

Research on Deep Space TT&C VLBI Digital Baseband Converting Methods Based on Parallel Down-conversion

Hong Ma, Xin Lian, Xueshu Shi, Zhu Chen, Shaojie Wei

Abstract Very Long Baseline Interferometry (VLBI) is a radio observation method that currently has the highest precision. To solve the problem of the requirement for the hardware to have an overly high processing speed, a wideband VLBI digital baseband converter based on parallel down-conversion is designed, combining parallel processing with polyphase filtering, which can greatly reduce the requirement for processing speed and relieve the pressure on the hardware and has helped to solve the bottleneck problem of digital signal processing. The simulation results show that this wideband VLBI digital baseband converter successfully realizes functions of down-converting, filtering, and decimation to a digital IF signal, and at the same time, the data rate is greatly reduced. So it could realize wideband receiving and processing and has helped for real-time signal processing.

Keywords VLBI, digital baseband converter, wideband, parallel down-conversion

1 Introduction

Very Long Baseline Interferometry (VLBI) is a somewhat new radio interferometry technique which was developed in the late 1960s [1], and it is an astronomical observation method that can obtain the highest resolution and measuring accuracy. Currently deep space exploration has become a hotspot which is researched by many different countries. With super high angle res-

olution, the VLBI technique has an important application value in the field of deep space exploration.

The VLBI digital baseband converter is an important part of the VLBI system, undertaking tasks of data acquisition, frequency band selection, and baseband conversion. It conducts digital down-conversion to the input IF signal and changes it into a baseband signal, then filters and decimates to improve signal quality and reduce the data rate, in preparation for the subsequent digital signal processing.

Currently there are two methods for implementing a VLBI digital baseband converter—uniform channelization filtering and direct down-conversion based on quadrature mixing [2]. [3] and [4] use the uniform channelization filtering method. It has high computational efficiency, but the band selection is not flexible enough, and it needs to consider the spectrum inversion phenomenon. [5] uses the direct down-conversion method containing quadrature mixing and multi-level low-pass filtering and decimation. This method has the capability of full spectrum processing, and the center frequency and band selection are flexible. However, considering the requirement of the wideband receiving and the rapid development of AD devices, the signal sampling rate continues to increase, and the data rate is correspondingly increased, which increases the hardware processing speed requirements. When the sampling rate is too high, the hardware processing speed cannot meet the requirements and would not work normally, leading to a digital signal processing bottleneck problem. How to solve this problem and realize wideband receiving and processing have important significance [6].

Addressing the shortcomings of the direct down-conversion method, this paper proposes a new kind of wideband VLBI digital baseband conversion method

based on parallel down-conversion. It can greatly reduce the requirement for processing speed and relieve the pressure on the hardware and has helped to solve the bottleneck problem of digital signal processing in the VLBI system.

2 Key Technology of VLBI Digital Baseband Conversion

The VLBI digital baseband converter is the first component after the AD device in the VLBI system. Its input is the digital IF signal which is gotten from the receiver via high-speed sampling. The receiver usually requires that different bandwidth signals can be processed, so the VLBI digital baseband converter is required to have flexible bandwidth and center frequency. VLBI digital baseband conversion mainly consists of key technologies such as digital down-conversion, digital filtering, and decimation.

2.1 Digital Down-conversion

The implementation structure of digital down-conversion is shown in Figure 1 [7].

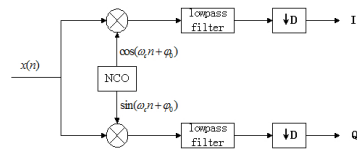


Fig. 1 Digital down-conversion implementation structure.

The numerically controlled oscillator (NCO) generates a quadrature digital local oscillator (LO) signal, whose frequency and initial phase can be set by the frequency control word and the phase control word. The digital IF signal gotten from AD sampling and the digital LO signal generated by the NCO are mixed, producing sum and difference frequency components. Then the high frequency components of the signal are filtered out by the low-pass filter and are decimated D times and decelerated. Finally, the zero center frequency output signal is obtained.

The NCO is one of the main factors that determine the performance of digital down-conversion. Its function is to generate a stable digital LO signal.

2.2 Polyphase Structure of FIR Filter

The polyphase structure of the FIR filter can geminately reduce the processing speed of hardware and relieve the pressure on the hardware.

Suppose the Z-transform of the impulse response of the FIR digital filter is

$$H(z) = \sum_{n=0}^{N-1} h(n) \cdot z^{-n} \quad (1)$$

After a series of derivations, Equation (1) can be turned into the following form:

$$H(z) = \sum_{k=0}^{D-1} z^{-k} \cdot H_k(z^D) \quad (2)$$

where $H_k(z) = \sum_{m=0}^{M-1} h(mD+k) \cdot z^{-m} = \sum_{m=0}^{M-1} h_k(m) \cdot z^{-m}$; $n = mD + k, (m = 0, 1, 2, \dots, D-1; N = M \cdot D)$.

This is the polyphase structure of FIR filter $H(z)$. In the multi-rate signal processing, this structure is usually equivalently transformed into the form of filtering after decimation.

In the polyphase filter structure, branch filters are located behind the decimators, so filtering is conducted after deceleration, thus greatly reducing the processing speed requirements and improving the real-time processing capabilities.

2.3 Efficient Digital Filter

The half-band filter is a FIR filter whose frequency response $H(e^{j\omega})$ meets the following relation:

$$\omega_C = \pi - \omega_A \quad (3)$$

$$\delta_s = \delta_p = \delta \quad (4)$$

The stopband width of the half-band filter $(\pi - \omega_A)$ and the passband width (ω_C) are equal, and the passband and stopband ripple are also equal. The coefficients are all zeros at even points, except for the

zero point. So it has high computational efficiency and needs only half the amount of computation, which is suitable for real-time processing, and it has a particularly important role in the multi-rate signal processing.

When the decimation rate D is a power of 2, M half-band filters can be used to accomplish decimation of the high multiples, whose decimation rate $D = 2^M$.

The cascaded integrator-comb (CIC) filter is a filter whose impulse response meets the following relation:

$$h(n) = \begin{cases} 1, & 0 \leq n \leq D-1 \\ 0, & \text{others} \end{cases} \quad (5)$$

where D is the order of the CIC filter and also the decimation factor. The coefficients of the CIC filter are all 1, so this kind of filter needs only addition and not multiplication. So it has small resource consumption and high calculation efficiency, and so it can complete decimation of any integral number of multiples.

3 Program Design Based on Parallel Down-conversion

3.1 Digital Down-conversion Based on Parallel Down-conversion

Briefly, digital down-conversion is multiplication of the input signal and the output LO signal of the NCO, and then to low-pass filter and decimate, so the final mixer output is obtained. Its mathematical expression can be written as:

$$y(n) = x(n) \times e^{j2\pi f_L n T_s} = x(n) \times e^{j2\pi \frac{f_L}{f_s} n} \quad (6)$$

where, f_L is the output LO frequency of the NCO and f_s is the sampling frequency and also the clock frequency. Suppose $n = iD + p$, $0 \leq p \leq D-1$, where i is the number of branches. So

$$\begin{aligned} y(iD + p) &= x(iD + p) \times e^{j2\pi \frac{f_L}{f_s} (iD + p)} \\ &= x(iD + p) \times e^{j[2\pi \frac{f_L}{f_s} i + 2\pi \frac{f_L}{f_s} p]} \end{aligned} \quad (7)$$

Suppose $y_p(i) = y(iD + p)$, $x_p(i) = x(iD + p)$, then the output of the p -th branch $0 \leq p \leq D-1$ is:

$$y_p(i) = x_p(i) \times e^{j[2\pi \frac{f_L}{f_s} i + 2\pi \frac{f_L}{f_s} p]} \quad (8)$$

It can be seen that the mixer output $y(n)$ can be divided into a timing combination of D output branches. Each branch is the mixture of the branch structure of the input sequence and the LO signal of the corresponding NCO. The output LO signal of each NCO is respectively:

$$S_p = e^{j[2\pi \frac{f_L}{f_s} i + 2\pi \frac{f_L}{f_s} p]}, 0 \leq p \leq D-1 \quad (9)$$

So the clock frequency of each branch is f_s/D , and the initial phase differences of the output LO signal of the NCO between adjacent branches are all $2\pi \cdot \frac{f_L}{f_s}$. As is seen, using this equivalent branch structure is equivalent to reducing the clock frequency of NCO from f_s to f_s/D , greatly reducing the processing speed of the hardware, thereby reducing the difficulty of the hardware implementation of the NCO.

From the above parallel structure, we can think of the polyphase structure of the FIR filter, so we can combine the parallel mixer outputs with the polyphase filter, so that the data rate of each branch can remain at a relatively low level, greatly reducing the processing speed of the hardware.

3.2 Design of the Whole Project

Based on the above derivation analysis, this paper intends to adopt an eight-branch parallel down-conversion structure to implement a wideband VLBI digital baseband converter; its implementation structure is shown in Figure 2.

The digital IF signal is obtained by high-speed AD sampling of the input analog IF signal, and it is divided into eight branches of parallel data streams through series-parallel conversion; the data rate of each branch is reduced to 1/8 of the original. The eight branches of the data stream are respectively mixed with the corresponding NCO output, and then a polyphase FIR filter structure is used to perform low-pass filtering on the eight branches of mixed output, so that the baseband signal is obtained. Then a two-time decimation polyphase filter structure is used again, to further improve signal quality and lower the data rate.

As to the NCO of each branch, f_{LO} is the LO frequency of the NCO output which is expected. When designing, it can be controlled by the frequency control word according to requirements, to get the equivalent

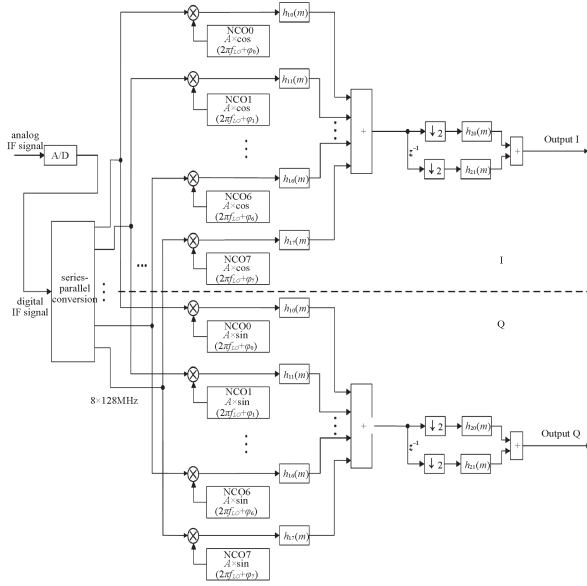


Fig. 2 Implementation structure of the wideband VLBI digital baseband converter.

LO frequency f_L that is wanted. In the above parallel down-conversion structure, the LO frequency of each branch NCO should be set to $f_{LO} = \text{mod}(f_L, f_s/D)$, where f_s is the sampling frequency, D is the number of branches, and N is the digit of phase accumulator. And the initial phase difference of adjacent branch NCO output is $\Delta\varphi = 2\pi \cdot \frac{f_L}{f_s}$, so the initial phase of each branch NCO output is set to $\varphi_p = 2\pi \cdot \frac{f_L}{f_s} p$, where p is the serial number of the branch ($p = 0, 1, \dots, D-1$).

According to the different bandwidths of the output signal, the working mode is divided into wideband mode and narrowband mode. The output bandwidth of wideband mode can be 16 MHz, 8 MHz, 4 MHz, 2 MHz, 1 MHz, or 0.5 MHz. Multi-stage half-band filtering and decimation are conducted on the above obtained I and Q signal, and the stage of the half-band filter is selected according to the output bandwidth requirement. At last, shaping filtering and decimation are conducted on the above output signal, and the final output is obtained. The implementation diagram is shown in Figure 3.

The output bandwidth of narrowband mode can be 200 kHz, 100 kHz, 50 kHz, 25 kHz, 16 kHz, 8 kHz, 4 kHz, 2 kHz, or 1 kHz. In this mode, multi-stage CIC filtering and decimation are conducted on the obtained I and Q signal, and the decimation time of the CIC filter is selected according to the output bandwidth require-

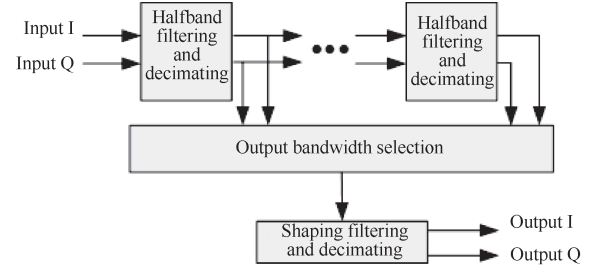


Fig. 3 Diagram of wideband mode processing.

ment. At last, compensating filtering, shaping filtering, and decimation are conducted on the above output signal, and the final output is obtained. The implementation diagram is shown in Figure 4.

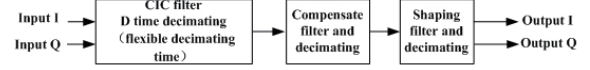


Fig. 4 Diagram of narrowband mode processing.

4 Simulation Verification

According to the above design scheme, simulations of the entire program are conducted using MATLAB software. At the same time, the scheme is implemented by writing VHDL codes, and the corresponding simulations are conducted too. Here suppose the input IF signal is a linear FM signal, whose frequency range is $f_{in} = 287\text{--}290$ MHz, sampling rate is $f_s = 1$ GHz, desired output LO frequency of NCO is $f_L = 288$ MHz, and number of branches is $D = 8$. In the simulation, the wideband output mode is used, and the stage of the half-band filter is set to 2.

Firstly, a linear FM signal as input is generated by MATLAB, whose frequency range is $f_{in} = 287\text{--}290$ MHz, and its frequency spectrum is shown in Figure 5.

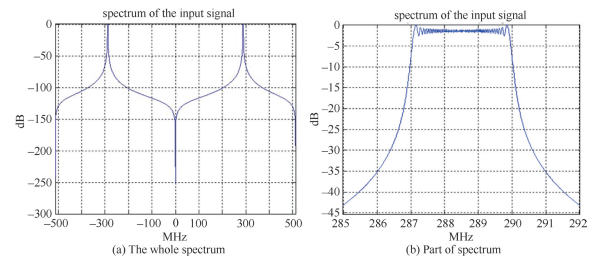


Fig. 5 Frequency spectrum of input signal.

Then the simulations of the entire scheme are conducted using MATLAB, the input signal is processed by the VLBI digital baseband converter, and the frequency spectrum of the output signal is shown in Figure 6.

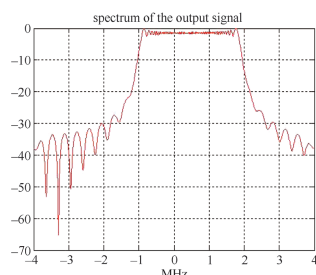


Fig. 6 Frequency spectrum of output signal in MATLAB simulation.

Meanwhile, the VHDL codes are programmed step by step to implement the wideband received VLBI digital baseband converter. Simulations are conducted using ModelSim software. The input signal is the same as with the above simulation, and the simulation time is 100 μ s, so the corresponding output is obtained.

Then the above output data is read with MATLAB, and its frequency spectrum is obtained as shown in Figure 7. Figures 6 and 7 show that the input sig-

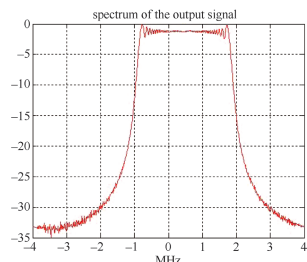


Fig. 7 Frequency spectrum of output signal in ModelSim simulation.

nal is processed by the VLBI digital baseband converter and the obtained output signal is a linear FM signal whose frequency range is $f = -1-2$ MHz. It shows that the frequency spectrum of the linear FM signal whose frequency range $f_{in} = 287-290$ MHz is moved to $f = -1-2$ MHz. And it is known, according to the theory of direct down-conversion, that the frequency range should be $f = (287 - 288)$ MHz $-(290 - 288)$ MHz $= -1-2$ MHz. So the simulation results of the scheme meet with the theoretical value, the output is correct, and the desired goal is achieved.

The scheme in this paper greatly reduces the requirement for processing speed and relieves the pressure on the hardware. Thus the hardware can support

a higher sampling rate and wider band signal receiving and processing.

5 Conclusion

After the above scheme design and simulation verification, the proposed implementation method of wideband VLBI digital baseband converter based on parallel down-conversion can realize the functions of down-conversion, low-pass filtering, and decimation of the digital IF signal, and the output is correct. It has features for more than wideband receiving, the frequency can be set flexibly, and the output bandwidth can be optional. But also, the requirements for the processing speed of the hardware are greatly reduced, and this can solve the bottleneck problem of DSP. And it has helped to achieve wider bandwidth receiving and processing and also helped to achieve real-time signal processing. It has a high reference value and can promote the development of the VLBI system and fields such as software, radio, and data acquisition.

References

1. Qian Zhihan, Wu Linda. Very Long Baseline Interferometry. Beijing: Surveying and mapping press, 1998: 1-14.
2. Liang Sheng, Yang Wenge. Design of a VLBI Digital Baseband Converter Based on Polyphase Structure. Development & Innovation of Machinery & Electrical Products, 2011, 24(1): 149-151.
3. IVS Memorandum 2006-003v01, IVS-WG3 Report on the Backend System.
4. Chen Lan, Luo Jintao, Xiang Ying, et al. Polyphase based VLBI digital baseband converter with adjustable IF center frequency and bandwidth. Computer engineering and application, 2010, 46(2): 55-59.
5. Gino Tuccari, Walter Alef, Alessandra Bertarini, et al. DBBC Development Status. Proceedings of the 5th IVS General Meeting. St. Petersburg, Russia: IVS, 2008: 376-380.
6. Xiang Ying, Zhu Renjie, Gino Tuccari, et al. Wideband digital SSB down converter. Acta electronica sinica, 2006, 34(11): 1978-1980.

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