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研究论文

CVN 硬盘系统和软件相关处理在 e-VLBI 试验中的应用

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摘要: 介绍了中国 VLBI 网 (CVN) 的 e-VLBI 技术研究进展。 CVN 包括上海佘山、乌鲁木齐南山 2 个固定观测站和云南昆明的流动站, 以及上海天文台的 2 台站硬件相关处理机。 2003 年上海天文台自行研制了基于 PC 技术的 VLBI 数据记录、回放系统, 命名为 CVN 硬盘系统, 并成功将其安置于 CVN 观测站和处理机系统。硬件处理机经过改造后, 已能处理来自硬盘和原有磁带系统的数据。从 2003 年至今, 中国 VLBI 网采用该硬盘系统进行了多次 VLBI 观测和 e-VLBI 试验。在 CVN 硬盘系统基础上, 软件相关处理技术的研究也得以开展。软件相关处理原型程序已经被用于台站条纹检测、卫星条纹搜索和数据处理中。该软件获得的计算结果被成功用于国内第一个 3 台站卫星 VLBI 的延迟和延迟率闭合试验, 以及国内首次利用 VLBI 数据进行的卫星定轨试验。除此之外, 该软件还用作硬件处理机的条纹引导器。为适应未来 "嫦娥" 月球探测工程, CVN 将扩展成含有 4 个观测站和 2 个相关处理机 (硬件、软件) 的实时 VLBI 网。今后, e-VLBI 将被应用于月球卫星导航以及测地和天体物理的 VLBI 观测。

关 键 词: 天文观测设备与技术; 硬盘阵列; 软件相关处理机; e-VLBI ; 中国 VLBI 网
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CVN Harddisk System and Software Correlator in e-VLBI Experiments

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Abstract: This paper presents some e-VLBI progress of CVN (Chinese VLBI Network).

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Presently CVN consists of two fixed stations located in Shanghai Sheshan and Urumqi Nanshan, one mobile station in Yunnan Kunming, and one 2-station hardware correlator (Shanghai correlator) in Shanghai Astronomical Observatory (SHAO). In 2003, a PC-based VLBI data recording and playback unit named CVN harddisk system was developed at SHAO and several systems were installed in CVN. Several e-VLBI experiments have been performed with this system since 2003. Now the Shanghai correlator is able to process the data from harddisks or tapes. Based on the CVN harddisk system, a prototype software correlator was developed and used in the station fringe checkout, the fringe search of the satellite signal and data processing. The first domestic 3-station delay, delay rate closure test of the satellite VLBI observation and the first domestic satellite orbit determination test using VLBI were successfully accomplished based on the results of the software correlator. Besides, the software correlator acts as the fringe guider of the Shanghai correlator. To satisfy the requirements of the Chinese lunar exploration project, CVN will be upgraded to a realtime VLBI network, including 4 stations and two new realtime correlators (hardware and software). e-VLBI will be applied to the lunar satellite navigation, as well as other geodetic and astronomical observations in the future.

Key words: astronomical facilities and technique; harddisk array; software correlator; e–VLBI; Chinese VLBI network

1 Introduction

From the beginning of the Very Long Baseline Interferometry (VLBI) to several years ago, the only suitable data storage technology was magnetic tape recording, which was characteristic of VLBI. However the tape system is not only very unstable but also expensive. Besides, usually it takes more than one week or longer time to transport the tapes from stations to the correlator, so there is a delay of one week or more between observations and correlations. Nevertheless, things are different now. With the development of the computer and electronic industry, a new technology dubbed "e-VLBI" appears; "e" refers to electronic transfer of VLBI data [1]. e-VLBI consists of two phases, near real-time VLBI and strict real-time VLBI [2]. The former means data are firstly recorded on the harddisk arrays and then transmitted from the stations to the correlator through a communication network. In the strict real-time VLBI mode, the observation data are transmitted and correlated simultaneously. Sometimes data need to be stored for correlating and analyzing repeatedly or checkout, so the high-speed harddisk is still an important intermediate recording device or a buffer even in the strict real-time VLBI. Actually, most e-VLBI observations are near real-time VLBI based on the harddisk system at present [3].

Compared with the traditional "tape-VLBI", the salient features of the tapeless e-VLBI are faster data turnaround, higher reliability and lower operational costs. Faster data turnaround is the prominent merit of e-VLBI, which means more rapid transmission of data to correlation center and consequent reduction in processing. It is valuable in some time-sensitive domains, such as station fringe checkout, observation for the spacecraft navigation, intensive UT1 (Universal Time) estimation, crustal deformation detection, etc [2,3,5~7]. Now VLBI is heading for e-VLBI.

The high-speed mass capacity harddisk and the software correlator are two important e-VLBI techniques. To a certain extent, the rapid development of e-VLBI is promoted by some VLBI harddisk systems and software correlators. Actually several harddisk systems (Mark5, K5, PCEVN) and software correlators (K5, SOFTC) have been developed recently [1,11,4,9]. For example, the Joint Institute for VLBI in Europe (JIVE) got the first Europe e-VLBI image with Mark5 in Jan. 2003 [8]. Furthermore, the JPL's software correlator SOFTC has been used operationally for spacecraft navigation for over 2 years [9]. At the same time, the National Institute of Information and Communication Technology (NICT) in Japan developed the K5 software correlator and tried to use it in the geodetic and satellite VLBI data processing [4]. Although most existing VLBI correlators are hardware correlators, the processing speed of the software correlators based on general computers is getting faster and it seems that it will become feasible to use software correlators for the routine VLBI observations in 2010 or beyond [10,11].

At present, the Chinese VLBI Network (CVN) consists of three VLBI stations and one correlator. Shanghai Sheshan and Urumqi Nanshan stations are fixed stations with a 25-meter antenna respectively. The third one located in Kunming, southwest China, is a mobile VLBI station with a 3-meter antenna [12]. The 2-station hardware correlator is placed in Shanghai Astronomical Observatory (SHAO). Until 2002, the tape was the only data media for CVN. Since then SHAO has carried out the research on e-VLBI and has achieved several fruits. For example, the self-developed harddisk systems and formatter have been mounted in the stations and the software correlator has been used for the e-VLBI data processing.

2 CVN PC-Based VLBI Data Recording and Playback Harddisk System

The CVN harddisk system originated from the replacement of the existing Shanghai correlator tape playback system made by Penny & Giles (P&G) company. The P&G tape system was so unstable that it brought lots of troubles to the correlator and even affected its operation. Although we did our best and tried to repair them, there was little improvement [13]. In addition, the data of Kunming station (S2 format) could not be processed by the existing Shanghai correlator. For this reason, we thirsted for a low cost and reliable harddisk system to replace the existing tape playback unit. e-VLBI is another stimulus of the CVN system. In 2002, there were already several new developed PC-based VLBI data recording/playback harddisk systems like Mark5, K5 and PCEVN, etc. These harddisk systems are the key to e-VLBI, but none of them was compatible with the Shanghai correlator (VLBA model). Since then, the VLBI Techonlogy Laboratory of SHAO has begun to develop a cheap and stable PC-based VLBI data recording/playback system named CVN harddisk system. In order to make it, from the very beginning, we decided to use, as far as possible, the commercial off-the-shelf (COTS) components, like the ordinary industrial PC and the IDE (Integrated Device Electronics) harddisk. This harddisk system has been mounted at the CVN stations for more than one year, and totally replaced the tape system in the domestic VLBI observations.

Figure 1 shows the structure of the CVN harddisk system. The hardware platform is an ADLINK NuPRO-841 industrial PC mainboard. The IO (Input and Output) interface is an ultra-high speed digital IO board — ADLINK PCI-7300B, which is a 32-channel, 40 MHz PCI (Peripheral Component Interconnection) data IO board. The maximum IO speed reaches 80 MB/s. Debian Linux is the operation system of the CVN system. The received data are stored in the ordinary Linux files. One CVN unit has four 120 GB IDE harddisks and data are written to (or read from) these four harddisks simultaneously. Such mode increases the recording/playback speed remarkably. The pivotal control software is self-developed.

The special recording and playback interfaces, as shown in Figure 2 and Figure 3, were designed to fulfill the harddisk–formatter and the harddisk–correlator communication and control tasks. With this recording/playback interface, the CVN harddisk system is compatible with a Mark4 formatter (in the recording mode) and the Shanghai correlator (in the playback mode)[13].

In the recording mode, the data and clock signals from a Mark4 VLBI formatter are transformed from the ECL (Emitter-Coupled Logic) level to the TTL (Transistor-Transistor Logic level with the recording interface, and then received by the PCI-7300B IO board. The recording)

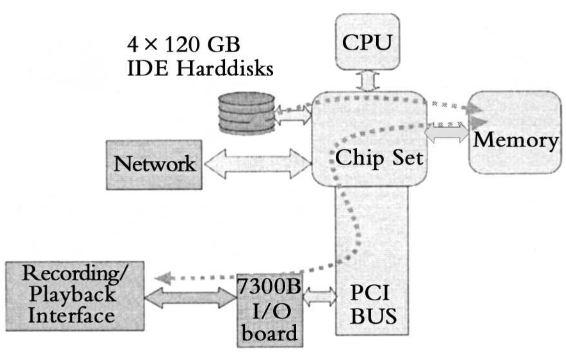

Fig. 1　Structure of CVN harddisk system

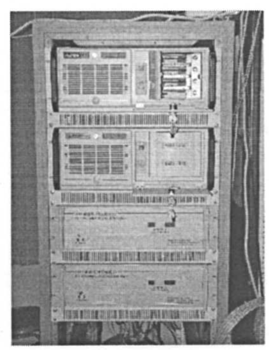

Fig. 2　CVN harddisk system playback unit (upper) with plackback interface (lower)

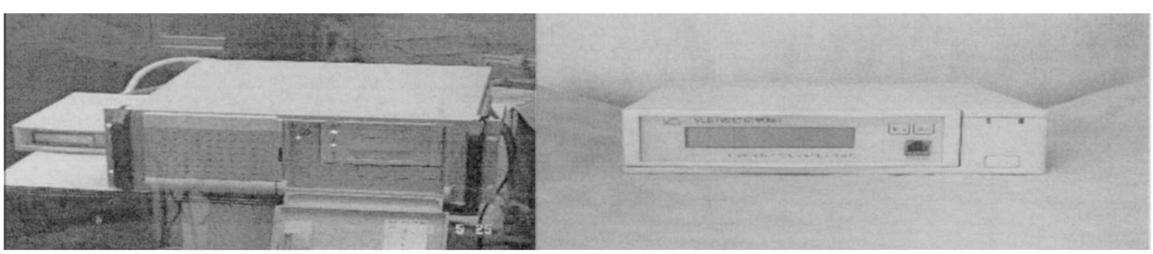

Fig. 3　CVN harddisk system (left) with the recording interface (right)

interface is able to decode the Mark4 format data and display UTC (Universal Time Coordinated), track information, etc. The harddisk system checks the data quality with software before recording; thereby the data are recorded only if there are no parity or frame errors.

The playback interface receives the control and monitor commands from the correlator through RS232 and MCB ports, and then adjusts the output data speed accordingly. Therefore, from the view of the Shanghai correlator, there is no difference between a CVN harddisk playback system and a P&G tape playback unit.

The typical recording speed of one CVN harddisk unit is 288 Mbps (32track@9 MHz), and the maximum recording speed is up to 576 Mbps (32track@18 MHz). With four 120 GB disks, one unit can record about 7-hour data (32track@4.5 MHz), which is equivalent to the 80 ips tape speed. The maximum playback rate is up to 288 Mbps (32track@9 MHz).

The milestones of the CVN system are:

Mar. 2003: Recording test at Sheshan station;

Apr. 2003: Disk-disk & disk-tape playback test;

May 2003: First fringe demonstrated between Nanshan and Sheshan;

May 2003: First e-VLBI fringe test between Nanshan and Sheshan (disk-internet-disk, by FTP (File Transfer Protocol));

Apr. 2004: First domestic 3-station VLBI satellite observation with Nanshan, Sheshan, Kunming stations.

3 Software Correlator

Since the cost performance of the commercial computer increases greatly, there seems to be a tendency of using software correlator instead of hardware correlator to process the VLBI data in the future. It is appealing that once the VLBI data are stored in the harddisks, they become accessible to PC. This means that data on harddisks can be processed by a software correlator running on a general PC. Therefore, after having the CVN harddisk system, we began studies on the software correlator. A prototype software correlator (Matlab version) has been developed. Now this software correlator has three uses, viz. station checkout, rapid fringe search of satellite observation and VLBI correlation.

3.1 Station Checkout

The first application of the software correlator was the station fringe checkout. This type of short time observation can be used to verify the proper operation of target stations. Such a capability is highly valuable to confirm proper operation of all stations participating in important observations in advance of the start of those observations [5].

In the station checkout observations, two kinds of radio source were selected. The downlink telemetry signal of a Geostationary Earth Orbit (GEO) satellite was selected as the first observed object, because the orbit of a GEO satellite is easy to calculate and the telemetry signal is a very strong man-made radio source. The signal-to-noise ratio (SNR) of a GEO satellite is so strong that the software correlator is able to find the legible fringes with a very few of data. The observation time was only 0.5 s; and the corresponding data were 8 Mbytes that could be easily transmitted from each station through FTP. Another source was a strong extragalactic source,

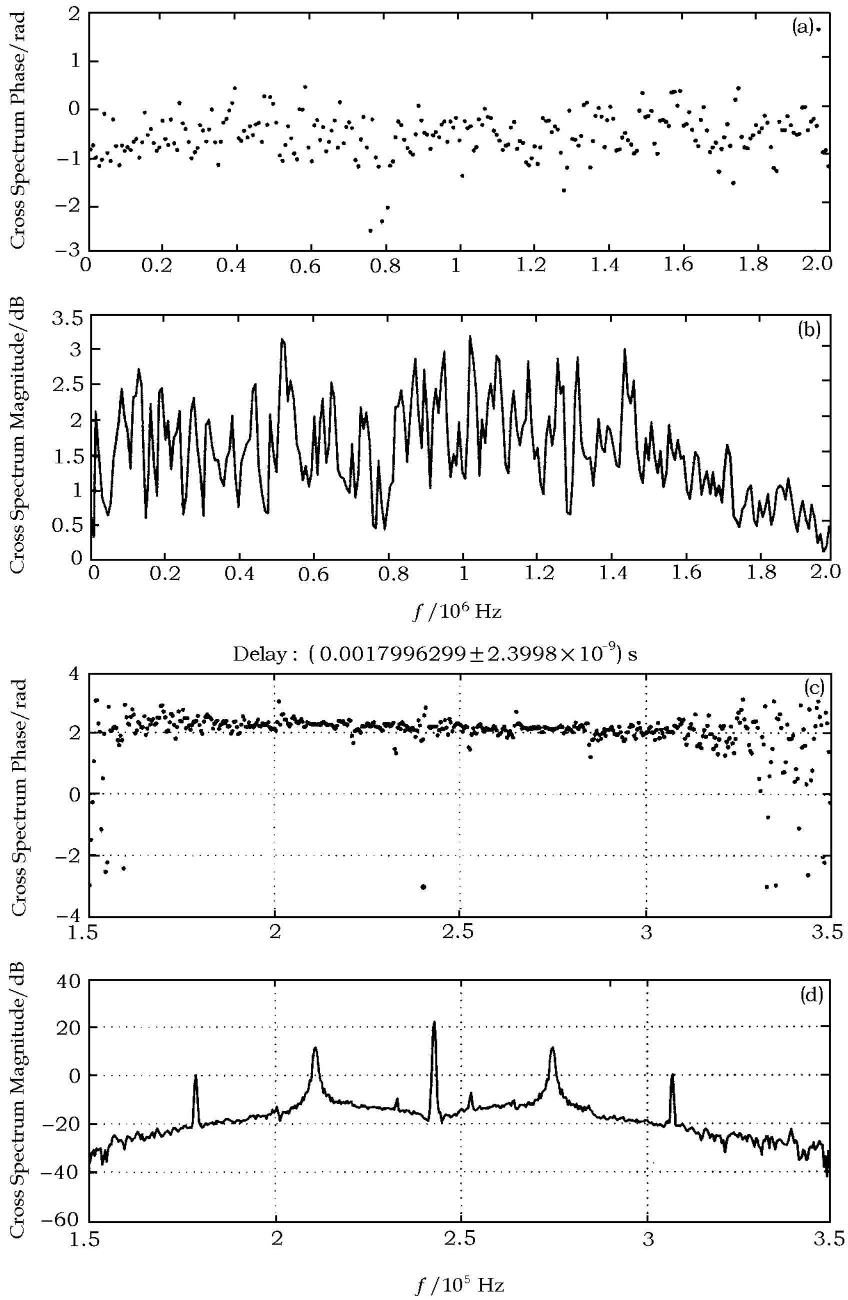

Fig. 4　Fringe checkout using software correlator, phase ((a), (c)) and amplitude ((b), (d)) spectra, DA193 ((a), (b)), GEO satellite telemetry signal ((c), (d))

for example, DA193. When observing DA193, it needed about 30 s data (about 500 Mbytes) to get legible fringes. Figure 4 shows the fringes of a GEO satellite and DA193 produced by the software correlator.

The software correlator once successfully found that the local oscillator frequency shift (about 106 Hz) of the Nanshan station, as well as the abnormal instrumentation delay (up to 200 ms) caused by the Kunming station. Now the station checkout can be finished in an hour under normal conditions.

3.2 Rapid Fringe Search of Satellite Observation

In order to study how to use VLBI in the spacecraft navigation in the near future, we have performed several satellite VLBI observations since 2003. In these experiments, the antennas tracked the downlink telemetry signals of satellites. After observations, we soon found that there were delay and delay rate errors in the correlator's model. The errors caused by the imprecise predicted satellite orbit were so big that the Shanghai (hardware) correlator could not find any fringe by itself. This meant that the predicted satellite orbit was not precise enough to be used in the VLBI correlator directly. So in the satellite observations, it is necessary to automaticallysearch the fringes under conditions of without any priori delay model and then to produce the delay and delay rate or DOD (Differential of One - way Doppler) values. Because the observed value is for

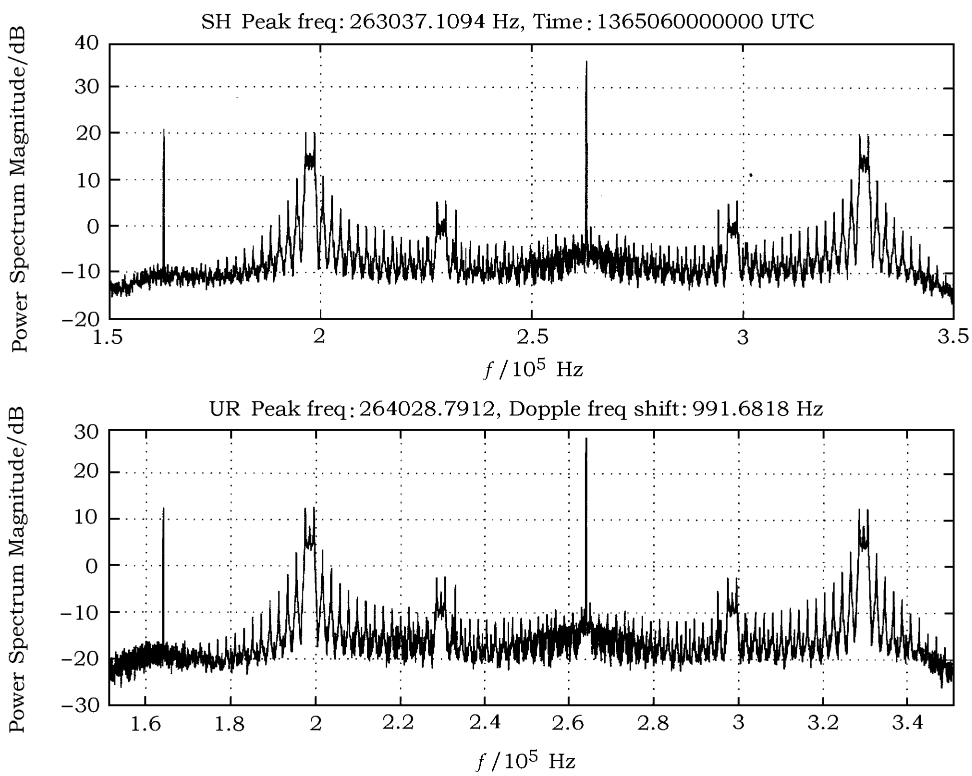

Fig. 5 Spectra of satellite downlink telemetry signals, Sheshan (up), Nanshan (down)

correlator's model correction, it must be more accurate than the priori calculated value. This is very important in the satellite signal processing, and the software correlator was used for such kind of rapid fringe search.

Spectral analysis shows that the spectrum structure of a satellite telemetry signal is quite different from that of a continuum extragalactic sources (Figure 5). The telemetry signal is a narrow band signal with a strong carrier wave in the center of the spectral domain, as well as several tones. In the rapid fringe search mode, firstly, the software correlator computes the frequency difference of the carrier waves received by two stations, namely DOD, corresponding to the fringe rate (Figure 6); secondly, this value is applied to stop the fringe; finally, the correlator uses both XF and FX methods to correlate the signals and to find out the group delay (Figure 7). The residual DOD is also produced (Figure 8). After several iterations, the final detected fringe is produced (Figure 9). This procedure takes only several minutes.

Although in the rapid fringe search mode, the integration period is about 0.5 s and the software correlator does not perform the Fractional Sample Time Correction (FSTC), the precision of DOD can still reach about several mHz, and the group delay error is less than 10 ns on the Nanshan–Sheshan baseline. Considering that the narrow bandwidth of the telemetry signals is

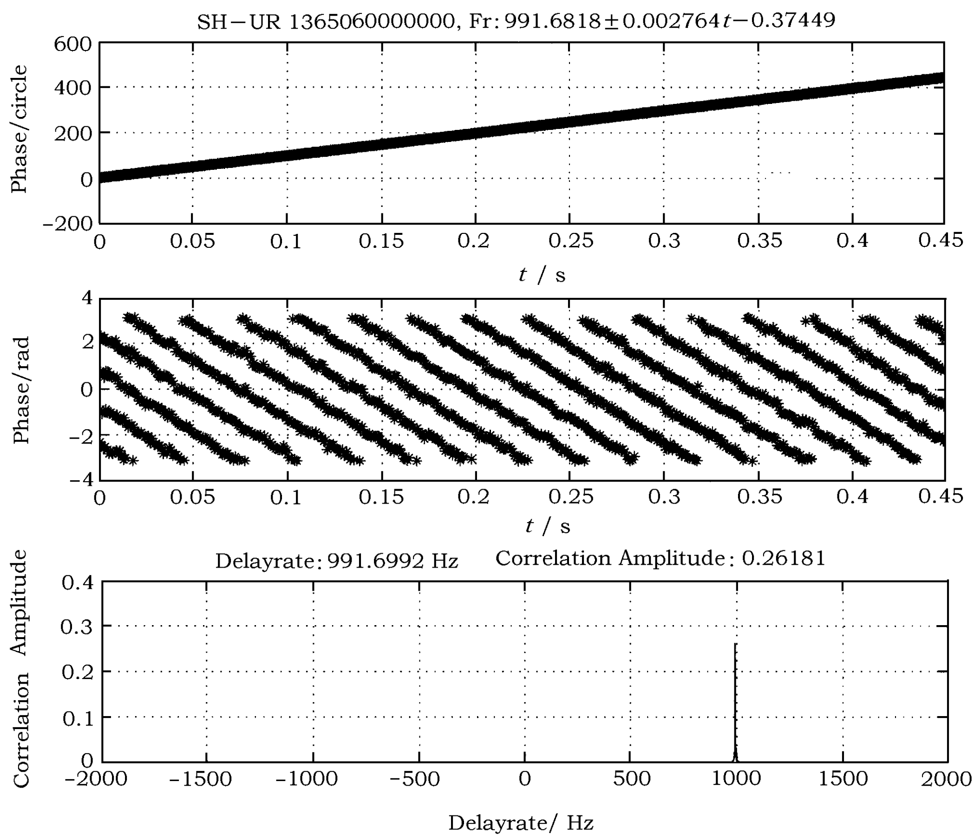

Fig. 6　DOD search window

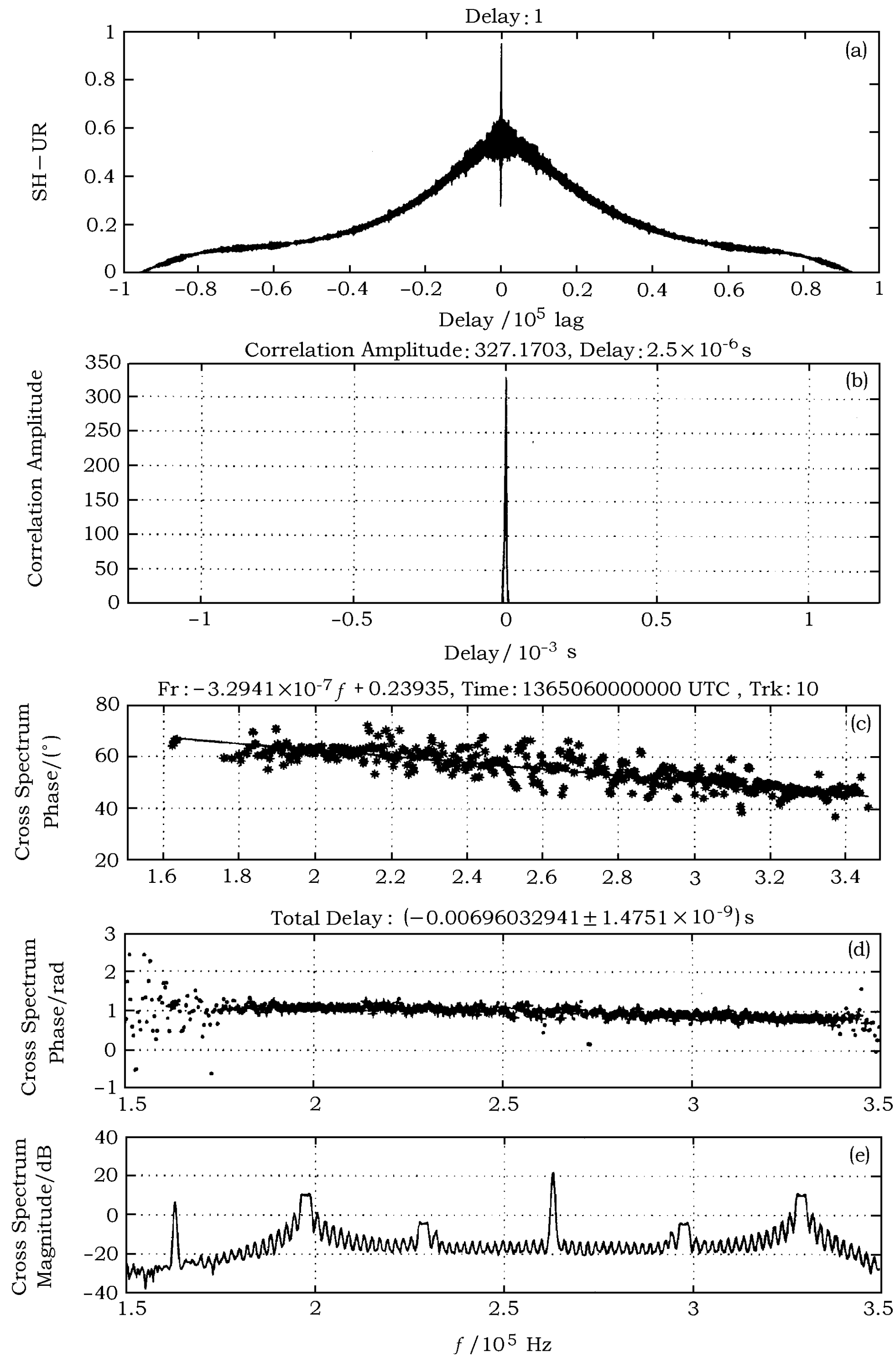

Fig. 7 Delay search window, XF method ((a), (b)), FX method ((c), (d), (e))

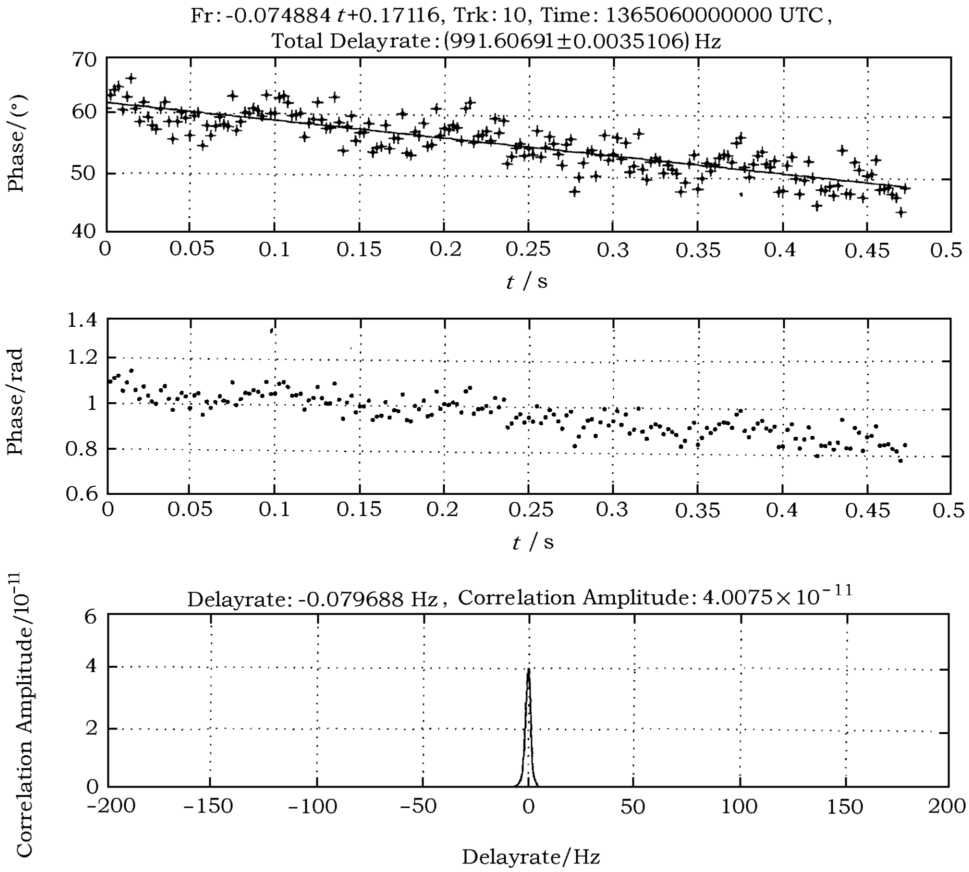

Fig. 8　Residual DOD

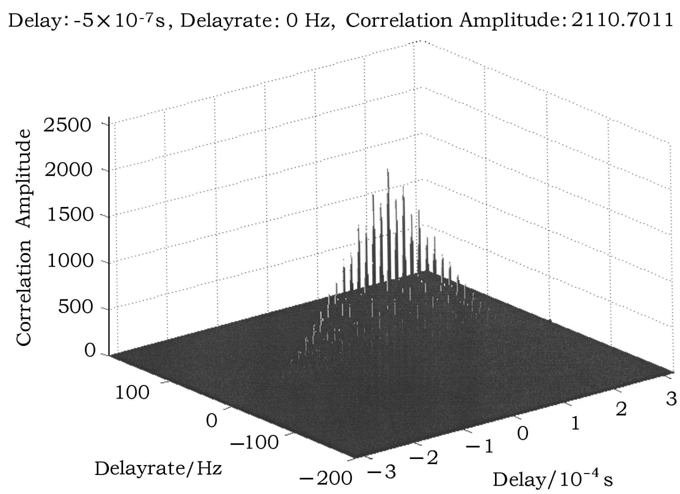

Fig. 9　Detected fringe of TC-1 between Sheshan and Nanshan

only 200~400 kHz, the software correlator's results are favorable. Now the software correlator acts as the fringe guider of the Shanghai correlator.

The software correlator was applied to TC-1, the first satellite of the Geospace Double Star program. TC-1 with its orbital altitude 550~60000 km was launched on Dec. 30, 2003 [14]. It is a spin stabilization satellite and the spin period is approximate 4 s. CVN observed TC-1 in its launch phase.

Figure 10 and Figure 11 show the delay/DOD of TC-1 in one minute interval. The calculated values were computed based on predicted satellite orbit. The observed value was produced by the software correlator. The reconstructed value was the polynomial fitting of the observed value. O-C (Observed-Calculated) was as large as about 15 μs; and O-C DOD was about 0.15 Hz. In the PSD (Power Spectral Density) of O-C (delay/DOD), there is a remarkable 0.256 Hz frequency component, which is very close to the satellite spin frequency. Apparently, O-C reflects the predicted orbit error; the periodical fluctuations of DOD and delay are caused by the satellite spin. Such spin effect affects the final precisions of the delay and delay rate. The elimination method is under study. The reconstructed value removes the distinctive satellite spin effect on the

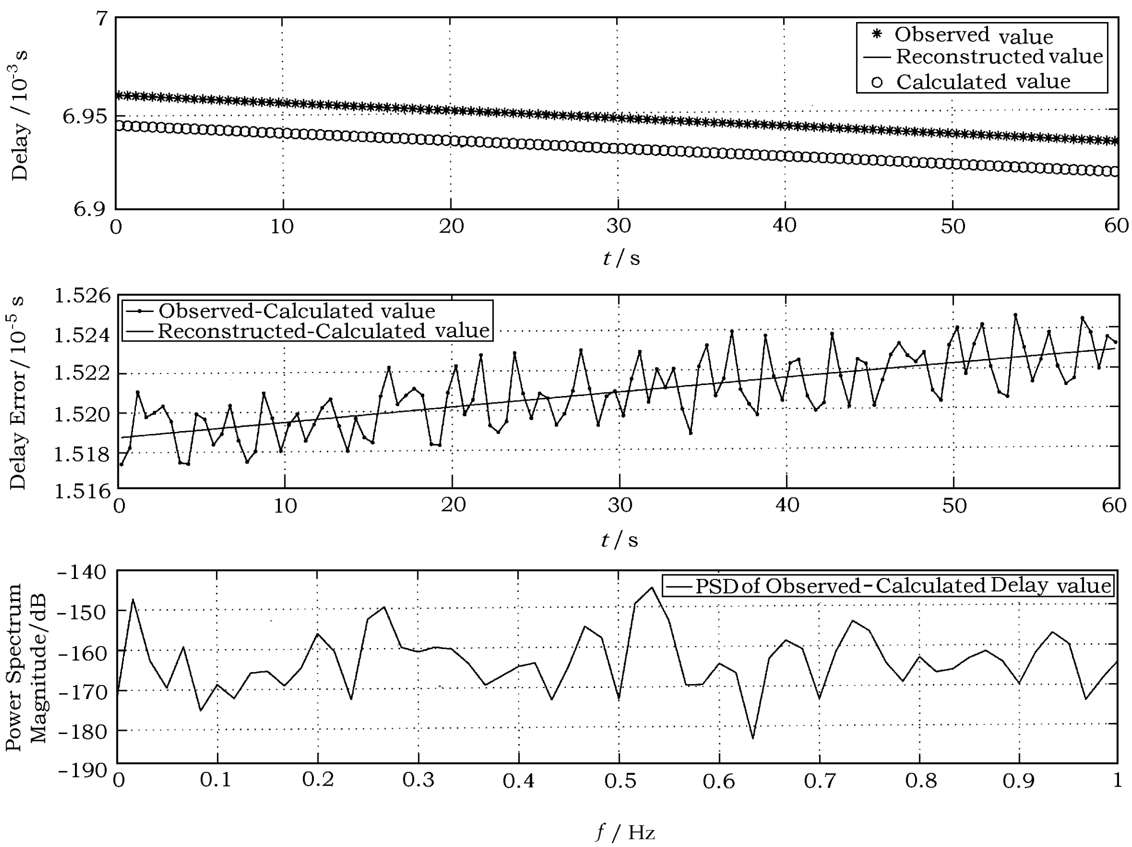

Fig. 10 Delay of TC-1 (launch phase) on Nanshan and Sheshan baseline

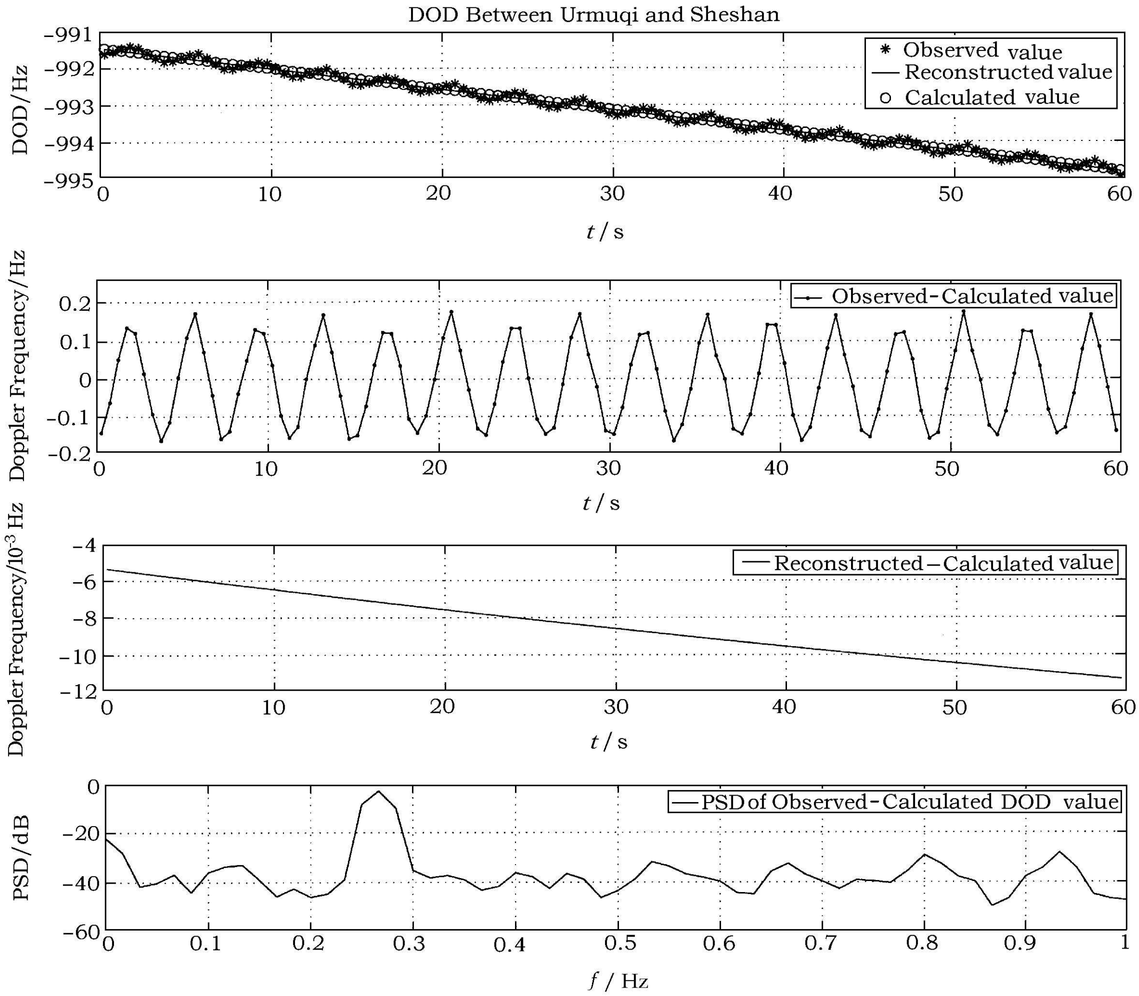

Fig. 11　DOD of TC-1 (launch phase) on Nanshan and Sheshan baseline

fluctuation of the group delay and DOD, so the difference between the reconstructed value and the calculated value reflects the real orbit error. The difference was used to modify the correlator model computed from the predicted orbit, therefore the Shanghai correlator could complete the satellite signal correlation.

The software correlator also can be applied to continuous VLBI data correlation. When there is an accurate delay model, the software correlator can compensate the delay/delay rate more precisely and performs longer integrations like the Shanghai correlator. Although the speed of the software correlator is slower than that of the hardware correlator currently, its correlation result is good enough to be the benchmark of the hardware correlator. Besides, the software correlator was used to process the short time reference radio source observation data. A faster and more powerful software correlator prototype (C version) has been finished and used in the VLBI data correlation.

4 e-VLBI Data Transmission Experiment and 3-station Observation

Two CVN harddisk systems were placed in the Nanshan station and the Sheshan station in 2003. Since then, dozens of satellite, extragalactic source and maser source VLBI observations have been successfully made with the CVN harddisk systems. In the satellite observations, the differential VLBI mode was tested for the preparation of the lunar satellite navigation in the future.

Among these observations, we performed several e-VLBI data transmission experiments. The first domestic e-VLBI fringe test was on the Nanshan–Sheshan baseline by disk-internet-disk mode in May 2003. Hardly had the observation finished, the Nanshan station transmitted the data from the local harddisks to the ones located in SHAO through Internet. The disks of Sheshan were taken to SHAO by car at the same time. The software correlator firstly processed some data, found out fringes, and then both the Shanghai correlator and the software correlator correlated the other data guided by the searched delay and delay rate values. Now such kind of e-VLBI station checkout becomes a routine before every important domestic observation.

Although the domestic communication network speed was only about 50 KB/s in the FTP mode, the experiments still showed the e-VLBI potential of CVN. Experiments also revealed that the domestic communication network was the bottleneck of e-VLBI; whereas it is inspiring that the network speed will increase a lot supported by the lunar project in the near future. e-VLBI or even strict realtime VLBI is feasible at that time.

In Apr. 2004, having mounted the self-developed VLBI formatter on the Kunming station, we made the first domestic 3-station VLBI satellite observation with Nanshan, Sheshan and Kunming stations. A 20 min 3-station delay/delay rate closure test was performed with the software

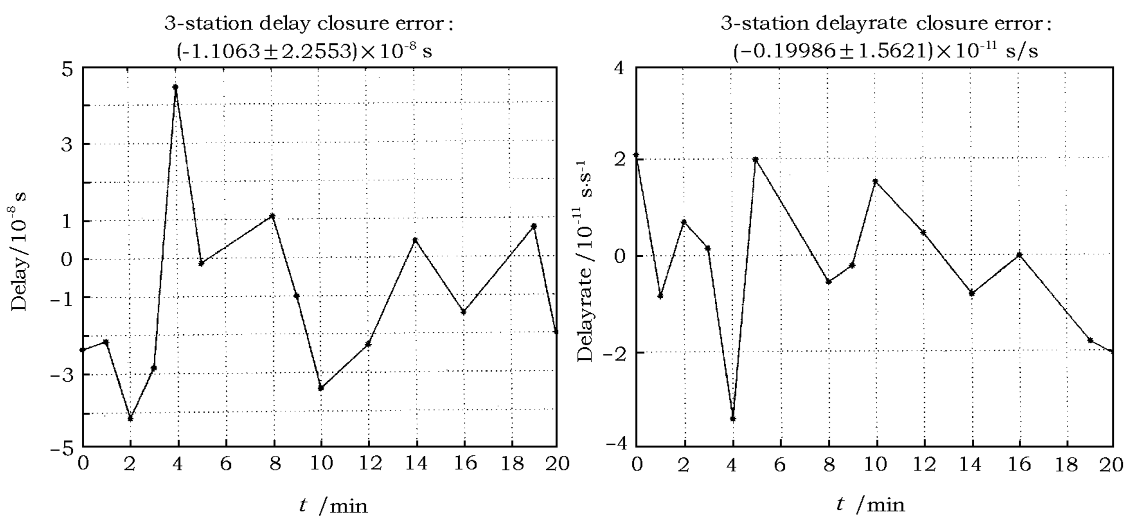

Fig. 12 3-station satellite observation delay closure error (left) and delay rate closure error (right) correlator (Figure 12). The bias and the RMS (Root Mean Square) of the closure error was (-11 ± 23) ns, with the integration time 0.5 s. The closure errors reflected the total VLBI measurement errors. Since it was a narrow band observation, considering that the Kunming station is only a 3 m antenna, much less than Nanshan or Sheshan 25 m antennas, the results are quiet good. The first domestic satellite orbit determination test using VLBI data was successfully accomplished based on the results of this software correlator [15].

5 Realtime VLBI in Chinese Chang'e Lunar Exploration Project

Besides the harddisk system and the software correlator, the VLBI laboratory of SHAO is developing other e-VLBI equipments, such as the formatter and DBBC (Digital Base Band Convertor), which will be used in the realtime CVN. The prototype formatter was placed in Kunming and used for the 3-station satellite VLBI experiments.

According to the Chang'e project, China will launch its first lunar satellite in two years and the realtime VLBI will be used in the satellite navigation. For these reasons, two new big antennas will join CVN in two years. One 50 m antenna will be placed in Miyun, suburb of Beijing; another 40 m antenna will be placed in Kunming to replace the existing small mobile one. At the same time, SHAO will build two 5-station realtime correlators, one is a hardware correlator, and another is a software one. The software correlator will be the backup of the hardware correlator. The high-speed optical fiber network will connect all stations and correlators. Because the data speed in the lunar project is much slower than the regular geodetic or astronomical observations, realtime, multiple station software correlator running on multi PC servers will be practicable.

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