VLBI in China
--Past, Present and Future

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"Dawn of a New Era for Black Hole Jets in Active Galaxies"
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Past

- 1970s VLBI Network Concept
- First fringe Sh-Ef, 1987 Shanghai 25m
- 1993 Urumqi 25m, APSG program
- VLBI tracking in lunar project, 2006
  Beijing 50m & Kunming 40m + correlator
1967: First VLBI Experiments in USA and Canada

Three groups -- one Canadian, another a collaboration between the National Radio Astronomy Observatory (NRAO) and Cornell University, and a third at MIT and Haystack Observatory -- were each working to achieve the first VLBI observation.

1975 A research group in ShAO submitted a proposal on the feasibility study of VLBI development in China.
1981 Nov: First fringe detected between Shanghai and Effelsberg.
First trans-Eurasian continent VLBI experiment in the world!
Shesan 25m telescope (end of 1987)

Nanshan 25m telescope, 1993
Asia Pacific Space Geodynamics (APSG) (1996-)

A proposal to organize the APSG was first presented at the WEGENER meeting in St. Petersburg in June 1994. The main objective of the Asia-Pacific Space Geodynamics (APSG) Program is to unite all relevant activities in the region into a cooperative research project in plate tectonic, crustal motion and deformation, and sea level change in the area.
Chang'E National Project (2004-)

- CE-1: Oct 24, 2007 (482d/494d)
- CE-2: Oct 1, 2010
- CE-3: ~2012

Orbiting

Landing

returning
Chinese VLBI Network (CVN):
4 stations + soft/hard-ware correlators

Coverage:
E-W: 34°  S-N: 18°

Baseline length:
1115km to 3249km
## Technical specs of CVN antennas

<table>
<thead>
<tr>
<th></th>
<th>Shanghai</th>
<th>Urumqi</th>
<th>Beijing</th>
<th>Kunming</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Structure</strong></td>
<td>BWG, Cassegrain</td>
<td>BWG, Cassegrain</td>
<td>Prime focus</td>
<td>BWG, Cassegrain</td>
</tr>
<tr>
<td><strong>Size in Diameter (m)</strong></td>
<td>25</td>
<td>25</td>
<td>50 (30 +20)</td>
<td>40 (25+15 )</td>
</tr>
<tr>
<td><strong>Pointing (arc-sec)</strong></td>
<td>20</td>
<td>15</td>
<td>19</td>
<td>30</td>
</tr>
<tr>
<td><strong>Az/El Slewing rate</strong></td>
<td>1.0/0.6</td>
<td>1.0/0.5</td>
<td>1.0/0.5</td>
<td>1.0/0.5</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>38%/40%</td>
<td>54%/52%</td>
<td>60%/68%</td>
<td>64%/47%</td>
</tr>
<tr>
<td><strong>Recording terminal</strong></td>
<td>Mark5B, 5A, VLBA, S2, K4</td>
<td>Mark5B, K4</td>
<td>Mark5B</td>
<td>Mark5B</td>
</tr>
</tbody>
</table>
Technical developments

Chinese VLBI Data Acquisition System (CDAS)
- 4 Ifs input, 512M BW each
- 16 Ch. output / VSI-H
- 2 VSI-H interface
- 1 / 2 / 4 bit output

Active Hydrogen Maser

<table>
<thead>
<tr>
<th>Time scale [seconds]</th>
<th>Our maser SOHM-4A</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&lt;3.00E-13</td>
</tr>
<tr>
<td>100</td>
<td>&lt;1.50E-14</td>
</tr>
<tr>
<td>1000</td>
<td>&lt;5.00E-15</td>
</tr>
<tr>
<td>10000</td>
<td>&lt;2.00E-15</td>
</tr>
<tr>
<td>86400</td>
<td>&lt;2.00E-15</td>
</tr>
</tbody>
</table>
CE3 Orbit determination accuracy

- VLBI group delay residuals and orbit determination results:
  - ~ 1ns in trans-lunar orbit
  - ~ 0.5ns in lunar orbit.
  - 100 × 100km circumlunar orbit accuracy: 20m
  - 100 × 15km circumlunar orbit: 30m
  - Descent trajectory: < 100m

Real time: from observation to VLBI solution < 1 minute
Phase-reference results of CE-3 Rover

- Target: Rover using the Lander as the Calibrator.
- The accuracy of the relative position between Lander and Rover is ~1m (0.5mas).
Present

- 2012 Tianma 65m telescope, VLBI center
- pre-study of Space VLBI
- 2016 FAST 500m
- 2017 VGOS station
~40% increase of the sensitivity of CVN with the 65-m Tianma (65-m) telescope in Shanghai

Full cm wavebands (1.3-50 GHz); active surface

## Receiver Frequency Range & Performance

<table>
<thead>
<tr>
<th>Bands</th>
<th>L</th>
<th>S</th>
<th>C</th>
<th>X</th>
<th>Ku</th>
<th>K²</th>
<th>Ka</th>
<th>Q²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength $\lambda(\text{cm})$</td>
<td>21/18</td>
<td>13</td>
<td>6/4.5</td>
<td>3.6</td>
<td>2.5/2.0</td>
<td>1.35</td>
<td>0.9</td>
<td>0.7</td>
</tr>
<tr>
<td>Frequency $f$ (GHz)</td>
<td>1.25–1.75</td>
<td>2.2–2.4</td>
<td>4.0–8.0</td>
<td>8.2–9.0</td>
<td>12.0–18.0</td>
<td>18.0–26.5</td>
<td>30.0–34.0</td>
<td>35.0–50.0</td>
</tr>
<tr>
<td>FWHM (&quot;@CF, 1.02λ/D&quot;)</td>
<td>628</td>
<td>410</td>
<td>157</td>
<td>110</td>
<td>69</td>
<td>43</td>
<td>29</td>
<td>22</td>
</tr>
<tr>
<td>Efficiency $\eta_A$ (%, best elev=50°)</td>
<td>55</td>
<td>60</td>
<td>60</td>
<td>55</td>
<td>55</td>
<td>50*</td>
<td>50*</td>
<td>50*</td>
</tr>
<tr>
<td>DPFU (K/Jy, 1.20$\eta_A$)</td>
<td>0.66</td>
<td>0.72</td>
<td>0.72</td>
<td>0.66</td>
<td>0.48</td>
<td>0.60*</td>
<td>0.60*</td>
<td>0.60*</td>
</tr>
<tr>
<td>Tsky (K)</td>
<td>12</td>
<td>12</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td>25</td>
<td>25</td>
<td>26</td>
</tr>
<tr>
<td>Trec (K)</td>
<td>14</td>
<td>21</td>
<td>12</td>
<td>22</td>
<td>15</td>
<td>35</td>
<td>35</td>
<td>40</td>
</tr>
<tr>
<td>Tsys (K)</td>
<td>26</td>
<td>33</td>
<td>22</td>
<td>32</td>
<td>27</td>
<td>60</td>
<td>60</td>
<td>70</td>
</tr>
<tr>
<td>SEFD (Jy, Tsys/DPFU)</td>
<td>39</td>
<td>46</td>
<td>31</td>
<td>48</td>
<td>56</td>
<td>100*</td>
<td>100*</td>
<td>117*</td>
</tr>
<tr>
<td>Thermal noise (mJy, 1σ (B_w=128MHz, T_{on}=10 min))</td>
<td>0.142</td>
<td>0.165</td>
<td>0.110</td>
<td>0.175</td>
<td>0.202</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SEFD = \frac{2kT_s}{A_c} = \frac{2kT_s}{\eta_A A_s} = \frac{8kT_s}{\eta_A \pi D^2}

$$\sigma = \frac{\text{SEFD}}{\sqrt{T_{on} B_w}}$$

 opportunity for mJy science observation!
CVN-VLBI Center

Hardware correlator  CVN software correlator  DiFX correlator
Main Scientific Objectives:

- High-resolution imaging of emission structure surrounding super-massive black hole (SMBH) to study
  - SMBH Shadow (e.g. M87)
  - Disk structure & dynamics, SMBH mass (water mega-masers)
  - Astrophysical Jet in Active Galactic Nuclei (AGN)

Specifications:

- Two 10-m (in diameter) space antennas
- Three frequency bands (8, 22 & 43 GHz)
- Dual polarization (LCP/RCP)
- Date rate (1.2 Gbps, or 2.4 Gbps)
- Angular resolution: 20 micro-arc-second
- Optimized orbits for a better (u,v) coverage
  - Apogee: 60,000 km
  - Perigee: 1,200 km
  - Inclination: 28.5 deg
- Life time: 3 year
High precision reflector: 10m diameter with a surface accuracy better than 0.4mm (RMS)
FAST - Five-hundred-meter Aperture Spherical Telescope

- Unique Karst depression as the site
- Active main reflector
- Cable - parallel robot feed support

Approved in Nov 2005;
Start full construction in 2010;
9 bands from 70MHz to 3 GHz
Commissioning in Sept 2016
New 13-m VGOS antenna at Sheshan

Dec. 2017

Mk4/DiFX fourfit 3.12 rev 1320

3C273_zwbstn, No0046, CL
SEVGOS - TIANMA65, fgroup X, pol RR

Fringe quality 9
SNR 12622.5
Int time 17.982
Amp 3590.104
Phase -50.8
PFD 0.0e+00
Delays (µs)
SBD 0.002538
MBD -0.012204
Fringe rate (Hz) 0.023665
Ion TEC 0.000
Ref freq (MHz) 6246.0000
AP (sec) 2.000
Exp. VT02c
Exper # 16363
Yr:day 2017.339
Start 003010.00
Stop 003200.00
FRT 003010.00
2017.339/02/2355
2016.110/01/2737
RA & Dec (J2000)
(Overview of VGOS in CAS)

(1) 13m diameter antenna
(2) very high slew rates
   12° /s in azimuth
   6° /s in elevation
(3) freq range 1.2 ~ 9 GHz
(4) eff > 50%

Corporation with SHAO, XAO and CHO, NTSC has already completed construction of VGOS in CAS, include three observation stations and one data processing center in Xi’an.

(Credit: X.-H. Yang)
CVN \((Km+My+Sh+Ur)\) + Onsala 20-m + Medicina 32-m;
2009 Aug 5-6;
24 hr;
X-band;
5 GPS sources

JIVE Correlator
Pulsar Astrometry with CVN

CVN (Km+Sh+Ur); PSR B0329+54 (200 mJy @ 1.4 GHz); phase-ref ~3 hr (2008 Oct 16) @ S-band; software correlator (DiFX)

Figure 1  The (u, v) coverage obtained for PSR B0329+54 at 2.2 GHz from 3 baselines formed from the CVN antennas Shanghai Kunming and Urumqi.

Figure 4  Image of PSR B0329+54 observed with CVN at 2.2 GHz. Contour levels are spaced linearly at 8.0 mJy beam$^{-1}$ (2$\sigma$). The peak flux density is 23 mJy beam$^{-1}$. 
unique two stations in CVN (EAVN) — short spacing

Tianma 65 m telescope

<table>
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<tr>
<th>Baseline ~ 6.1 km</th>
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Sheshan 25 m telescope
Detection of a compact jet component

For two point source brightness

\[ T_b(x, y) = \delta(0, 0) + \rho \times \delta(x - x_0, y - y_0), \]

The amplitude of visibility function is given:

\[ |V(u, v)| = 1 - \rho \times \cos 2(\theta - PA). \]

\( PA \) is a position angle of the 2nd comp. wrt the 1st comp.

(Kawaguchi et al. 2015)
Among 3321 sources (red+green) in the ecliptic plane, 556 sources detected (green).

VLBI Ecliptic Plane Survey (VEPS)

(Shu et al. 2017)
Pulsar Astrometry with VLBA+TM

- pulsar parallaxes via relative astrometry (differential astrometry) to get distances and transverse velocities

<table>
<thead>
<tr>
<th>NAME</th>
<th>PSRJ</th>
<th>P0</th>
<th>DM</th>
<th>S1400</th>
</tr>
</thead>
<tbody>
<tr>
<td>B0458+46</td>
<td>J0502+4654</td>
<td>0.638565 s</td>
<td>42.19 cm^{-3} pc</td>
<td>2.50 mJy</td>
</tr>
<tr>
<td>B2334+61</td>
<td>J2337+6151</td>
<td>0.495370 s</td>
<td>58.41 cm^{-3} pc</td>
<td>1.40 mJy</td>
</tr>
</tbody>
</table>

(Yan et al.)
EAVN campaign 2017, Mar –May. (K and Q band), contemporized with the EHT (Apr 3-14) campaign.

<table>
<thead>
<tr>
<th>Obs. Code</th>
<th>Date</th>
<th>Sources</th>
<th>Freq. Band</th>
<th>Stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>a17077a</td>
<td>Mar 18 UT12:45-19:45</td>
<td>M87</td>
<td>K</td>
<td>KaVA, Tm, Ur, Ht, Ks</td>
</tr>
<tr>
<td>a17078a</td>
<td>Mar 19 UT11:40-18:40</td>
<td>M87</td>
<td>Q</td>
<td>KaVA, Tm</td>
</tr>
<tr>
<td>a17086a</td>
<td>Mar 27 UT13:10-23:10</td>
<td>M87+SgrA</td>
<td>Q</td>
<td>KaVA, Tm</td>
</tr>
<tr>
<td>a17093a</td>
<td>Apr 3 UT13:20-23:25</td>
<td>M87+SgrA</td>
<td>K</td>
<td>KaVA, Tm, Ur, Ht, Ks, Mc</td>
</tr>
<tr>
<td>a17094a</td>
<td>Apr 4 UT12:35-22:35</td>
<td>M87+SgrA</td>
<td>Q</td>
<td>KaVA, Tm</td>
</tr>
<tr>
<td>a17099a</td>
<td>Apr 9 UT12:20-22:20</td>
<td>M87+SgrA</td>
<td>Q</td>
<td>KaVA, Tm, Ny</td>
</tr>
<tr>
<td>a17104a</td>
<td>Apr 14 UT12:00-22:00</td>
<td>M87+SgrA</td>
<td>Q</td>
<td>KaVA, Tm</td>
</tr>
<tr>
<td>a17107a</td>
<td>Apr 17 UT11:45-18:45</td>
<td>M87</td>
<td>K</td>
<td>KaVA, Tm, Ur, Sj, Ht, Ks, Mc, Nt</td>
</tr>
<tr>
<td>a17108a</td>
<td>Apr 18 UT11:40-21:40</td>
<td>M87+SgrA</td>
<td>Q</td>
<td>KaVA, Tm</td>
</tr>
<tr>
<td>a17114a</td>
<td>Apr 24 UT09:20-16:20</td>
<td>M87</td>
<td>K</td>
<td>KaVA, Tm</td>
</tr>
<tr>
<td>a17115a</td>
<td>Apr 25 UT09:15-16:15</td>
<td>M87</td>
<td>Q</td>
<td>KaVA, Tm</td>
</tr>
<tr>
<td>a17116a</td>
<td>Apr 26 UT15:55-21:55</td>
<td>SgrA</td>
<td>Q</td>
<td>KaVA, Tm, Sj</td>
</tr>
<tr>
<td>a17130a</td>
<td>May 10 UT08:20-17:20</td>
<td>M87</td>
<td>K</td>
<td>KaVA, Tm, Mc</td>
</tr>
<tr>
<td>a17131a</td>
<td>May 11 UT08:15-17:15</td>
<td>M87</td>
<td>Q</td>
<td>KaVA, Tm</td>
</tr>
<tr>
<td>a17145a</td>
<td>May 25 UT14:10-20:12</td>
<td>SgrA</td>
<td>Q</td>
<td>KaVA, Tm</td>
</tr>
<tr>
<td>a17146a</td>
<td>May 26 UT07:20-14:20</td>
<td>M87</td>
<td>Q</td>
<td>KaVA, Tm</td>
</tr>
</tbody>
</table>
An very impressive start with EAVN imaging!

**EAVN vs KaVA**, factor of improvement in dynamic range

Extended source, M87, ~1.3

Point source, SgrA*, >1.5

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KaVA+T6+Ur+Ht; K band
rms: 0.28 mJy/b

Hada (2017)
Talk today

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KaVA+T6; Q band
rms: 1.1 mJy/b

Zhao (2017)
Talk on Jan 27
World wide cooperation

10th DiFX users and developers meeting, 2016

East Asia VLBI workshop, 2016

EHT-JCMT observation, 2017

China-South Africa bilateral workshop in Radio Astronomy, Geodesy and Space science, 2017
Future

- 2018 CE4/5 lunar mission, KaVA+T6 (Ur) open use
- 2019 VLBI observations with FAST
- 2020+ QTT 110m Chinese mm-VLBI array

...
Roadmap for Starting EAVN Common-Use

- **2018 March:** [Edition of the status report](addition of EAVN-related items (system performance of Chinese telescope(s), user support, etc.) to the current KaVA SR)
- **2018 April:** [Release of EAVN Call for Proposals 2018B](Wajima’s report, Sep 2017)
Global Simultaneous MF VLBI Network

- Yebes 40m (K/Q/W)
- Effelsberg 100m (K/Q/W)
- Xinjiang (K/Q/W)
- KVN 21m x 3 (K/Q/W/D)
- KASI: 500km
- VERA 20m x 4 (K/Q)
- Sardinia 64m (K/Q/W)
- Tianma 65m (K/Q/W)
- NAOJ: 2,400km
- NRAO: 7,300km
- VLBA MK 25m (K/Q/W/D)
- ATNF: 7,900km
- ATCA 22m x 6 (K/Q/W)

(Credit: T. Jung)
VLBI observations at L-band with FAST in the era of SKA
QTT 110 m telescope (near Urumqi) will be available in 2020s
Thank you for your attentions!