

Design and Evaluation of Digital Baseband Converter Sub-channel Delay Compensation Method on Bandwidth Synthesis

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Abstract. *The effect of sub-channel delay on bandwidth synthesis is investigated to eliminate the “phase step” phenomenon in bandwidth synthesis during the test of CDBE (Chinese Digital Backend). Through formula derivation, we realize that sub-channel delay may cause phase discontinuity between different sub-channels. Theoretical analysis shows that sub-channel delay can induce bandwidth synthesis error in group delay measurement of the linear system. Furthermore, in the differential delay measurement between two stations, bandwidth synthesis error may occur when the LO (Local Oscillator) frequency differences of corresponding sub-channels are not identical. Error-free conditions are discussed under different applications. The phase errors among different sub-channels can be removed manually. However, the most effective way is the compensation of sub-channel delay. A sub-channel delay calculation method based on Modelsim is proposed. The compensation method is detailed. Simulation and field experiments are presented to verify our approach.*

Keywords

VLBI, bandwidth synthesis, digital baseband converter, phase step, delay compensation, sub-channel delay

1. Introduction

VLBI (Very Long Baseline Interferometry) has become a significant approach in astronomy, geodesy and deep space exploration due to its long operation range and extremely high angular resolution. As the requirement of measurement precision is increasing dramatically, IVS (International VLBI Service for Geodesy & Astrometry) has launched VLBI2010 project to achieve 1-mm position accuracy in the future [1]. A new generation VLBI system has been built to overcome the limitations of the existing infrastructures. As the emergence of Digital Backend/Digital Baseband Converter, more attentions have been

paid to the issues on high sampling rate, better in-band performance, high flexibility and efficient implementation methods [2–4]. Little attention has been paid to the sub-channel delay. Typical systems include RDBE [5] by NRAO (National Radio Astronomy Observatory) and MIT Haystack, the most recent DBBC3 [6] in EVN (European VLBI Network), ADS3000+ [7], CDAS (Chinese Data Acquisition System) [8] and CDBE (Chinese Digital Backend) [9].

Rogers [10] proposed bandwidth synthesis theory first in 1970 and discussed the factors that determine the optimal choice of frequency channels. Then, Molinder [11] detailed the tradeoff between bandwidth synthesis measurement accuracy and spanned bandwidth, source strength, antenna size and efficiency, system noise temperature, and data volume. Further, Gorham [12] proposed an approach toward choosing optimal sets of frequency channel for better bandwidth synthesis measurement accuracy. Bagri [13] introduced an accurate spacecraft measurement method based on frequency synthesis and the error budget was explained in detail. Recently, the influence of clock-offsets differences among different channels on bandwidth synthesis were investigated in [14]. A method based on a priori delay, whose derivatives up to the third order, was proposed to eliminate the influence. However, little research has been conducted on the impact of digital baseband converter's sub-channel delay on bandwidth synthesis.

We designed and implemented a novel VLBI Digital Baseband converting and recording system named CDBE (Chinese Digital Backend) in 2012 [9]. “Phase step” phenomenon was observed in the measurement of CDBE's single station group delay, and differential delay between two CDBEs by bandwidth synthesis. Therefore, in this paper, we first analyze the influence of digital baseband converter's sub-channel delay on bandwidth synthesis, and two conclusions are reached 1) Sub-channel delay will deteriorate bandwidth synthesis accuracy in the group delay measurement of a linear system; 2) Sub-channel delay will also affect the measurement accuracy of differential delay between two stations when the corresponding

LO frequency differences are not identical. Based on the analysis, we believe that the most effective way to eliminate the influence of sub-channel delay is to compensate it to zero. Thus, we proposed an efficient dynamic sub-channel delay measurement method based on Modelsim. Furthermore, the sub-channel delay compensation strategy is presented on FPGA. Simulation results show that bandwidth synthesis accuracy was improved by two or three orders of magnitude with delay compensation. Field experiments based on CDBE also demonstrate the validity of our proposed compensation method.

The paper is organized as follows. In Sec. 2, reasons of “phase step” are derived respectively in the measurement of single station’s group delay and differential delay between two stations. Next, influencing factors are discussed for different digital baseband converter implementation structures and an effective way to eliminate “phase step” is proposed. Section 3 describes how to calculate sub-channel delay and the compensation method is presented in detail. Simulations and field experiments based on CDBE are performed to verify the effect of sub-channel compensation in Sec. 4 and Sec. 5. Finally, conclusions are summarized in Sec. 6.

2. Influence of Sub-channel Delay on Bandwidth Synthesis

The VLBI delay measurement precision is proportional to the recording bandwidth. The wider the recording bandwidth, the higher is the measurement accuracy. However, the recording bandwidth is limited by the recording speed. It’s impossible to record signal with ultra wide bandwidth. To overcome this limitation, bandwidth synthesis [10] was proposed by Rogers to obtain a comparative high measurement accuracy by limiting the total bandwidth. According to bandwidth synthesis theory, wideband signal is divided into many separate narrow band sub-channels in the frequency domain. The delay and delay rate of each sub-channel is obtained at first. Then, a more accurate delay can be obtained by a linear least square fitting to the measurement results of all the sub-channels. Bandwidth synthesis was initially proposed for the measurement of differential delay between two stations. It indicates a basic principle in delay measurement that the wider the measurement bandwidth, the more accurate is the delay measurement [15]. Therefore, the concept of bandwidth synthesis can be extended to the measurement of group delay of single station to improve its measurement precision.

2.1 Group Delay Measurement of Single Station

The RF (Radio Frequency) receiver illustrated in Fig. 1(a) is equivalent to the mathematical model in Fig. 1(b). For simplicity, assume that the RF receiver is a linear system, and the received signal is

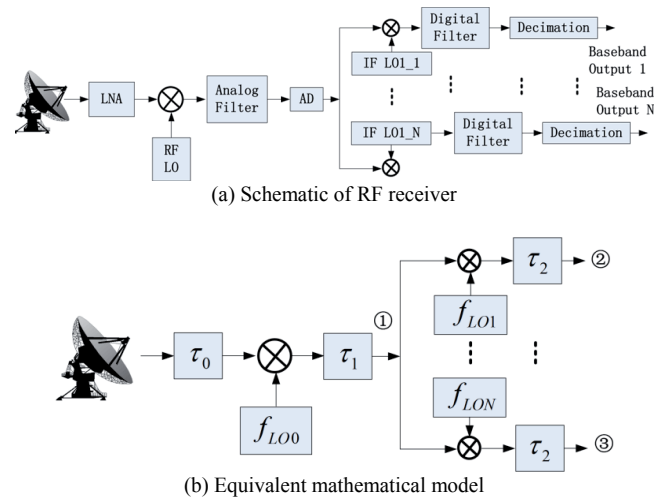


Fig. 1. RF receiver and the equivalent mathematical model.

$$x(t) = \cos(2\pi f_1 t) + \cos(2\pi f_2 t) + \cos(2\pi f_3 t) + \cos(2\pi f_4 t) \quad (1)$$

where $f_1, f_2, f_3,$ and f_4 are the frequencies of the received tones. The phases of tones at label ① (see Fig. 1(b)) are

$$\begin{cases} \Phi_{1_1} = -2\pi f_1 \tau_0 - 2\pi(f_1 - f_{LO0})\tau_1 \\ \Phi_{1_2} = -2\pi f_2 \tau_0 - 2\pi(f_2 - f_{LO0})\tau_1 \\ \Phi_{1_3} = -2\pi f_3 \tau_0 - 2\pi(f_3 - f_{LO0})\tau_1 \\ \Phi_{1_4} = -2\pi f_4 \tau_0 - 2\pi(f_4 - f_{LO0})\tau_1 \end{cases} \quad (2)$$

where τ_0 is the delay before analog down-converting, f_{LO0} is the frequency of analog LO, τ_1 is the delay before sub-channel dividing. In (2), tones f_1 and f_2 are outputs from sub-channel 1, while tones f_3 and f_4 are outputs from sub-channel 2. Then, the tones’ phases at label ② and ③ (see Fig. 1(b)) are

$$\begin{cases} \Phi_{2_1} = -2\pi f_1 \tau_0 - 2\pi(f_1 - f_{LO0})\tau_1 - 2\pi(f_1 - f_{LO0} - f_{LO1})\tau_2 \\ \Phi_{2_2} = -2\pi f_2 \tau_0 - 2\pi(f_2 - f_{LO0})\tau_1 - 2\pi(f_2 - f_{LO0} - f_{LO1})\tau_2 \\ \Phi_{3_1} = -2\pi f_3 \tau_0 - 2\pi(f_3 - f_{LO0})\tau_1 - 2\pi(f_3 - f_{LO0} - f_{LON})\tau_2 \\ \Phi_{3_2} = -2\pi f_4 \tau_0 - 2\pi(f_4 - f_{LO0})\tau_1 - 2\pi(f_4 - f_{LO0} - f_{LON})\tau_2 \end{cases} \quad (3)$$

Group delays derived by the tones in the same sub-channel are

$$\begin{cases} \tau_{gd1} = -\frac{\Phi_{2_2} - \Phi_{2_1}}{2\pi(f_2 - f_1)} = \tau_0 + \tau_1 + \tau_2 \\ \tau_{gdN} = -\frac{\Phi_{3_2} - \Phi_{3_1}}{2\pi(f_4 - f_3)} = \tau_0 + \tau_1 + \tau_2 \end{cases} \quad (4)$$

Equation (4) indicates that group delays of different sub-channels are identical. Therefore, the delay can be calculated by the tones in each sub-channel. For a linear system, the bandwidth synthesis group delay can be calculated by the two most outside tones f_1 and f_4 as in (5)

$$\tau_{gd} = -\frac{\Phi_{3_2} - \Phi_{2_1}}{2\pi(f_4 - f_1)} = \tau_0 + \tau_1 + \tau_2 + \frac{f_{LO1} - f_{LON}}{f_4 - f_1} \tau_2. \quad (5)$$

By comparing (5) with (4), we find that there is an error term for the group delay calculated by different sub-channels' tones. The error term is determined by the sub-channel delay τ_2 , with a weighting factor k as

$$k = \frac{f_{LO1} - f_{LO2}}{f_4 - f_1} \quad (6)$$

The underlying reason for the occurrence of the error term in (5) is that different sub-channel LO frequencies break the original frequency relationship before demux. When the tones of different sub-channels pass the same delay, the corresponding phase variances are different from the original ones. Thus, a phase error $\Delta\phi_i$ is added, as shown in Fig. 2.

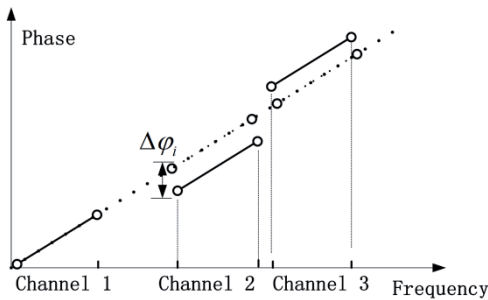


Fig. 2. Sketch of the “phase step” phenomenon in bandwidth synthesis.

In Fig. 2, the dotted line denotes the tones' nominal phases. The solid lines denote the actual phases of the tones in different sub-channels. We can see that the group delay of each sub-channel is identical (the slopes are the same). However, the actual phases are located around the nominal line. So we cannot obtain the delay correctly by bandwidth synthesis. We call this phenomenon as “phase step”. The above conclusion is derived from absolute phase values of tones. In practice, although the phases may be ambiguous, our conclusion still fits.

The phase errors among different sub-channels can be eliminated manually by calculating the specific error values. However, the calculation is tedious, inefficient, and of low accuracy. From (5), we can derive a conclusion that if and only if $f_{LO1} = f_{LO2}$ or $\tau_2 = 0$, the error is zero. Whereas, the LO frequency of each sub-channel is arbitrary. The condition $f_{LO1} = f_{LO2}$ is not always satisfied. Furthermore, LO frequencies are not equal in the application of bandwidth synthesis. Therefore, we draw a conclusion that the sub-channel delay has to be compensated to zero to eliminate the error term.

2.2 Differential Delay Measurement between Two Stations

Assume the differential delay between station 2 and station 1 is τ_g . From (3), we can calculate the phases of the tones at station 2 as

$$\begin{cases} \Phi'_{2,1} = -2\pi f_1(\tau_0 + \tau_g) - 2\pi(f_1 - f_{LO0})\tau_1 - 2\pi(f_1 - f_{LO0} - f'_{LO1})\tau_2 \\ \Phi'_{2,2} = -2\pi f_2(\tau_0 + \tau_g) - 2\pi(f_2 - f_{LO0})\tau_1 - 2\pi(f_2 - f_{LO0} - f'_{LO1})\tau_2 \\ \Phi'_{3,1} = -2\pi f_3(\tau_0 + \tau_g) - 2\pi(f_3 - f_{LO0})\tau_1 - 2\pi(f_3 - f_{LO0} - f'_{LO2})\tau_2 \\ \Phi'_{3,2} = -2\pi f_4(\tau_0 + \tau_g) - 2\pi(f_4 - f_{LO0})\tau_1 - 2\pi(f_4 - f_{LO0} - f'_{LO2})\tau_2 \end{cases} \quad (7)$$

According to the correlation of the tones between two stations, the differential phases are

$$\begin{cases} \Delta\Phi_{2,1} = \Phi_{2,1} - \Phi'_{2,1} = 2\pi f_1\tau_g + 2\pi(f_{LO1} - f'_{LO1})\tau_2 \\ \Delta\Phi_{2,2} = \Phi_{2,2} - \Phi'_{2,2} = 2\pi f_2\tau_g + 2\pi(f_{LO1} - f'_{LO1})\tau_2 \\ \Delta\Phi_{3,1} = \Phi_{3,1} - \Phi'_{3,1} = 2\pi f_3\tau_g + 2\pi(f_{LO2} - f'_{LO2})\tau_2 \\ \Delta\Phi_{3,2} = \Phi_{3,2} - \Phi'_{3,2} = 2\pi f_4\tau_g + 2\pi(f_{LO2} - f'_{LO2})\tau_2 \end{cases} \quad (8)$$

Then, differential delays between two stations can be obtained by the tones in the corresponding sub-channels

$$\begin{cases} \tau_{g1} = -\frac{\Delta\Phi_{2,2} - \Delta\Phi_{2,1}}{2\pi(f_2 - f_1)} = \tau_g \\ \tau_{gN} = -\frac{\Delta\Phi_{3,2} - \Delta\Phi_{3,1}}{2\pi(f_4 - f_3)} = \tau_g \end{cases} \quad (9)$$

From (9), we can see that the differential delays calculated by corresponding sub-channels are the same and correct. Then, according to bandwidth synthesis theory, we can obtain the differential delay by a wider bandwidth, tones f_1 and f_4 as

$$\begin{aligned} \tau'_g &= -\frac{\Delta\Phi_{3,2} - \Delta\Phi_{2,1}}{2\pi(f_4 - f_1)} \\ &= \tau_g + \frac{(f_{LO2} - f'_{LO2}) - (f_{LO1} - f'_{LO1})}{f_4 - f_1} \tau_2 \\ &= \tau_g + \Delta\tau_g \end{aligned} \quad (10)$$

where $\Delta\tau_g$ is the error term, $\Delta f_N = f_{LO2} - f'_{LO2}$, and $\Delta f_1 = f_{LO1} - f'_{LO1}$. From (10), we can derive that when one of the following three conditions is satisfied, the error term is zero:

- a) $f_{LO2} = f'_{LO2}$ and $f_{LO1} = f'_{LO1}$;
- b) $\Delta f_N = \Delta f_1$;
- c) $\tau_2 = 0$.

2.2.1. The LO Frequency is Equal to Each Other

Condition (a) is the special case of condition (b). Assume the tone emitted by the radio source or spacecraft is f . Then, the received tones at two observation stations become f' and $f' + f_d$, respectively, where f_d is the Doppler frequency difference between two stations.

If $f_d < B$, where B is the recording bandwidth, the corresponding LO frequencies can be set to be the same, and condition (a) is satisfied.

Whereas, if $f_d > B$, the corresponding LO frequencies should be different. Otherwise, the received tones at one of the stations may be located outside the recording bandwidth. Here, condition (a) cannot be satisfied.

Condition (a) can be satisfied in the observation of the radio source. The received signal is a kind of wideband signal. Thus, the recording bandwidth is usually wider than Doppler frequency difference.

Whereas, for the observation of spacecraft, the received signals are usually tones, and the recording bandwidth is relatively narrow. Therefore, condition (a) may not be satisfied in some cases.

2.2.2. The Difference of Corresponding LO Frequency is Equal to Each Other

Condition (b) is related to the down-conversion scheme of digital baseband converter. Assume the tones received at station 1 are f_{s1} and $f_{s1} + \Delta f$, where Δf is the frequency difference between the tones. Tone f_{s1} passes through sub-channel 1, and Tone $f_{s1} + \Delta f$ passes through sub-channel 2. Correspondingly, the tones received at station 2 are $f_{s1} + f_d$ and $f_{s1} + f_d + \Delta f$, where f_d is the Doppler frequency difference between two stations. Tone $f_{s1} + f_d$ passes through sub-channel 1, and Tone $f_{s1} + f_d + \Delta f$ passes through sub-channel 2. Both of the tones at the two stations are down-converted to zero. Then the condition is investigated according to different down-conversion schemes of digital baseband converter.

Firstly, for the digital baseband converter with the orthogonal mixing scheme, the frequency relationship between tones does not change after down-conversion. So the LO frequencies of different sub-channels have the relationship as

$$f_{s1LO2} = f_{s1LO1} + \Delta f, \quad (11)$$

$$f_{s2LO2} = f_{s2LO1} + \Delta f \quad (12)$$

where f_{s1LO1} and f_{s1LO2} are the LO frequencies of sub-channel 1 and 2 at station 1, f_{s2LO1} and f_{s2LO2} are the LO frequencies of sub-channel 1 and 2 at station 2. From (11) and (12), the following equation can be obtained

$$f_{s2LO2} - f_{s1LO2} = f_{s2LO1} - f_{s1LO1}. \quad (13)$$

Consequently, condition (b) is satisfied.

Secondly, for the digital baseband converter with the PFB (Polyphase Filter Bank)+FFT scheme, once the channelization structure is confirmed, the LO frequency of each sub-channel is constant. If the two stations have the same channelization structure, the corresponding LO frequencies are the same. Then, condition (a) is satisfied.

Thirdly, for the digital baseband converter with the combined structure of PFB+FFT and orthogonal mixing scheme, such as CDBE, the cases are complicated. The channelization structure has broken the original frequency relationship. So condition (b) is not always satisfied.

2.2.3. The Sub-channel Delay is Zero

In the actual observation, the digital baseband converters at the two stations may be different in down-conversion schemes, so the cases may be very complicated [16], [17]. Condition (a) and (b) both have limitations. Therefore, the most simple, general, and reliable approach is to compensate the sub-channel delay to zero.

3. Calculation and Compensation of Sub-channel Delay

3.1 Sub-channel Delay Calculation Methods

The process of down-converting is implemented digitally on FPGA. The delay of a digital circuit is constant. So once the scheme of digital baseband converter is confirmed, the delay of each module in a sub-channel can be calculated separately. The delay summation of all the modules is the sub-channel delay.

The main module, which delays the signal, is a digital filter. VLBI is a strict linear system. The digital filters adopted are all FIR filters. The group delay of FIR filter is related to its architecture. Different architecture has different group delay. For the common symmetric distributed architecture, the relationship between the group delay and the number of filter coefficients is

$$\tau_{filter} = \frac{N-1}{2} T_{clock} \quad (14)$$

where N is the number of filter coefficients, T_{clock} is the working clock cycle.

Static method is tedious and requires high professional knowledge. Filter delay of each stage should be calculated. In addition, the specific architecture of each filter should be known clearly.

To realize the easy, efficient and reliable measurement of sub-channel delay, a novel dynamic measuring method is proposed. In dynamic method, the sub-channel module is treated as a black box. Sub-channel delay is measured by Modelsim simulation. The detailed processing flow is shown in Fig. 3.

First of all, testing signal is generated in Matlab. Digital PCAL (Phase Calibration) signal is adopted in this step. Then, related VHDL/Verilog files are loaded into Modelsim project. Write the testbench according to the input/output interface and timing relationships. Make a simulation,

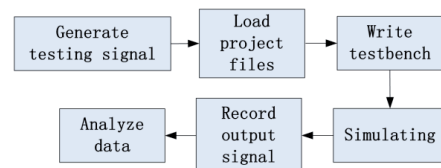


Fig. 3. Flow chart of dynamic measurement method.

and record the outputs meanwhile. Afterwards, calculate the phases of PCAL tones in Matlab [18]. Finally, the group delay of sub-channel is obtained.

Dynamic method does not require knowledge of the architecture of the filter. It is efficient to obtain the sub-channel delay. The result is reliable since it is simulating actual cases.

3.2 Sub-channel Delay Compensation Method

In design and implementation of our proposed compensation method, we adopt a data stream based processing strategy. Each data stream is attached with a valid signal to control its validity, which makes the delay compensation easy. We should only obtain the sub-channel delay by dynamic method first, and then convert the delay to working clock cycles. Finally, we shift the data valid signal according to the clock cycles, and then the sub-channel delay is compensated.

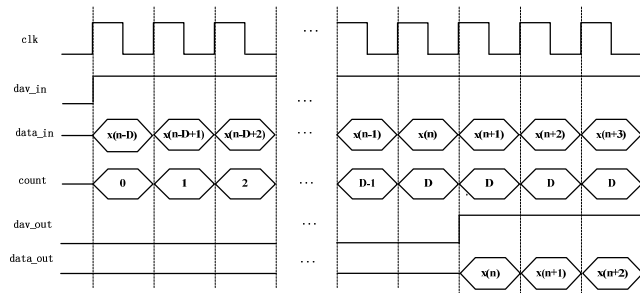


Fig. 4. Timing diagram of delay compensation module.

As illustrated in Fig. 4, *clk* is the working clock, *dav_in* is the input data valid signal, *data_in* is the input signal, *count* represents the working clock cycle counter, *dav_out* is the output data valid signal, *data_out* is the output signal. Suppose the filter delay equals to D working clock cycles. Delay compensation is to drop the first D output signal data and delay the *dav_out* D working clock cycles. Then the Sub-channel delay is compensated to zero.

There are three advantages of sub-channel delay compensation.

1) Phases among different sub-channels can realize seamless combination directly by the compensation of sub-channel delay. Thus, the bandwidth synthesis fitting precision can be improved.

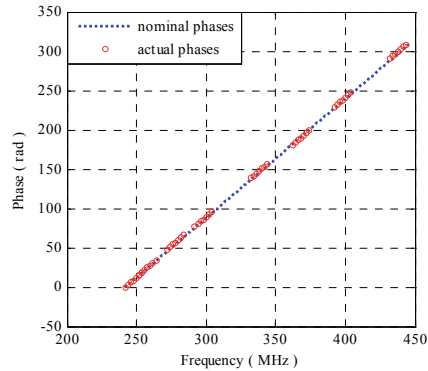
2) The total delay of digital baseband converter is constant and independent of the output bandwidth, which makes the delay compensation in VLBI correlator easier.

3) The total delay of station instrument decreases by the compensation of sub-channel delay, which can diminish or eliminate the phase ambiguity of PCAL signals.

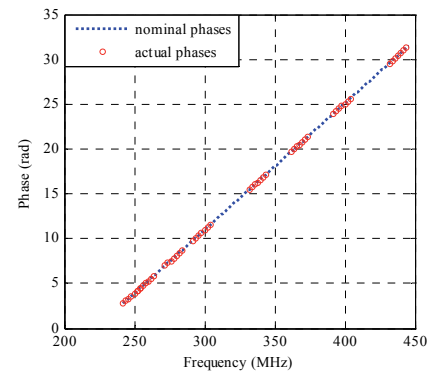
4. Simulation

4.1 Group Delay Measurement of Single Station

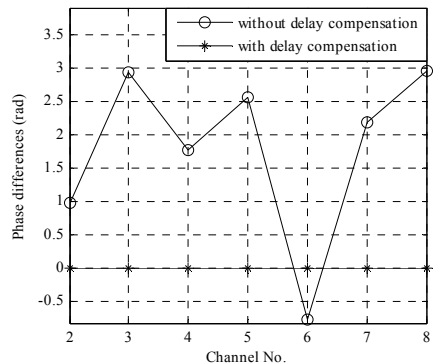
To verify the effectiveness of sub-channel delay compensation, CDBE models based on the combined structure of PFB+FFT and orthogonal mixing down-conversion were built [19]. Digital PCAL signal with a 2 MHz PRF (Pulse Repetition Frequency) was generated in Matlab as the testing signal. The number of output sub-channels was



(a) Phases splicing without delay compensation.



(b) Phases splicing with delay compensation.



(c) Phase differences between sub-channels and nominal line.

Fig. 5. Phases splicing of different sub-channels.

eight, and the output bandwidth was 16 MHz. The digital LO frequencies of sub-channels were set at 240 MHz, 250 MHz, 270 MHz, 290 MHz, 330 MHz, 360 MHz, 390 MHz, and 430 MHz, respectively, with a bandwidth span of 206 MHz. CDBE models with/without sub-channel delay compensation were simulated separately in Modelsim. The simulation outputs were recorded, and then analyzed in Matlab. The tones' phases of each sub-channel were unwrapped and spliced together, as shown in Fig. 5.

The dotted line in Fig. 5(a), (b) denotes the nominal phase line, which is the extension of phases of sub-channel 1. The circled lines in Fig. 5(a), (b) denote the phases of the other sub-channels, which are supposed to fit the nominal line. In order to see the "phase step" clearly, we obtain the mean phase differences between the actual phases and the nominal ones of each channel, shown in Fig. 5(c). From Fig. 5(c), it is clear to see that the phase differences without sub-channel delay compensation are relatively large. The "phase step" is evident. In contrast, after delay compensation, the phase differences decrease to the order of 0.001 rad, which indicates that delay compensation is effective.

By the linear least square fitting of each sub-channel and the entire bandwidth, the group delays and RMS (Root Mean Square) errors of each sub-channel and bandwidth synthesis are shown in Tab. 1.

Sub-Channel Number	Without Delay Compensation		With Delay Compensation	
	Delay (ns)	RMS (ns)	Delay (ns)	RMS (ns)
Channel 1	241.190	0.017	22.464	0.022
Channel 2	241.126	0.024	22.394	0.038
Channel 3	241.242	0.039	22.496	0.035
Channel 4	241.175	0.040	22.412	0.044
Channel 5	241.210	0.025	22.453	0.035
Channel 6	241.195	0.014	22.435	0.024
Channel 7	241.163	0.035	22.412	0.065
Channel 8	241.245	0.037	22.475	0.048
Bandwidth Synthesis	242.731	0.884	22.462	0.002

Tab. 1. Group delays and RMS errors without / with delay compensation.

Tab. 1 indicates that the delay of CDBE decreases greatly from 241 ns to 22 ns when sub-channel delay is compensated. The residual 22 ns is the common delay before divided into sub-channels. The accuracy of bandwidth synthesis increases by two orders of magnitude by compensating sub-channel delay from 0.884 ns to 0.002 ns. Furthermore, compared with the RMS errors of sub-channels with delay compensation, the measurement precision is improved from the order of 0.01 rad to 0.001 rad by bandwidth synthesis.

4.2 Differential Delay Measurement of Double Stations

In order to verify the conclusion that "phase step" phenomenon occurs when the differences of corresponding LO frequencies are not identical. We set the LO frequen-

cies of station 1 at 240 MHz, 250 MHz, 270 MHz, 290 MHz, 330 MHz, 360 MHz, 390 MHz, and 430 MHz, respectively. In contrast, the LO frequencies of station 2 were set at 240.5 MHz, 250 MHz, 270.5 MHz, 290 MHz, 330.5 MHz, 360 MHz, 390.5 MHz, and 430 MHz, respectively. The differences between the corresponding LO frequencies were 0.5 MHz or 0 MHz. Assume the signal of station 2 was delayed by 4.8828 ns compared with station 1. Digital PCAL was adopted as the testing signal with a 2 MHz PRF. The bandwidth was 16 MHz. CDBE models with/without sub-channel delay compensation were simulated separately in Modelsim by PCAL signal and delayed PCAL signal. Outputs of two stations were correlated to obtain the differential delays between the corresponding sub-channels. The bandwidth synthesis results were obtained by linear least square fitting of phase differences of all the sub-channels. The measurement results are shown in Tab. 2 and Fig. 6.

We can see clearly from Fig. 6(a) and Tab. 2 that the "phase step" phenomenon is evident and the bandwidth synthesis result cannot be obtained correctly before delay compensation. The "phase step" phenomenon disappears after delay compensation, and the bandwidth synthesis measurement accuracy is improved by one order of magnitude compared with the sub-channels' results. Simulation results demonstrate the correctness of our conclusion.

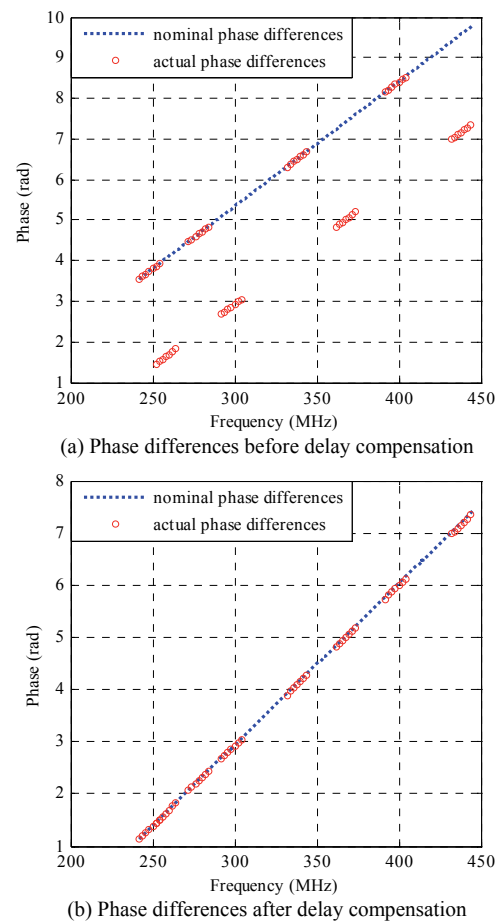


Fig. 6. Phase differences with different LO frequency differences.

Sub-Channel Number	Before Delay Compensation		After Delay Compensation	
	Delay (ns)	RMS (ns)	Delay (ns)	RMS (ns)
Channel 1	4.886	0.020	4.913	0.018
CHANNEL 2	4.907	0.024	4.869	0.036
Channel 3	4.877	0.051	4.736	0.045
Channel 4	4.875	0.052	4.822	0.049
Channel 5	4.885	0.028	4.889	0.068
Channel 6	4.900	0.031	4.851	0.042
Channel 7	4.910	0.022	4.941	0.057
Channel 8	4.856	0.036	4.813	0.049
Bandwidth Synthesis	4.149	1.310	4.882	0.003

Tab. 2. Differential delays and RMS errors with different LO frequency differences.

5. Field Experiments

A series of field experiments were conducted to verify the effectiveness of sub-channel delay compensation in CDBE instrument.

5.1 Phase Frequency Characteristic Measurement of Single Station

A test system was established as shown in Fig. 7. The atomic clock was a Symmetricom Datum X72 rubidium clock, which generates 10 MHz clock reference and 1 pps. The reference clock of PCAL generator and LO were at 100 MHz, which was synchronously generated by Agilent E8257C signal generator through the external 10 MHz reference from the atomic clock. The whole system was coherent. PCAL generator can generate a comb signal with the bandwidth of 40 GHz, which was used as the testing signal.

Parameters of CDBE were set as follows. The number of output sub-channels was four. The output bandwidth was 16 MHz, with a quantization bit of 8 bit. The LO frequencies were set at 308 MHz, 320 MHz, 332 MHz, and 344 MHz, with an overlap of 4 MHz. Thus, the bandwidth span was 52 MHz. The PRF of comb signal was 100 kHz, and S/Φ was 30 dBHz.

PCAL signals were recorded and then analyzed to verify the delay compensation effectiveness. The phases of the tones in the overlap band of adjacent sub-channels are shown in Fig. 8.

The phases of the tones in the overlap bands coincide with each other, as shown in Fig. 8. Phase differences on both sides of the overlap bands are relatively large due to the effect of filter transition band. The average phase difference of tones in overlap band except both sides is 0.0019 rad (0.109°), which is equivalent to a group delay measurement RMS error of 8.22 ps for a linear system with a bandwidth of 52 MHz. The test results demonstrate that our proposed sub-channel delay compensation is effective, and the compensation precision is high.

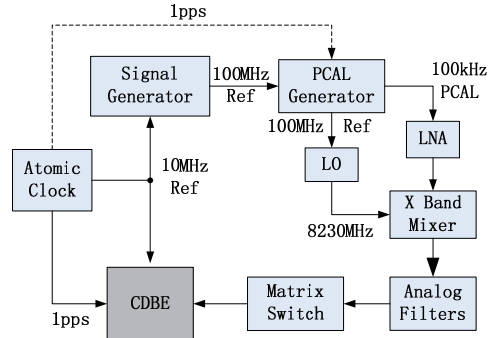


Fig. 7. Block diagram of single station test system.

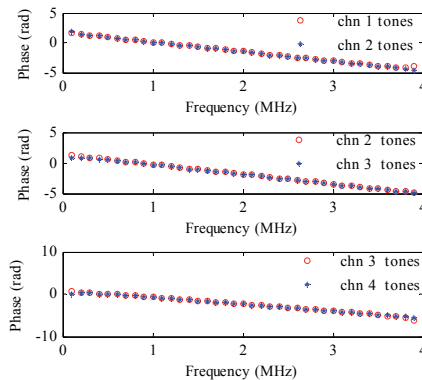


Fig. 8. Phases comparison of overlap tones in adjacent sub-channels.

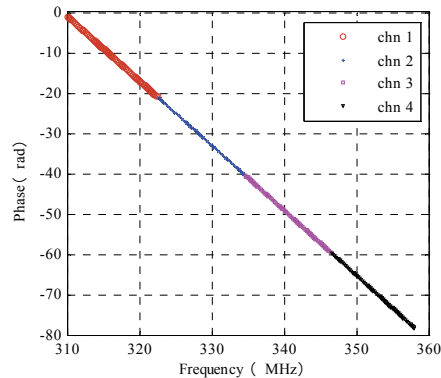


Fig. 9. Phase-frequency characteristics of the combination band.

The whole phase-frequency characteristic of the entire 52 MHz bandwidth can be obtained by the phase combination of the sub-channels according to their original frequency relationship, which is illustrated in Fig. 9.

From Fig. 9, we can see that the phases change smoothly at the joints of adjacent channels, which verifies the validity of sub-channel delay compensation again. Due to the seamless combination of the phases of different sub-channels, we can obtain the group delays of each sub-channel and that of the entire band, as shown in Tab. 3.

Tab. 3 demonstrates that group delays of the sub-channels are different and the RMS error of bandwidth synthesis is larger than that of the sub-channels, which

does not fit in with the expectation. The reason is that the analog transmission channel is nonlinear. The nonlinear characteristic of the testing band can be obtained by a linear polynomial fitting of phase-frequency characteristic, as shown in Fig. 10.

Sub-Channel Number	Group Delay (ns)	RMS (ns)
Channel 1	255.283	0.149
Channel 2	254.783	0.251
Channel 3	257.615	0.211
Channel 4	258.786	0.102
Bandwidth Synthesis	256.359	0.347

Tab. 3. Linear group delays and RMS errors of the testing system.

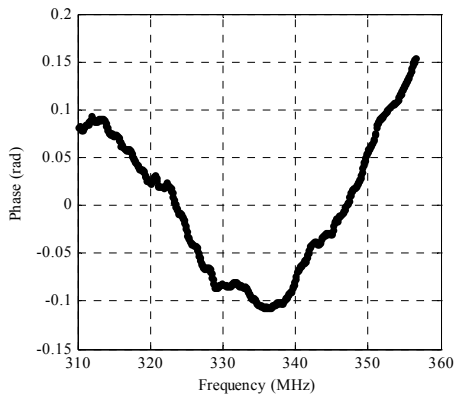


Fig. 10. Nonlinear characteristic of the whole test band.

5.2 Zero Baseline Interferometry Test

A ZBI (zero baseline interferometry) test was conducted to verify the effectiveness of our proposed sub-channel delay compensation method in interferometry. The architecture of the testing system is shown in Fig. 11.

PCAL signal and channel noise were injected into LNA (Low Noise Amplifier) as the testing signal, which passed through the same path. The LO frequencies of each sub-channel of CDBE_A were set at 270 MHz, 282 MHz, 294 MHz, 306 MHz, 318 MHz, 330 MHz, 342 MHz, and 356 MHz, respectively. The LO frequencies of CDBE_B were set at 270 MHz, 282.5 MHz, 294 MHz, 306.5 MHz,

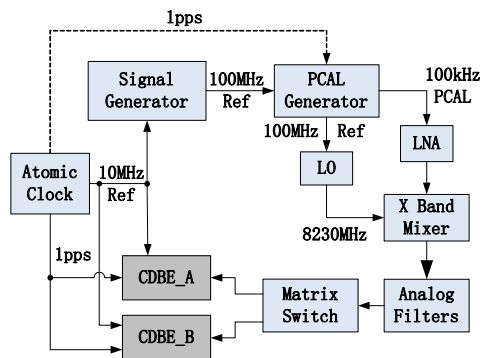


Fig. 11. Block diagram of zero baseband interferometry testing system.

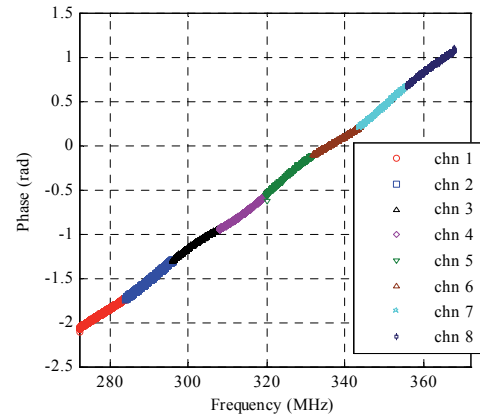


Fig. 12. Zero baseline interferometry results.

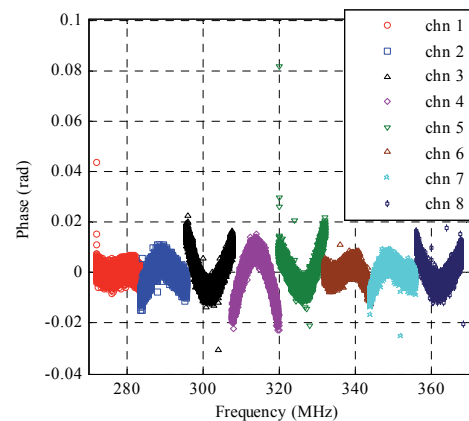


Fig. 13. Zero baseline interferometry results with PCAL calibration.

318 MHz, 330.5 MHz, 342 MHz, and 356.5 MHz, respectively. The frequency differences of the corresponding LOs were 0.5 MHz or 0 MHz, which were different. The other parameters were set the same as those in the single station test in Sec. 5.1.

The results of ZBI are presented in Fig. 12. We can see that the joints of adjacent sub-channels converge well, which indicates that our proposed sub-channel delay compensation is effective. Instrument differential delays between two CDBEs are involved in the ZBI results, which should be removed by PCAL signals. The phases calibrated by PCAL signals are illustrated in Fig. 13. The measurement results are shown in Tab. 4.

Sub-Channel Number	Differential Delay (ps)	RMS (ns)
Channel 1	0.078	2.017
Channel 2	5.879	4.164
Channel 3	8.524	6.761
Channel 4	7.127	8.410
Channel 5	0.108	6.404
Channel 6	3.262	2.831
Channel 7	5.017	3.375
Channel 8	4.996	4.965
Bandwidth Synthesis	0.086	0.590

Tab. 4. Calibrated zero baseline interferometry results.

From Fig. 13, we can see that the nonlinear characteristic of sub-channels is evident, which shows the differences of phase-frequency characteristic between the analog signal conditioning modules at the front of two CDBEs. Nonlinearity results in large RMS errors in sub-channel differential delay measurement, which can be improved by bandwidth synthesis as illustrated in Tab. 4.

6. Conclusion

We realized that sub-channel delay of CDBE can introduce phase discontinuity between different sub-channels. For the group delay measurement of a linear system, the phase discontinuity will deteriorate the precision of bandwidth synthesis. For the measurement of differential delay between two stations, "phase step" phenomenon will occur when the corresponding LO frequency differences between the two stations are not identical. The phase errors among different sub-channels can be removed manually. However, the most effective way is to compensate for the sub-channel delay to zero.

A dynamic sub-channel delay measuring method based on Modelsim is proposed. Sub-channel delay can be compensated to zero by shifting calculated clock cycles of the attached data valid signal. Simulation results demonstrate that the accuracy of bandwidth synthesis can be improved by two or three orders of magnitude by our proposed sub-channel delay compensation method, when the corresponding LO frequency differences between the two stations are not identical. Field experiments results show that the sub-channel delay compensation is effective. The nonlinear characteristics of the whole test band can be obtained with sub-channel delay compensation.

The contribution of our proposed sub-channel delay compensation method can be summarized as follows:

- 1) Phases between different sub-channels can be combined seamlessly, which improves fitting accuracy of bandwidth synthesis.
- 2) The total delay of CDBE is constant and independent of output bandwidth, which makes the delay compensation in VLBI correlator easier.
- 3) The total delay of station instrument decreases, which can diminish or eliminate the phase ambiguity of PCAL signals.

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