Chapter 42
Research on High-Precision Measurement and Calibration Technology for Carrier Phase Consistency of Digital Beam Array Navigation Signal Simulator

Dexiang Ming, Yangyang Liu, Xiaopeng Zhong and Xiye Guo

Abstract Digital beam array navigation signal simulator is a kind of important equipment to develop, test and verify multi-element anti-jamming satellite navigation terminal with cables. According to the working principle of anti-jamming satellite navigation terminal, the carrier phase consistency is a key indicator to signal simulator. Thus, measurement and correction of carrier phase consistency is an important part in the design of digital beam array signal simulator. In this paper, for this problem, an innovative technical solution is proposed for high-precision calibration based on carrier interferometer. This solution uses two array elements to measure delay mutually, based on the signal phase of one, directly detecting the phase of another. After analysis of theory and validation of experiment, the solution can achieve high measurement accuracy that is less than 0.1° of the relative phase among the array elements, and the price is small.

Keywords GNSS · Digital beam array navigation signal simulator · Carrier phase consistency · High precision · Measurement and calibration

42.1 Introduction

Digital beam array navigation signal simulator is a kind of important equipment to develop, test and verify multi-element anti-jamming satellite navigation terminal with cables, and is also guarantee and support to improve the anti-jamming

D. Ming (✉) · X. Zhong · X. Guo
College of Mechatronics Engineering and Automation, National University Defense Technology, Changsha 410073, People's Republic of China
e-mail: mdxnihao@263.net

Y. Liu
College of Physical and Electronics, Central South University, Changsha 410083, People's Republic of China

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_42,

capability of weapons and equipment. In order to ensure the precision of the phase consistency, we need to take measurement adjusting and periodic calibration. Therefore, measurement and correction of zero value [1–3] of carrier phase is an important part in the design of digital beam array signal simulator. The zero value is a relative value between each array element, not absolute value that is from baseband to the antenna, and generally requires less than one degree. The traditional method [4–6] of measurement measures the absolute delay of phase by tracking loop, and this requires the closed-loop measurement system as a reference. Using the closed-loop measurement system will make error larger, and requires high synchronized performance of the closed-loop measurement. The conventional closed-loop measurement cannot achieve high measurement accuracy. In response to this problem, an innovative technical solution is proposed for high-precision calibration based carrier interferometry in the design of digital beam array signal simulator. The solution uses two array elements to measure delay mutually, based on signal phase of one, directly detecting the phase of another, and can achieve high measurement accuracy that is less than 0.1° with small price.

42.2 Principles of Measurement and Calibration

The schematic diagram of high-precision measurement and calibration based on the carrier interferometry measurement is shown in Fig. 42.1. The emitting unit of simulator has a total of k ports, and the signal waveform that is output by DAC at each emitting port is: $x_k(t) = \sin((\varpi - \varpi_{LO})t + \varphi_k)$. The phase delay caused by down-conversion and filtering system is: $\phi_k - \varphi_k$. The signal waveform that reaches antenna aperture is: $A_1 \sin(\varpi t + \phi_1)$.

The synthesized signal is $y(t) = \sum_{k=1}^{K} A_k \sin(\varpi t + \phi_k)$, formed by the signal of k ports. Since each signal has completely the same frequency, the k and j channel

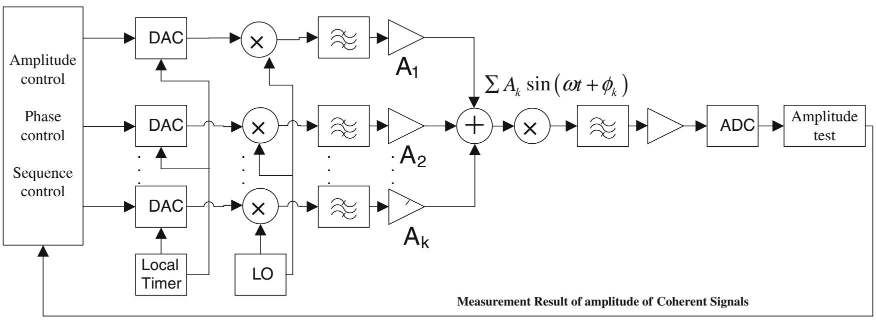

Fig. 42.1 Schematic of high-precision measurement and calibration

signal, only has the phase difference, that is $\phi_k - \phi_j$, and amplitude difference, so each signal is actually fully coherent signal. We can take full advantage of this coherence to achieve the detection of the phase difference, that is $\phi_k - \phi_j$.

The following example illustrates the high-precision measurement principle of phase difference, $\phi_k - \phi_j$, using two channel signals.

42.2.1 Principle of Coherent Measurement of Carrier Phase Consistency

Firstly we study phase measurement principle of two coherent signals. Without loss of generality, suppose the waveform of first channel signal that arrives at the antenna aperture planes as a reference waveform, the waveform is:

$$x_1(t) = A_1 \sin(\varpi t + \phi_1) \tag{42.1}$$

The waveform of k channel:

$$x_k(t) = A_k \sin(\varpi t + \phi_k) \tag{42.2}$$

The synthesized signal of 1 and k channel is:

$$\begin{aligned} y(t) &= A_1 \sin(\varpi t + \phi_1) + A_k \sin(\varpi t + \phi_k) \\ &= A_1 \left(\sin(\varpi t + \phi_1) + \frac{A_k}{A_1} \sin(\varpi t + \phi_k) \right). \end{aligned} \tag{42.3}$$

After trigonometric transform:

$$\begin{aligned} y(t) = A_1 \Big\{ & \sin(\varpi t)\cos(\phi_1) + \cos(\varpi t)\sin(\phi_1) \\ & + \frac{A_k}{A_1}[\sin(\varpi t)\cos(\phi_k) + \cos(\varpi t)\sin(\phi_k)] \Big\} \end{aligned} \tag{42.4}$$

$$\begin{aligned} y(t) = A_1 \Big\{ & \sin(\varpi t)\left[\cos(\phi_1) + \frac{A_k}{A_1}\cos(\phi_k)\right] \\ & + \cos(\varpi t)\left[\sin(\phi_1) + \frac{A_k}{A_1}\sin(\phi_k)\right] \Big\} \end{aligned} \tag{42.5}$$

$$y(t) = A_1 \sqrt{\left[\cos(\phi_1) + \frac{A_k}{A_1}\cos(\phi_k)\right]^2 + \left[\sin(\phi_1) + \frac{A_k}{A_1}\sin(\phi_k)\right]^2} \sin(\varpi t + \delta\phi_k) \tag{42.6}$$

Merge the Eq. (42.6), we get:

$$y(t) = A_1\sqrt{1 + 2\frac{A_k}{A_1}\cos(\phi_1 - \phi_k) + \left(\frac{A_k}{A_1}\right)^2}\sin(\varpi t + \delta\phi_k) \tag{42.7}$$

It can be seen that the synthesized waveform relative to the first channel signal $x_1(t) = A_1\sin(\varpi t + \phi_1)$, the amplitude enhancement factor is:

$$\begin{aligned}\sqrt{P_k(\phi_1 - \phi_k)} &= \frac{A_1\sqrt{1 + 2\frac{A_k}{A_1}\cos(\phi_1 - \phi_k) + \left(\frac{A_k}{A_1}\right)^2}}{A_1} \\ &= \sqrt{1 + 2\frac{A_k}{A_1}\cos(\phi_1 - \phi_k) + \left(\frac{A_k}{A_1}\right)^2}\end{aligned} \tag{42.8}$$

That is:

$$P_k(\phi_1 - \phi_k) = 1 + 2\frac{A_k}{A_1}\cos(\phi_1 - \phi_k) + \left(\frac{A_k}{A_1}\right)^2 \tag{42.9}$$

Therefore, the power enhancement factor of the synthesized signal waveform is a function of the phase error $\phi_1 - \phi_k$. We can get $\phi_1 - \phi_k$ by $P_k(\phi_1 - \phi_k)$. Since $\frac{A_k}{A_1}$ can be accurately measured and only $\cos(\phi_1 - \phi_k)$ is unknown in the Eq. (42.9), so $\phi_1 - \phi_k$ can be calculated as Eq. (42.10).

$$\cos(\phi_1 - \phi_k) = \frac{P_k(\phi_1 - \phi_k) - 1 - \left(\frac{A_k}{A_1}\right)^2}{2\frac{A_k}{A_1}} \tag{42.10}$$

Define the right side of Eq. (42.10) as a concept d_k:

$$d_k \triangleq \frac{P_k(\phi_1 - \phi_k) - 1 - \left(\frac{A_k}{A_1}\right)^2}{2\frac{A_k}{A_1}}. \tag{42.11}$$

We can get the measurement equation:

$$\cos(\phi_1 - \phi_k) = d_k \tag{42.12}$$

Based on $P_k(\phi_1 - \phi_k)$, d_k can be calculated; thereby $\phi_1 - \phi_k$ can be calculated.

There is only one observed quantity in this measurement principle, so the measurement accuracy cannot meet the demand. In order to improve the measurement accuracy, we should better use more observed quantities.

In order to obtain more observations, the best method is to change the phase of reference signal of the first channel manually, forming M corrections of observations $\phi_1(m), m \in [1, M]$ Suppose the M scanning phases generated manually of the first channel can scan 2π phase angles.

$$\phi_1(m) = \frac{2\pi}{M}m, \quad m = 1, 2, 3, \ldots, M \tag{42.13}$$

For each correction value $\phi_1(m), m \in [1, M]$, after observing for a few times, we can get one observed value that is $d_k(m)$. And we also will get a measurement sequence as shown in Eq. (42.14):

$$\cos(\phi_1(m) + \phi_1 - \phi_k) = d_k(m) \tag{42.14}$$

Reference [7] describes the sine phase detection method: obtain $\tan(\phi_1 - \phi_k)$ through the orthogonal measurement method, and then through $\tan(\phi_1 - \phi_k)$ we can obtain $\phi_1 - \phi_k$. Thus, here directly give $\tan(\phi_1 - \phi_k)$ according to $d_k(m)$:

$$\tan(\phi_1 - \phi_k) = \frac{\sum_{m=1}^{M} d_k(m)\sin(\phi_1(m))}{\sum_{m=1}^{M} d_k(m)\cos(\phi_1(m))} \tag{42.15}$$

If $\phi_1(m) = \frac{2\pi}{M}m, \quad m = 1, 2, 3, \ldots, M$, we get:

$$\sum_{m=1}^{M} \sin(\phi_1(m)) = 0 \tag{42.16}$$

$$\sum_{m=1}^{M} \cos(\phi_1(m)) = 0 \tag{42.17}$$

Take Eqs. (42.16) and (42.17) into the expression $\tan(\phi_1 - \phi_k)$, and remove $-1 - \left(\frac{A_k}{A_1}\right)^2$, we can obtain:

$$\tan(\phi_1 - \phi_k) = \frac{\sum_{m=1}^{M} P_k(\phi_1 - \phi_k, m)\sin(\phi_1(m))}{\sum_{m=1}^{M} P_k(\phi_1 - \phi_k, m)\cos(\phi_1(m))} \tag{42.18}$$

This $\phi_1(m) = \frac{2\pi}{M}m, \quad m = 1, 2, 3, \ldots, M$experimental phase scanning process is necessary, not only to improve the precision of the phase measurement, and eliminate various amplitude error. In fact, $\sin(\phi_1(m))$, $\cos(\phi_1(m))$, is a narrow-band filter, and can eliminate most of the DC noise, like $P_k(\phi_1 - \phi_k, m)$.

42.2.2 Procedure of Measurement

According to the above principle, the method of calibration process is described as follows:

Step 1: Measuring the reference signal power, P_1, of the first channel.

Fix the first channel signal, as a reference signal, and calculate its power by self-measurement loop.

Step 2: Measure the relative power $P_k(\phi_1 - \phi_k, m)$ of the total M experimental synthetic signal of the k channel.

Holding the first channel signal power, open the k channel, close the other signals except the first and k channel signal.

For the k channel signal, change the phase of the baseband carrier signal of the first channel signal, $\phi_1(m) = \frac{2\pi}{M}m, \quad m = 1, 2, 3, \ldots, M$, in which $M = 16$. Each channel signal holds 50 ms to calculate the signal power for self-measurement loop. Within a cycle of 50 ms, calculate enhancement factor, $P_k(\phi_1 - \phi_k, m)$, that is the power of the synthesized signal by measurement loop respect to the power of the first channel signal.

Step 3: calculate the relative phase difference $\phi_1 - \phi_k$.

According to $P_k(\phi_1 - \phi_k, m)$, calculate $\tan(\phi_1 - \phi_k)$ by Eq. (42.18), then look up the tan table, and $\phi_1 - \phi_k$ can be obtained.

42.2.3 Analysis of Measurement Accuracy

According to the Reference [7], we estimate the accuracy of the formula (42.18). If the observation noise variance is σ_P, the measurement accuracy of the phase is:

$$\sigma(\phi_1 - \phi_k) \approx \sqrt{\frac{2}{M}}\sigma_P \times \frac{180}{\pi} \text{ (Degree)} \tag{42.19}$$

If we take $P_s = -40\text{dBmW}$, $N_0 = -174\text{dBmW}$, and B = 20 Hz, σ_P, can be estimated as Eq. (42.20):

$$\sigma_P = \sqrt{\frac{N_0 B}{P_s}} \approx 10^{-6} \tag{42.20}$$

$$\sigma(\phi_1 - \phi_k) \approx 2.0 \times 10^{-5} \text{ (Degree)} \tag{42.21}$$

Thus, this phase detecting method can achieve high accuracy.

42.3 Tests and Analysis of Results

In order to verify the above theory, we take the experimental instruments as follows to test:

Signal Source: IFR2025
Power divider: Mini—ZAPD-2-21-3 W
Synthesizer: Mini—ZAPD-2-21-3 W
Spectrum analyzer: Agilent 8563E
Phase shifter: Spectrum LS-0170-1121

42.3.1 Test Results of Power Synthesis

Experimental connection relationship is shown in Fig. 42.2. The signal source sends 1.5 GHz single carrier with low phase noise to the power divider, forming completely same phase signals of two ways. The synthesized signal is then fed into a spectrum analyzer to measure the power of the synthesized signal.

According to Fig. 42.2, firstly measure power of the synthesis signal of two channels. Then remove one, and measure power of the remaining channel signal. The experimental results measured are shown in Table 42.1.

From Table 42.1, we can get that the power of two completely same phase coherent signal respect to without synthetic beam, will be enhanced 6 dB. Since the power divider is a linear device, and the correctness of the synthesis formula (42.3) is also verified.

42.3.2 Test Results of Amplitude Changing Caused by Phase Changing

The connection relationship of verification test of amplitude variations caused by phase changes is shown in Fig. 42.3.

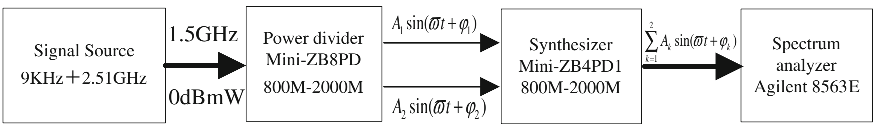

Fig. 42.2 Test schematic of power synthesis of two channels

Table 42.1 Test results of power synthesis of two channels

	Synthesis of two channels (dB)	Synthesis of one channels (dB)
Relative power of synthesized signal	0	−6.33
Theoretical value	0	−6

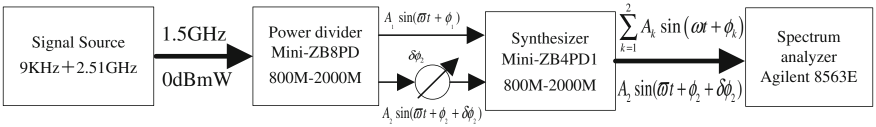

Fig. 42.3 Test schematic of amplitude changing caused by phase changing

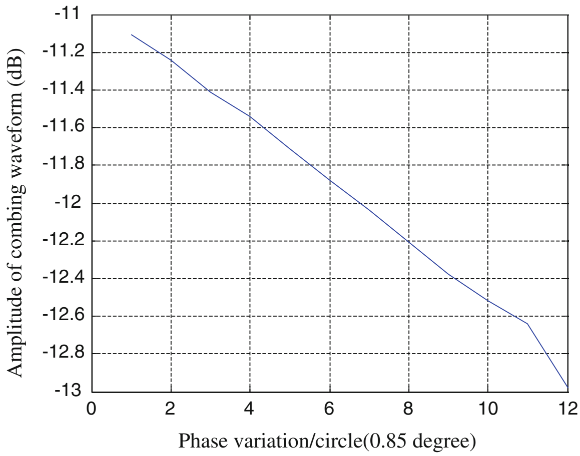

Fig. 42.4 Line of relationship of phase change and synthesis waveform (connect one SMA)

1. **Test after connecting one SMA**

Spectrum phase shifter moves only 7°. Therefore, connect an SMA connector in front of the synthesizer to increase the signal delay, and compensate insufficient of the Spectrum phase shifter. The phase shifts 45°. After connecting, change the phase shifter of Spectrum phase shifter, we can get the relationship between the relative power change of synthesized waveform and number of turns of Spectrum phase shifter that is shown in Fig. 42.4.

As shown in Fig. 42.4, the Spectrum's phase shifter changes one lap (0.85°), the amplitude substantially changes 0.13 dB. At this time, the phase difference is relatively small, at the peak of the cosine wave, and is not very sensitive to the change in phase. DSP can sense 0.13 dB amplitude variations. It proves that we can detect the phase difference changes by detecting the power change of synthesized signal.

2. **Test after connecting two SMA**

Spectrum phase shifter moves only 7°. Therefore, connect two SMA connectors in front of the synthesizer to increase the signal delay, and compensate insufficient of the Spectrum phase shifter. The phase shifts 90°. After connecting, change the phase shifter of Spectrum phase shifter, we can get the relationship between the relative power change of synthesized waveform and number of turns of Spectrum phase shifter that is shown in Fig. 42.5.

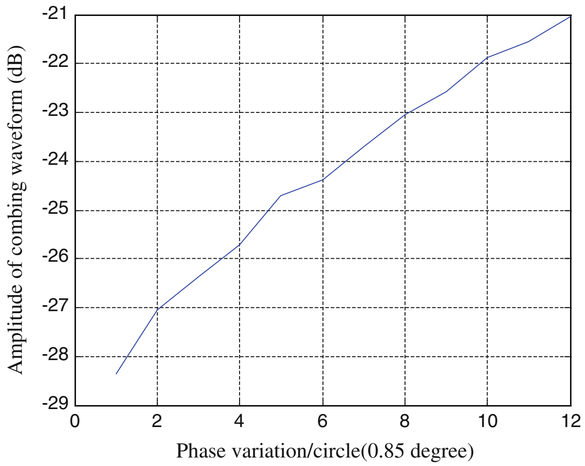

Fig. 42.5 Line of relationship of phase change and synthesis waveform (connect two SMA)

As shown in Fig. 42.5, the Spectrum's phase shifter changes one lap (0.85°), the amplitude substantially changes 0.67 dB. At this time, the phase difference is large, at the middle of the cosine wave, and is sensitive to the change in phase. DSP can sense 0.67 dB amplitude variations. It proves that we can detect the phase difference changes by detecting the power change of synthesized signal.

3. **Test after connecting three SMA**

Spectrum phase shifter moves only 7°. Therefore, connect three SMA connectors in front of the synthesizer to increase the signal delay, and compensate insufficient of the Spectrum phase shifter. The phase shifts 135°. After connecting, change the phase shifter of Spectrum phase shifter, we can get the relationship between the relative power change of synthesized waveform and number of turns of Spectrum phase shifter that is shown in Fig. 42.6.

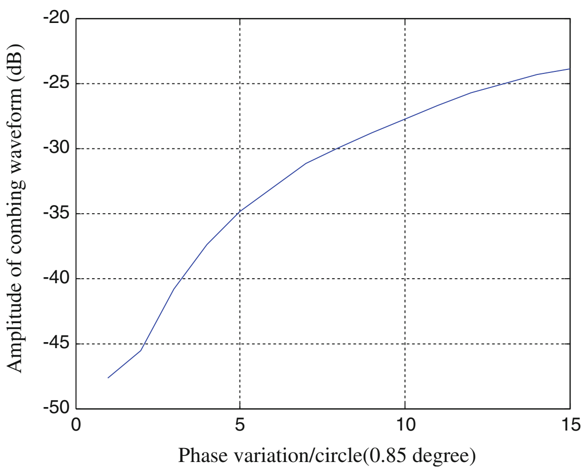

Fig. 42.6 Line of relationship of phase change and combining waveform (connect three SMA)

As shown in Fig. 42.6, the Spectrum's phase shifter changes one lap (0.85°), the amplitude substantially changes 4–2 dB. At this time, the phase difference is relatively large, at the down of the cosine wave, and is very sensitive to the change in phase. DSP can sense 2–4 dB amplitude variations. It proves that we can detect the phase difference changes by detecting the power change of synthesized signal.

42.3.3 Conclusions

In this paper, an innovative solution of high-precision measurement calibration is presented based on carrier interferometry to measure and correct carrier phase consistency in the design of digital beam array signal simulator. This solution can measure the relative phase difference of each synthesis signal precisely and in real time, and is irrespective of other zero-value error interferences. After test and analysis, the algorithm has high measurement accuracy that is less than 0.1° of phase difference and good anti-jamming performance, which demands less to the amplitude of the reference signal, and reduces the requirements to self-correction circuit. It is a kind of good measurement correction method of carrier phase consistency.

References

1. Jaffer AG (2002) Sparse mutual coupling matrix and sensor gain phase estimation for array auto-calibration. In: Proceedings of IEEE rader conference 2002, pp 294–297
2. Wang B, Wang Y, Guo Y (2004) Mutual coupling calibration with instrumental sensors. Electron Lett 40(7):406–408
3. Jun Y (2007) The research of the signal simulation theory and technologies for satellites navigation. School of National University of Defense Technology, Changsha
4. Kohei M (2001) Experiments of DOA estimation by DBF array antenna at 2.6 GHz. IEICE Trans on Commu E84-B(7):1871–1875
5. Godara LC (1997) Application of antenna to mobile communication, Part II: beamforing and direction arrival consideration. Proc IEEE 85(8):1195–1245
6. Ertel R, Hu Z, Reed J (1999) Antenna array hardware amplitude and phase compensation using baseband antenna array outputs. IEEE Veh Technol Conf 3:1763–1795
7. Kay SM (2011) Fundamentals of statistical signal processing: estimation and detection theory. Publishing House of Electronics Industry, Beijing, p 2