A Giant Step: from Milli- to Micro-arcsecond Astrometry
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The Chinese VLBI network and its astrometric role

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Abstract. In this report we present the current status of the Chinese VLBI network (CVN), and the results of satellite tracking experiments in the past few years related to realtime processing of the CVN dataflow and the reliability and precision of the CVN measurements. We briefly outline the prospective astrometric roles of CVN in the studies of long-term monitoring of extragalactic radio sources, densification of radio celestial reference frame, determination of Earth Orientation Parameters and linkage parameters of reference frames as well as the observation of pulsars for deep space autonomous navigation.

Keywords. astrometry, ephemerides, reference systems, Earth, Moon, planets and satellites: general

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1. Current status of the Chinese VLBI network

The two 25m radio telescopes at Sheshan of Shanghai and Nanshan of Urumqi began astrometric observations since 1987 and 1993, respectively. The Chinese mobile VLBI consists of a 3m antenna and an S2 system. Observations could also be recorded by a hard disk system, which is compatible with the Mark5. In May 2006, two new antennas with diameters of 50m at Miyun near Beijing and 40m at Fenghuangshan of Kunming participated in tracking experiment of the Smart-1, a lunar satellite of the European Space Agency (ESA). The correlation center of the Shanghai Astronomical Observatory (SHAO) has successfully developed a five-station FX correlator and a system with PC-based hard disk recorder and playback. The dataflow rate per station is 256 Mbps. Up to now, in the background of the Chinese lunar exploration project, Chang'E-1 (CE-1), the Chinese VLBI Network (CVN) has been developed into four permanent antennas, one mobile station and a correlation center.

As shown in Fig. 1, the CVN extends geographically by over 34° east-west and 18° south-north, with baselines ranging from 1115km to 3249km. Table 1 lists some technical specifications of the four CVN permanent antennas, which are all equipped with the Mark5 recording system.

2. CVN and CE-1

Since the 1960s VLBI techniques have been demonstrating high precision in astrometry and geodesy studies, especially in establishing the celestial and terrestrial reference frames as well as determination of the Earth Orientation Parameters (EOP). In the Chinese lunar exploration project CE-1, VLBI is expected to contribute to real-time monitoring of the satellite orbit especially during the lunar capture stage. CVN is mandated to fulfill a 10-minute task, that is, to provide the spherical coordinates of the satellite within a delay of 10 minutes, with a precision of 0.2 arc-seconds near perilune. This presents a great challenge to the ordinary processing of the VLBI dataflow, including the preparation

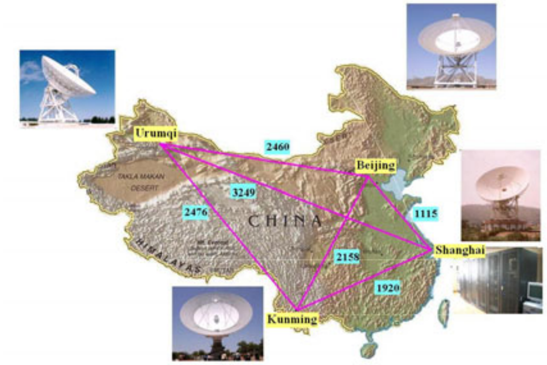

Figure 1. Geographical distribution of CVN

Table 1. Technical specifications of CVN antennas

Specifications	Shanghai	Beijing	Urumqi	Kunming
Begins operation	1987	2006	1993	2006
Structure	BWGC[1]	Prime focus	BWGC	BWGC
Diameter[2]	25m	50m	25m	40m
Pointing precision (arcsec)	20	19	15	30
Slewing rate (AZ/EL, d/s)	1.0/0.6	1.0/0.5	1.0/0.5	1.0/0.5
Receiver	L, C, S/X, K	S/X	UHF, L, C, S/X, K	S/X
Efficiency at S/X band	38%/40%	60%/68%	54%/52%	64%/47%
Recording terminal	Mark5A, VLBA, S2	Mark5A	Mark5A	Mark5A

[1] BWGC — Beam wave guide Cassegrain
[2] Diameter of the main reflection plane

of schedule, antenna tracking, data recording and transfer, correlation, extraction of VLBI observables, correction of systematic behavior and atmosphere delays, as well as deduction of the target spherical coordinates from observations.

Figure 2 shows a realtime processing of the CVN dataflow. The schedule is sent via internet to the antennas. The tracking data are also transferred via internet to the correlation center. The data are processed simultaneously by the hard and software correlators and then observables are extracted. As the antennas are tracking the satellite, observations from collocated GPS receivers are sent to the correlation center too and atmospheric delay information is extracted. This information is combined with the VLBI observables and the systematic behavior corrections deduced from observations of extragalactic radio sources in order to deduce the angular position of the satellite. All these steps are processed with a delay of less than ten minutes. At the end of the tracking pass the orbit is also determined.

In the middle of 2006 ESA offered a great opportunity to the CVN people to test their hardware and software with a goal of completing the 10-minute task by tracking the Smart-1, an ESA lunar satellite. Figure 3 shows the difference between the angular positions of the Smart-1 deduced from CVN realtime measurements and the ESA reconstructed orbit, which was post-stage determined with high precision. After removing some outliers, the standard deviation of the difference is about 0.1arcsec, which demonstrates CVN measurements are reliable and with sufficient precision for identifying the lunar capture of CE-1 satellite.

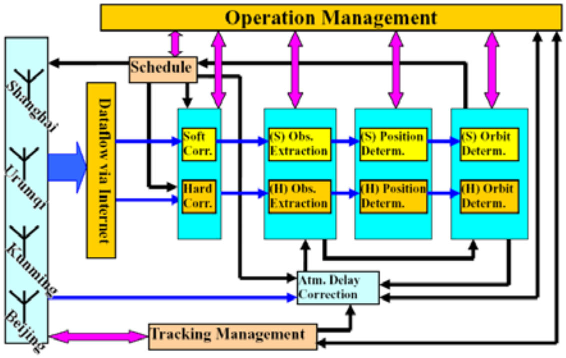

Figure 2. The realtime processing of CVN dataflow

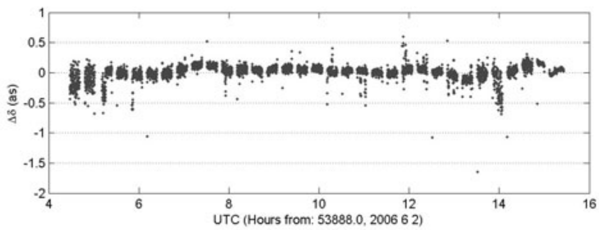

Figure 3. Comparison of the CVN realtime measurements and the ESA reconstructed orbit

3. CVN and the prospective high precision astrometry

CVN has undergone tremendous development by contributing to Chinese national projects and will definitely continue to do so. For example, in subsequent stages of the Chinese lunar exploration Chang'E-2 and Chang'E-3, VLBI will be applied to track the orbiter and lander relative to radio sources. In the Chinese Martian exploration project Yinghuo-1, VLBI will be the main facility for determining satellite's position and orbit. At the same time, CVN is also capable of doing some high-precision astrometric studies, especially in the framework of international cooperation. If CVN is combined with the Russian antennas, the geographical coverage will be about 3500km north-south and 6000km east-west, that would be very promising in studies of space geodesy, astrometry and spacecraft monitoring. The coordinates of the new antennas must be precisely determined, and a local survey at collocation sites with other space geodesy techniques should be done.

3.1. *Spacecraft tracking and reference frames tie*

As a strong support for ranging and Doppler observations, VLBI is very useful in improving angular position precision of spacecrafts. The CVN geometry is very competitive in high precision positioning of spacecrafts, significantly contributing to deep space exploration. By tracking an orbiter, the dynamical origin of longitude (equinox) can be determined. With phase referencing techniques, the tie parameters between the radio and dynamical reference frames can be determined. Analyzing VLBI observations of the orbiter, lander and extragalactic radio sources helps to reach a comprehensive understanding of the probing data and to refer them to a unified reference system.

3.2. *Monitoring extragalactic radio sources*

The extragalactic radio sources (ERS) are fiducial objects of the International Celestial Reference Frame (ICRF) (Ma, *et al.* (1998)), which represents one of the most outstanding scientific contributions of VLBI. However, these sources may have structures and be subjected to changes. Historical observations of the defining ICRF sources are very limited, and the number of observations per source is not even. For instance, among all observed sources by the end of 2005, about 70% were observed only in one to three sessions. It has been encouraged internationally to conduct regular monitoring of these sources. With the current CVN geometry and equipment infrastructure, several dozens of defining sources could be monitored on a regular basis. With the participation of large antennas (70m antenna in Ukraine and the Chinese FAST (Jin *et al.*(2008))) some weak sources, especially those near the ecliptic, could be observed, which would densify ICRF and serve to deep space exploration.

3.3. *Radio stars and pulsars*

It is believed that many radio stars may have planetary systems. By referring to ERS, a precise time series of the proper motion of a radio star can be accumulated (Boboltz, *et al.* (2007)), and small variation in the proper motion would reveal the existence of an extrasolar planetary system. Based on the rotation and orbital motion of the Earth, pulsar timing observations could reveal information of the dynamical equinox, which serves as the origin of longitude. By referring to ERS the proper motion and annual parallax of pulsars can be precisely determined, which is useful to the studies of stellar evolution and to deep space autonomous navigation.

3.4. *Quick EOP service*

By making the EOP results quickly available to the community, would then enable some important scientific and practical applications. Currently IVS has two sessions per week, R1 and R4, and are processed rapidly. CVN can regularly conduct the EOP determination. At the start of this program, the CVN geometry requires careful checks to evaluate the EOP precision and accumulate experience.

3.5. *Monitoring the baseline length*

VLBI is capable of determining continental distances of several thousand kilometers with the precision to a centimeter and even down to a few millimeters. Simultaneous observations of CVN and international antennas could be used in the studies of the Earth's crust motion and deformation. Variations in the baseline length is also related to tides, loading, and atmosphere modelling.

Acknowledgements

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