Chinese VLBI Network and e-VLBI Technology Applications in Chinese Lunar Exploration Program

Zhong Chen and Weimin Zheng

Abstract Very long baseline interferometry (VLBI) is derived from the synthetic aperture radio observation method invented in the last century. By combining a number of large aperture radio telescopes distributed over long distance, a virtual giant radio telescope is logically created. Global and regional VLBI observation networks has extremely high spatial angular resolution, which has been widely used in astrophysics, geodesy and deep space exploration aircraft tracking. In the Chinese Lunar Exploration Program (CLEP), domestic VLBI network adopted real-time e-VLBI technology as part of TT&C system has been providing fast and accurate orbit and positioning services during the Chang'E serie missions. It works for trajectories of Earth-Moon flying, orbiting, descending, and returning to earth, made great contributions for orbit measurement. This paper introduces the general work of China VLBI network and detailed e-VLBI technology application in the three phases of CLEP, gives the details about system developments, operations and performance of the VLBI observation system. Final is the outlook of VLBI system future plan in deep space exploration missions and scientific programs.

Keywords Chinese VLBI network · China lunar exploration project · e-VLBI · Real-time · Orbit determination

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1 Introduction

1.1 Very Long Baseline Interferometry

Four major discoveries of modern astronomy in the 1960s: pulsars, quasars, cosmic microwave background radiation, and interstellar organic molecules are all benefited from the invention and application of radio telescopes. Until now, 6 Nobel Prizes for astronomy have been awarded to radio astronomy related discoveries.

Very Long Baseline Interferometry (VLBI) technology is an important radio astronomy method derived from the 1960s, as shown in Fig. 1. It combines multiple globally distributed radio telescopes into a virtual giant synthetic aperture radio telescope. In order to maintain time and frequency synchronization, each VLBI station has high stability time-frequency precision reference source—atomic clock as the independent local oscillation. The VLBI network has extremely high-precision spatial angular resolution which greatly improved the ability of astronomical observations.

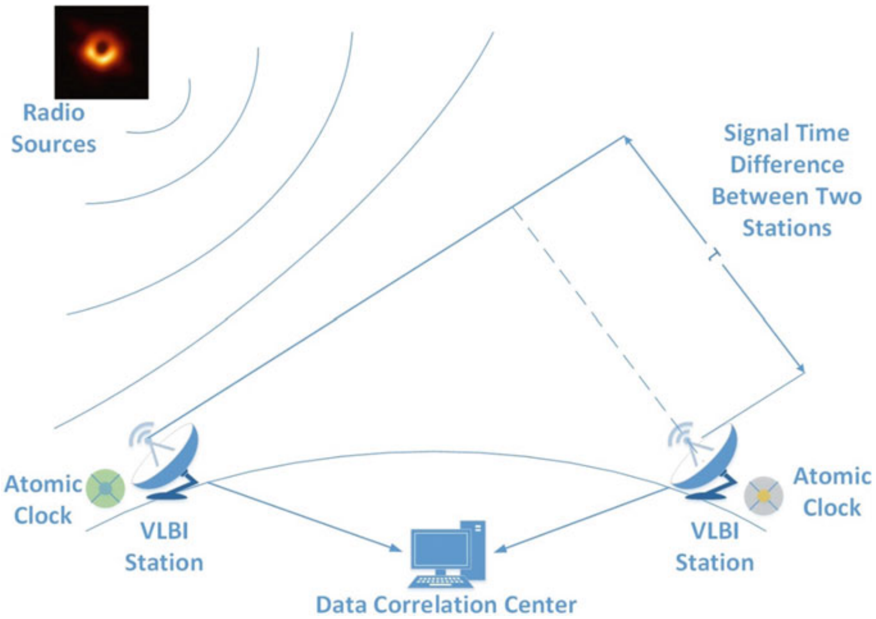

Fig. 1 VLBI schematic diagram

1.2 VLBI Application

The VLBI observation network itself is a "distributed" large scientific instrument. Observation data obtained from all stations is recorded synchronously according to the atomic clock time scale in the disk system. All raw observation data is collected to data processing center for correlation to obtain data products of time delay and the time delay rate, representing the precise time lags of radio sources signal reaching the different antennas. The accuracy of VLBI's delay measurement is directly proportional to the data recording bandwidth. Higher data rates usually lead to higher accuracy of results. Because of its extremely high space angular resolution, VLBI has an important role in astrophysics, astrometry, geodesy, and spacecraft orbit determination. For astrophysics, VLBI is an important tool for researches of universe origin, galaxies evolution, massive black holes in the galaxy centers, and interstellar organic molecules. For astrometry and geodesy, VLBI help for precise positioning of dense radio sources inside and outside the galaxy, establishment of celestial sphere reference system and earth reference system, measurement of earth rotation orientation parameter and precise coordinates of VLBI observation stations, and movement of continental crustal deformation. In field of deep space exploration, VLBI can provide high-precision measurements of the precise orbit and positioning of lunar and deep space probes, as well as relative motion between extraterrestrial planet surface probes [1].

1.3 Real-Time e-VLBI

Traditional VLBI experiments record the raw observation data into magnetic media, such as tapes and disks. After that, these media are delivered to special data processing center. It usually takes several weeks or months to obtain the final scientific data. The disadvantages of traditional operation mode are: the record data bandwidth of the magnetic recording equipment cannot meet the rapid increasing requirement of ultra-wideband observation, no real-time monitoring and adjustments of the observation instruments status, no easy way for new technologies and devices rapid testing and verifications. With the development of high-performance commercial computers and high-speed network data transmission, real-time electronic transmission VLBI (e-VLBI) technology based on digital VLBI data acquisition terminal, recording and high-speed network data transmission and processing emerges.

e-VLBI technology organically connect geographically distributed observation stations and VLBI data processing centers, by data transmission through high-speed cross-regional educational and scientific networks. With e-VLBI technology observation data collection and correlation processing can be done in real time. Broadband observation and distributed processing also become possible. Even more, scientists can check the data online when the observation is going on, that's kind of WYSIWYG. Depend on the bandwidth of networking, e-VLBI mode could be near real-time or real-time, both modes improve resource utilization of radio telescope network, and meet the need of deep space exploration probe by real-time tracking and measurement.

e-VLBI has three real-time operation modes: real-time, near real-time and post transmission. Real-time mode has the shortest data turnout time when doing transfer. Near real-time mode has observation data buffered and then transferring by not so quick or stable speed, with jitter time ranging from ten seconds to several minutes. The post-transmission mode has the raw data recorded in the disks and then played back to the data center through the narrow bandwidth network afterwards. Usually the real-time mode are widely used int e-VLBI observations.

Because of the advantages of e-VLBI, it has been developed rapidly in the past years and has played an important role in radio astronomy and deep space exploration fields. The Chinese VLBI Network (CVN) has successfully applied the e-VLBI technology in the orbit determination mission of China Lunar Exploration Project(CLEP).

2 Chinese VLBI Network

The Chinese VLBI network is under the lead of Shanghai Astronomical Observatory (SHAO) of Chinese Academy of Sciences (CAS), consists of 5 stations and 1 data center (Table 1). These five radio telescope stations are Tianma and Seshan Station of SHAO, Miyun Station of National Astronomical Observatory of China (NAOC), Kunming Station of Yunnan Astronomical Observatory (YNAO), Nanshan Station of Xinjiang Astronomical Observatory (XAO). The VLBI data processing center is located in SHAO's seshan campus.

Table 1 CVN stations information

Station name	Diameter (m)	Frequency (GHz)	Completed year	Dedicated bandwidth (Mbit/s)	Internet bandwidth (Gbit/s)
Seshan (Sh)	25	1.6, 2.3, 5, 6.7, 8.4, 22	1987	10,000	2
Nanshan (Ur)	26	1.6, 2.3, 5, 8.4, 22	1994	200	0.3
Miyun (My)	50	2.3, 8.4	2006	200	–
Kunming (Km)	40	2.3, 6.7, 8.4	2006	200	1
Tianma (T6)	65	1.6, 2.3, 5, 8.4, 15, 22, 32, 43	2012	10,000	2

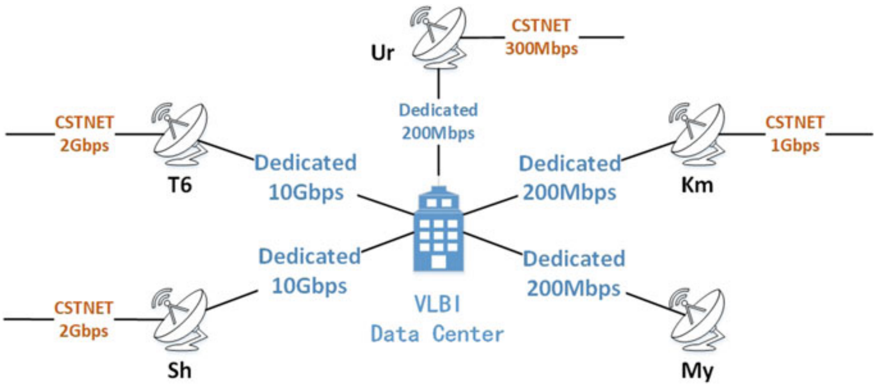

Fig. 2 CVN communication network topology

VLBI stations and the data center are connected by dedicated fiber network links, only used in real-time tracking and measurement system for Chinese lunar exploration probes (Fig. 2). Tianma, Seshan and Kunming stations are also connected to international stations and VLBI data centers through China Science and Technology Network of CAS (CSTNET), been carrying out international astronomy and geodesy e-VLBI data transmission.

In January 2019, Tianma station and 500-m spherical radio telescope (FAST) successfully performed the first joint experimental VLBI observation. The observation got successful clear result, verified the capability of FAST VLBI equipments performance and joint observation possibility between FAST and CVN station.

3 Application of CVN and e-VLBI in CLEP

3.1 Chinese Lunar Exploration Project

The first extraterrestrial planet that mankind explored is the Moon. Since the beginning of this century, China started its own lunar exploration project, proposed a three-step plan of “Orbiting, Landing, and Sample-returning”, also known as the Chang’E Project, will completed trilogy in 2020 [2].

The first phase of CLEP began with the launch of Chang’E-1 probe (CE-1) in October 2017 and successfully flied to and orbited the Moon. The first attempt of lunar exploration mission successfully verified and mastered the lunar exploration technologies.

The second phase of CLEP included two missions, Chang’E-2 (CE-2) in 2010 and Chang’E-3 (CE-3) in 2013. The CE-2 mission tested new X-band telemetry, tracking and command system (TT&C) for the first time, later it became the first lunar probe transfer from Moon orbit to Lagrange L2 point in the world. After that it continued the overflight detection of the Toutites asteroid. The Chang'E-3 mission implemented in 2013 was the first time for Chinese lunar probe to soft landing on the Moon, with Yutu rover released for patrol detection of the Moon [3, 4].

The third phase of CLEP includes the Chang'E-5 lunar return reentry tester mission (CE-5T1) and the Chang'E-5(CE-5) mission. In 2014, CE-5T1 mission was successfully carried out and the key technology of the lunar-earth high-speed reentry return technology was verified, which will be put into use by CE-5 probe when returning from Moon.

In 2018, China finished the Chang'E-4 (CE-4) mission. The mission was divided into two periods: the CE-4 relay satellite was launched in May 2018 and successfully entered the Earth-Moon L2 point and circling with Halo trajectory, ready for deep space data relay service. The CE-4 probe, which was launched in December at the same year and became the first man-made probe landed on the far side of the Moon in January 2019 [5, 6].

3.2 VLBI Measurement System for CLEP

Since the start of CLEP, the VLBI system is been part of TT&C system. Before CLEP, the unified S-band measurement and control system (S-USB) was used for near-Earth satellite orbit measurement. The distance of the lunar probe to earth is hundreds of thousands of kilometers to millions of kilometers, which is beyond the system limit of the old USB system. In terms of short-arc orbit determination, the S-USB system has the advantages of fast ranging and speed measurement, but the angle measurement is not good enough at the distance between the earth and the moon. This became a challenge for the telemetry and tracking. With recommendation from Chinese Academy of Science with simulations and analysis proof , the project experts team decided to take advantage of Chinese VLBI network and together with the upgraded USB system, jointly provided tracking service for CLEP.

When the VLBI system has real-time measurement capabilities, it can work perfectly with S-USB system to get accurate orbit and position of the lunar probe. Therefore, since the CE-1 mission, the innovative combination uses of the S-USB + VLBI comprehensive measurement system has been the key technology for TT&C system [7].

The VLBI measurement system is developed and implemented under the lead of SHAO. The system consists of five stations and one command and data processing center.

(1) VLBI Stations

VLBI station have radio telescope, highly sensitive receiver, time-frequency reference system, data acquisition and recording system, monitoring system, control and communication network system and power supply system. The radio telescope reflector converges weak signals from outer space. Receiver system is for filtering

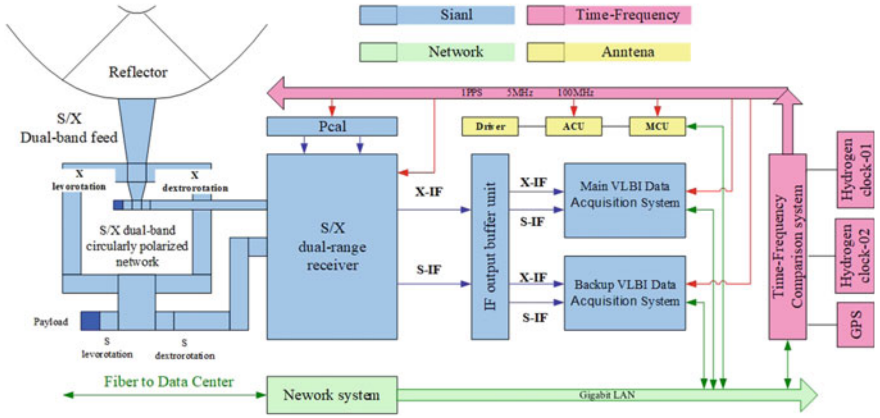

Fig. 3 VLBI station system composition structure diagram

noises and amplifying signals in a specific frequency range. Time-frequency reference system provides stable high-precision time-frequency reference signal source. Data acquisition and recording system is for collecting, recording or transmitting raw observation data with VLBI-specified universal data format. Station monitoring system is for unified collection and display of the overall systems status. The network system is responsible for data transmission and control messages communication. Power supply system provides essential electricity for the station devices.

VLBI station system composition is shown as Fig. 3.

The scene of the each CVN radio telescope are shown as Fig. 4.

During the Chang'E observations, once VLBI system received the observation tasks, data center prepared the schedule files and sent them to each station through the dedicated network. Each radio telescope automatically tracking the probe according to the control schedule files. Raw observation data was acquired and transmitted to Shanghai VLBI data center in real time.

Tianma, Seshan and Nanshan station are all traditional VLBI stations for astrophysics, astrometry, and geodesy observation. Miyun and Kunming station are the Ground Research and Application System (GRAS) of CLEP. GRAS's task is scientific data downlink reception from Chang'E probes. Both My and Km stations are also equipped with extra VLBI data system. With proper task planning, My and Km station are switched from time to time to serve the GRAS and VLBI jobs.

(2) VLBI Center Data Processing and Information System

The VLBI data processing center is the brain of the VLBI measurement system, controlling the overall systems scheduling and coordinated operations. It consists of command and control hall alone with server and network equipments room. During the lunar exploration missions, VLBI data center receives the commands from TT&C headquarter and uploads VLBI measurement results to the headquarter. VLBI center coordinates synchronous observation and data transmission from each station to data center, and then with two parallel data processing

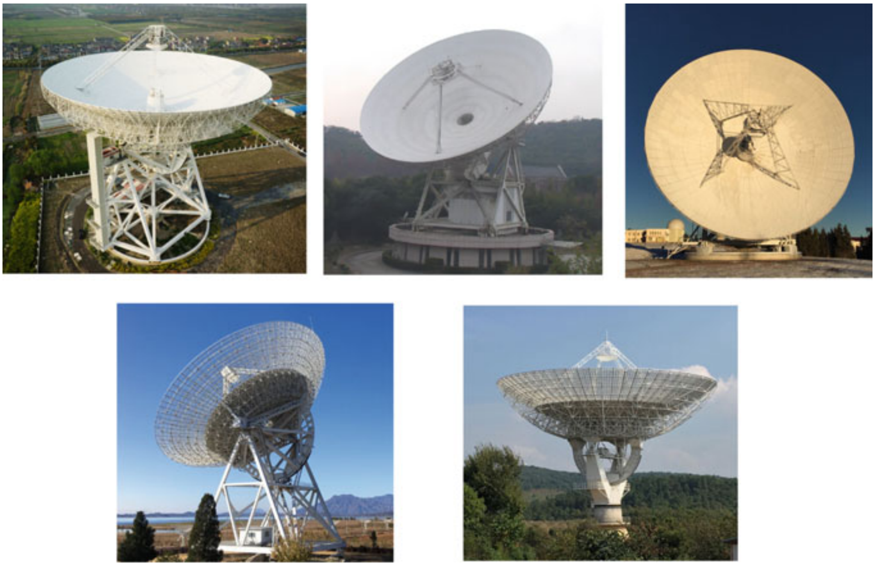

Fig. 4 CVN Station. Top left to bottom right: T6, Sh, Ur, My, Km

pipelines that backup each other the result data is generated in real time. The IP-based audio and video collaboration system connected the headquarter, VLBI center and stations was best for online real-time communication and consultation.

The VLBI center hardware platform is composed of pipeline data processing computing systems, data storage system, network communication system, distributed display system, command and dispatch system, and auxiliary support system like uninterrupted power system, cooling system and so on. The information system is the key component providing high-reliability and real-time computing power to digest data streams. The composition of the pipeline processing hardware platform of the VLBI center is shown in Fig. 6.

Fig. 5 VLBI data center and server room. Left: Centrally control hall, Right: Server and network device room

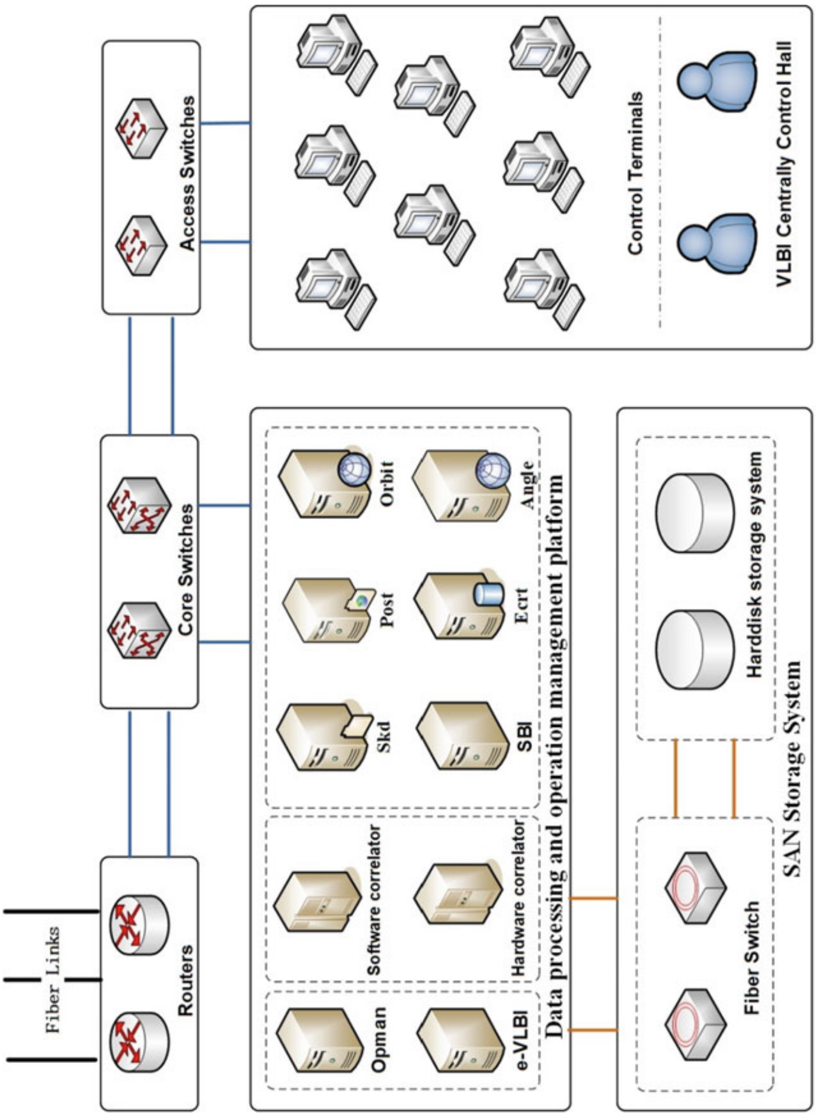

Fig. 6 VLBI center hardware system composition diagram

Data processing pipeline software system can be divided into the following configuration items: schedule, signal simulation, e-VLBI, software and hardware correlators, post-processing, phase delay calc, propagation medium error correction, orbit determination, angle positioning, station status monitoring, and operation manager. Among them, the e-VLBI, post-processing, and operation manager items are the most important software in data processing pipeline.

The functions of each software item of the VLBI center are as follows.

- Schedule (Skd): prepare vex (VLBI Experiment Definition) files needed by stations observing and data center processing
- Signal simulation: signal simulation for lunar and deep space exploration aircraft and calibration radio sources, produce simulation raw VLBI data set
- e-VLBI: control the data acquisition of multiple stations and synchronously transmit data streams to the VLBI center in real time and distribute them to software and hardware correlators
- Correlator: the core of VLBI data processing system. Its function is correlating multi-station raw observation data to obtain single-channel delay, delay rate and phase information of radio source and satellite. There are two types of correlator: software and hardware. Software correlator uses special high-performance data processing software based on MPI and OpenMP parallel computing techniques, running on a high-performance computer cluster platform. The hardware correlator uses a dedicated signal processing platform based on Field Programmable Gate Array (FPGA) chips for parallel data processing. Software and hardware correlators back up each other, providing high reliable real-time correlating capabilities
- Post-processing: its input source data is correlators products, with propagation medium error correction models and using bandwidth synthesis method to get accurate delay and delay rate results
- Same beam processing (SBI): receiving the signals of the two space targets in one radio telescope same beam, and with this special kind data it calculates the differential phase of two targets to eliminate various propagation medium errors when these radio signals reaches the telescope
- Propagation medium error correction (Ecrt): generate the models of signal propagation errors introduced by the earth's atmosphere, ionosphere and other medium. This information is necessary for other data processing software items and is crucial for final data accuracy
- Orbit determination: Obtain precise lunar probe orbit information during the flight to or circling around the Moon
- Angle positioning: Obtain the precise position information of the lunar lander on the Moon surface
- Station status monitor: remotely monitoring and centrally display various devices status of VLBI observation stations. It dynamically shows operation parameters and status of radio telescopes, receivers, data terminals and time-frequency equipment, etc.

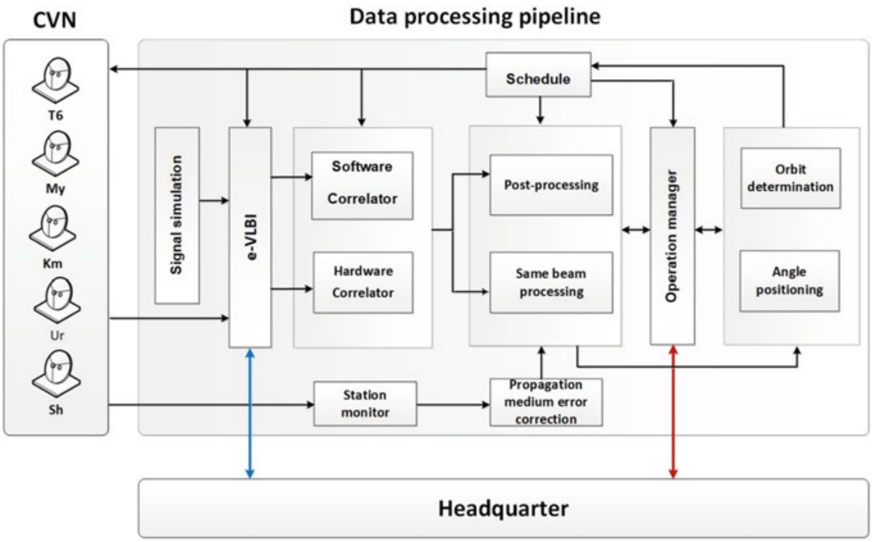

Fig. 7 Data processing pipeline and operation diagram

- Operation manager: Receive the task information for VLBI system including observation plans and other instructions issued by the TT&C headquarter, and send the VLBI data products to the headquarter

  The data processing pipeline of the VLBI center is shown as Fig. 7.

(3) Real-time e-VLBI system

Due to timeliness requirement of space probe tracking and measurement, it's necessary to upgrade the traditional VLBI astronomical observation network with real-time capability. Real time e-VLBI sub-system is the key for real-time system upgrading. Recent years with serveral technological upgrading such as VLBI acquisition terminal transformed to digital system, $\times 86$ computer based platform of raw observation data collection, transmission and distribution, software correlator based-on high-performance computing technology, real-time data stream pipeline processing technologies, CVN has completed the technical innovations and was capable for real-time lunar mission [8].

Concerning e-VLBI digital data terminal development history, in the first phase of CLEP, CVN kept using the traditional VLBI analog signal terminal and developed a new hard disk recording and transmission system named CVNHD (CVN Highspeed Disk System) and deploied them to each CVN station. So CVN had near real-time tracking and observation capability with 16 Mbps/station data rate. In the second phase of CLEP, a new VLBI standard high-speed disk recording system Mark5B was adopted. And the raw data rate increased to 32–64 Mbps/station. In the third phase of CLEP and the CE-4 missions, a more advanced broadband digital terminal and $\times 86$ server-based recording and transmission system developed, which further increase e-VLBI data rate to 128 Mbps/station.

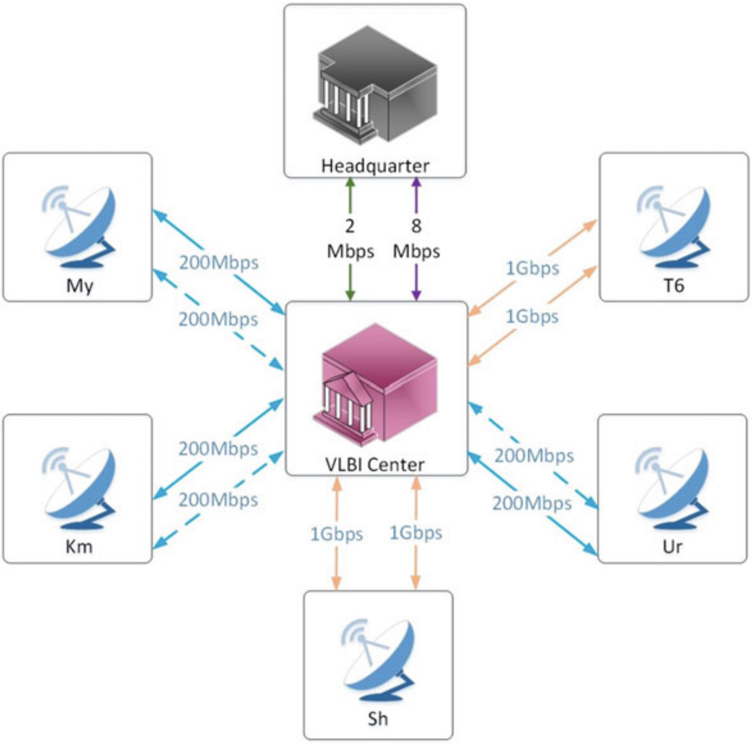

Fig. 8 e-VLBI network link topology

In order to ensure the stability and reliability during the long term run of Chang'E missions, each station was established two dedicated fiber links to VLBI data center to make sure uninterrupted e-VLBI data stream synchronized transmission, as shown in Fig. 8.

In the network device layer of communication system, the Open Shortest Path First Interior Gateway Protocol (OSPF) and Bidirectional Forwarding Detection (BFD) protocol are used together to provide an active-standby backup way to assure high-reliability. The network link switching time is reduced from the seconds to the milliseconds if one link was broken, which greatly reducing the jitter time of e-VLBI data retransmission, made no obvious time delay among stations data streams.

3.3 *Application in CLEP Phase I*

Before involved in CLEP, CVN only had 2 + 1 observation stations (Sh and Ur Station, Yunnan Kunming Mobile Station) and two-station FX-type hardware correlator. The FX-type hardware correlator was based on special designed ASIC-chip technology, at that time the general computer performance was far more enough for VLBI correlation. The data exchange between the station and correlator center depended on high density tapes. There was no possibility to do near real-time or real-time VLBI observation by tape system. In order to meet the requirements of quick turnout of Chang'E probe observation, CVN developed a number of key technologies including: VLBI space probe tracking observation technology, real-time data acquisition, recording and transmission system, real-time correlator, S-band post-processing, lunar probe orbit determination and positioning, etc.

Here is the key components of system construction and technologies developments.

(1) CVN shared use with two big telescopes of GRAS My and Km station, together with existed stations, comprised a reasonable layout of east-west and south-north baseline in China. Its longest baseline length was more than 3200 km. This network increase the observation time slot and space resolution than the previous CVN network.
(2) Due to the low speed and relative high bit error rate of the magnetic tape system, it is not suitable for high-precision real-time VLBI data recording and transmission. To solve this limitation, SHAO developed a near real-time data recording, transmission and playback system CVNHD. It's a harddisk system with special design based on $\times$ 86 industry computer platform. CVNHD used commercial high-speed A/D sample card for VLBI raw data acquisition, which improved the data rate and eliminated the instability of tape system. CVNHD system provided essential conditions for carrying out various observation experiments and tests before CE-1 mission. By CVNHD system, 4 VLBI stations were successfully connected to VLBI data center by networking data stream, which transformed radio observation network to aerospace observation capable network. In order to solve the bottleneck of data transfer rate, the default Linux network stack was adjusted and tuned to maximize network data throughput. By increasing the kernel memory buffer of TCP and UDP protocol, utilizing Ping-Pong memory buffer mechanism in data transfer software, carefully choosing kernel congestion control algorithm, e-VLBI system parallelly and synchronously transfered multiple station data to VLBI center. In the first phase of CLEP, the real-time performance of the e-VLBI system was averaged by 40s.
(3) The core of VLBI data processing system is the correlator, it's a special designed data processing system for VLBI. In the system design period, VLBI data center decided to use twotype solutions based on hardware and software platform. The software correlator was a stand-alone version of the multi-station data correlating system with fringe searching function integrated in. The fringe searching function is for precise correlator model reconstruction come into play when the lunar probe orbit maneuver or the initial theory orbit is too coarse. The software correlator system was developed by C language, using multithreading and OpenMP libraries to achieve multi-core parallel computing acceleration. In the CE-1 mission, the software correlator played a key role in the data processing pipeline of the VLBI center. The hardware correlator was developed on FPGA chip and was the another correlating system leaded the second data processing pipeline as backup.

(4) Post-processing obtains the multi-channel delay and delay rate data results in the S frequency band, which is one of important data products sent directly to the TT&C headquarter. The post-processing software is the most sophisticated scientific computing software in VLBI data process. It adopted dynamic configuration methods to achieve flexibility while still capable of interactive analysis. A real-time graphical display interface helps instantly display data results as the observation was going on, provided operational status at the data quality level.
(5) In the CE-1 mission, TT&C system used USB and VLBI systems for joint orbit determination. The orbit determination software in VLBI center use both data sets of USB and VLBI to do joint orbit calculation for each observation segments such as Earth-Moon midway trajectory correction, lunar orbit capturing, and circumlunar trajectory. Orbit determination software also can give near term prediction orbit based on historic accumulated data before next probe observation.
(6) In the pipeline data processing system of the VLBI center, rapid data exchanging between heterogeneous software systems rely on a special tuned Network File System (NFS) with fine control of access permissions. It simplifies software data interface design and provides intermediate data storage.

By attended the CE-1 mission, CVN broke through the limitation of traditional system and mastered the lunar probe tracking and measurement technologies, especially established data processing system for space aircraft observation. The VLBI system got real-time performance of 6–7 min which was better than the design target of 10 min for VLBI tracking system. That's the first giant leap for CVN.

3.4 Application in CLEP Phase II

(1) Chang'E-2 mission

The launch of Chang'E-2 was the begging sign of second phase of CLEP. It's a pilot test probe for CE-3, aimed for key technologies verification. VLBI system attended the new X-band telemetry and tracking technology verification included differential doppler signal (DOR) interferometry technique [9].

X-band DOR signal has higher frequency than the S-band, by applying a higher-precision propagation medium error correction model to new adaptability improved data processing software, VLBI system contributed the probe detection accuracy to better than 1 mm/s and 100 m, and all data products were obtained within 10 min. Through the software optimization and hardware upgradation on CE-1 VLBI system, the raw data rate increased to 32 Mbps/station.

After successfully supported CE-2 formal task, the VLBI system continued to participate in the expansion experiments periods, including transfer from the lunar orbit to the Lagrange L2 point between Sun and Earth, and thereafter flew to the Tutattis asteroid to verify the TT&C capability with maximum distance of 80 million kilometers. The VLBI system had showed the very important tracking and measurement ability for the space distance more than 80 million kilometers from earth.

(2) ChangE-3 mission

The CE-3 mission was the first time for China to soft land on an extraterrestrial planets surface. This very challenging mission posed new requirements for VLBI system in the short arc trajectory measurement. During the system developments for CE-3 mission, VLBI broke through a series of key technologies and built some new systems, such as new generation digital baseband VLBI data terminal, ΔDOR (Delta Differential One-Way Ranging/Doppler) measurement technology, newly built Tianma 65-m radio telescope, real-time VLBI data processing, same-beam phase delay measurement for two nearby lunar targets, high-precision orbit determination and positioning [10].

The brand new digital VLBI data terminal replaced the old analog ones, which is capable of multibit sampling. ΔDOR observation and corresponding data processing system with new models and algorithm was developed for higher precision measurement. Same beam observation and data analysis system specified created for relative motions detection of the CE-3 lander and Yutu-1 lunar rover. The new big telescope joined into CVN network was Shanghai Tianma radio telescope which greatly improved the whole CVN sensitivity and resolution for lunar spacecraft tracking. VLBI data center moved to new building and updated new IT hardware platform which was conducive to software performance. VLBI phase reference mapping method in radio astronomy was also creativity applied to get the accurate location of the CE-3 lander on Moon mare surface.

The real-time e-VLBI system upgraded as well. First, with the new generation VLBI digital baseband converter system CDAS (Chinese Data Acquisition System) wider frequency band sampling and higher rate data collection was possible. High-speed real-time data collection, local storage and transmission system based on the commercial ×86 COST (Commercial Off The Shelf) computers was developed and put in use with VLBI standard Mark5B data format support. New e-VLBI system had the capability of synchronous data collection and dual-channel distribution from 5 stations to VLBI data center, and also had the functions of data format decoding and error correction on the software correlator front side. The real time performance of data stream transfer of new e-VLBI system was reduced from 30 to 1s. At the same time, the parallel data processing pipelines in the VLBI center were upgraded both in architecture and algorithm to meet 1-min real-time requirement for the whole VLBI system. To improve data exchange efficiency, new NAS (Network Attached System) and NFS protocol had been carefully adjusted to shorten the directories and files caching time and latency, minimized the attribution modification operations so as to help real-time data processing systems coupled more tightly. The overall VLBI system real-time performance for CE-3 was finally boosted from 10 to 1 min [11].

ΔDOR observation is one kind of differential observation way for deep space probe tracking. When observing, radio telescope shift pointing targets between the spacecraft and nearby reference radio sources on celestial sphere. This observation mode can eliminate common errors exist in signal receiving chain of each station. Corresponding computing systems for ΔDOR observation data in VLBI center were also setup. Key units such as DOR data correlating system, post processing dedicated for DOR signal, joint orbit determination and positioning based on X-band USB and VLBI data, are successful developed and passed the system proficiency testing before actual use. For precise relative motion detection of CE-3 lander and rover, T6 telescope is the most suitable for same beam interferometry observation and new kind of SBI data processing system joined VLBI data processing pipeline. SBI software could extract the differential delay and delay rate of two lunar objects and capable of real-time accurately monitoring relative motion [12, 13].

Technological innovation and system upgradation happened in stations and data center was a big leap for CVN. These improvements are not only better served the CE-3 mission but also laid an important foundation for the subsequent lunar and deep space exploration missions. Because of the VLBI system's work and high accuracy results during CE-3 traskcing and measuring, TT&C system headquarter wrote a letter phrasing VLBI system for its "Outstanding Contribution".

3.5 Application in CLEP Phase III

The third phase of CLEP is the CE-5T1 test mission and CE-5. The main purpose of the CE-5T1 mission was to test the lunar return spacecraft and verify the high-speed earth orbit reentry return technology.

The VLBI system accurately tracked the CE-5T1 probe as usual and provided high-precision orbit results during the high-speed reentry when the probe returned from Moon. This technical verification mission provided guarantees and paved the way for CE-5 official mission. On 24 November 2020, CE-5 was lunched and started its way to the Moon.

3.6 Chang'E-4 Mission

The CE-4 probe, a back-up for CE-3, the scientific goal was adjusted to land manmade detector on the South Pole-Aitken Basin, far side of the Moon [14]. There is no direct way to do communicate with the ground station from back side of the Moon. So before CE-4 lander and rover mission, a relay satellite "Que Qiao" was launched May 2018 and sent to orbit around the Lagrange L2 point between earth and Moon for relay communication. During the CE-4 soft landing on the lunar far side, relay satellite was providing continuous relay communication services for CE-4 probe and ground station. So the accurate orbit of Que Qiao was crucial as it's the bridge for telemetry and communication. For VLBI system, a time-sharing working mode was created to successive observation of CE-4 probe and relay satellite. The switching time of two types observation is within 70 min. The CE-4 and the relay satellite observation still use the radio source calibration as system calibrator. The observation source change strategy is "5 min radio source—5 min CE-4 probe or relay satellite".

From May to June 2018, VLBI system successfully served the trajectory measuring task of the relay satellite. From December 2018 to January 2019, VLBI system successfully provided tracking service for CE-4 probe landing.

For the CE-4 mission, the main innovations of the VLBI system includes: the first time S-band ΔDOR VLBI observation and signal data processing, the first time achieved the precise Halo orbit of the lunar relay satellite at Lagrange L2, realized rapid switching of the time-sharing observation and supported two different space probes.

3.7 Technical Performance Statistics

(1) Real-time performance

The traditional radio astronomy observation network has upgraded from none-time-sensitive system to real-time tracking system for CLEP. The e-VLBI data system achieved high reliability of real-time data transmission with zero data lost when the network link or devices failure occurred. The overall real-time performance is better than requirement assigned by TT&C headquarter [15]. Table 2 summarizes the statistics of the real-time work of previous tasks.

Table 2 e-VLBI operation status for CLEP

Mission	Transfer mode	Station to center network link	VLBI data rate	Link switching	Real-time target	Real-time actual
CE-1	Near real-time	SDH 34 Mbps, IP-VPN (100 Mbps)	16 Mbps	Manual >30 m	<10 m	<6 m
CE-2	Near real-time	2 × MSTP (100 Mbps)	32 Mbps	Manual >15 m	<10 m	<4 m
CE-3	Real-time	2 × SDH 155 Mbps	64 Mbps	Automatic <3 s	<1 m	<40 s
CE-5T1	Real-time	2 × SDH 155 Mbps	64 Mbps	Automatic <3 s	<1 m	<40 s
CE-4	Real-time	2 × MSTP 200 Mbps	128 Mbps	Automatic <3 s	<1 m	<40 s

(2) Data products quality

The direct measurement results of the VLBI network for the spacecraft is signal delay and delay rate. Measurement methods covers △VLBI, △DOR and SBI. The quality of VLBI data products are shown in Table 3.

(3) Data volume

After long term servings for CLEP, VLBI system has accumulated lot of data product. It's not only for real-time tracking task, but also could be used to carry out other scientific researches such as interstellar medium and solar wind. VLBI data products statistics is showed as Table 4.

Table 3 Measurement accuracy of previous lunar missions

Mission	Frequency	Obs. mode	Delay target (ns)	Actual delay (ns)
CE-1	S	△VLBI	12	6
CE-2	S	△VLBI	12	5
CE-3	X	△DOR, SBI	4	1
CE-5T1	X	△DOR	4	1
CE-4 relay probe	S	△DOR	5	1
CE-4 lander&rover	X	△DOR	3	0.6

Table 4 Statistics and data volume of data product

Mission	Data products	Data volume	Realtime work time	Extended work time
CE-1	Skd, Correlator, Post-process, orbit, angle, Ecrt	17 TB	1 month	6 months
CE-2	Skd, Correlator, Post-process, orbit, angle, Ecrt	31 TB	1 month	26 months
CE-3	Skd, Correlator, Post-process, sbi, orbit, angle, Ecrt	6.8 TB	1 month	4 months
CE-5T1	Skd, Correlator, Post-process, sbi, orbit, angle, Ecrt	1.8 TB	2 weeks	6 months
CE-4 relay probe	Skd, Correlator, Post-process, sbi, orbit, angle, Ecrt	2.3 TB	1 month	2–8 years
CE-4 lander&rover	Skd, Correlator, Post-process, sbi, orbit, angle, Ecrt	2.2 TB	1 month	/

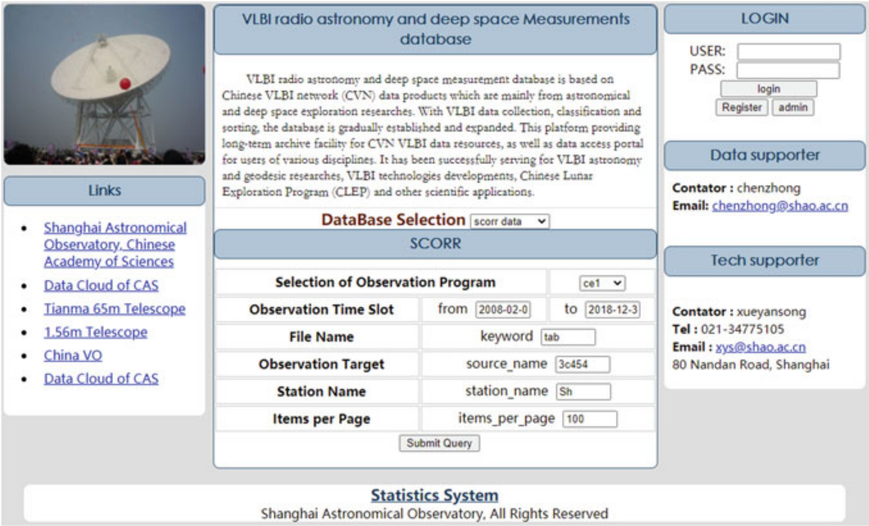

Fig. 9 VLBI radio astronomy and deep space exploration database

After the data protection period, VLBI data products will be public available on web site (https://www.vibi.csdb.cn) (Fig. 9). The web hosted on the national basic scientific data sharing service platform, SHAO is responsible for web site maintenance and data sharing service.

4 Future Plans

Following three phases of CLEP, China will continue its aggressive lunar and deep space exploration programs. Next one is Mars exploration program and it was launched at the end of July 2020. Following may be asteroid exploration plan. The fourth phase of CLEP is under discussions. For the long term there are some proposals about Mars sampling and return program. CVN and VLBI measurement system will continue to provide real-time observation and precise orbit and angle determination services for these space exploration programs. With different space missions being carried out the time slots would be very likely overlapped. The number of existing observation stations and VLBI data center capabilities is not enough for multiple deep space exploration missions, especially in need of parallel tasks execution. VLBI has made plan to establish two new 40-m radio telescope in Tibet Autonomous Region and JiLin province, northeast of China. Also planning transfer a 40-m antenna in ShanXi province to be VLBI observation capable. With totally 7 domestic stations, two subnets could be configured for concurrently tracking two targets at the same time. The optimized configuration of the observation subnet in the nurture is shown as Fig. 10.

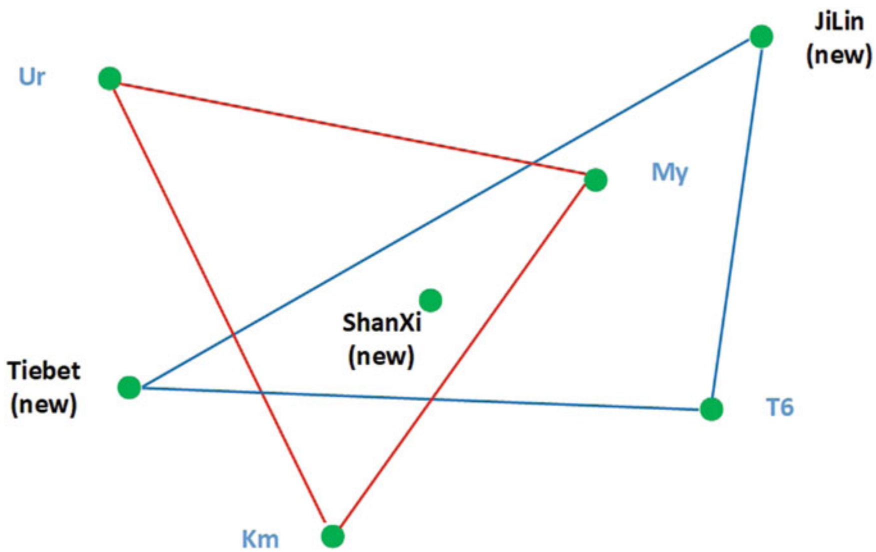

Fig. 10 Future plan of VLBI two subnet configuration

The VLBI data center also needs to expand the data processing system capacity and develop new software pipeline system suitable for dual subnet data processing. To improve the level of automation and intelligent operation, multi-task and multi-target cooperative operation system (MTMOS) is essential for automatic operation, especially in the circumstance of the complexity of two subnet and two pipelines. With MTMOS, manual operations could be replaced by efficient machine operations with fewer people. The preliminary architecture design of the multi-task multi-target VLBI system is shown in Fig. 11.

There is another plan to use the 4.2m-diameter antenna on the lunar relay satellite to carry out joint observation between the lunar orbit VLBI telescope and ground station to test the lunar-earth VLBI ultra-long baseline experiments.

SHAO is also proposing a space low frequency VLBI program. In its plan two 30-m (or even larger) space radio telescopes will be launched with an orbital altitude of up to 90,000 km (The baseline of the telescope to the Earth is up to 10,000 km). The space telescope operating frequency is between 30 MHz and 1.7 GHz (including the four main bands of 30 MHz, 74 MHz, 330 MHz and 1.67 GHz). The highest resolution is 2mas at 300 MHz and 0.36mas at 1.7 GHz. The space low frequency radio telescope array program is not only a big step on the basis of the ground VLBI array, but also a giant improvement in angular resolution and sensitivity by several folds. The unique low-frequency band is an area has not been touched by previous space VLBI projects. With these space areas, scientific breakthroughs in fields of cosmology, gravitational waves, and exoplanets is expected to be achieved. All international cooperation are welcome.

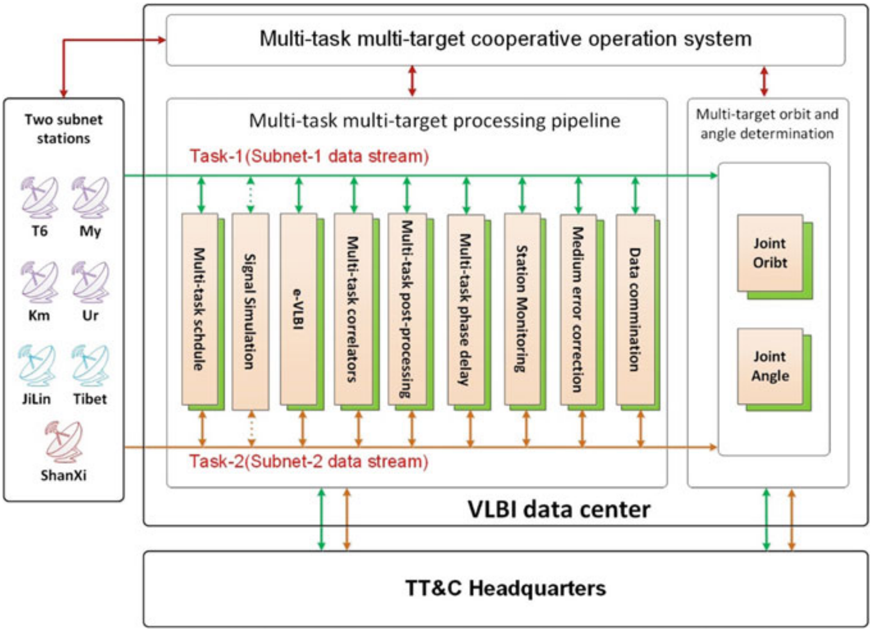

Fig. 11 Preliminary architecture design of the multi-task multi-target VLBI system

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