Technical Progress of the Chinese VLBI Network

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Abstract In recent years, the Chinese VLBI network has been greatly promoted by Chinas Lunar Exploration Project (CLEP) and the VLBI Global Observation System (VGOS). The new VGOS station will be put into trial observation in 2018. Both the new VGOS wideband VLBI terminal and the integrative data acquisition and transmission VLBI terminal for deep-space tracking have been installed. The correlator has been successfully applied to lunar probes and GEO satellites for phase reference precision positioning experiments. In combination with geodetic observations, precision comparisons have been performed with the DiFX and K5 correlators, and the CVN correlator is planned to be used for IVS data processing. According to the plan, a new VGOS station is under construction and it will join the CVN at the end of 2018. Besides, the first multi-purpose Earth-Moon baseline space VLBI experiment will be carried out, extending the CVN baseline length to 300,000 km.

Keywords VGOS, Chang'E lunar probes, VLBI terminal, software correlator, Earth-Moon space VLBI

1 Introduction

The Chinese VLBI Network (CVN) includes five antennas and one data-processing center now. The new Shanghai VGOS station is located in the Tianma 65-m telescope park. The Shanghai Astronomical Observatory (SHAO) has carried out development work on VLBI digital baseband converters and software correlator for many years. The new CDAS2 terminals data rate is up to 16 Gbps with VDIF output data format and it has the ability of 1–16 bits quantization. A general purpose software VLBI correlator for space probe tracking, geodesy, and astrophysics is under development. Aside from Chinas Lunar Exploration Project (CLEP), it was applied to Chinas Chang'E-3 (CE-3) lunar lander phase referenced VLBI positioning experiment. It will be used in Chang'E-5 (CE-5) dual objects same beam VLBI tracking as well as routine IVS data processing. According to comparison results from geodesy observations, the results of the Shanghai software correlator (SCORR) are highly consistent with the DiFX and K5 correlator results.

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2 TmVGOS Station

Fig. 1 The TmVGOS antenna (left), VLBI terminals (middle), and observation room (right).

A new VGOS station is under construction near the Tianma 65-m radio telescope. The antenna is manufactured by CETC-54 institute. The system consists of UDC, CDAS2, Mark 6, and DBBC3; a hydrogen maser imported from Russia is already running. The station will install a real-time reference point monitoring system. The first fringe test was completed in September using an ambient temperature test receiver. Experimental observations with a cooled receiver are expected for the end of 2018.

3 Digital Terminal

Due to the requirements of CLEP and VGOS, a new VGOS wideband VLBI terminal and an integrated data acquisition and transmission VLBI terminal for deep-space tracking were installed. Table 1 shows a comparison of these terminals.

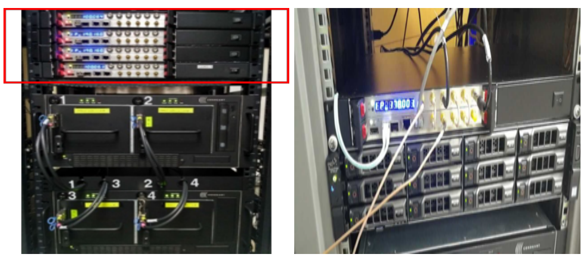

Fig. 2 VGOS Wideband VLBI terminal (left). Integrated data acquisition and transmission VLBI terminal for deep-space tracking (right).

The Chinese VLBI Data Acquisition System (CDAS) is the first generation digital BBC installed at CVN stations for astronomy, geodesy, and deep space observations. It has four Intermediate Frequency (IF) channels and the maximum data rate is 2,048 Mbps with 2-bit quantization capabilities. Due to the different requirements of astronomy, geodesy, and deep-space observations, the second generation VLBI backend CDAS2 was designed. For quasar observations, CDAS2 can work in the wide bandwidth with 1 or 2-bit quantization, while in deep-space probe observations, it can work in the narrow bandwidth with multi-bit quantization.

The VGOS wideband VLBI terminal and the integrated data acquisition/transmission VLBI terminal for deep-space tracking are both based on the CDAS2 platform installed in a 1U chassis.

The VGOS wideband VLBI terminal CDAS2-PFB needs four CDAS2 modules which are implemented with PFB algorithm, shown in Figure 2 (left). Each CDAS2-PFB can process a dual-polarized intermediate frequency signal with 512-MHz bandwidth. Each 512-MHz bandwidth has been divided into 16 sub-channels by the PFB algorithm. The data sent from a single 10 GE SPF+ port on each module are up to 4,096 Mbps. The VGOS wideband VLBI terminal is composed of four CDAS2-PFB modules and has the capability to process four dual-polarized IF signals and to send the data to a Mark 6 through four SFP+ ports. The total data rate is up to 16,384 Mbps.

The integrated data acquisition and transmission VLBI terminal for deep-space tracking only needs one CDAS2 module implemented with DDC algorithm, called CDAS2-DDC, shown in Figure 2 (right). It is suitable for S/X dual-band system. There are also two IF channels, one for S-band and the other for X-band. The functionionality of the CDAS2-DDC is the same as CDAS [1].

Considering briefly the developing cycle, a general purpose and low-cost VLBI terminal based on ROACH2 platform, in collaboration with the Xinjiang Astronomical Observatory (XAO), is under development. This is a general purpose terminal for VLBI and pulsar observations by upload different softwares.

Table 1 Comparison of the various terminals.

	CDAS	CDAS2-PFB	CDAS2-DDC	Roach2
Algorithm	DDC	PFB	DDC	PFB
Total Band-width(MHz)	4IF $\times$ 512	2IF $\times$ 512 $\times$ 4	2IF $\times$512	2IF $\times$ 512
Max Data Rate(Gbps)	2	16	2	2
Data Format	/	VDIF	MK5B	MK5B
Interface	VSI	SFP+$\times$ 4	SFP+$\times$ 1	SFP+$\times$ 1
Sample Bits	1/2	1/2	1/2/4/8/16	1/2
Subband-width(MHz)	1/2/4/8/16/32	32	0.5/1/2/4/8/16/32	32
Max Channels	16	120	16	15
Key Processer	Xilinx XC 4VLX160	Xilinx XC 7K355T	Xilinx XC 7K480T	Xilinx XC 6VSX475
Recorder	Mark5B+	Mark6	Commercial server	GPU server
Target	IVS, Lunar project	VGOS	Lunar and Deep space mission	VLBI, Pulsar(XAO +SHAO)

By the end of 2018, the CDAS3 platform will be finished. The maximum data rate is up to 32 Gbps. Furthermore, an RF sampling solution has been put on the schedule. It will cover up to 14-GHz bandwidth.

4 Software Correlator

SCORR was originally developed for Chinas Lunar Exploration Project (CLEP), including CE-1, 2, 3, CE5T1, and CE-4 experiments. In these missions, it has played an important role in orbital determination of the spacecraft. The software correlator is written in C and uses MPI and pthread for parallelization. At present, the correlator supports multiple types of raw data formats, including Mark 5A, Mark 5B, and VDIF. As a correlator, which is mainly used in China's space missions in its early stage, it features real-time data processing for high reliability. Besides this, it supports real-time satellite signal fringe search, which means it is able to construct delay models by searching delay and delay rate from raw data. This function is especially useful during orbital maneuver when no fringe is available with predicted models.

CE-4 Queqiao relay satellite was launched on May 21, 2018. The CE-4 lander and rover will land on the lunar far-side surface at the end of 2018. We used VLBI technology in CE-4 successfully.

4.1 Specification of SCORR

SCORR consists of several modules such as Data Preprocess, Phase Calibration Signal (PCAL) extractor, Fringe searcher, Spacecraft Delay Model Reconstruction, and Correlation, among others.

Table 2 The specifications of SCORR.

Frequency Channel	16–16,384
Output Format	CVN, FIT-IDI, Mk4
Developing Language and Library	C, C++, CUDA, IPP, MPI, PThread, OpenMP
Computing Platform	Cluster+GPU+Storage Server
Data Recorded Format	MK5B,VDIF
Application	Deep Space, Geodesy, Astronomy, Spacecraft phase-reference VLBI experiments, and others

We hope to upgrade SCORR to a general purpose software correlator and support astronomy, geodesy, and deep-space observations. Table 2 lists the specifications of SCORR.

In the Rendezvous and Docking (RvD) phase of CE-5 Orbiter and Ascender, we plan to track the orbiter and the ascender in some special same beam VLBI cases. New dual objects algorithm are developed. We also developed a new fringe searcher algorithm for reducing the computation. For a real-time system, the calculation speed should be increased two times. GPU and IPP libraries are used to increase the computational capabilities.

4.2 Comparison with Other Popular Correlators

To verify the precision of SCORR, we have carried out detailed comparisons with other popular correlators, including DiFX [3, 4] and K5 developed by NICT, Japan. The comparison data is from IVS observing session K14349, which lasted for one hour and included four stations: Ny, Sh, Ts, and Wz.

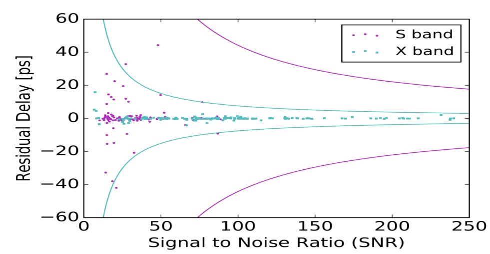

Fig. 3 Discrepancy of residual delay as a function of SNR. The blue and magenta curves correspond to theoretical uncertainties in S- and X-band, respectively.

In the comparison with DiFX, we did the correlation using the same delay model for both correlators. For this reason, the DiFX delay models were replaced with the SCORR models. Figure 3 shows the discrepancy of residual delay. The two correlator results fit quite well. The weighted root mean square is 9 ps in S- and 3 ps in X-band. The discrepancy of delay rate is within 0.1 ps/s. The SNR difference is within 0.5%.

The delay models of K5 are calculated for a reference station instead of the geocenter in SCORR and

DiFX; we had to make corrections to the K5 results. Figure 4 shows the comparison result. The discrepancies of the multi-band delay in X- and S-band are around 13 ps and 80 ps, respectively. Besides that, there is a constant offset for each baseline, which is due to the different usages of PCAL signals.

The constant offset will be removed in the post-processing. Discrepancies of the delay rate are within 0.5 ps/s and 1 ps/s for X- and S-band, respectively. The comparison test results show a good agreement of SCORR with the DiFX and K5 correlators. SCORR is accurate enough to process IVS observations.

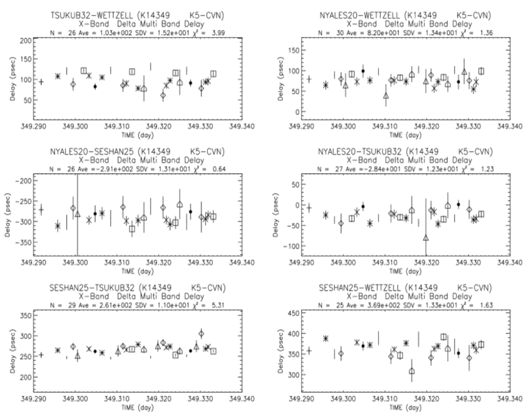

Fig. 4 Comparison of the multi-band delay in X-band for the K5 and CVN software correlators.

5 Satellite Observation Experiments

To assess the ability of satellite positioning using the CVN, several satellite observation experiments were carried out. The results show that the CVN is very effective, and its angular accuracy can reach tens of mas (milli-arcsecond) or even better.

Two Chinese VLBI antennas (Seshan & Urumqi) were used to test GPS observations of GPS-PRN28. Figure 5 shows the clear fringe of GPS-PRN28. That means Chinese VLBI antennas can observe near-earth satellites.

Figure 6 shows VLBI imaging results of a GEO satellite when using five Chinese VLBI antennas (Seshan, Kuming, Urumqi, Kashi, Jiamus). The ∼10 m (∼50 mas) positioning accuracy was achieved which met well the current meter-level GEO satellite positioning accuracy.

Phase referenced VLBI was also used to determine the CE-3 lander position. Two sessions were carried out. The positioning results discrepancy between these two sessions was ∼12 mas (∼10.5 mas in right ascension, ∼5.9 mas in Declination), which equals to ∼2 4m positioning discrepancy.

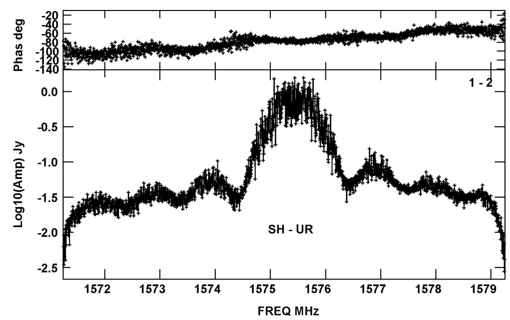

Fig. 5 Cross-spectrum of GPS-PRN28 on the baseline Sh–Ur.

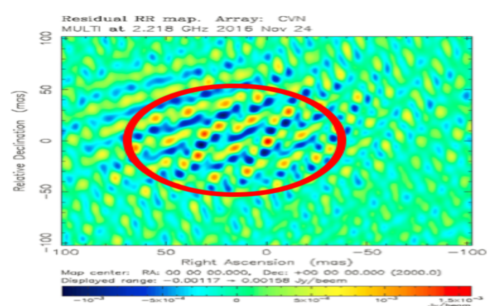

Fig. 6 GEO satellite phase referenced VLBI observation result.

6 VLBI Application in CE-4

ChangE-4 (CE-4) is the fourth Chinese lunar mission. It is the first time to land on and explore the far side of the moon. Queqiao relay satellite, which will establish the communication between the Earth and the CE-4 prober landing on the far side of the Moon, was launched on May 21, 2018. Now, it is orbiting around the Earth-Moon L2 point. The CE-4 probe will be launched at the end of 2018. As with previous missions, VLBI observations were used in the orbit determination of the relay satellite.

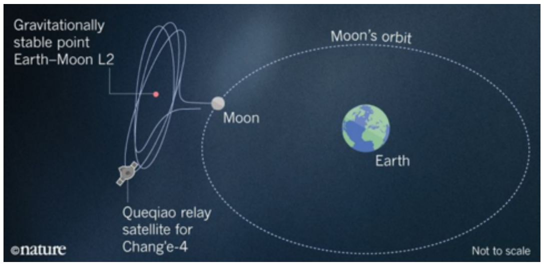

Fig. 7 Queqiao relay satellite tracks the Moon from a gravitationally stable point Earth-Moon L2 [5].

In the Queqiao mission, the CVN made use of S-band Delta-DOR in real time orbit measurement and CDAS2-DDC was successfully used for the first time. The whole CVN system performed much better than expected. More than 80% of the delays are better than 0.2 ns and the orbit determination errors were generally at the hundred meter level.

7 Earth-Moon Space VLBI

In the next mission of CLEP, there will be another relay satellite in lunar orbit. VLBI payloads such as the receiver, the H-maser, and VLBI terminal will be mounted on the relay satellite. Because of the longest baseline up to 400 km, cooperated with the ground based big antennas, the first Earth-Moon baseline space VLBI experiments of deep space probe tracking, astrometry, and astrophysics experiments will be carried out.

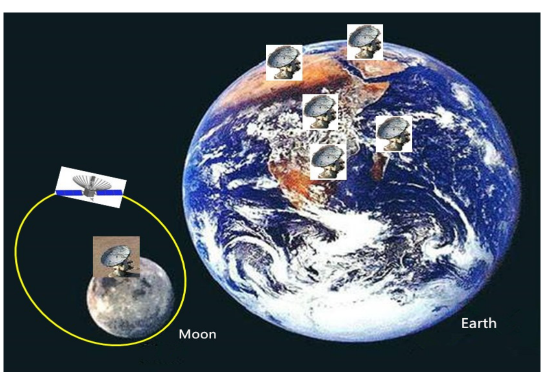

Fig. 8 The first Earth-Moon space VLBI experiment will be carried in the next lunar mission.

8 Conclusion

The CVN has made numerous technical advances. There will be more antennas to join the CVN in the future. We plan to carry out research on ultra-broadband receivers, 14-GHz bandwidth direct RF sampling terminals, GPU-based software correlators, and space VLBI technology.

Acknowledgements

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