Chapter 43
A Study on High Precision Calibration of Zero Value for Navigation Signal Simulator

Xiaopeng Zhong, Zhenwu Tang, Zhijun Meng and Dexiang Ming

Abstract As a high precision source, the navigation signal simulator is possible to simulate the navigation signal which arrived at the antenna of receivers in all kinds of dynamic or static scene, providing a realistic and controllable environment for receiver performance testing. It not only needs higher signal simulation accuracy, but also needs methods and means of high-precision test measurement for itself. The measurement of zero value which is a key indicator has an important effect on its testing as well as the correctness and reliability of receiver's measurement. The traditional measurement of zero value is to make use of an oscilloscope to observe the measured waveform and manually measure the time delay between of flip point and the rising edge of 1PPS signal, and average the measurements. This method will not only introduce measurement errors, but also difficult to locate the flip point accurately due to the low power signal. In this paper, the analysis of the measurement principle of zero value was first introduced, and then a new method was proposed which oscilloscope was used to store the measurement data. In this method, interpolation was first applied to the sampled data, and then the Hilbert transform and polynomial interpolation fitting were used to extract the envelope to find the zero value. The actual results show that the method can improve work efficiency, and is capable to raise the zero value measurement accuracy up to 1 cm.

Keywords GNSS · Beidou · Navigation signal simulator · Zero value · Calibration · Hilbert transform · High precision

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J. Sun et al. (eds.), *China Satellite Navigation Conference (CSNC) 2013 Proceedings*, Lecture Notes in Electrical Engineering 243,
DOI: 10.1007/978-3-642-37398-5_43,

43.1 Introduction

The Satellite Navigation Signal simulator is a high precision integrated testing and simulation equipment, which not only provides a critical test and supports for various types of military and civilian navigation receiver equipment [1], as well as other aspects of scientific research, production, application, testing, inspection, simulation training, but also provide an important tool for the study of the compatibility and interoperability features between China's second-generation Beidou satellite navigation system and other navigation system, such as GPS, GLONASS, Galileo.

As high-precision navigation signal source, the signal accuracy of the simulator itself should be higher than the tested devices. However, on the one hand, due to the inherent characteristics of its own design and hardware, there are some deviations between the output signal and ideal value; on the other hand, by the external impact of electromagnetic environment, random error also will be found in the output signal. Therefore, the research on calibration method of output signal of simulator is of great significance for the protection of its reliability and credibility.

Among all the calibration items, the zero value measurement directly impact the control precision of pseudo range, the consistency between the code and carrier channels also will be greatly reduced, which will introduce additional errors, affecting the truthfulness and accuracy of the receiver performance testing. Therefore, among the formal production and testing, a zero calibration will be needed, and the zero value will be deducted from the system.

This article briefly describes the basic principles of the cause of zero value of the navigation signal simulator zero value and measurement with oscilloscope. Heavy workload against the traditional methods of measurement, the efficiency is low, there is the disadvantage of manual measurement error, and this paper describes an oscilloscope store measurement for zero value calibration. Using this method can not only improve work efficiency, reduce manual measurement error, but also improve the accuracy of the zero value measurement up to 1 cm (RMS, 60 s).

43.2 The Basic Principles of Zero Value Measurement

43.2.1 Cause of Zero Value

According to the principle of simulators [2], the RF cell need to produce satellite signal follow the pseudorange computed by the mathematical simulation cell, and the deviation should match the index commanded. But, there are still more deviation between theoretical value and actual value, for the signal producer will finish several parts such as mathematical computation, baseband combination and up-conversion.

The system zero value usually should be several ten microseconds, and changes according to the cable length. In the case of zero-pseudorange, the zero value means the time delay between the head of pseudocode and 1PPS, as shown in Fig. 43.1.

In the design of GNSS simulator, zero value would have a big effect while the existence of different channel in same frequency or different frequency which is a key index, and used in navigation terminate. It a base method for BeiDou/GPS and other system to get the code phase measured using usual device [3].

43.2.2 Measurement Through Flip Point

Most navigation signal using BPSK modulation scheme. In this modulation scheme, when the baseband signal sequence change from "1" to "0" or in reverse, the carrier will have a phase flip of π radian, as shown in Fig. 43.2.

Ideally, the amplitude of the carrier maintains the same at the both side of the flip point. However, in order to reduce the effect of Inter-Symbol Interference, the baseband signal uses a cosine roll off for processing before up conversion [4, 5]. In the actual signal testing, there is a transition area near the flip point [6] shown in Fig. 43.3, the center of the recess is the "turning" point.

Using the oscilloscope to observe the navigation RF signal out from simulator, and set the oscilloscope triggered by the channel which 1PPS signal coming from, then we can observe the waveform on the oscilloscope. When the head and tail has the same symbol, the wave shows in Fig. 43.3a, while different, the wave shows in Fig. 43.3b. And due to the cyclical changes of the navigation message, the figure will alternate between 43.3a and 43.3b. This phenomenon always appears at the

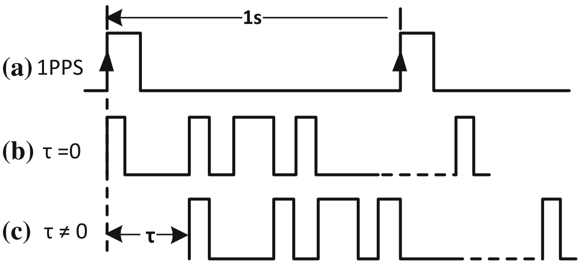

Fig. 43.1 Relationship between 0 phases of Pseudo code and 1PPS

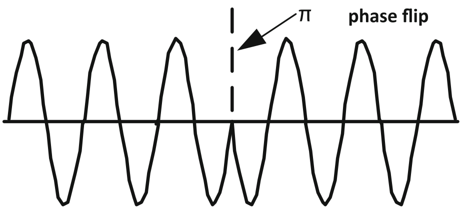

Fig. 43.2 Phase flip diagram of BPSK modulation

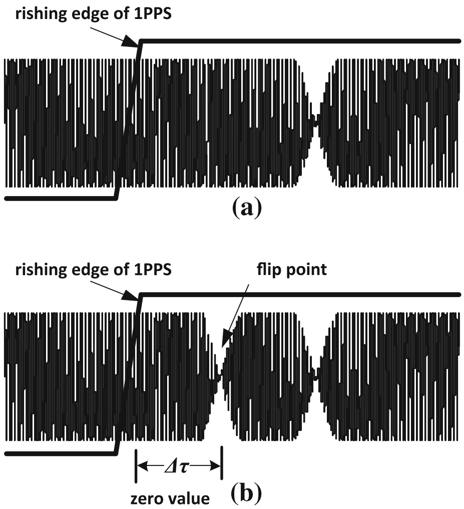

Fig. 43.3 Diagram of flip point

beginning of the navigation message. The point which closing and opening with time go by is the so-call "flip point". As show in Sect. 43.2.1, the zero value turn out to be the time delay between the point and rising edge of 1PPS signal. So, the zero value can be measure using the message of this point and the message of the 1PPS.

43.3 Zero Value Measurement Method

43.3.1 Oscilloscope Manual Measurements

The key of system zero value measurement is to position the flip point exactly, and measuring the distance of the turning point to the center of rising edge of 1PPS. In order to obtain the distance, a direct measurement of the time-domain by oscilloscope can be used. Because the oscilloscope needs to sample the RF navigation signal which has a very high frequency, the oscilloscope requires a higher sampling rate. Its measurement connection relationship is shown in Fig. 43.4.

The actual measurement following these steps: (1) First, the channel 1 of oscilloscope is connected to the 1PPS signal output port which has the same source

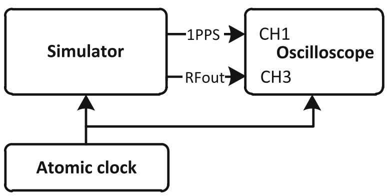

Fig. 43.4 Connection of direct measuring

with the DAC clock, channel 3 is connected to the RF output of the oscilloscope, and the oscilloscope is set to be triggered by channel 1; (2) In the case that pseudo ranges has been set to zero, set the signal output as a single frequency and static BPSK modulation with signal satellite; (3) When the oscilloscope has a stable display, locate the 1PPS rising edge, and find the start of the Barker code in this vicinity, reads out the time span between flip point and the rising edge of 1PPS; (4) track the position of the flip point for a long period of time, and recorded on the oscilloscope readings; (5) Repeat (1) to step (4), using the formula (43.1) averaging several measurements, and using the root mean square error [formula (43.2)] to calculate the value of zero uncertainty.

$$E(\tau) = \frac{1}{n}\sum_{i=1}^{n}\tau_i \tag{43.1}$$

$$D(\tau) = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}[\tau_i - E(\tau)]^2} \tag{43.2}$$

Table 43.1 shows the zero-value test results using this method of B1 frequency.

Using the method for measurement, we need to manually adjust the time axis of the oscilloscope to get the time span; also we get the estimation by our eyes directly. This kind of measurement makes a heavy workload, and because of the error introduced by manual adjustment and visual cannot be eliminated, the measured results have some uncertainties. Also, because this method can only measure a 1PPS pulse rising edge each time, it cannot provide a long time, continuous observation of the zero value which jitters and wanders as time goes by.

43.3.2 Oscilloscope Sampling Storage Measurement

In order to reduce the error cause by manual adjustment and visual deviation, the method shown in Fig. 43.5 can be used to get zero. First, we store the sample data for a long time by the high speed storage oscilloscope. After the data has been prepared, we used software to analysis and process the data, finding the time distance between flip point and the center of the rising edge; finally we get the zero value by compute the average value we have obtained.

Table 43.1 Zero value test data (after calibration)

Times	1	2	3	4	5
Zero value (ns)	112.5886	112.4604	112.2022	112.3112	112.2748
Times	6	7	8	9	10
Zero value (ns)	112.2330	112.5386	112.1704	112.5204	112.2294
Mean (ns)	112.3529		Standard deviation	0.149377 ns (0.0448 m)	

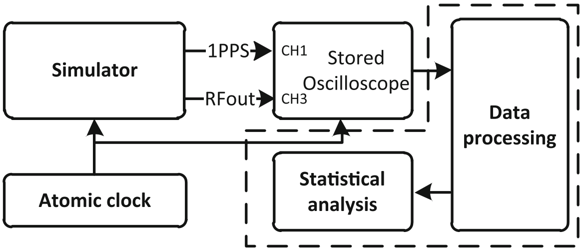

Fig. 43.5 Connection of stored-measuring

The processing of sampled data is the key of data storage measurement method. In order to get the precise value of zero, some procession are needed, including the data interpolation, envelope extraction process, envelope polynomial fitting and statistical analysis.

1. Data interpolation

If the sampling rate of the channel of oscilloscope has only reach 20 GHz, the resolution between two points can only be 0.015 m. In order to improve the processing accuracy of the collected signal, the data was process with interpolation before calculating.

The common interpolation processing includes Lagrange interpolation, Newton interpolation, Hermiter interpolation. Although the Hermiter interpolation method can equal the derivative values of the interpolation-node, but the solution of the base function is still to be known and it also need much computation, this paper mainly consider the first two methods. In this paper, the Lagrange linear interpolation was used, and data was processed in pieces of segment (Fig. 43.6).

For the two adjacent data points $P_k(t_k, \tau_k)$, $P_{k+1}(t_{k+1}, \tau_{k+1})$, the Lagrange interpolation function is created as

$$L(t) = \tau_k \cdot l_k(t) + \tau_{k+1} \cdot l_{k+1}(t), t_k < t < t_{k+1} \quad (43.3)$$

While $l_k(t) = \frac{t - t_{k+1}}{t_k - t_{k+1}}$ and $l_{k+1}(t) = \frac{t - t_k}{t_{k+1} - t_k}$ are the base functions. For M times interpolation, the n-th interpolation point is represented as

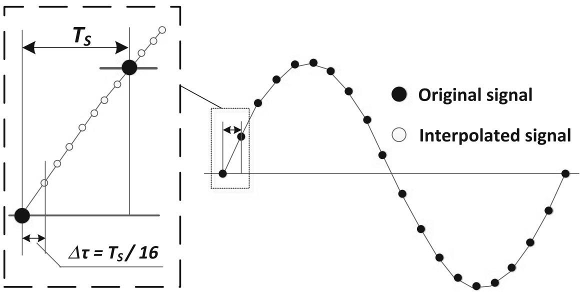

Fig. 43.6 Diagram of data interpolation

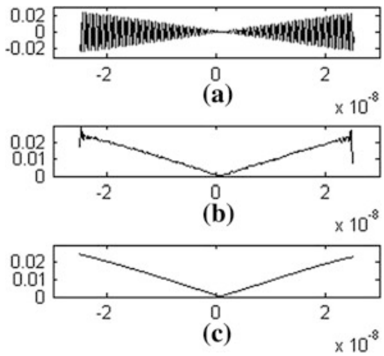

Fig. 43.7 Processing of discrete data

$$P_n\left(t_k + n \cdot \frac{T_s}{M}, L\left(t_k + n \cdot \frac{T_s}{M}\right)\right) \tag{43.4}$$

If $M = 16$, the virtual sampling rate would be 320 GHz, and signal processing accuracy raising up to 1 mm at this time.

2. Envelope extraction by Hilbert Transform

Figure 43.7a shows a piece of the data sampled by oscilloscope, where the 0 moment corresponds to the center of rising edge center of 1PPS, the flip point located at the intersection of the envelope of the RF sample waveform.

The envelope can be extracted using the Hilbert transform method [7]. For a real signal, the Hilbert transform is defined as

$$\hat{x}(t) = x(t) * \frac{1}{\pi t} = \frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{x(\tau)}{t-\tau}d\tau \tag{43.5}$$

Take the Fourier transform of $\hat{x}(t)$ and we can be obtained

$$\begin{aligned}\hat{X}(f) &= F[x(t) * 1/(\pi t)] = X(f) \cdot F[1/(\pi t)] \\ &= X(f) \cdot [-j\mathrm{sgn}(f)]\end{aligned} \tag{43.6}$$

Which $F[\cdot]$ represent Fourier Transform, and $\mathrm{sgn}(\cdot)$ represents the sign function. It is shown that the Hilbert transform is equivalent to a 90° phase shifter. So, for a narrowband signal $f(t) = A(t)\cos(\omega t + \varphi(t))$ with slowly changing envelop $A(t)$, the Hilbert transform can be

$$\hat{f}(t) = A(t)\sin(\omega t + \varphi(t)) \tag{43.7}$$

and we can get its analytical signal as

$$\begin{aligned}\bar{f}(t) &= f(t) + j\hat{f}(t) \\ &= A(t)\cos(\omega t + \varphi(t)) + j \cdot A(t)\sin(\omega t + \varphi(t)) \\ &= A(t)e^{j[\omega t + \varphi(t)]}\end{aligned} \tag{43.8}$$

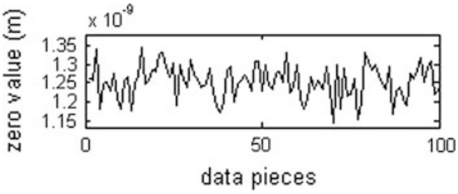

Fig. 43.8 Statistic values of 100 pieces sample data

so we can get the signal envelop according the following formula

$$A(t) = \sqrt{f^2(t) + \hat{f}^2(t)} = |\bar{f}(t)| \tag{43.9}$$

For each period of the signal acquisition, the Hilbert transform is used to extract the envelope, the results is shown in Fig. 43.7b.

3. Envelope Polynomial Fitting

The envelop extracted by Hilbert transform is not smooth, and there still has a small ripple in the envelope, the direct use of the intersection of the envelope to estimate the zero value will make the introduction of a larger error.

Because the envelope is approximately linear change at the flip point, so the one-order linear fit can be used to process the envelopes of both sides, and the fit polynomial is

$$f(t) = a + b \cdot t \tag{43.10}$$

The fitting result is shown in Fig. 43.7c. In this case, the obtained intersection of two curves of the horizontal axis value should be the zero value.

43.4 Results

The zero value determination takes a long time to track the measurement, it's a statistical value. Figure 43.8 shows the change of zero value obtained using oscilloscope storing measurement way.

During curve fitting, the fitting lines of the envelope will cause large errors due to truncation of the both ends. The use of these data will affect the precision of curve fitting, thus affecting the extraction of zero values. In order to improve the handling of precision, the actual data processing is required to strike out the part of the point. The relationship of the removed points and the zero value is shown in Table 43.2.

Table 43.2 shows us that the using of the data storage means to get the zero value can obtained a high processing accuracy.

Table 43.2 Relationship between excluding point and standard deviation of zero value

Excluding point	0	20	40	60	80
Standard deviation (m)	0.00988	0.00965	0.00932	0.00929	0.00958

43.5 Conclusions

The accurate measurement of the zero value makes a very important meaning for the precision of the control of pseudoranges, channel consistency and stability of the zero value. Using oscilloscope to measure the zero value directly is not only inefficient, but also will introduce artificial measurement error, the measurement accuracy cannot be guaranteed. And the store measurement mode can simplify the measurement steps, and make full use of the software and signal processing algorithms, we can optimize the processing of the sampled data. Actual measurements show that the zero value can be estimated using the stored measurement mode to achieve high accuracy and improve the figure to 1 cm, it is possible to meet the needs of some testing occasions.

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