Software Correlator in the Chang'E-3 Mission

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Abstract During the real-time phase of the Chang'E-3 lunar exploration mission, the VLBI group delay accuracy was better than 1 ns, and the delay turnaround time was less than 45 seconds. The software correlator was the primary correlator of the VLBI center and worked for nearly one month with high stability and real-time ability. Compared with the versions in the previous lunar missions, this correlator can process data in parallel mode on multiprocessors using MPI and OpenMP. This paper introduces the software correlator structure and its current situation.

Keywords Software correlator, Lunar exploration, e-VLBI, fast fringe search, phase calibration tone extraction

1 Introduction

The CVN real-time software correlator (CRSC) is used in the Chang'E-3 (CE-3) mission. The CVN (Chinese VLBI Network) consists of five stations (Shanghai Tianma 65-m, Shanghai Sheshan 25-m, Yunnan 40-m, Urumqi 25-m, and Beijing 50-m) and one data processing center at the Shanghai Astronomical Observatory. The Shanghai Sheshan station is the backup of the Tianma station. CRSC is the key component of the data processing center. According to the CE-3 mission requirements, the design objectives of CRSC focus on stability and real-time performance. During the mission, the software correlator's continuous working period was up to approximately 11 hours per day, and the data latency for CRSC should be less than 25 seconds. Development of CRSC was begun in 2007. The early version of CRSC took part in the CE-1 and CE-2 missions as primary equipment and did a good job in 2007 and 2010. In 2012, the basic parallel version correlator executed the CE-2 extended mission of flying over the second Solar-terrestrial Lagrange point. Last year, the real-time parallel version software correlator completed the CE-3 task successfully based on e-VLBI technology. CRSC is written in high-level languages such as C, Python, Matlab, and so on. It implements a parallel algorithm using MPI (Message Passing Interface) and OpenMP (Open Multi-Processing). CRSC runs on commodity computer hardware. It has high scalability and flexibility. It also has a good degree of parallelism. The code of CRSC is accelerated using the Intel Performance Primitive Library (IPP) vector arithmetic libraries. After several years of development, CRSC has many capabilities such as Fast Fringe Search, Phase Calibration (PCAL) tone extraction and FITS-IDI format transformation, and real-time visibility monitoring.

2 Main Functions

As an FX-style correlator, the data latency of CRSC was less than 25 seconds during the CE-3 mission. If it was not in the fringe search mode, the latency could be less than 10 seconds. Besides, it has the function of PCAL extraction.

The hardware platform is a commercial blade cluster. It has five I/O nodes (one quad-core CPU of E7-

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Table 1 CRSC specifications.

Processing Mode	Real-time & post-processing
Station number	1–20
Real-time fast fringe search	4 stations
IF number	1, 2, 4, 8, 16
Frequency channel	24–4096/IF
Integration period	0.1–60 seconds
Input data format	Mark 5
Output data format	CVN, FITS-IDI
Maximum data speed	1.4 Gbps/station

4820, 128 GB memory, 300 GB + 12 TB storage), 16 computation nodes (six CPUs/node, dual-core CPU of E5-2640, 32 GB memory, 300 GB storage), and two management nodes (one dual-core CPU of E5-2620 24 GB memory, 900 GB + 214 GB storage). The management network is 10G Ethernet, and the computation network is InfiniBand.

Fig. 1 The computational platform of the CRSC in CE-3.

The station data were transported to the data receiving server in the Data Center through the fiber link in the real-time mission. The different correlator items exchange data through NFS (Network File System).

2.1 Real-time Fast Fringe Search

In general, during orbital maneuver phases, the accurate orbit cannot be provided in advance, so the correlator cannot work properly in such conditions. The fast fringe search module first extracts the main car-

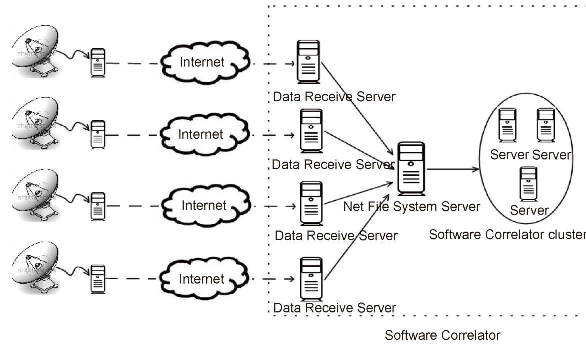

Fig. 2 Data flow diagram of the Chang'E 3 Mission.

rier frequencies from the signals of different stations, produces the delay rate, and then compensates for the delay and delay rate. After several iterations, the accurate delay and delay rate are found. They are used to modify the predicted model. Following the reconstructed delay model, the software correlator can produce the correct results (Figure 3). MPI, OpenMP, and IPP are adopted to increase the computing speed. This on-site fringe search and delay model reconstruction procedure takes place every five seconds in the CE-3 mission to guarantee real-time correlation.

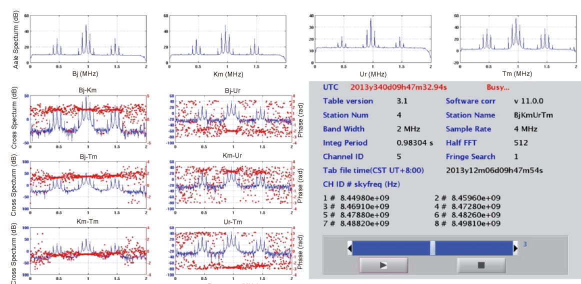

Fig. 3 The cross-correlation phase spectrum (red points) and amplitude spectrum (blue points) of every baseline using the fast fringe search function from Quick Viewer GUI.

2.2 Phase Calibration Tone Extraction

PCAL tones are injected at the front end of a VLBI antenna in order to provide a convenient means to estimate instrumental delays [2]. CVN antennas rely on the software correlator to extract the PCAL tones. CRSC can extract all tones in CE-3 (eight channels, 2 MHz bandwidth).

2.3 Real-time Visibility Monitoring

The new Quick Viewer (QV) module was added to monitor CRSC output results in real time with a Graphical User Interface (Figure 3). The information of channel frequency, station names, sample rate, integration period, FFT point, fast fringe search mode, and cross-correlation amplitude/phase spectrum can be displayed on the GUI. It is very convenient to monitor the important status of the software correlator and even the CVN in the CE-3 mission.

2.4 FITS and CVN Output Format

The preceding software correlator only supported CVN output format specifically designed for satellite navigation. Considering the astronomical and geodetic data processing usage, the new CRSC version supports the standard FITS-IDI format output and can be processed by AIPS directly.

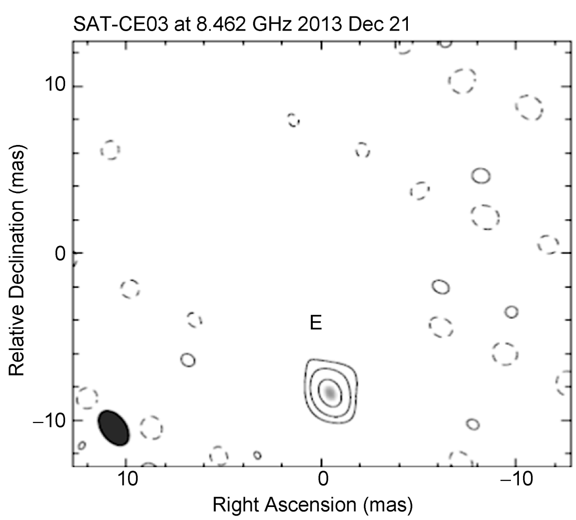

Fig. 4 CE-3 Rover image obtained from CRSC FITS output using Difmap.

3 Conclusions

The CRSC has already been utilized in the CE-3 mission successfully. A number of significant improvements have been made. However, the real-time ability and the robustness also need to be improved, and astronomical application functions will be added. Besides the lunar exploration missions, more astronomy and geodesy data will be processed by CRSC in the future.

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