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The Contribution of CVN to the CE-1 Mission

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Abstract. In this report we present the current status of the Chinese VLBI network (CVN), the results of satellite tracking experiments in the past few years as related to the realtime processing of the CVN dataflow and the reliability and precision of the CVN measurements. In particular, we report on the realtime monitoring of the orbit evolution of the Chang'E-1 satellite by the CVN.

1. Current Status of the Chinese VLBI Network

The two 25 m radio telescopes at Sheshan of Shanghai and Nanshan of Urumqi began astrometric observations in 1987 and 1993, respectively. The Chinese mobile VLBI consists of a 3 m antenna and an S2 system. Observations could also be recorded on a hard disk system, which is compatible with the Mark 5. In May 2006, two new antennas with diameters of 50 m at Miyun near Beijing and 40 m at Fenghuangshan of Kunming participated in the 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. The CVN extends geographically by over 34° east-west and 18° south-north, with baselines ranging from 1115 km to 3249 km. Tabl. 1 lists some technical specifications of the four CVN permanent antennas, which are all equipped with the Mark 5 recording system.

Table 1. Technical specifications of CVN antennas

Specifications	Shanghai	Beijing	Urumqi	Kunming
Operation	1987	2006	1993	2006
Structure	BWGC[1]	Prime focus	BWGC	BWGC
Diameter, m	25	50	25	40
Pointing, $''$	20	19	15	30
Slewing, A/E, $^\circ/s$	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
S/X efficiency, %	38/40	60/68	54/52	64/47
Terminal	Mark 5A, VLBA, S2	Mark 5A	Mark 5A	Mark 5A

[1]BWGC — Beam wave guide Cassegrain

2. The CVN Tracking Experiments of Satellites in the Past Few Years

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 in the determination of the Earth Orientation Parameters. In the Chinese lunar exploration project CE-1, VLBI is expected to contribute to realtime monitoring of the satellite orbit especially during the lunar capture stage. The CVN is mandated to fulfill a 10-minute task, that is, to provide the spherical coordinates of the satellite within a delay of 10 min, with a precision of 0.2 arcsec near perilune. This presents a great challenge to the ordinary processing of the VLBI dataflow, including the preparation 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.

2.1. The CVN Dataflow in the Realtime Running Mode

In the CVN realtime running mode, the schedule is sent via internet to the antennas. The tracking data are also transferred via internet to the data analysis 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 co-located GPS receivers are sent to the data analysis center too and atmospheric delay information is extracted. This information is combined with the VLBI observables and the systematic behavior corrections including the clock bias and the instrument delay 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.

2.2. The Tracking of the Smart-1

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, a lunar satellite. Fig. 1 shows the difference between the angular positions of the Smart-1 deduced from the 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 0.1 arcsec, which demonstrates CVN measurements are reliable and with sufficient precision for the identification of the lunar capture of CE-1 satellite [2].

2.3. The Tracking of the TC-1

On Jan. 23, 2007, the CVN tracked a Chinese satellite TC-1. Fig. 2 shows the comparison of the angular positions with the orbit prediction. Before UTC 15.3 h the angular positions stem from four tracking antennas, while after that the antenna at Shanghai dropped out of the tracking. It is noticed that the data points before this epoch are more dispersed than afterwards. At first glance, this phenomenon shows some confliction with the common sense. Does this mean that the angular position determined from three antennas is better than from four? Or there is some problem in the tracking data of Shanghai? Or is it solely because there are some faults in the reduction algorithm and/or the software?

The angular coordinates (α, δ) at an epoch are deduced from the interpolated delays of data series according to baselines. When there are four tracking antennas, the independent delays are three and the two unknowns are deduced in a least squares adjustment (LS), which is unbiased estimation. While for the case of three tracking antennas, the two unknowns are deduced from only two independent delays and so the solution is unique. The unique solution is constrained to the adopted a priori geocentric distance of the satellite, which is smooth because it is the prediction of the initial orbit but could be in error by the magnitude of kilometers. So the unique solutions are less dispersed as demonstrated by Fig. 2 but could be seriously biased [1].

2.4. Realtime Monitoring of the CE-1 Orbit Evolution

CE-1, the first Chinese lunar satellite was launched on Oct. 24, 2007. It took about two weeks for the CE-1 to fly into the designed orbit to become a lunar satellite. The CVN began tracking of the CE-1 every day from Oct. 27 to Nov. 30, 2007, and timely provided the delay, rate and angular positions with a time lag of about five minutes. Since Dec. 18, 2007 the CE-1 entered into the long-term operation phase and the CVN changes the tracking mode as two-days per week.

The state vectors $(\vec{r}, \dot{\vec{r}})$ are deduced from the delay, rate, range and Doppler

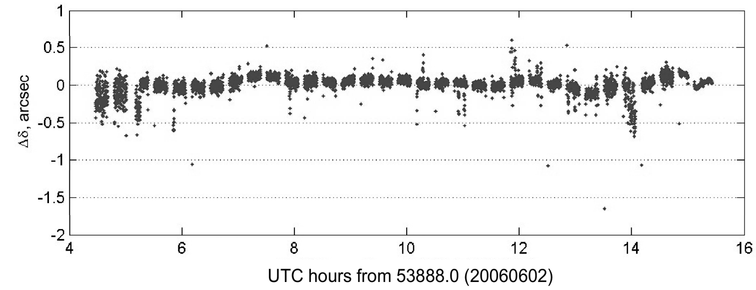

Figure 1. Comparison of the CVN realtime measurements and the ESA reconstructed orbit of Smart-1

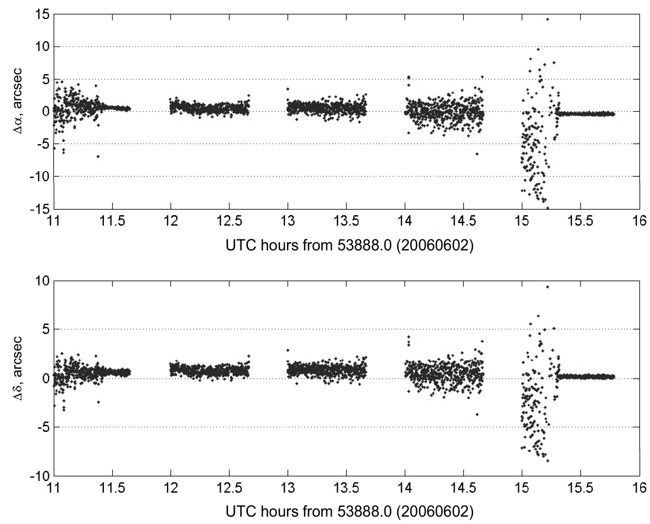

Figure 2. Comparison of the angular position determination with the TC-1 orbit prediction

observations and it is easy to transform them into the orbit elements. As demonstrated in Tabl. 2, by monitoring the evolution of the orbit eccentricity, we quickly declared the successful capture of the CE-1 by the Moon with a time lag of about five minutes because the eccentricity of a parabolic orbit is distinctively different from an ecliptic orbit. By the reduction of the state vectors we also successfully monitored the processes of the orbital manoeuvres, Tabl. 3 is an example.

Table 2. Monitoring the capture of CE-1 by the Moon

ymd	h:m:s	GC	a, km	e	Nb
hyperbolic orbit					
20071105	03:13:01	M	6618.708	1.29441	14
20071105	03:13:31	M	6641.511	1.29340	14
20071105	03:14:00	M	6664.319	1.29238	10
very near to a parabolic orbit					
20071105	03:17:07	M	3406.991	1.08194	08
captured					
20071105	03:20:53	M	2990.028	0.84911	06
20071105	03:20:58	M	3016.474	0.84918	06
elliptic orbit					
20071105	03:42:01	M	6205.055	0.68567	12
20071105	03:42:30	M	6154.900	0.68305	12
20071105	03:43:00	M	6155.691	0.68311	12

Table 3. Monitoring the orbit manoeuvre process (20071106)

h:m:s	a, km	e	$i,^\circ$	$\Omega,^\circ$	$\omega,^\circ$	$M,^\circ$
03:21:14	6015.141	0.67682	87.524	265.446	102.952	−3.881
03:22:43	4418.871	0.56143	87.503	265.290	105.717	−5.781
03:26:29	3360.283	0.42134	87.555	265.223	107.499	−4.906
03:28:46	3056.361	0.36189	87.581	265.279	105.912	−1.674
03:29:26	2971.901	0.34367	87.583	265.281	105.908	−0.747
03:33:46	2601.796	0.25105	87.578	265.396	100.429	10.520
03:36:43	2704.682	0.27867	87.531	265.484	101.783	14.158

3. Closing Remarks

Based on the methodology and software system of data reduction of the regular astrometric and geodetic VLBI, the reduction of the instantaneous state vectors of spacecraft by using VLBI tracking data is realized, which has contributed to the realtime orbit monitoring of the CE-1 with high precision. Compared to the precise and short-arc orbit determination, the reduction of the state vectors is characterized by the loose requirement on the length of tracking arc, no need on the precisely modelling of forces exerting on the satellite, geometrically monitoring the quality of the tracking data and the spacecraft orbit. Practice has shown it is a quick and practicable method.

The CVN has got tremendous development by contributing to Chinese national projects and it will definitely keep doing so. In the next stage of the Chinese lunar exploration, for example, 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 maintenance technique for the determination of satellite position and orbit.

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