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VLBI observations with the Kunming 40-meter radio telescope *

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Abstract The Kunming 40-meter radio telescope is situated in the yard of the Yunnan Astronomical Observatory (Longitude: $102.8°$ East, Latitude: $25.0°$ North) and saw its first light in 2006 May. The Kunming station successfully joined the VLBI tracking of China's first lunar probe "Chang'E-1" together with the other Chinese telescopes: the Beijing Miyun 50-meter radio telescope, Urumqi Nanshan 25-meter radio telescope, and Shanghai Sheshan 25-meter radio telescope, and received the downlinked scientific data together with the Miyun station from October of 2007 to March of 2009. We give an introduction to the new Chinese VLBI facility and investigate its potential applications. Due to its location, the Kunming station can significantly improve the $u - v$ coverage of the European VLBI Network (EVN), in particular, in long baseline observations. We also report the results of the first EVN fringe-test experiment of N09SX1 with the Kunming station. The first fringes in the European telescopes were successfully detected at 2.3 GHz with the ftp-transferred data on 2009 June 17. From scheduling the observations to performing the post correlations, the Kunming station shows its good compatibility to work with the EVN. The imaging result of the extended source 1156+295 further demonstrates that the Kunming station greatly enhances the EVN performance.

Key words: radio telescopes — instrumentation: interferometers: VLBI

1 INTRODUCTION

The Kunming 40-meter radio telescope is a new Chinese VLBI facility situated on Phoenix Mountain, ~ 10 km east of the city of Kunming. The new facility superseded the 3-m mobile VLBI station of the Yunnan Astronomical Observatory. The mobile station was installed on a truck and was mainly used for carrying out geodetic VLBI observations (Cai & Xia 1993).

The Kunming 40-m radio telescope was built for participating in China's Lunar Exploration Program (CLEP[1]), which plans to launch a series of Lunar probes and landers to explore the Moon. Since these lunar missions are 400 000 km away from the Earth, the traditional Chinese Unified S-Band (USB) tracking system is limited by the precision of measuring angular positions and the requirement of the long observing time. However, the astronomical e-VLBI technique can provide

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[1] *http://www.clep.org.cn/*

high-precision angular positions almost in real time (Zhang 2006). In view of this advantage, the idea of building two more radio telescopes and a new correlator was presented to upgrade the Chinese VLBI network (CVN) to provide a high-resolution tracking service (Qian et al. 2004). The concept was further demonstrated by the tracking observations of a few deep-space satellites (Wang 2006; Li 2008). In addition, the large telescopes can guarantee that downlinked scientific data can be received with high quality at a high data rate of 3 Mbps (Jin et al. 2006) even in the worst case where the signal intensity is much lower than expected.

The Kunming 40-m (Zhang et al. 2008) and Miyun 50-m radio telescopes (Jin et al. 2006) were constructed in 2005–2006 after successful commissioning and scientific verification. An FGPA-based correlator (Zhu et al. 2008) and a software correlator (Zheng & Lun 2008) were also developed to support the real-time correlation at Shanghai Astronomical Observatory. With these new facilities and the existing Urumqi Nanshan and Shanghai Sheshan 25-m radio telescopes (Hong et al. 2003), the CVN went on to a new stage. The CVN project was proposed in 1979 and was actively developed by the Shanghai Astronomical Observatory (Wan & Qian 1988; Ye et al. 1991). The project plans to carry out geodetic, geodynamic, astrometric, and astronomical VLBI applications. The Shanghai Sheshan VLBI station was completed in 1987; the Urumqi Nanshan station in 1994; the Kunming 3-m mobile VLBI station in 1999; and the first CVN correlator (Zhang et al. 2003) in 2000.

This paper will present an introduction to the VLBI observing system of the Kunming station, investigate its potential applications in international VLBI observations, and report the results of its first European VLBI observations.

2 VLBI OBSERVING SYSTEM

2.1 Antenna

The Kunming 40-m radio telescope was designed and produced by the CETC (China Electronics Technology Group Corporation) 39$^{\rm th}$ Institute [2].

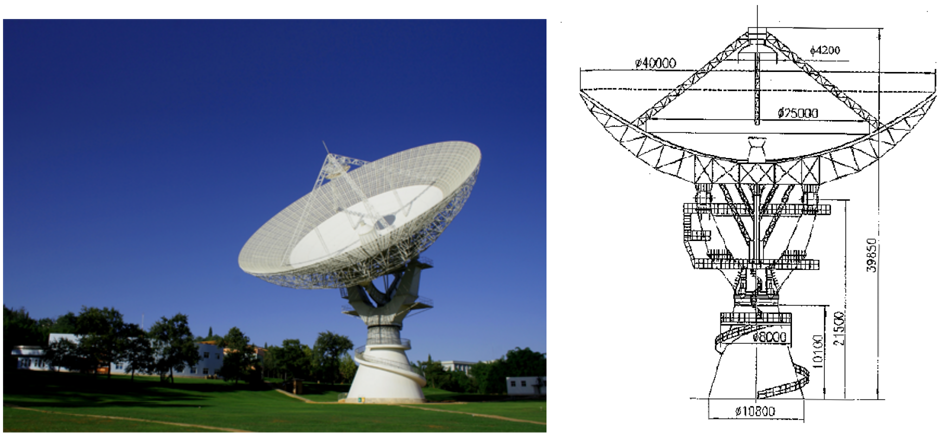

Fig. 1 Kunming 40-m radio telescope. *Left*: its photo; *Right*: its designed structure.

Figure 1 shows the photo of the Kunming 40-m radio telescope (left) and its designed structure (right). The Kunming telescope is a parabolic-hyperbolic/Cassegrain antenna system with an F/D ratio of 0.33. The parabolic main reflector is on an altitude-azimuth mount and has a diameter of

[2] *http://www.cetc-39.com/*

40 m. The inner 26-m surface consists of 208 aluminium panels in nine rings fixed on a steel support structure. Each panel is secured by five vertical screws: four at the corners and one at the center. These panels were manufactured to achieve a surface accuracy of < 0.6 mm. The outer ring-like part is a stainless steel-welded wire mesh with a surface rms of < 2.2 mm. The hyperbolic secondary reflector consists of aluminium panels with a diameter of 4.2 m and a surface rms of 0.3 mm.

The Kunming telescope has a pointing accuracy of $28''$. The first sidelobe is lower than -20.12 dB. The antenna efficiencies are 60.2% and 47.0% at 2.3 and 8.4 GHz, respectively. Based on the antenna efficiency, the conversion factor of DPFU (degree per flux unit) can be estimated by $\mathrm{DPFU} = \frac{A\eta}{2k}$, where A is the receiving area of the telescope and k is the Boltzmann constant. For Kunming station, it is 0.23 K Jy^{-1} at 2.3 GHz and 0.20 K Jy^{-1} at 8.4 GHz. These measurements were performed by Zhang et al. (2008) for the first time in 2006 July. The loss of antenna efficiency at high frequency is mainly the result of low surface precision of the outer wire mesh.

2.2 Receiver

The available receiver at Kunming station is currently in the S/X band. The receiver was developed by the CETC 16th Institute [3]. The Gifford-McMahon cooler is used to make the first flat have a temperature < 80 K and the second flat < 20 K. The circular polarization signal was amplified by a HEMT low-noise amplifier and then converted down to the IF signal. Figure 2 shows the bandpass shape of the IF signal. At frequencies > 2.4 GHz, there are some external RFIs. The receiver has a good bandpass shape at X band.

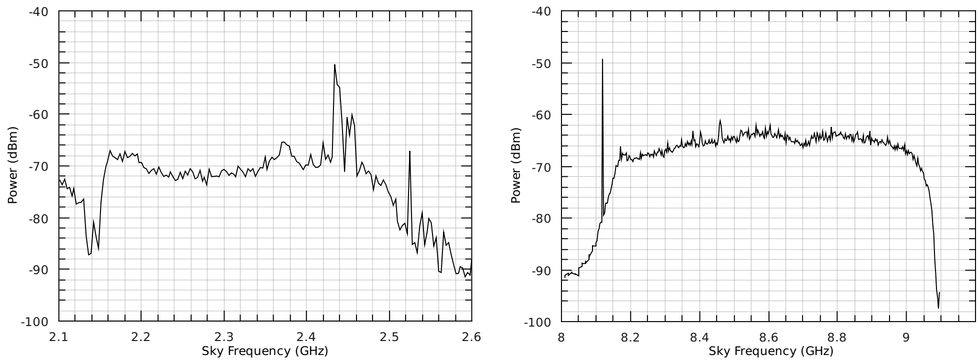

Fig. 2 Bandpass of the S/X band receiver. *Left*: S band; *Right*: X band.

Table 1 lists the characteristic parameters of the S/X band observing system. The columns give (1) band, (2) observing frequency range, (3) available local oscillators (LOs), (4) system temperature, (5) antenna efficiency, and (6) DPFU (degree per flux unit). The LOs of 1600 and 9100 MHz are currently used. The other two LOs (2020 and 8100 MHz) are kept for the MK4 terminal, which is not available at Kunming station. Due to the absence of hardware, the system temperature could not be directly measured. The system temperature in Column (4) was estimated from the EVN observations of N09SX1 at 2.3 GHz (See Sect. 4) and EY008A at 8.4 GHz. The latter is the second EVN observations with Kunming station to study five GHz-peaked-spectrum radio sources. By using amplitude self-calibration, the amplitude scale factor of Kunming station can be found. Based on the scale factor, the system temperature can be determined.

[3] *http://www.cetc16.com/*

Table 1 Performance of the S/X Band Observing System at the Kunming Station

Band	Freq. (MHz)	LOs (MHz)	$T_{\rm sys}$ (K)	η	DPFU (K Jy^{-1})
S	2150 – 2400	1600, 2020	80	60.2%	0.23
X	8200 – 9000	8100, 9100	96	47.0%	0.20

2.3 VLBI Terminal

Figure 3 shows the structure of the VLBI terminal at Kunming Station. The amplified IF signals (500 – 1000 MHz) are transmitted by coaxial cable from the S/X receiver in the feed room to the IF distributor in the equipment room of the station building. The IF distributor distributes the IF signal to eight baseband converters (BBCs), where selected frequency bands are converted to baseband frequencies. The baseband signals are transmitted to sampler modules, where they are digitized at a rate of 32 MHz, in a 2-bit analog to digital (A/D) converter. The samplers are sent to the formatter. Finally, the formatted digital data are recorded by the MK5A recorder. A computer running the field system is used to control all the VLBI devices, except the antenna, and to monitor the system performance. The time and frequency system consists of an H-maser and a GPS receiver. The GPS clock is used to monitor the long term behavior of the H-maser. The phase-calibration signal was fed into the feed to monitor the variations in the instrumental phase.

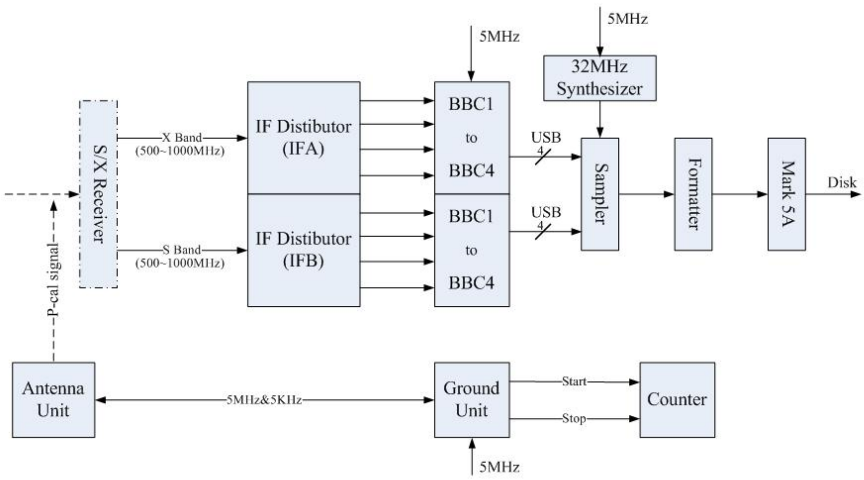

Fig. 3 Block diagram of Mark IV hardware.

The terminal was mainly designed for the VLBI observations of space missions. The maximum output data rate of the formatter is 128 Mbps, which is high enough to sample the signal of any space mission. Each BBC only has an upper side band. The available filters have a bandwidth of 16, 8, 2, and 1 MHz. The available BBC LOs are in the format of 0.29, 0.69, and 0.99 MHz in 500–1000 MHz. Together with the receiver LOs, the required sky frequency should be at 0.29, 0.69, and 0.99 MHz (up-converted) at S band, and 0.71, 0.31, and 0.01 MHz (down-converted) at X band.

A noise diode was installed to perform VLBI imaging observations, which need system temperature data to calibrate the correlation amplitude. Recently, the diode has been connected with the FS system computer. Based on the noise diode, the system temperature can be measured during the scan gap. Because the Kunming BBCs do not support auto gain control, the total power will be monitored during the scan of VLBI observations. However, the noise diode does not work stably and there is a long electronic delay caused by the BBCs, so the measured Tsys curve shows large scattering and is now useless. Since the amplitude calibration system cannot work properly, there is no antenna efficiency curve available for correcting the elevation-dependent effect in any astronomical observations.

2.4 Upcoming Upgrade

The Kunming station has recently installed the Chinese data acquisition system (CDAS) to supersede the current analog BBCs. The CDAS was developed at Shanghai Astronomical Observatory (Zhang et al. 2008). It accepts four IF signals. Each IF can have a bandwidth up to 512 MHz. The wide-band IF signal was sampled and then digitally filtered. Both the analog and digital AGCs were used to get the stable power level and optimal sample statistics. There are 32 output subbands, compatible with currently used BBCs (16 USB/16 LSB). The available bandwidths of each subband are from 0.5 to 32 MHz. Furthermore, an MK5B recorder was also installed to support the CDAS with a recording data rate of up to 2 Gbps. Because the CDAS uses the digital filter technique, the new backend has a much flatter phase across the whole observing frequency. Currently, the new terminal is still undergoing tests.

3 VLBI OBSERVATIONS

The Kunming station is one of a few VLBI stations in the world located at lower latitudes. Table 2 lists its geographic coordinates. The low latitude gives the Kunming telescope the ability to observe most southern sky sources ($\delta > -60°$). Because of its location, the Kunming station plays an important role in domestic and international VLBI observations.

Table 2 Geographic Coordinates of the Kunming 40-m Radio Telescope

	Longitude	Latitude	Above sea level
The Kunming Station	$102°47'42''$ E	$25°01'33''$ N	1985 m

3.1 Chinese VLBI Network

As a facility of VLBI for the CLEP, the Kunming 40-m radio telescope successfully participated in the VLBI tracking observations of the Chang'E-1 (CE-1) lunar probe with the other three telescopes more than one hundred times (Li 2008). Besides these tracking observations, the CVN has the capability to perform astrometric VLBI observations (Li et al. 2008). The CVN can facilitate studies of long-term monitoring of the ICRF (International Celestial Reference Frame) radio sources, densification of radio celestial reference frame, determination of Earth Orientation Parameters and linkage parameters of reference frames as well as observations of pulsars for deep space autonomous navigation.

In addition to the astrometric observations, the CVN is able to carry out some astrophysical observations which require properly calibrated visibility amplitudes as well as phases to image radio sources. To investigate the CVN imaging performance, we made some u–v coverage plots with the NRAO software SCHED. Figure 4 shows the simulated u–v coverage of a source at a different declination. The left panel is a source at $\delta = -20°$; the middle panel at $\delta = 20°$; the right panel at $\delta = 60°$. The red u–v tracks are the baselines to the Kunming telescope, which are mainly distributed in the North-South direction. Because the Kunming station has a lower latitude, the CVN u–v coverage still looks nearly circular for low-declination sources. Compared with sources at $\delta = -20°$, the source at $\delta = 60°$ has better u–v coverage. The high-declination source has a higher elevation for all the telescopes, so the long u–v tracks are available to improve the u–v coverage. The longest baseline of the CVN is 3249 km (Sheshan–Urumqi), corresponding to an angular resolution of 2.3 mas at 8.4 GHz. Currently, the only available observations for the four stations are at 2.3 and 8.4 GHz.

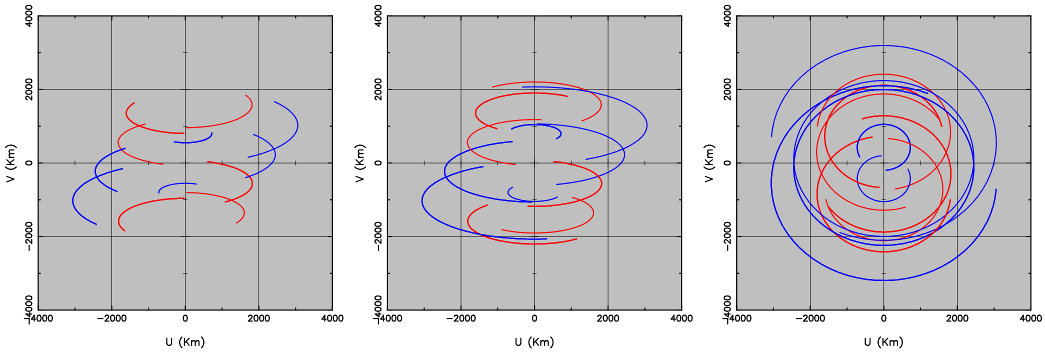

Fig. 4 Simulated u–v coverage with the CVN for a source at declination: -20° (*left*), 20° (*middle*), and 60° (*right*) observed at 8.4 GHz. The red lines highlight the baselines to the Kunming 40-m radio telescope.

The CVN has a common view for $\sim$ 6 hours for a source at $\delta = -20^\circ$, $\sim$ 10 h for a source at $\delta = 20^\circ$, and $\sim$ 16 h for a source at $\delta = 60^\circ$. If all the four telescopes participate in the CVN observation, both the amplitude and phase self-calibrations will be available to improve the image sensitivity. If a telescope was lost for some reason, only the phase self-calibration is available. Such outcomes can be avoided if a few fast ftp-fringe tests are performed during the CVN observations.

In these tracking experiments, the Kunming telescope provides three baselines: 1920 km to Shanghai, 2158 km to Miyun, and 2476 km to Urumqi. Among all the CVN baselines, the baseline from Miyun to Kunming has the highest baseline sensitivity. If we use a 64 MHz bandwidth (8 BBCs, 8 MHz/BBC, 2 bit sampling, RCP polarization) to observe a source for 10 min at 8.4 GHz, a noise level of $5\sigma \sim 9$ mJy can be achieved.

3.2 European VLBI Network

The European VLBI Network[4] is a collaboration of the major radio astronomical institutes in Europe, Asia, and South Africa; it performs high angular resolution observations of cosmic radio sources. The Sheshan and Urumqi 25-m radio telescopes have already joined the EVN. Through the participation of the two Chinese telescopes, the EVN resolution is improved by a factor of three. The new Kunming and Miyun telescopes are also as important as the other two telescopes used for the EVN observations. Table 3 lists the sensitivities of the nine available EVN telescopes at S/X band in the EVN status table[5].

Figure 5 shows the simulated u–v coverage with the Kunming 40-m radio telescope and the EVN telescopes. The utilized EVN telescopes are Sheshan, Urumqi, Effelsberg, Westerbork, Medicina, Noto, Onsala, Metsähovi, and Yebes. The left panel plots the u–v coverage for a source at declination $\delta = -20^\circ$; the middle at $\delta = 20^\circ$; the right at $\delta = 60^\circ$. The last row of Table 3 lists the baseline lengths to the Kunming station. The red lines highlight the baselines between the Kunming station

[4] *http://www.evlbi.org*

[5] *http://www.evlbi.org/user_guide/EVNstatus.txt*

Table 3 Sensitivity of the EVN Telescopes at 2.3/8.4 GHz and the Baseline Length to the Kunming 40-m Radio Telescope

	KM	SH	UR	MH	ON	MC	NT	WB	EF	YS
SEFD (Jy) at 2.3 GHz	350	800	680	4500	1110	400	770	60	300	
SEFD (Jy) at 8.4 GHz	480	800	480	3200	1000	320	770	120	20	200
Baseline length (km) to KM	0	1920	2476	6646	7283	7641	7652	7666	7728	8630

SEFD represents the system equivalent flux density in Jy (i.e. Tsys/DPFU). KM: Kunming; SH: Sheshan; UR: Urumqi; MH: Mesähovi; ON: Onsala; MC: Medicina; NT: Noto; WB: Westerbork; EF: Effelsberg; and YS: Yebes.

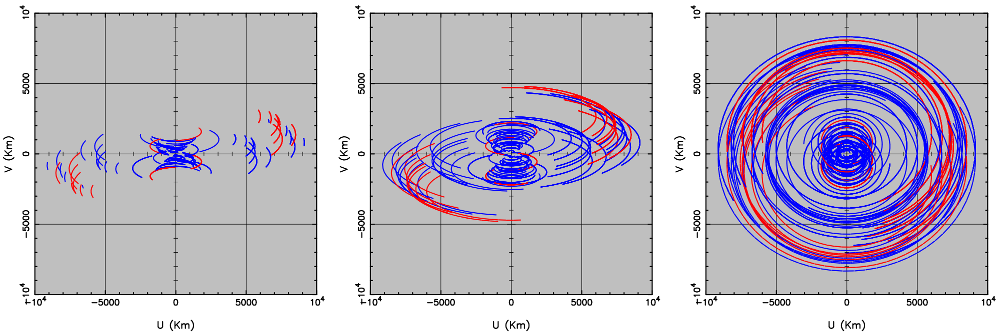

Fig. 5 The u–v coverage with Kunming+EVN for a source at declination: -20° (*left*), 20° (*middle*), and 60° (*right*) observed for a maximum time of 24 hours at 8.4 GHz. The red lines highlight the baselines to the Kunming 40-m radio telescope.

and the EVN telescope. The Kunming telescope provides another seven long (> 6500 km) baselines to the EVN telescopes. The addition increases the number of long baselines by a factor of 1.5, and significantly improves the u–v coverage. For the low-declination source in the left panel, the Kunming station provides the highest resolution in the North-South direction.

4 KUNMING IN THE FIRST EVN EXPERIMENT

4.1 N09SX1 Observations

The Kunming telescope participated in the EVN network monitoring experiment N09SX1 on 2009 June 17 for the first time to test its compatibility with the EVN processor. The experiment used 8 BBCs (4 at 2.3 GHz, 4 at 8.4 GHz), 8 MHz BBC filters, and RCP polarization only. The data recording rate was 256 Mbps at the EVN stations (Urumqi, Sheshan, Effelsberg, Medicina, Onsala, and Westbork) by 2 bit sampling and 128 Mbps (maximum data rate of the formatter) at the Kunming station by 1 bit sampling. The LO sum frequencies were in a format of 0.99 MHz to keep the same setup as the next EVN user experiment. Since the format did not match the required format at the Kunming station, there was a 20 KHz LO offset at X band. The observations started at 12h00m00s UT and ended at 16h30m00s UT. During the 4.5 h experiment, three strong sources were observed to check the station setup by correlating a few seconds of ftp-uploaded data. The NRAO software SCHED was used to schedule the experiment. To run 1-bit sampling at the Kunming station, a separate schedule file was produced.

4.2 First Fringes from the EVN Telescopes

The observations of N09SX1 had four ftp fringe-test scans to check the station setup before the user experiment. Each ftp scan lasted four seconds. The first ftp scan started at 13h28m56s UT. The first EVN fringes from the Kunming telescope [6] were detected right away by the JIVE software correlator with a 4 s integration time and 1024 channels per subband. The initial clock delay and rate were obtained from the GPS monitoring data. Since these fringes were just used to check the station setup, the clock delay error (–13 lags) was not corrected and the fringes did not sit at the center. The fringes at 8.4 GHz from Kunming station were not detected because of the LO offset, as we expected.

4.3 Data Correlation

The final production correlation was done at JIVE using a 2 second integration time and 16 frequency points per subband. The FS log file of the Kunming station basically followed the EVN requirement and was used to create the vex file, an input file including all the necessary parameters for the JIVE correlator to do correlation. After the fringe search, the fringes from the Kunming station were located at the center of the lag window. Figure 6 shows the plots of the cross correlation phase and amplitude versus frequency points. As a result of the fringe search, the residual phase slope is very small. The visibility data in IDI-Fits format can be downloaded for the public on the web page [7] of the EVN Data Archive.

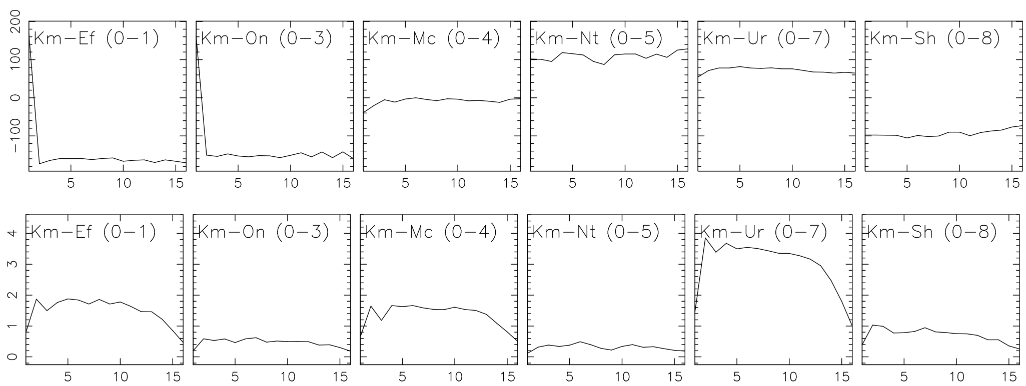

Fig. 6 Cross correlation phase (*top*) and amplitude (*bottom*) versus frequency plots of the baselines from the EVN telescopes. The visibility data were from scan 1 and IF 1. The amplitude was not calibrated here.

The data were calibrated by the EVN pipeline, which is a program that uses ParselTongue to provide access to the AIPS tasks from a Python script. The *a-priori* amplitude calibration used system temperature and antenna gain. The phase was aligned by the global fringe fitting and bandpass calibration. The pipeline results have been displayed on the web page [8] of the EVN data archive.

[6] *http://www.evlbi.org/tog/ftp_fringes/N09SX1/index.html*
[7] *http://archive.jive.nl/scripts/arch.php?exp=N09SX1*
[8] *http://archive.jive.nl/scripts/arch.php?exp=N09SX1*

Table 4 Comparison of the EVN Image with and without the Kunming Station

Array	Maj (mas)	Min (mas)	P.A. (°)	$\sigma_{\rm rms}$ (mJy b^{-1})	$S_{\rm peak}$ (Jy b^{-1})	$N_{\rm antenna}$	$N_{\rm baseline}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
KM+EVN	7.17	1.89	15.8	0.30	1.91	8	28
EVN	8.20	2.04	10.5	0.45	1.87	7	21

Col. (1): used array; Cols. (2)–(4): the size of major and minor axes and the position angle of the beam; Col. (5): off-source image noise level; Col. (6): image peak brightness; Cols. (7,8): number of the used telescopes and baselines.

4.4 EVN Image Firstly Improved by the Kunming Station

There were three sources (1156+295, 4C 39.25, and OQ 208) observed in N09SX1. The sources 4C 39.25 and OQ 208 are two slightly resolved compact sources at 2.3 GHz. The source 1156+295 is an extended source (Hong et al. 2004), a suitable object for investigating the EVN imaging performance.

Figure 7 shows manual imaging results of the source 1156+295 using the data calibrated by the EVN pipeline. To image the extended structure, natural weighting was used in Difmap (Shepherd et al. 1994). The left image shows the images made with the Kunming and EVN stations. The contours are drawn starting from $3\sigma_{\rm rms}$ at –2, –1, 1, 2, 4, ... The middle image shows the image result when we flagged out the baselines from Kunming in the self-calibrated data. The map parameters are listed in Table 4. The columns give: (1) array; (2) and (3) sizes of major and minor axes of the restoring beam; (4) position angle of the beam; (5) image noise level (1σ); (6) peak flux density; (7) number of antennas, and (8) number of baselines. Without the Kunming station, the image noise level is ~ 1.5 times higher; the size of the major axis of the restoring beam is increased significantly; the position angle of the major axis rotates $5°$ clockwise. The image fidelity was strongly affected by the side lobe of the synthesized beam.

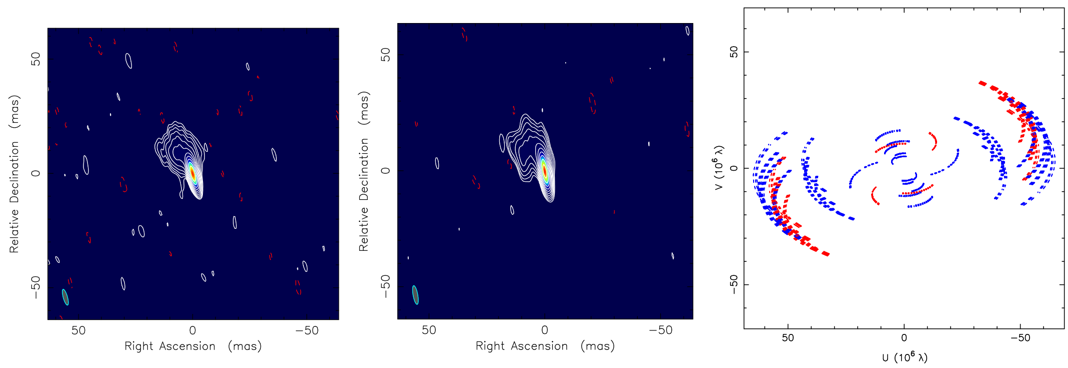

Fig. 7 2.3 GHz intensity image of the quasar 1156+295. *Left*: the image made with the Kunming and EVN telescopes; *Middle*: the image made with only the EVN telescopes; *Right*: the u–v coverage of the observations. The red points are the baselines from the Kunming 40-m radio telescope.

These differences can be explained from the u–v coverage (Fig. 7, Right). The red points highlight the baselines to Kunming. Without Kunming, a quarter of the visibility data is lost, so the image noise level gets higher. Since the loss is mainly on the long baselines, the restoring beam and the Gaussian fit of the dirty beam become larger. The rotation of its major axis is a result of the loss of the visibility data in the NW-SE direction.

5 SUMMARY

The Kunming 40-m radio telescope is a new VLBI facility located at a lower latitude ($\sim 25^\circ$). As a key facility, the Kunming station participated in the CE-1 observations in 2007–2008. In this paper, we introduce its current status, and the upcoming upgrade; we also investigate the u–v coverage of the CVN observations and the EVN observations with the Kunming station. We also report the results of the first EVN experiment N09SX1 with the Kunming station on 2009 June 17. The first fringes from the EVN telescopes were successfully detected, which show that Kunming station has a good compatibility to work with the EVN. Finally, we demonstrate that Kunming station significantly improves the EVN imaging performance by an extended source 1156+295.

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