Algorithm and Simulation Analysis of VLBI Data Correlation Processing

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Abstract As a radio astronomical technique with very high angular resolution, Very Long Baseline Interferometry (VLBI) has been widely used in the high precision deep space probe tracking activities. VLBI correlation processing consists of integer and fractional sample delay correction, fringe stopping algorithms, and so on. Simulation results have proven that the algorithm is correct and valid. Moreover, the mission data used in the correlative calculation yield clear interference fringes residual delay and residual delay rate through the bandwidth synthesis. We compared the fringes obtained using different integration times; it has high significance for the further development of VLBI research.

1 Introduction

Very Long Baseline Interferometry (VLBI) is a radio interferometry technique developed since the 1960s. The principle of VLBI is receiving a signal from a distant source at two radio telescopes where the signals are recorded on storage media. After a subsequent correlation processing parameters are estimated that reflect the position and state of motion of the source space. It is currently the highest angular resolution astronomical observation technique, reaching sub-mas resolution and better. With the development of China's

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aerospace industry, spacecraft extend from near-Earth orbit to the moon and deeper space, resulting in higher requirements for aerospace measurements and control ability. VLBI is one of a limited number of deep space exploration methods we can rely on; therefore, it can provide high-precision measurement information for deep space navigation [1, 2, 3].

The VLBI system consists of two or more observation antennas and a data processing center. The VLBI data correlation processor is the core equipment of the data processing center and is a complex high-speed signal processing system. Its main function is to detect interference fringes and to calculate the correlation value or the corresponding cross power spectrum for each frequency channel. While in the early days VLBI data processing mainly used hardware correlators, in recent years the software correlation technology, based on modern high performance PCs or server platforms, has been highly valued in Europe and the United States. Software correlation has become a research hotspot in VLBI [4, 5, 6]. This paper summarizes the FX algorithm of the VLBI software correlator. Using this algorithm we obtain clear interference fringes residual delay and residual delay rate through bandwidth synthesis. This is very important for the future development of VLBI research.

2 The Basic Principle of VLBI

2.1 VLBI Measurement Principle

The basic principle of VLBI observations is shown in Figure 1. When two radio telescopes on Earth at different locations align a radio source simultaneously,

they receive the radio radiation of pulsar together. The observed radio source is a very distant extragalactic object; therefore, radio waves can be considered as a plane wave when they arrive at the Earth [7]. Due to the different distances of the two antennas to the radio source, there is a distance difference L. The time of the radio signal to reach the two antennas will be different, resulting in a time delay τ_g and delay rate $\dot{\tau}_g$.
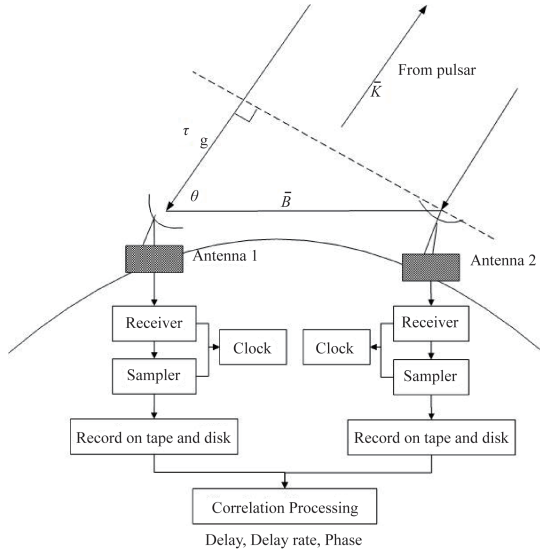

Fig. 1 The basic principle of VLBI observations.

The geometric relationship of the VLBI observation is

$$L = c \cdot \tau_g, \tag{1}$$

where c is the velocity of light. If D is the baseline between the two antennas and θ is the angle between the observed pulsar direction and the baseline, then

$$\tau_g = \frac{1}{c}(D \cdot \cos(\theta)). \tag{2}$$

Due to the motion of the Earth, the baseline vector position changes, so τ_g is a function of time t and the time derivative, called time delay rate $\dot{\tau}_g$, is

$$\dot{\tau}_g = \frac{1}{c}\frac{\partial}{\partial t}(D \cdot \cos(\theta)). \tag{3}$$

The observed data of each station are transmitted to the data processing center through a certain way, and the delay and delay rate of signal reaching each station can be calculated by correlation processor, so as

to determine the angle of the source relative to the station. The VLBI observation principle for spacecraft is similar: correlation processing of the spacecraft signal received at two stations provides the angle between the spacecraft and the two measuring stations. This can be used to determine the orbit information of the spacecraft.

2.2 The Basic Principle of the Correlation Processing

The correlation processing is the core of the VLBI data processing, and it is divided into XF type and FX type. The XF correlator calculates the cross-correlation function and Fourier transform first, and then gets the power spectrum. But FX does the Fourier transform of the signal first and then the cross-correlation power spectrum is calculated. The performance of FX is better, but the development is difficult. It has many advantages such as less operation scale and hardware overhead, modularity, and extensibility.

At present, the processing mode of the FX is further advanced. The principles of its data correlation processing is that using the initial value provided by the delay and delay rate model and doing a series of correlation operations such as integer bit correction, fringe stop, FFT, fractional bit correction, and cross multiplication to get the cross-correlation power spectrum of the radio source and spacecraft. Then the correlation fringe is obtained through phase unwrapping; the slope of the correlation phase fringe relative to frequency is the residual delay that we seek. Accurate delay results corrected by residual are used to determine the spacecraft orbit.

2.3 The VLBI Correlation Algorithm

The mathematical model of correlation processing has been introduced in several papers [3, 4, 5], e.g., integer sample time compensation, fringe stopping, FFT, fractional sample time compensation, cross multiplication, and cross spectrum accumulation. We do not describe it here further.

Finally, the actual delay and delay rate can be received by residual delay and residual delay rate plus

the model value of the delay and delay rate. All the stations must do the delay compensation and fringe stopping when the geocenter is the reference, and then the cross-spectral estimation can be used to get the residual delay and residual delay rate.

3 Calculation and Analysis

3.1 Simulation Analysis

The correlation processing algorithms are verified through simulation and calculation. Reference station is 1, the length of the baseline between two stations is 30,000 m, frequency sampling of signal is 1 MHz, the sampling time interval is 1 μs, the initial delay equal to 5*10-5 s, and the ideal fringe rate is -629.804 Hz. The Gaussian white noise signal S1 is generated by Matlab as signal of the station 1, and we do correlation calculation using the signal S1 and S2 which is constructed by the delay.

Under the condition that the fringe rate is constant, we calculate the time delay for the initial values to 46 μs, 47 μs, 50 μs, 51 μs, 52 μs, and 54 μs. Assuming the delay to be constant, we calculate the time delay rate for the initial values of -633.804 Hz, -630.804 Hz, -629.804 Hz, -628.804 Hz, -626.804 Hz, and -625.804 Hz. The results of the residual delay and residual fringe rate are shown in Table 1 and Figure 2.

Table 1 Statistics for the residual delays and residual fringe rates.

Initial delay/μs	Residual delay/s	Precision/s
46	$+4.000076 \cdot 10^{-6}$	$7.66 \cdot 10^{-11}$
47	$+3.000089 \cdot 10^{-6}$	$5.61 \cdot 10^{-11}$
50	$-7.606533 \cdot 10^{-25}$	$5.24 \cdot 10^{-11}$
51	$-1.000062 \cdot 10^{-6}$	$5.48 \cdot 10^{-11}$
52	$-1.999952 \cdot 10^{-6}$	$6.01 \cdot 10^{-11}$
54	$-3.999984 \cdot 10^{-6}$	$7.19 \cdot 10^{-11}$

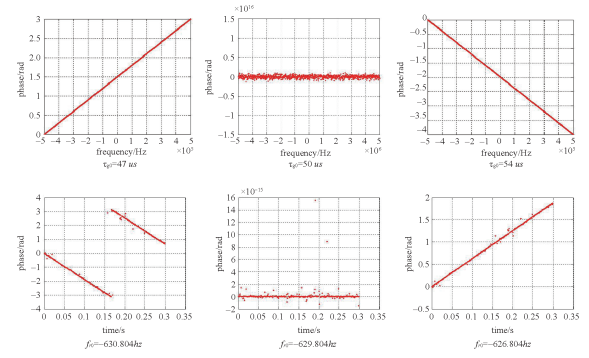| Initial fringe rate/Hz	Residual fringe rate/Hz	Precision/Hz
-633.804	$+3.998936$	0.000360
-630.804	$+0.999742$	0.000259
-629.804	$+5.8473 \cdot 10^{-17}$	0.000256
-628.804	-0.999742	0.000259
-626.804	-2.999213	0.000273
-625.804	-3.998935	0.000360

Fig. 2 Schematic diagram of the simulated signal interference fringe.

3.2 Mission Data Analysis

We complete the correlation processing of a single baseline by using the CE-3 database with the data processing method described above. Since the measurement data of the mission is DOR tone signal, a clear interference fringe could be obtained in the main carrier channel when doing the correlation calculation. The residual delay and residual delay rate could be calculated by the phase of the tone signal of the other channel based on the bandwidth synthesis technique. The spectrum analysis of the original data is shown in Figure 3. We can clearly see the tone signal in the four channels.
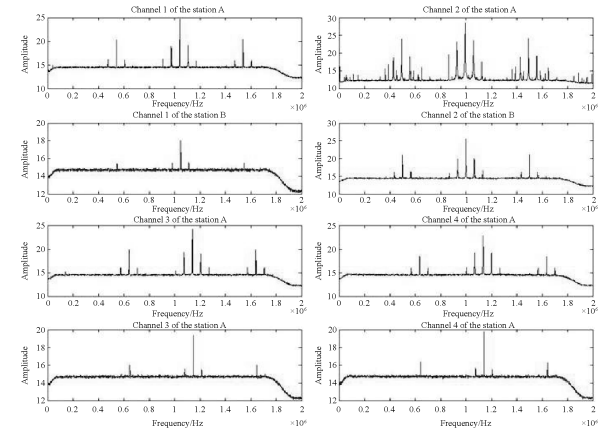

Fig. 3 The spectrum of the raw data in the four channels.

We finish the correlation processing with the mission data by setting the integration time to 5 s and 60 s,

respectively. The results of the interference fringes are shown in Figure 4. The residual delay and residual delay rate are shown in Figure 5; the long time integral is better when the model value is accurate.
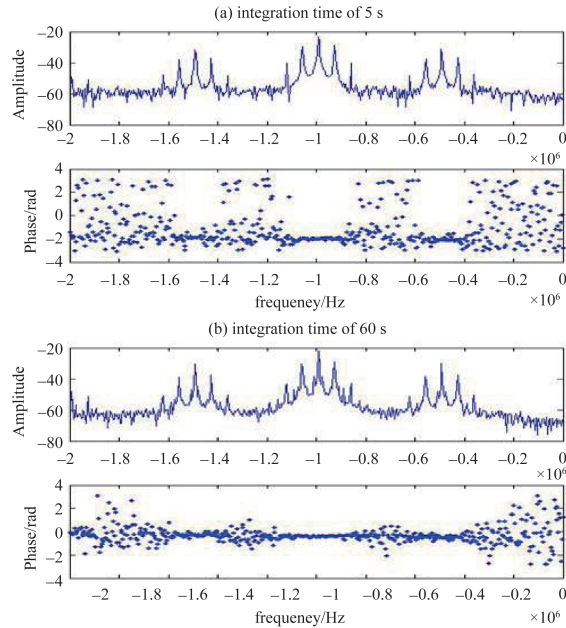

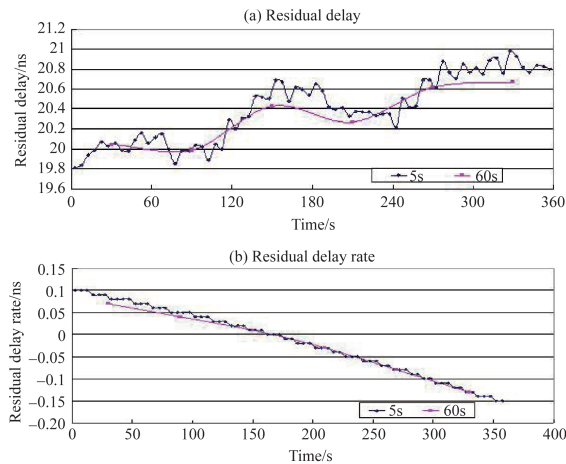**Fig. 4** The interference fringes with different integration times.

Fig. 5 The resulting residual delay and residual delay rate.

4 Conclusions

Based on the introduction of VLBI software related processing method, the paper has given the model and calculation formula of the integer sample time compensation, fringe stopping, FFT, fractional sample time compensation, cross multiplication, and cross-spectrum accumulation. The clear interference fringe, accurate value of delay and fringe rate can be determined by simulation and mission data. We can see from the simulation results that the residual delay precision is up to 10^{-11} s and the residual fringe rate precision is up to 10^{-4} Hz. This proves the validity of the correlation algorithm. Finally, using mission data in the correlative calculation, we obtained clear interference fringes residual delay and residual delay rate through the bandwidth synthesis and compared the fringes of different integration time. It has high significance for further VLBI research.

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