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Architecture design of GPS software receiver and implementation of its acquisition algorithm with fine frequency estimation

Zhu Xuefen Chen Xiyuan Li Zigang

(School of Instrument Science and Engineering, Southeast University, Nanjing 210096, China)

Abstract: The design of a global positioning system (GPS) software receiver is introduced. This design uses the concept of software radio, and it consists of the following parts: front-end, acquisition, tracking, synchronization, navigation solution and some assisting modules. In the acquisition module, the acquisition algorithm based on circular correlation is utilized. The input data and the local code are converted into the frequency domain by means of the fast Fourier transform (FFT). After performing circular correlation, the initial phase of the C/A code can be obtained and the carrier frequency can be found in 1 kHz frequency resolution, which is too coarse to use for the tracking loop. In order to improve the frequency resolution, the fine frequency estimation through a phase relationship is then achieved, by which, the frequency resolution is improved dramatically. Experiments show that the inaccuracy of the carrier frequency can be estimated within a few hertz by the fine frequency estimation method, and the fine frequency attained can be directly used for the tracking loop.

Key words: GPS software receiver; acquisition algorithm; circular correlation; fine frequency estimation

Research and development continue to extend the capabilities and to increase the robustness of global positioning system (GPS) receivers. With the development of the software radio technique, the user's terminal equipment, GPS software receivers have been improved rapidly. GPS software receivers are quite valuable in evaluating potential improvements due to their flexibility. Unlike conventional GPS receivers, a GPS software receiver is mainly realized by software except for the front-end part. New algorithms can easily be developed without changing the design of the hardware[1]. In addition, software receivers afford batch data processing options that are not available in hardware implementations.

The software radio idea in this design concludes that the input signal is digitized as close to the antenna as possible. Once the signal is digitized, digital signal processing is used to obtain the necessary information through software algorithms[2]. The acquisition method based on circular correlation with a fine frequency estimation is introduced in this paper. The circular correlation is the discrete Fourier transform (DFT)-based technique which is able to search all possible code offsets in one DFT-based computation, dramatically reducing the computational burden. The circular correlation in the frequency domain is very suitable for the acquisition module of GPS software receivers. After performing circular correlation on a 1 ms input signal, the starting point of a certain C/A code and the carrier frequency in a 1 kHz frequency resolution can be found, which is too coarse for the tracking loop. The desired frequency resolution should be within a few tenths of a hertz. In this paper, the phase relationship approach is adopted to find the fine frequency resolution. By doing this, the frequency resolution is dramatically improved. The fine frequency attained can then be directly used for the tracking loop.

1 Architecture Design of GPS Software Receiver

Considering the current development level of the involved hardware technology, the RF front-end is still necessary in this design of the GPS software receiver[3], the architecture design of which is shown in Fig. 1.

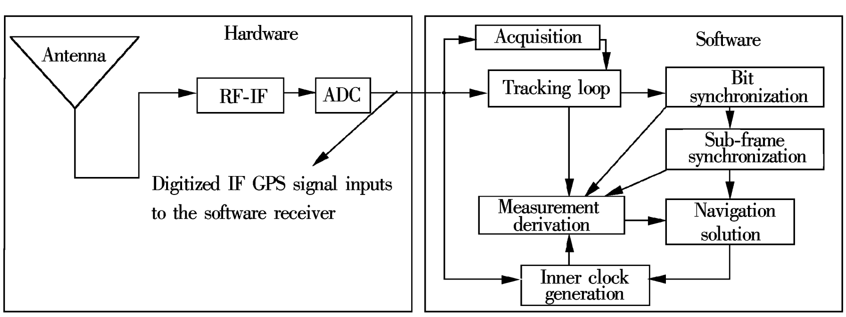

Fig. 1 Architecture design of the GPS software receiver

The signals transmitted from the GPS satellites are received from the antenna through the RF-IF chain. They are amplified to a proper amplitude and the frequency is converted from radio frequency (RF) to a desired intermediate frequency (IF). Then an analog-to-digital converter (ADC) is used to digitize the output signal[4]. The antenna, RF-IF chain, and ADC are the hardware used in this receiver.

After the signal is digitized, software is used to process it. The digitized IF GPS signal inputs are saved in an input data

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Biographies: Zhu Xuefen (1983—), female, graduate; Chen Xiyuan (corresponding author), male, doctor, associate professor, chxiyuan@seu.edu.cn.

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file. After reading these samples into memory, the acquisition stage first provides the initial code offset and Doppler estimates. With these initial values, a tracking loop is able to keep track of the GPS signals and to provide pseudo-range and carrier phase estimates. Sub-frame synchronization is used to demodulate the navigation message, to obtain satellite ephemeris, and to remove the transmit time ambiguity. Finally, the user position is computed and the inner clock bias is removed to improve the quality of the pseudo-range measurements in the navigation solution stage[5]. To enable a successful operation, a few assisting modules, including a measurement derivation module to obtain the pseudo-range, carrier phase and Doppler, and an inner clock generation module to maintain an inner GPS timer are also developed.

2 The Acquisition Algorithm Based on Circular Correlation and Fine Frequency Estimation

Acquisition is one of the most important steps in developing a GPS software receiver because one must detect the signal and then can carry out the tracking step[6]. The acquisition involves correlating the incoming signal with a local signal replica, which is characterized by particular values of the carrier frequency and the code phase.

A correlation between the input signal $x(n)$ and the locally generated code l_{si} can be written as

$$r(n) = \sum_{m=0}^{N-1} x(m) l_{si}(n+m) \tag{1}$$

where N is the length of the input signal. The local code l_{si} can be represented as

$$l_{si} = C_{si} \exp(\mathrm{j}2\pi(f_{\mathrm{IF}} + f_{\mathrm{d}})t)$$

where C_{si} is the C/A code of the i-th satellite; f_{IF} is the frequency of the digitized IF GPS signal at the front-end output; f_{d} is the Doppler frequency shift.

If the DFT is performed on $r(n)$, the result is

$$\begin{aligned} R(K) &= \sum_{n=0}^{N-1} \Big[\sum_{m=0}^{N-1} x(m) l_{si}(n+m) \Big] \mathrm{e}^{-\mathrm{j}2\pi kn/N} = \\ &\sum_{m=0}^{N-1} x(m) \Big[\sum_{n=0}^{N-1} l_{si}(n+m) \mathrm{e}^{-\mathrm{j}2\pi(n+m)k/N} \Big] \mathrm{e}^{\mathrm{j}2\pi mk/N} = \\ &L_{si}(k) \sum_{m=0}^{N-1} x(m) \mathrm{e}^{\mathrm{j}2\pi mk/N} = L_{si}(k) X^*(k) \end{aligned} \tag{2}$$

It can also be written as $R(k) = \sum_{n=0}^{N-1} \sum_{m=0}^{N-1} x(n+m) l_{si}(m) \mathrm{e}^{-\mathrm{j}2\pi kn/N} = L_{si}^*(k) X(k)$

If the $x(n)$ is real, $x(n)^* = x(n)$, where $*$ is the complex conjugate. Using this relationship, the magnitude of $R(k)$ can be written as

$$|R(k)| = |L_{si}^*(k) X(k)| = |L_{si}(k) X^*(k)| \tag{3}$$

The relationship can be used to find the correlation of the input signal and the locally generated signal.

For the convenience of computation, FFT is used to take the place of DFT; thus, the signal acquisition can be denoted as

$$R(m) = \mathrm{IFFT}[\mathrm{FFT}(x(m)) \mathrm{FFT}^*(l_{si}(m))] \tag{4}$$

After taking the IFFT, the maximum absolute value can be found. The value is compared with a predetermined threshold. If the value is larger than the threshold, the signals are acquired successfully[7]. And the corresponding code delay and coarse carrier frequency can also be obtained at the maximum value.

The block diagram of the acquisition of the GPS C/A code signal by circular correlation is shown in Fig. 2.

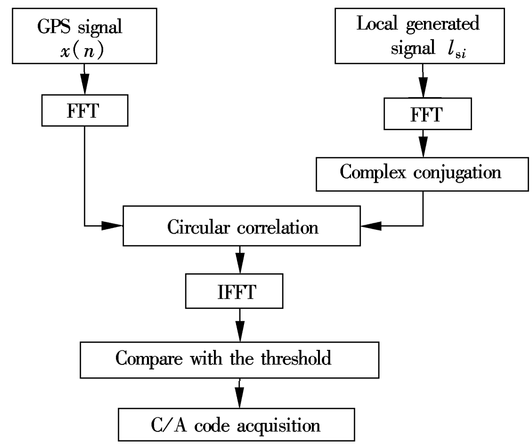

Fig. 2 Flowchart of the circular correlation acquisition algorithm

Then the fine frequency estimation through the phase relationship is performed[1,7]. Once the beginning point of the C/A code is found, the C/A code can be stripped from the input signal, and the input becomes a continuous wave (CW) signal. If the highest frequency component in 1 ms of data at time m is $X_m(k)$, k represents the frequency component of the input signal, and the initial phase $\theta_m(k)$ of the input can be found from the DFT outputs as

$$\theta_m(k) = \tan^{-1}\left(\frac{\mathrm{Im}(X_m(k))}{\mathrm{Re}(X_m(k))}\right) \tag{5}$$

where Im and Re represent the imaginary and real parts, respectively. Assume that at time n, a short time after m, the DFT component $X_n(k)$ of 1 ms of data is also the strongest component, because the input frequency will not change rapidly during a short time. The initial phase angle of the input signal at time n and the frequency component k is

$$\theta_n(k) = \tan^{-1}\left(\frac{\mathrm{Im}(X_n(k))}{\mathrm{Re}(X_n(k))}\right) \tag{6}$$

These two phase angles can be used to find the fine frequency as

$$f = \frac{\theta_n(k) - \theta_m(k)}{2\pi(n-m)} \tag{7}$$

Using Eq. (7), a much finer frequency resolution can be obtained.

In order to keep the frequency unambiguous, the phase difference $\theta_n(k) - \theta_m(k)$ must be less than 2π. If the phase difference is at the maximum value of 2π, the unambiguous bandwidth is $1/(n-m)$, where $n-m$ is the delay time between two consecutive data sets.

3 Experimental Analysis and Results

In this paper, all the experiments and simulations are carried out in the School of Instrument Science and Engineering, Southeast University. A type NewStar 210 GPS signal digitizer V1.0 of the OlinkStar Company is used as the RF front-end in this design of GPS software receivers. As shown in Fig. 1, the RF front-end used in this paper can collect GPS signals and down-convert the frequency of the signals from 1 575.42 MHz (RF) to 20.491 635 MHz (IF) and digitize it at 16.367 667 MHz. With this arrangement, 1 ms of data contains about 16 367 points. The central frequency of the digitized IF GPS signal is at 4.123 968 MHz(without a Doppler frequency shift).

First, the circular correlation acquisition algorithm is used on 1 ms data[8] to find the beginning point of the C/A code and search the frequency range of (4 123.968 ± 10) kHz in 1 kHz steps. The experimental data contain nine satellites, numbers 3, 6, 15, 16, 18, 21, 22, 26, 29. Most of the satellites in this data are reasonably strong(such as satellite 15), and they can be found from 1 ms of data. Some are weak(such as satellite 16), in order to confirm this signal, several milliseconds of data need to be added to apply the coherent integration method or the non-coherent integration method[1]. The analysis of this kind of method is out of the scope of this paper. The acquisition results of satellite 15 and satellite 16 on 1 ms input data are shown in Fig. 3 and Fig. 4. It can be seen that the correlation peak in Fig. 3 is very clear. We can make a qualitative decision, namely, satellite 15 is now detected. While the correlation peak of satellite 16 is not clear enough to make a decision concerning satellite visibility.

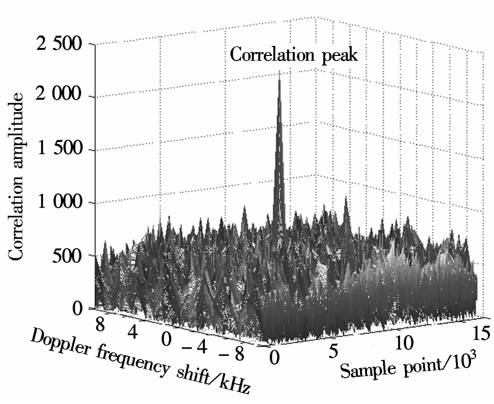

Fig. 3 Acquisition results of satellite 15

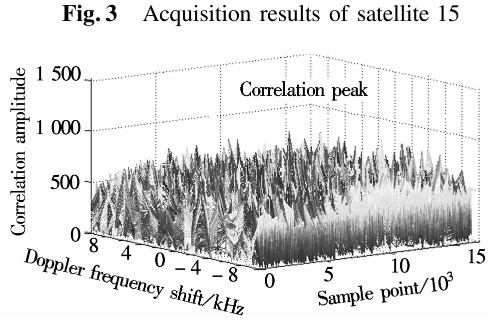

Fig. 4 Acquisition results of satellite 16

The beginning point of the C/A code of satellite 15 is shown in Fig. 5. It can be seen that the correlation peak appears at point 8 358, so the beginning point of the C/A code in 1 ms input data is at point 8 358.

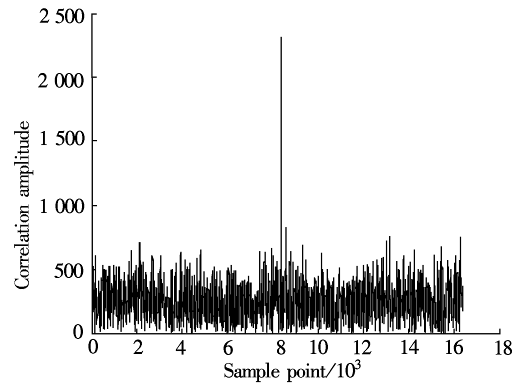

Fig. 5 Beginning of C/A code of satellite 15

The amplitudes of the 21 frequency components separated by 1 kHz are shown in Fig. 6. The highest component occurs at the 12th frequency component. The coarse carrier frequency can be evaluated to be 4 124.968 kHz with the resolution of 1 kHz.

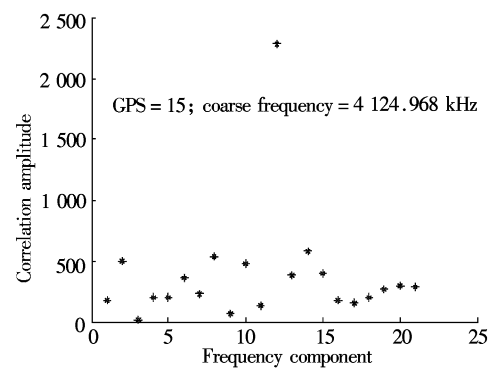

Fig. 6 Frequency component of the despread signal

Then fine frequency estimation based on phase relationship is performed, which uses 5 ms of consecutive data starting from the beginning of the C/A code to find the fine frequency. Multiplying these data with five consecutive C/A codes, the result should be a CW signal 5 ms long[9]. Evaluate each highest frequency component $X_n(k)$ on each 1 ms data, where $n = 1, 2, 3, 4$, and 5. Because $n - m$ is the delay time between two consecutive data sets, here $n - m = 1$ ms. Then find the phase angle from Eq. (5). The difference angle can be defined as $\Delta\theta = \theta_{n+1} - \theta_n$, and Eq. (7) can be rewritten as $f = \frac{\theta_{n+1} - \theta_n}{2\pi \times 10^{-3}}$. Then the fine frequency can be evaluated. Since there are 5 ms of data, there will be four sets of fine frequencies. The average value of these four fine frequencies will be used as the desired fine frequency value to improve accuracy. After performing the acquisition algorithm based on circular correlation and the fine frequency estimation, it can be concluded that the beginning of the C/A code of satellite 15 is at point 8 358 and its fine frequency is evaluated as about 4 125.486 232 077 1 kHz, which is obviously very fine.

Since the data are actually collected, the accuracy of the fine frequency is difficult to determine because the real Doppler frequency is unknown. Here different portions of the data are utilized to attain the fine frequency accuracy[7]. Six fine frequencies are calculated from six portions of the input data. The six different portions each are 5 ms long and the starting points are shifted by 1 ms. Then, each two adjacent 5 ms data have 4 ms data that are the same. Therefore, the calculated fine frequency should be close. The evaluated six fine frequencies of satellite 15 are shown in Tab. 1.

Tab. 1 Six fine frequencies of satellite 15

Sequence number	Fine frequency/kHz	Difference/Hz
1	4 125.486 2	0
2	4 125.479 3	6.9
3	4 125.487 1	−0.9
4	4 125.484 6	1.6
5	4 125.487 7	−1.5
6	4 125.494 8	−8.6

The frequency difference can be considered as the inaccuracy of the acquisition method. From Tab. 1, it can be easily seen that, the frequency resolution is improved dramatically and the inaccuracy of the acquisition method is very small, within a few hertz. Then, the fine frequency attained can be directly used for the tracking loop[10].

4 Conclusion

The design of GPS software receivers based on the concept of a software radio is a kind of new and developing mode of global navigation satellite system(GNSS) receivers development, compared with traditional hardware GNSS receivers. In this paper, the architecture design of GPS software receivers is proposed. Utilizing real GPS satellite data, the acquisition method based on circular correlation with a fine frequency estimation is presented. As demonstrated by experiments, the frequency resolution can be improved dramatically. The acquisition algorithm proposed is suitable for this kind of GPS software receiver.

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GPS 软件接收机的构建及其精频捕获算法的实现

祝雪芬　陈熙源　李滋刚

(东南大学仪器科学与工程学院,南京 210096)

摘要:介绍了一种 GPS 软件接收机的设计方法. 该设计采用软件无线电设计理念,主要包括前端模块、捕获模块、跟踪模块、同步模块、导航解算模块以及其他辅助模块. 捕获模块采用基于圆周相关的捕获算法,通过 FFT (快速傅立叶变换)分别作用于输入信号和本地码信号将运算变换到频域内处理. 该算法可得到 C/A 码起始相位和分辨率为 1 kHz 的载波频率信号,但此载波频率精细度差,不能直接用于跟踪环路. 为提高载波频率分辨率,采用基于相位关系计算的精频估计算法. 实验表明应用精频捕获算法得到的载波精频估计误差在几赫兹以内,可直接用于后续跟踪环路.

关键词:GPS 软件接收机;捕获算法;圆周相关;精频估计

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