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CVN Software Correlator Development and Applications in Chinese Lunar Exploration Mission

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Abstract. Being able to achieve very high angular resolution, the Chinese VLBI Network (CVN) was used as an auxiliary facility to track the Chinese lunar probe Chang'E-1 (CE-1) besides the traditional Unified S-Band (USB) command system. With great flexibility, the software correlator is well suited for VLBI deep-space tracking applications, so two software correlators (NRSC and WBSC), based on the commercial multiple processor servers were developed for the narrow band near real-time data processing and the wide band non-real-time data processing, respectively. NRSC has the abilities of fast satellite fringe search and multi-channel phase calibration abstraction, which are especially useful in spacecraft tracking. As the main correlation equipment, the software correlator played an important role in the one-month critical near real-time tracking mission, when CE-1 probe transferred from the phase orbit to the circumlunar orbit in 2007. Operation results indicate that the software correlator has the characteristics of flexible structure, reliability, scalability and it will be used in more CVN geodesy and astronomy observations, as well as deep-space exploration scientific activities in the near future.

1. Introduction

The Chinese VLBI Network (CVN) was used as an auxiliary facility to help the traditional Unified S-Band (USB) command system to fulfill the Tracking, Telemetry and Control (TT&C) task of the first Chinese lunar probe Chang'E-1 (CE-1). This mode is dubbed USB + VLBI.

CVN consists of four VLBI stations (in Shanghai, Beijing, Kunming and Urumqi) and a data processing center (in Shanghai Astronomical Observatory). The stations and the data center are connected by network.

In the tracking mission, the data center accomplished all the tasks such as VLBI observation schedule, data correlation, post processing, atmosphere delay correction, position determination and orbit determination and supplied the Beijing Aerospace Control Center (BACC) with the measurement results including delay, delay rate, and angle position. It also participated in the orbit determination and prediction. To achieve high reliability, there are two independent data processing subsystems in the data center, while the software correlator and the hardware correlator is the kernel of them respectively.

CE-1 was successfully launched at 18:05 on Oct. 24, 2007. Three days later, CVN began to carry out a 2-stage tracking mission. The first stage was a near real-time critical flying mission, from Oct. 25 to Nov. 30, 2007. In this period the data was sent to the VLBI data center by network directly. The observation mode was 4-channel (2 S-band + 2 X-band) with the data rate of 16 Mbps/station. The tracking time was 15 hours/day. In this stage, all the data sent to the center must be processed in 10 minutes. The second stage was a non-real-time, long-term in-orbit operation mission, from Nov. 30, 2007 to the end of 2008. In this period, the data was first recorded on the Mark 5 hard disks and then sent to the data center by express mail. The data rate was up to 64-128 Mbps/station. The tracking time was 2 days/week. All the data sent to the center must be processed in 2 weeks.

To deal with the data correlation, we developed two software correlators. one is the Near Real-time Software Correlator (NRSC), another one is the Wide Band Software Correlator (WBSC).

2. Near Real-time Software Correlator

The fast development of the computer and network makes the VLBI software correlator based on the general-purpose computer becoming practical. Compared with the hardware correlator, software correlator is cheaper, more flexible and time saving, and so it is very suitable for the spacecraft tracking and navigation, besides geodesy and astronomy applications [1].

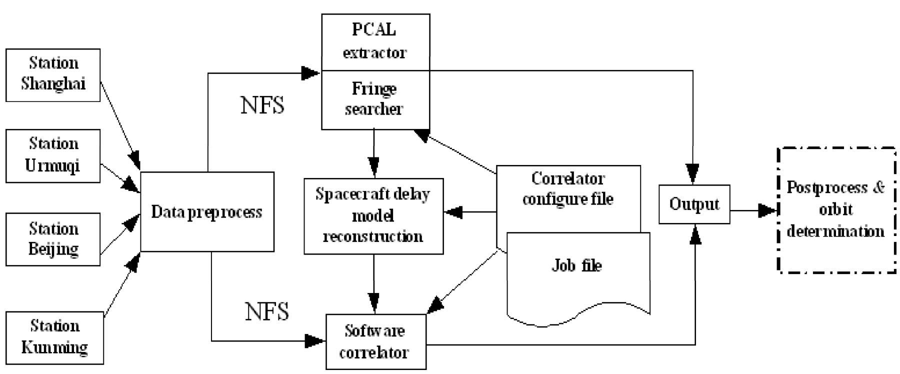

Figure 1. Block diagram of NRSC

We began the research of software correlator in 2003. The first prototype software correlator was a MATLAB program for fringe check through observing the satellite downlink telemetry signals. It was used in the first Chinese e–

VLBI experiment in 2003 [2]. At the beginning of the lunar project in 2004, a software correlator was needed as a debug tool and a slow speed backup of the hardware correlator. So it was designed as a 4-station correlator with speed of 8 Mbps/station. However, when NRSC was completed in 2007, it speed was up to 45 Mbps/station, when running on a 4-way, dual cores X86 PC server.

NRSC was a four station correlator (expanded to 10 stations later) with functions of near real-time correlation, fast satellite fringe search and PCAL (Phase Calibration) detection abilities (Tabl. 1). The data latency of NRSC is less than 3 minutes (Fig. 1).

In the near real-time mode, observation data are transferred to the center through network. To deal with the network congestion, we use a hard disk array as a data buffer. For this reason, a data preprocessing program was developed, which runs on a 4-way, dual core X86 architecture SMP PC server. This module receives the data from the station, and then performs data decoding, error correcting, synchronizing, and data dividing; then it stores the data into a batch of Linux files with one minute length on the disk array. Other modules can access them through the Network File System (NFS).

The software correlator module is the kernel. It adopts the FX structure and the parallel computation algorithm to fulfill the operations of decode, ISTC (Integral Sample Time Correction), Fringe stopping, FFT, FSTC (Fractional Sample Time Correction), MAC (Multiply And Accumulate). The hardware platform is a server identical to the preprocessing module platform.

Table 1. Specifications of the NRSC

Architecture	FX
Correlation station number	1~10
IF number	1-16
Frequency channel	32~4096/IF
Integration period	0.1~60 second
Input data format	Mark 5
Output data format	CVN
Fringe search	2-4 stations
Correlation speed	45 Mbps/station (4 stations)
Data turnover	< 3 minutes
PCAL detection	Yes

When doing correlation, a correlator needs accurate object delay models. For NRSC, such models are pre-calculated by the scheduler program and saved in the Job file. Usually the model of an extragalactic radio source is accurate enough. However, when tracking a spacecraft, if the prior orbit is inaccurate, there will be inevitable errors in the delay models. To solve this problem, a special program, the Fringe Searcher (FS), is integrated in the correlator system. This program is able to find out the onsite accurate delay and delay rate of the spacecraft automatically without any orbit information. Once getting the delay (delay rate) value from FS, the Spacecraft Delay Model Reconstruction (SDMR) program will renew the prior model to an accurate reconstructed one.

The PCAL extractor module is able to extract the amplitude and phase of every PCAL signal. It has been applied to evaluate station performance.

FS, PCAL extractor and SDMR are running on one server. So there are 3 same SMP servers: one for the software correlator module itself, the other two for FS, PCAL extractor and SDMR of the NRSC and the hardware correlator separately. The Operation System (OS) is a Redhat Linux Enterprise version. Pthreads technology was used to realize the parallelization computation.

3. Wide Band Software Correlator

In the CVN wide band observation mode, the maximal data speed is up to 128 Mbps/station. To process this kind of data, we used the existing three identical SMP PC servers to construct a 3 computation nodes PC cluster, as the platform of a wide band software correlator. Each node contains 4 dual core AMD CPUs, this Beowulf cluster totally contains 24 CPU cores. All the nodes are connected by a high speed Gigabit Ethernet switch. A hybrid parallelism, which combined the intra-node shared-memory programming mode and the inter-node message-passing programming mode, has been used in this prototype software correlator [3].

The Message Passing Interface (MPI) is used to allocate the inter-node correlation job and to complete the reduction operations. Utilizing the data parallelism, the software correlator allots the total integration period operations to 3 computation nodes equally. Inside each computation node, the operations of different model periods in one integration period are allotted to the 8 CPUs using the similar multi-thread algorithm in NRSC.

Experiment results indicate that the inter-node MPI mode and the intra-node multi-thread mode can increase the computation speed of the software correlator remarkably; meanwhile, this correlator still keeps good scalability and flexibility. It is able to deal with 10 station data correlation at most. When doing the 4-station correlation, the speed is about 124 Mbps/station. When there are 10 stations, the speed is about 45 Mbps/station. Compared with NRSC, the speed-up ratio is about 3.

4. Applications

In the CE-1 mission, according to the BACC commands, the CVN observation data from the stations were sent to the VLBI data center in real-time. In most situations, the center performed data processing and sent BACC the satellite delay, delay rate and the angle position in 5 minutes. In this critical period, NRSC was the main data processing equipment. All the data sent to BACC were correlated by NRSC.

After Nov. 30, the CE-1 probe entered the lunar orbit successfully, CVN changed the near real-time observatory mode into the long-term operation and post management mode. WBSC was also used in this period.

Actually, before the CE-1 mission, the software correlator has already been successfully used in many important experiments and observations: for example, the Chinese first VLBI joint track TC-1 experiment (Mar., 2005), the observation to determine the precise positions of the two new VLBI stations of Beijing and Kunming (May, 2006), the near real-time European SMART-1 and Chinese TC-1 satellite USB+VLBI joint tracking experiment (May 29 ∼ Jun. 1, 2006), the CVN tracking demonstration of Venus Express (Sep., 2006) and Mars Express (May, 2007). It was also a very important debug tool for the hardware correlator development and the station fringe check, as well as the station performance check.

In Dec. 20, 2006, we conducted a China-Japan 8-station joint VLBI tracking experiment. The object was the Japanese spacecraft GEOTAIL. We expanded NRSC to a 10-station correlator and completed the data processing.

5. Conclusions

The software correlator has validated its value in the CE-1 lunar probe tracking mission. It also indicates that the VLBI correlation algorithm is highly parallel and very suited to the multiprocessor computing environment. Based on the platform of high performance commercial SMP PC servers and the Linux operation system, the software correlator system is cost effective, reliable, flexible, portable, and scalable. We hope that the software correlator can be used for CVN astronomical and geodetic data correlation besides the deep space probe tracking in the future.

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