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Initial result of the Chinese Deep Space Stations' coordinates from Chinese domestic VLBI experiments

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Abstract China's Lunar Exploration Program (CLEP) prompted the design and construction of the globally distributed Chinese Deep Space Network (CDSN). This network consists of Jiamusi and Kashi stations in China, and Zapala station in Argentina. However, the positions of Jiamusi and Kashi are not accurate enough for future Chinese deep space missions, and geodetic Very Long Baseline Interferometry (VLBI) is the most effective way to determine their positions. Since the CDSN stations are equipped with narrow-band receivers, they cannot participate in current international VLBI sessions in which wide-band frequencies are utilized. Thus a cooperative geodetic program of the CDSN and Chinese VLBI Network (CVN, the VLBI tracking subsystem of the CLEP) was initiated to determine their positions, in which specially designed frequencies can be utilized, and some CVN stations can act as position reference stations owing to their precise positions from long-term international VLBI observations. Primary results have been obtained from the CDSN–CVN combined domestic VLBI experiments from September 28, 2014, through December 10, 2015. The positions of Jiamusi and Kashi are determined to be better than 10-mm precision in the X, Y, and Z directions, which are improved by a factor of approximately 20 over their a priori values.

Keywords VLBI, Chinese Deep Space Network, Chinese VLBI Network, station position determination, terrestrial reference frame

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1 Introduction

In order to support the China's Lunar Exploration Program (CLEP), the Chinese Deep Space Network (CDSN) was designed and constructed. The CDSN includes three globally distributed Chinese Deep Space Stations (CDSSs), i.e., the Jiamusi station (66-m antenna) in northeastern China, the Kashi station (35-m antenna) in northwestern China, and the Zapala station (35-m antenna) in Neuquén, Argentina. Jiamusi and Kashi were deployed in 2013 for the Chang'E-3 mission during the second stage of the CLEP, and Zapala will be operational in 2017 during the third stage of the CLEP. These stations are expected to participate in Very Long Baseline Interferometry (VLBI) measurements during future Chinese deep space missions [1].

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Accurate spacecraft navigation using radio-metric measurements requires good knowledge of the locations of the tracking stations [2]. However, the positions of Jiamusi and Kashi are only accurate to 20 cm, which would induce a position error of ∼15 km at Mars for VLBI measurement. The most effective method for determining positions of stations that have VLBI ability is to conduct dedicated geodetic VLBI experiments [3, 4], rather than local geodetic surveys and the Global Positioning System (GPS) measurements [5, 6].

Since the CDSSs are equipped with narrow-band receivers, they cannot participate in current international VLBI sessions[1] in which wide-band frequencies for bandwidth synthesis [7] are utilized. Thus a cooperative geodetic program of the CDSN and Chinese VLBI Network (CVN) [8] was initiated in 2014 to determine the positions of Jiamusi and Kashi, in which specialized frequencies can be designed anew and utilized to enable proper correlation, and to make full use of the wide-band receivers of the Chinese VLBI Stations (CVSs). The CVN includes the Beijing, Kunming, Seshan, and Urumqi stations, and performs as the VLBI tracking subsystem of the CLEP. In addition, some CVN stations can act as position reference stations in the combined network owing to their precise positions from long-term international VLBI observations.

The primary objectives of the program are to measure the positions and velocities of Jiamusi and Kashi. This program not only satisfies the urgent need for accurate CDSS positions for future Chinese deep space exploration of more distant objects, but also accumulates valuable data for scientific research and takes the first step toward the foundation and maintenance of a time-space reference frame based on the CDSN and CVN.

Since September 2014, seven 24-h S/X dual-band VLBI experiments named cdsn01–cdsn07, using the CDSN and CVN, have been conducted. The frequency and schedule design are provided in Section 2. Section 3 describes the data reduction and assessment. The global solutions and analysis are given in Section 4. The last section provides our conclusion.

2 Scheduling

Two CDSSs (Jiamusi and Kashi, denoted as Js and Ks hereafter) and four CVSs (Beijing, Kunming, Seshan, and Urumqi, denoted as Bj, Km, Sh, and Ur hereafter) were involved in the sessions from September 28, 2014, to December 10, 2015. The geographical distribution of the stations is shown in Figure 1. Statistics of these sessions are listed in Table 1. It can be seen that Js and Ks took part in six sessions, Km and Sh in five sessions, Ur in four sessions, and Bj in only two sessions. All sessions lasted 24 h, whereas Js observed for only 6 h in cdsn01, 19 h in cdsn03, and 21.5 h in cdsn04 owing to other experiments of higher priority or because of extreme weather conditions.

Observations for all sessions were scheduled using the VLBI scheduling software SKED [9]. Sessions cdsn01, cdsn02, cdsn04, and cdsn06 are geodetic, and all scheduled sources have compact structures and stable positions. Session cdsn03 is based on the schedule of an international VLBI session (named AOV001), in which 62 scheduled sources are not geodetically preferable[2]. Both cdsn05 and cdsn07 are astrometric sessions that have 10 astrometric sources being observed in 54 and 22 scans, respectively.

The CDSSs are equipped with narrow-band receivers, whereas the CVSs have wide-band receivers. Thus the frequency sequences for bandwidth synthesis should be designed anew for the CDSN–CVN sessions. Table 2 summarizes the frequencies utilized in the campaigns, and the corresponding root mean square (RMS) bandwidth and group delay precision. It can be seen that four S-band and four X-band frequencies are set at the same frequency ranges of 2200–2300/8400–8500 MHz shared by the CDSS and CVS receivers, and two more S-band channels and four more X-band channels are set at the CVSs for more precise group delays. Note that the frequencies of mode I are different from those of mode II, which have better performance than mode I from the perspective of the delay resolution function (DRF) [10,11]. Note also that the single-band bandwidth of mode II is twice that of mode I. Precisions in Table 2 are

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[1] http://lupus.gsfc.nasa.gov/sess/master16.html.

[2] ftp://gemini.gsfc.nasa.gov/pub/sked/catalogs/source.cat.geodetic.good.

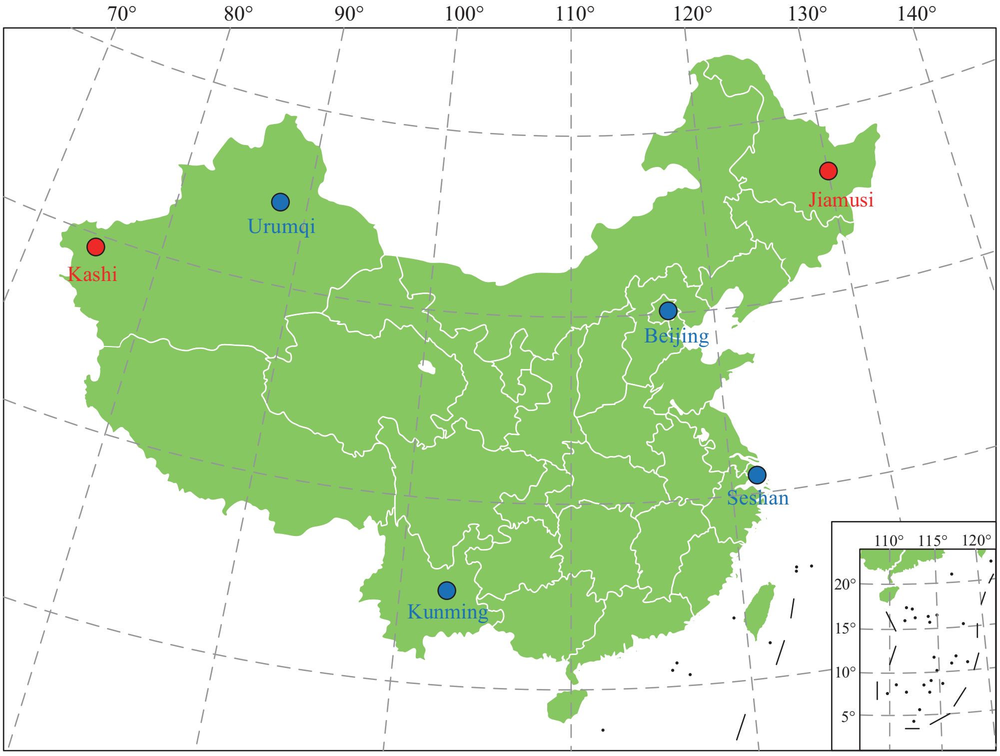

Figure 1 (Color online) Geographical distribution of stations involved in sessions cdsn01–cdsn07.

Table 1 Statistics of sessions cdsn01–cdsn07

Session	Date	Js	Ks	Bj	Km	Sh	Ur	Source	Scan	Observation	Mode	Raw data
cdsn01	09.28.2014	o	o	o	o	o		43	245	1703	Mode I (4 MHz)	Sets A & B
cdsn02	01.22.2015		o			o	o	42	199	597		
cdsn03	03.21.2015	o	o			o	o	126	277	832		Set C
cdsn04	09.17.2015	o	o		o	o		49	268	1455	Mode II (8 MHz)	
cdsn05	10.22.2015	o		o	o	o	o	48	227	2210		
cdsn06	11.13.2015	o	o		o			49	272	744		
cdsn07	12.10.2015	o	o		o		o	45	236	1395		

Table 2 Frequency sequences utilized in sessions cdsn01–cdsn07

Mode		Frequency sequences (MHz)	RMS bandwidth (MHz)	Precision (ps)
Mode I (4 MHz)	S_{CDSS}	2210.75+(0 10 30 85)	32.9	121
	S_{CVS}	2210.75+(0 10 30 85 120 125)	50.7	64
	X_{CDSS}	8210.75+(200 210 230 285)	32.9	121
	X_{CVS}	8210.75+(0 60 90 200 210 230 285 360)	113.0	25
Mode II (8 MHz)	S_{CDSS}	2201.75+(0 10 60 90)	36.7	77
	S_{CVS}	2201.75+(0 10 60 90 130 140)	54.0	43
	X_{CDSS}	8201.75+(200 210 260 290)	36.7	77
	X_{CVS}	8201.75+(0 20 40 200 210 260 290 380)	131.0	15

evaluated based on the precision estimation formula for multi-band group delay [12] assuming that the single-band signal to noise ratio ($\mathrm{SNR_{sb}}$) is 20.0 for a 4-MHz bandwidth (28.3 for a 8-MHz bandwidth). The RMS bandwidth in Table 2 is the RMS of the frequencies. Note that the group delay precision of mode II is much higher than mode I, mainly because of its doubled single-band bandwidth. Mode I is utilized in sessions cdsn01–cdsn03, and mode II in sessions cdsn04–cdsn07 (refer to the fifth column of Table 1).

In cdsn01, the S_{CVS}/X_{CVS} frequencies of mode I were set at Bj and Km, and their analog signals

Table 3 Frequency sequences utilized in sessions cdsn01–cdsn07

<table>
<tr><th>Station</th><th>Data set A</th><th>Data set B</th><th>Data set C</th></tr>
<tr><td>Sh, Ur</td><td>6S/8X, 1bit</td><td>4S/4X, 2 bit</td><td rowspan="2">4S/4X, 2 bit</td></tr>
<tr><td>Bj, Km</td><td colspan="2">6S/8X, 1 bit</td></tr>
<tr><td>Js, Ks</td><td colspan="3">4S/4X, 2 bit</td></tr>
</table>

were quantized to 1 bit/sample. For Sh and Ur, both the digital and analog baseband converters (BBC) were utilized in cdsn01. One BBC used the $S_{\rm CVS}/X_{\rm CVS}$ frequencies and 1 bit/sample settings as Bj and Km, and the other BBC used the $S_{\rm CDSS}/X_{\rm CDSS}$ frequencies and 2 bits/sample as Js and Ks. The same settings were used in cdsn02. Beginning with cdsn03, all signals were quantized to 2 bits/sample, and only the $S_{\rm CVS}/X_{\rm CVS}$ frequencies were utilized at the CVSs. The CDSSs used 2 bits/sample and the $S_{\rm CDSS}/X_{\rm CDSS}$ frequencies throughout all sessions. Therefore, two data sets were obtained for cdsn01 and cdsn02, whereas only one data set was obtained beginning with cdsn03 (refer to Table 3 and the last column of Table 1).

3 Data reduction and assessment

The DiFX software [13,14] was utilized to carry out the correlation. The fringe-fitting and initial solution were done using the HOPS[3] software developed by the MIT Haystack Observatory and the Calc/Solve software[4] developed by the Goddard Spaceflight Center (GSFC), respectively.

Since there were only four channels for S/X bandwidth synthesis of CDSSs, the drop of one bad channel would easily lead to a sub-ambiguity problem, which occasionally occurred during the fringe-fitting. In that case, the default delay search window was narrowed to prevent detection of the pseudo-peak of the DRF. This saved many affected observations. The computation of theoretical delays in Calc/Solve generally follows the latest IERS conventions [15], and the Niell Mapping Function (NMF) [16] was utilized to calculate the tropospheric delay at arbitrary elevations. The segment length of the linear spline for the clock and atmosphere models was set to 90 min rather than the usual value of 60 min to prevent over-parameterization, in that there were only approximately 10 scans/h.

Table 4 lists the post-fit weighted RMS (WRMS) residuals of the initial solution for sessions cdsn01–cdsn07, in which the number of used observations and estimated parameters are also listed. It shows the residuals vary between 30 and 70 ps, which is consistent with the expected precisions except for session cdsn06. In that session, the fringes with Ks had much lower amplitudes than expected owing to unknown reasons. This led to large residuals of baselines with Ks and thus the overall residuals. This was also encountered for cdsn07. Note that in cdsn04 and cdsn05, only approximately 57.7% and 58.0% of the scheduled observations were utilized for solutions, which were much lower than the other sessions. For cdsn04, the reason was the last three S-band channels and last four X-band channels of Km were dropped in fringe-fitting owing to their low amplitudes and scattering phases. This led to the X-band observations of Js-Km and Km-Ks being single-band delays with very poor precision. These were eliminated from the solution. Similar issues were also seen for Km in cdsn05. In addition, some X-band channels of Sh and all X-band channels of Ur in cdsn05 had the incorrect polarization, which led to much lower fringe amplitudes of the affected baselines and thus many outliers.

4 Global solution and analysis

The global solution used 5399 international S/X dual-band VLBI sessions from August 3, 1979, through December 29, 2015, including sessions cdsn01–cdsn07, which aimed to obtain the terrestrial reference frame (TRF), celestial reference frame (CRF), and Earth orientation parameters (EOP) series, and also to tie the station positions to the obtained TRF. Since VLBI delays are invariant with respect to the

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3) http://www.haystack.mit.edu/tech/vlbi/hops.html.

4) http://gemini.gsfc.nasa.gov/solve/.

Table 4 Statistics of initial solution results of sessions cdsn01–cdsn07

Session	Data set	Observations		Parameters estimated	Post-fit WRMS residuals (ps)		
		Used	Scheduled		All baselines	Minimum	Maximum
cdsn01	A	1542	1703	195	38	25 (Bj-Sh)	118 (Js-Sh)
	B	1582	1703	193	49	28 (Bj-Km)	80 (Ks-Sh)
cdsn02	A	548	597	108	33	19 (Sh-Ur)	101 (Ks-Sh)
	B	584	597	107	52	44 (Sh-Ur)	64 (Ks-Sh)
cdsn03	C	788	832	154	33	24 (Sh-Ur)	63 (Js-Sh)
cdsn04	C	840	1455	150	63	55 (Km-Sh)	71 (Ks-Sh)
cdsn05	C	1282	2210	196	43	32 (Bj-Sh)	166 (Js-Ur)
cdsn06	C	604	744	107	101	69 (Js-Km)	210 (Ks-Km)
cdsn07	C	1058	1395	150	69	35 (Km-Ur)	179 (Ks-Ur)

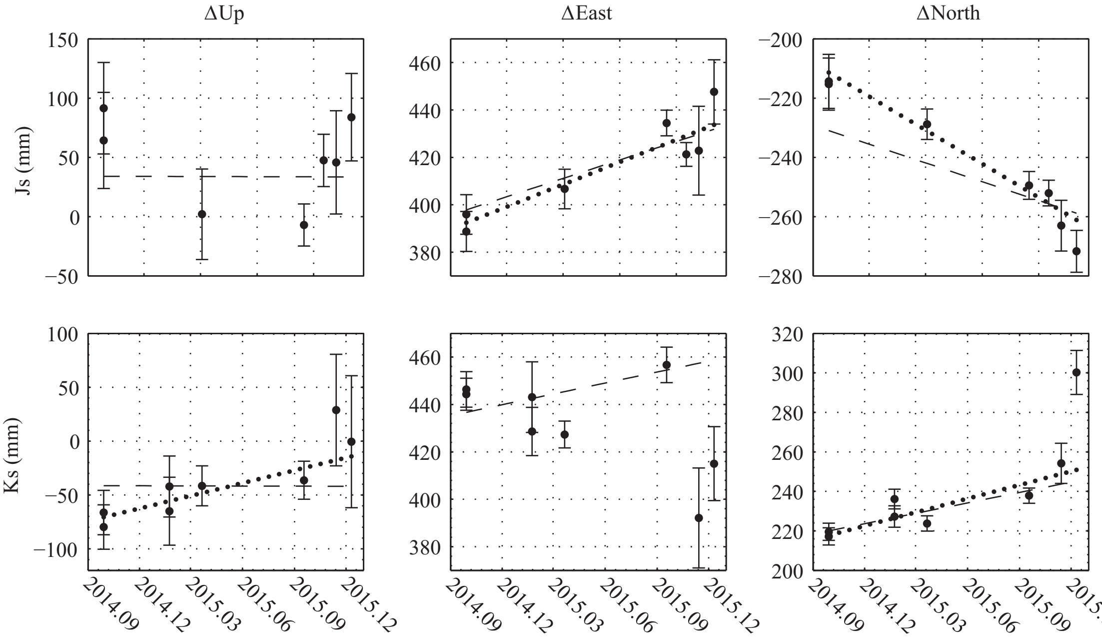

Figure 2 Coordinate adjustments in local up, east, and north directions of Js and Ks from September 2014 to December 2015. Dotted lines show the liner trends that appear in the local adjustments, and dashed lines show the globally estimated position and velocity.

translation and the rotation of site positions and velocities and rotation of source coordinates [3], no net-translation (NNT) and no net-rotation (NNR) constraints with respect to the ITRF2008 [17], and NNT constraints with respect to the ICRF2 [18], were imposed.

Station position and velocity can be precisely determined as global parameters only when there are several sessions with sufficient time spans [19]. Sh has accumulated 316 sessions with more than 190000 observations since 1988, and it was taken as one of the reference stations for NNT and NNR constraints. The first VLBI session of Km was conducted on July 20, 2011. Since then, 17 sessions have been carried out and proved to be reasonable for its position and velocity to be estimated globally.

First, a trial solution was carried out, in which positions of Js and Ks were estimated locally and their a priori velocities were set to 0 mm/year. Figure 2 shows the adjustments in the local up, east, and north directions of Js and Ks from September 2014 to December 2015. It can be seen that the local east and north position adjustments of Js, and the local up and north position adjustments of Ks, are consistent with the liner trends (shown as dotted lines).

In addition, velocities of Js and Ks could be interpolated from the Global Navigation Satellite System (GNSS) velocity products provided by the China Earthquake Administration$^{5)}$, which were determined

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5) http://www.cgps.ac.cn/camp_tslist.jsp.

Table 5 Position and velocity estimates of Jiamusi and Kashi stations from sessions cdsn01–cdsn07

Station	Epoch	Coordinate ± 1σ (mm), Velocity ± 1σ (mm/year)		
		X	Y	Z
Js	01.01.2014	−2872641934 ± 6	3331388963 ± 7	4603413776 ± 8
		−32 ± 2	−6 ± 2	−16 ± 2
Ks	01.01.2014	1150056308 ± 4	4870665344 ± 7	3943037086 ± 6
		−21 ± 3	−9 ± 2	16 ± 2

to be (−0.5, 29.4, −18.9) mm/year and (−0.45, 27.9, 20.8) mm/year in the local up, east, and north directions, respectively. Note that the trends obtained from the trial solution in such a short time span are roughly consistent with the velocities obtained from the GNSS products (except for the up direction of Ks). This indicates that the effectiveness and robustness of the data reduction and geodetic analysis, and that the interpolated velocities can provide strong and reliable constraints on the station positions of Js and Ks. Therefore, they were utilized as their a priori velocities, and constraints of (0.1, 3.0, 3.0) mm/year were imposed on their local up, east, and north velocity adjustments. With the modified settings, a formal solution was carried out.

The position and velocity estimates are listed in Table 5. It can be seen that the station positions of Js and Ks are determined to be accurate to better than 10 mm, which are improved by a factor of approximately 3 over the precision achieved in a single session. Velocity estimates of Js are (−0.5, 28.4, −23.2) mm/year in the local up, east, and north directions, respectively, and those of Ks are (−0.5, 18.4, 21.1) mm/year. Note that the velocity in the north direction of Js is ∼4 mm/year larger than the a priori value, and the velocity in the east direction of Ks is ∼10 mm/year smaller. The obtained positions and velocities are indicated by dashed lines in Figure 2 for comparison. The velocity estimates obtained from the formal solution represent a compromise between the local estimates and the a priori velocities obtained from the GNSS products.

5 Conclusion

The CDSN stations' positions have been obtained with the formal error better than 10 mm, which are improved by a factor of approximately 20 over their a priori values. This meets the goals of the cooperative geodetic VLBI program of the CDSN and CVN. It is believed that the foundation and maintenance of the time-space reference frame based on the combined network can be expected soon.

Future VLBI experiments are planned for the CDSN and CVN, which will further improve the precision of the estimates and accumulate valuable data for scientific research. The Js and Ks stations are located in areas sparsely occupied by international VLBI stations; therefore, their participation in international VLBI observations will make great contributions not only to their position and velocity determination, but also to the products of the International VLBI Service for Geodesy and Astrometry (IVS) [20]. In addition, their participation in the IVS is discussed as an option for the future.

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Conflict of interest The authors declare that they have no conflict of interest.

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