequency difference on frequency coordinate of 10MHz. So we can modify the measurement data of target's Doppler frequency to eliminate the relative error in frequency standard used to measure speed between base stations.

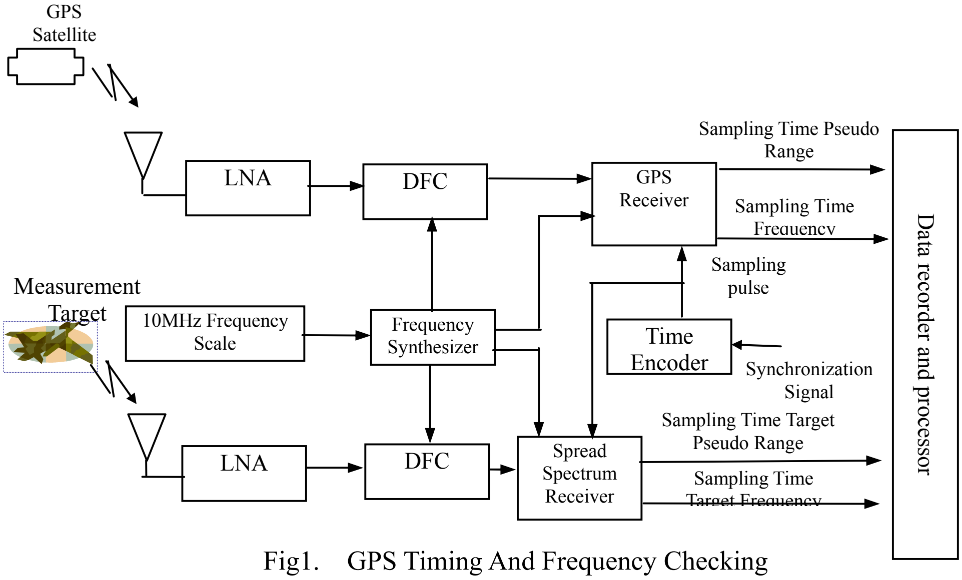

Fig1. GPS Timing And Frequency Checking

A. GPS Timing Principle

The timing receiver receives GPS satellite signals to get GPS system time, and then compares it with the local clock, achieving the time difference between the local clock and GPS system time (ref.[5]). The relation of user's clock time, satellite clock time and GPS system time is shown in fig.2.

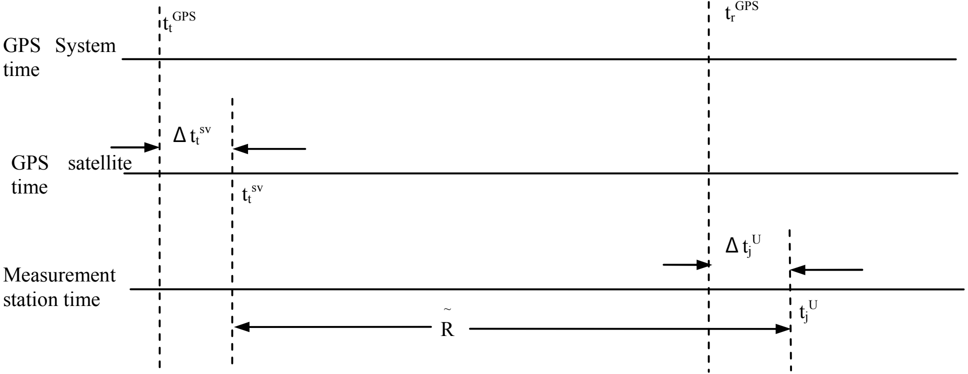

Fig2. GPS Time Relationship

In Fig.2,

t_t^{GPS} is the GPS time corresponding to the moment of sending the signal;
t_t^{sv} is the GPS satellite time corresponding to the moment of sending the signal;
t_j^U is the station local time corresponding to the moment of receiving the signal;
t_r^{GPS} is the GPS time corresponding to the moment of receiving the signal;
Δt_t^{sv} is the difference between GPS time and GPS system time;
Δt_j^U is the difference between the station time and the GPS system time corresponding to the moment of receiving the signal;
$\tilde{R}$ is pseudo range.

From Fig.2, we can get:

$$\tilde{R} = c \cdot (t_j^U - t_t^{sv}) = c \cdot (t_r^{GPS} + \Delta t_j^U - t_t^{GPS} - \Delta t_r^{sv}) \quad (1)$$

$$\Delta t_j^U = \tilde{R}/c - \left(R/c + \tau\right) + \Delta t_t^{sv} \quad (2)$$

$$\Delta t_t^{sv} = a_0 + a_1\left(t - t_{oc}\right) + a_2\left(t - t_{oc}\right)^2 + \Delta t_{GD} + \Delta t_r \quad (3)$$

In above expressions,

$R = \left[\left(X_s - X_j\right)^2 + \left(Y_s - Y_j\right)^2 + \left(Z_s - Z_j\right)^2\right]^{1/2}$ is the space distance from GPS satellite to the receiver.

X_s, Y_s, Z_s is the position coordinate of GPS satellites;
X_j, Y_j, Z_j is the position coordinate of the measurement station;
a_0, a_1, a_2 is the revise parameter of the satellite clock;
t is the satellite sending time;
t_{oc} is the reference time of the satellite clock revise parameter;
Λt_{GD} is the channel time delay of GPS receiver;
Λt_r is the revise term of the principle of relativity;

c is the speed of light;

τ is the epicheirema error, ionosphere and troposphere error, measurement station address error, multi-path effect error and receiver noise error.

From (1), (2) and (3), we can get the deviation between user clock and GPS system time.

B. GPS Frequency Checking Principle

At the same time of getting time sampling, we can get GPS satellite carrier Doppler $\tilde{f}_d^s$ from the output of the GPS receiver carrier tracking loop, and can get its relation with the local frequency scale.

$\tilde{f}_d^s = f_0^s + f_d^s - M\left(f_0^u + \Delta f_0^u\right) + \eta_f$ (4)

Therein,

$\tilde{f}_d^s$ is the carrier Doppler measurement value at the sampling time;

f_0^s is the standard frequency of the GPS satellite;

f_d^s is the carrier Doppler shift at the GPS satellite sampling time;

M is the frequency conversion times between ground frequency scale and satellite standard frequency;

f_0^u is the ground frequency scale;

Δf_0^u is the deviation of the ground frequency scale;

η_f is the Doppler measurement error of the GPS receiver.

And

$f_0^s = M f_0^u$ (5)

$\Delta f_0^u = \frac{1}{M}\left(f_d^s - \tilde{f}_d^s + \eta_f\right)$ (6)

We can get f_0^s from the epicheirema of the GPS system time corresponding to the receiver output sampling time, and the receiver accurate position. Then we can get the measurement station frequency standard deviation and put it in downlink receiver carrier Doppler data to modify.

$f_{dij} = f_0^m + f_{dij}^m - N\left(f_0^u + \Delta f_0^u\right) + \eta_f'$ (7)

f_{dij} is the target carrier Doppler shift outputting from the target receiver at the sampling time;

f_0^m is the nominal frequency of the airborne frequency scale,

f_{dij}^m is the actually Doppler shift at the sampling time;

N is the frequency transfer coefficient between ground frequency scale and the airborne nominal frequency;

η_f' is the Doppler measurement error of the target receiver.

$f_0^m = N f_0^u$ (8)

From formula（4）（5）（6）（7）（8）, we can get,

$$f_{dij}^{m} = f_{dij} + \frac{N}{M}\left(f_{d}^{s} - \tilde{f}_{s}\right) + \frac{N}{M}\eta_{f} - \eta_{f}'$$

Ⅲ. ANALYSIS OF THE PRECISION OF TIME AND FREQUENCY

A. Analysis of time precision

Through the analysis above we know that the satellite clock time error in each base station is the same since each base station receives signals from the same satellite, therefore the errors will not affect the time synchronization among base stations. Meanwhile τ relates to the distance to the satellite from each base station and to the characters of the receiver set up in each station. Each station has a different τ. Therefore, it is τ that affects the time synchronization among base stations. Referring to the base station distribution of multiple targets measurement system, in this paper we hypothesize a composition of four base stations that form a ca. 30x30km square and analyze the affect of each error source to time synchronization among base stations.

(1) The Effect of The Epicheirema

Although each station receives the same satellite's signal, the path from the satellite to station is different; therefore the effect of epicheirema error to the timing of each station is different. The difference is related to the distance between two stations. Let's hypothesize the epicheirema error has the same part in geocentric coordinate system

(2) The Effect of Ionosphere

The signal will suffer from refraction, time delay and attenuation effects when it propagates through ionosphere. These effects of ionosphere lie in the electron integral density of the propagation paths. The electron integral density is related to the position of measurement station, measurement season, and measurement time and satellite elevation. For single frequency users at middle latitude district, it can use below formula to modify by eight ionosphere revise parameters in satellite navigation message.

$$\Delta t_{\text{ionosphere}} = \begin{cases} F\left[5\times10^{-9} + Y\left(1 - X^{2}/2 + X^{4}/24\right)\right] & |X| < 1.57 \\ F\times5\times10^{-9} & |X| \geq 1.57 \end{cases}$$

therein,

$$F = 1 + 16(0.53 - E)^{3}$$

$$X = (t_{0} - 50400)/P$$

$$Y = \begin{cases} \alpha_{0} + \alpha_{1}\Phi_{m} + \alpha_{2}\Phi_{m}^{2} + \alpha_{3}\Phi_{m}^{3} & Y \geq 0 \\ 0 & Y < 0 \end{cases}$$

$$P = \begin{cases} 72000 & P < 72000 \\ \sum_{n=0}^{3}\beta_{n}\Phi_{m}^{n} & P \geq 72000 \end{cases}$$

t is GPS time;

Φ_m is the geomagnetism latitude (°) of the ionosphere geo subpoint, it is related to position of the measurement station and the elevation of the satellite relative to the measurement station.

From these formulas, we can estimate the effect of the ionosphere on each measurement station when the ionosphere influence is great.

If the distance between four stations is near enough that the ionosphere path is very similar, the integral electron density is equal, and then the effect of ionosphere on the time delay of four stations can be ignored.

(3) The Effect of Troposphere

The influence of troposphere to the signal transmitting is very complex. We can only adopt the model to modify. The time delay corresponding to the troposphere can be looked as the function of the altitude of the station, the altitude angle of the satellite and ratio of refraction. In this paper, we can adopt the simplified model as following:

$$t_{\text{对流}} = 7 / \sin(E) + 0.0143 / \left((tg(E)) + 0.0445 \right)$$

Just as the ionosphere's effect, the effect of troposphere on the time delay can be ignored.

(4) The Effect of Station Address Error

Measurement station address error is related to the method of geodetic measurement. If the difference GPS positioning method is adopted, the error of middle and short base line is below 1.5m. If the GPS double frequency geodetic fix meter and code absence technique is adopted, the 3D positioning precision is better than 1cm. Since the distance between four stations is short, the relative positioning precision can be very high, the error arises by the station address can be also ignored.

(5) The Effect of Multi-Path

The effect of multi-path can be divided into two groups: scatter multi-path fading and reflection multi-path fading. The former is because that the signal passes through random medium which will make the signal scatter into lots of similar beams. Each beam transmits along its own path, which can bring the different fading and phase shift; the latter is because that the reflect bodies near the receive antenna can reflect back to the antenna. The effect of reflect multi-path is related to the type of the receiver, the structure of antenna, the directional pattern of antenna and the environment of the antenna erection. For the correlation GPS receiver, the error can be restricted below 5ns if above mentioned conditions are satisfied. To the time synchronism between stations, the effect of multi-path can not be eliminated.

(6) The Effect of Receiver Error

Receiver error can be divided into system error and random error. System errors include the variance of the receiver group delay and check-zero residual error. The fix time delay of the receiver channel, including the time delay of antenna and cable, can be measurement in the factory, or ban be got through checking zero. The fix error can be acted as the equipment zero value and eliminated by software. Since it is not consistent between the receiver channels, the errors between the channels still exist after the zero value is eliminated. This error directly affects the synchronization precision. The channel error between two stations can be controlled within 8ns by adopt the high-powered RF elements and increase the intermediate frequency sampling rate. The random error mainly comes from the pseudo range measurement noise. Its value is related with the SNR, bandwidth of the equivalent loop single band noise, bandwidth of code correlator. It can be got from:

$$\sigma_t = \frac{T_c}{\alpha}\left\{\left[\left(B_n/2\right)\Big/\left(S/N\right)\right]\cdot\left[1+2B_e\Big/\left(S/N\right)\right]\right\}^{1/2}$$

therein ,

σ_t is the variance of the measurement noise;

α is loss factor;

B_n is bandwidth of the equivalent loop single band noise;

B_e is the bandwidth of code correlator;

T_c is bandwidth of code-element;

S/N is the ratio of signal to noise. It can reach 43dBHz if the high gain directional antenna is adopted and track the satellite with the high elevation.

In order to get specific numerical value, in this paper, we choose some experience value. α is 0.8, B_n is 0.15Hz， B_e is 1kHz， T_c is 977.5ns， then we can get:

$\sigma_t = 2.51ns$。

To the synchronization between the stations, the receiver error is difficult to counteract.

Sum up, the factors which bring the timing error is composed of three parts:

Multi-path effect error: 5ns;
Receiver noise: 2.51ns;
Receiver channel time delay: 8ns.

Then we can get the time synchronization precision between stations is better than 9.76ns.

B. Frequency Checking Precision

From (6), we can get that the measurement error of Δf_0^u mainly comes from the carrier Doppler error η_f of the GPS downlink signal and estimation error of the Doppler f_d^s at the GPS satellite sampling time.

Doppler Measurement Error of GPS Signal

This error is from the receiver thermo-noise, when we use three order COSTAS loop to track the carrier signal, there will be:

$$\eta_f = \frac{f_0}{c}\sigma_{\dot{R}} = B'_n\sqrt{\frac{B_n}{\alpha \cdot C/N_0}\left(1+\frac{B_e}{C/N_0}\right)}$$

C/N_0 is carrier to noise ratio of the GPS receiver input signal

B_n is the bandwidth of the equivalent loop single band noise;

α is loss factor;

B_e is the bandwidth of code correlator;

B'_n is bandwidth of the back loop filter.

In practical system,

C/N_0 is 43dB;

B_n is 5Hz; ;

α is 0.8;

B_e is 1kHz;

B'_n is 2Hz.

Then we can get:

$$\eta_f = 0.036Hz$$

The corresponding speed measurement error is $\sigma_{\dot{R}} = \frac{c}{f_0}\eta_f = 0.00686m/s$

Carrier Doppler f_d^s Estimation Error of GPS Satellite Signal

This system realizes the frequency checking through GPS signal. In (4), f_d^s is the GPS signal carrier Doppler nominal value of the receiver, so in the theory, it will cause the f_d^s estimation error during the process of GPS signal generation and transmission, and then it will cause the frequency checking error. It will be including:

(1) GPS Satellite Frequency Scale Error

GPS satellites adopt atomic frequency standard and quartz oscillator, it guarantees that the precision is higher than 10^{-13}, so this error can be ignored.

(2) The Propagation Path Error

From the analysis of the timing precision, we can conclude that this error is related with ionosphere error, troposphere error, station address error, multi-path error and the receiver time delay error. All these errors are slow changing and small, so they have little influence on the Doppler frequency. This error can be ignored.

(3) Epicheirema Error

From

$$\dot{R}^s_{ij} = \frac{(x_s - x_j)(\dot{x}_s - \dot{x}_j) + (y_s - y_j)(\dot{y}_s - \dot{y}_j) + (z_s - z_j)(\dot{z}_s - \dot{z}_j)}{\sqrt{(x_s - x_j)^2 + (y_s - y_j)^2 + (z_s - z_j)^2}} \quad (10)$$

can get that $\dot{R}^s_{ij}$ estimation error is caused by position error Δx_s, Δy_s, Δz_s and speed error $\Delta \dot{x}_s$, $\Delta \dot{y}_s$, $\Delta \dot{z}_s$ from the epicheirema. Commonly, position error of the epicheirema is better than 3m, speed error is better than 0.003m/s, station address error can be ignored.

From (10), we can get:

$$\Delta \dot{R}^s_{ij} = \left[\frac{\dot{x}_s - \dot{x}_j}{R} - \frac{\dot{R}}{R^2}(x_s - x_j)\right]\Delta x + \left[\frac{\dot{y}_s - \dot{y}_j}{R} - \frac{\dot{R}}{R^2}(y_s - y_j)\right]\Delta y + \left[\frac{\dot{z}_s - \dot{z}_j}{R} - \frac{\dot{R}}{R^2}(z_s - z_j)\right]\Delta z$$

$$+ \frac{x_s - x_j}{R}\Delta \dot{x} + \frac{y_s - y_j}{R}\Delta \dot{y} + \frac{z_s - z_j}{R}\Delta \dot{z}$$

Suppose that:

$\Delta x_s, \Delta y_s, \Delta z_s$, statistics independent, obey $\sigma(0, \sigma_r)$;

$\Delta \dot{x}_s, \Delta \dot{y}_s, \Delta \dot{z}_s$, statistics independent, obey $\sigma(0, \sigma_v)$.

Then

$$\sigma^2_{\dot{R}^S_{IJ}} = \frac{V_s^2 - \dot{R}^2}{R^2}\sigma^2{}_r + \sigma^2{}_v$$

$V_S = \sqrt{(\dot{x}_s - \dot{x}_j)^2 + (\dot{y}_s - \dot{y}_j)^2 + (\dot{z}_s - \dot{z}_j)^2}$ is module of the velocity vector from GPS satellite to measurement station, it is about 4000m/s;

$R = \sqrt{(x_s - x_j)^2 + (y_s - y_j)^2 + (z_s - z_j)^2}$ is the distance from satellite to measurement station.

$\dot{R}$ is radial velocity from satellite to measurement station. To high elevation, $\dot{R}$ is far less than V_S.

From above parameters, we can get:

$$\sigma^2_{\dot{R}^S_{IJ}} = \frac{V_s^2 - \dot{R}^2}{R^2}\sigma^2{}_r + \sigma^2{}_v = 0.003 m/s\,.$$

Sum up, the frequency checking error using GPS is mainly from receiver noise error and epicheirema error. For the different frequency carriers, we can get specific frequency precision and relative error.

Ⅳ. CONCLUSION

We have introduced in this paper a method to achieve high precision time and frequency using GPS. The detailed timing and frequency checking method is described, and the sources of errors that affect the precision of time and frequency are analyzed. Theoretically we have developed formula of the precision of timing and frequency checking in the system, and with detailed data we have displayed the precision of time and frequency that the system is able to reach.

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