VLBI Community: Current assessment and expectations for the future

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(Yamaguchi University)
VERA and JVN
VERA – a dedicated Japanese VLBI for astrometry

- 4 20m telescopes
- 2300 km, 22, 43 GHz
- Dual-beam for high-precision astrometry
  - ~10mas accuracy
  - Simultaneous observation of close pair: target and reference source
  - Systematic errors including atmospheric fluctuation are cancelled out

VERA’s high precision astrometry is mainly used for Galactic dynamics. Annual parallax and proper motions of water maser (22 GHz) sources are measured, and the gas dynamics of the galactic plane is studied.
Achievements of VERA

Measurement of distance and 3D motion by annual parallax and proper motion

Orion Molecular Cloud

Distance 480 pc
Galaxy rotation

VLBA/VERA/EVN
Galactic constants

Honma+ (2012)
52 SFRs
\[ R_0 = 8.05 \pm 0.45 \text{ kpc} \]
\[ \Theta_0 = 238 \pm 14 \text{ km/s} \]
\[ \Omega_0 = 29.57 \pm 0.78 \text{ km/s/kpc} \]

Update
144 SFRs
\[ R_0 = 8.16 \pm 0.26 \text{ kpc} \]
\[ \Theta_0 = 237 \pm 8 \text{ km/s} \]
\[ \Omega_0 = 28.99 \pm 0.39 \text{ km/s/kpc} \]

Rotation curve from 144 SFRs
\[(U_\odot, V_\odot, W_\odot) = (11.10, 12.24, 7.25) \text{ km/s} \text{ (Schorich, Binney, Dehnen 2012) assumed}\]

Now GAIA is producing a huge amount of astrometric data, and VERA is shifting the focus to imaging VLBI observation with EAVN collaboration
VLBI imaging observation by VERA
Jet-clump interaction in the heart of 3C84

C3 strong brightening along with flip

Size $\sim 0.15\text{pc}$

VERA/KaVA biweekly jet monitor

Nucleus

Japanese VLBI Network (JVN)
Imaging VLBI network including VERA and University’s telescopes

- Collaboration
  - NAOJ (VERA)
  - Hokkaido, Ibaraki, Tsukuba, Gifu, Osaka-Pref, Yamaguchi, Kagoshima universities
  - JAXA, NICT, GSI

- Specifications
  - 13 telescopes (11m ~ 64m)
    - 6~7 active telescopes
  - Baseline 50 - 2500 km
  - Frequency 6.7/8/22 GHz

- Operation
  - 500hr/yr
  - 100 observations/yr
Internal Motions of 6.7 GHz methanol maser motions of maser spots in Cep A (Sugiyama et al. 2014)

6.7 GHz Methanol Maser distribution in High-mass star forming region
Cepheus A HW2
(Sugiyama et al. 2008)
Internal Motions of 6.7 GHz methanol maser
motions of maser spots in Cep A (Sugiyama et al. 2014)

Rotation: 1.2 km/s, Infall: 2.4 km/s. The gas disk is rotating and infalling.
A systematic study of internal motion for 36 sources by JVN + Shanghai (a precursor observation of EAVN)
Time domain VLBI astronomy by JVN (A-project of NAOJ, since 2019)

• Advantage of university’s telescope: Long available time, flexible operation

Monitoring/Detecting ariable sources with amount of observing time

• Three main science targets of JVN
  • Periodic methanol maser
  • Extremely Compact HII region
  • Gamma-ray objects

• and various transient/variable targets
KaVA
(KVN+VERA)
KVN – multi-frequency mm VLBI

- 3 21m telescopes in South Korea
- Baseline 500 km
- 22, 43, 86, 129 GHz
  - Simultaneous observation at four frequencies with quasi-optic system
- Science
  - SiO/H2O/CH3OH Masers
    - Investigating spatial structures and dynamical effects from SiO to 22 GHz H2O maser regions (atmosphere to circumstellar envelope) according to stellar pulsation through simultaneous monitoring observations.
  - AGN / polarization

The key features of KVN are (1) capability of multi-frequency simultaneous observation, and (2) regular observation at mm wavelength. Imaging capability is greatly enhanced by co-observation with VERA.
KaVA – Combined array of KVN and VERA

- KaVA
  - KVN and VERA Array
  - 22, 43 GHz
  - Started in 2010
  - Open use since 2014
- Good imaging capability
  - Almost uniform array
  - 7 sites, 21 baselines
  - Baseline 300 - 2300 km
- The core of EAVN
KaVA (KVN and VERA Array)

- KaVA: KVN and VERA Array, 7station 21 baselines
- Open-use started since 2014
- KaVA Large Project starts in 2015

Demonstration of KaVA’s capability: Niinuma et al. (2014)
M87 jet motion monitor with KaVA

Hada et al. (2016)
Unveil jet acceleration zone with KaVA

- Question of M87 jet acceleration: where is the jet accelerated?
- Discovery of fast (~2-3c) motions in inner jet!
- Gradual acceleration between 500Rs – 20000Rs

Hada+2017 PASJ; Park+ in prep; Cui+ in prep

KaVA/EAVN

\[ \Gamma \sim z^{0.35 \pm 0.03} \]
“Heat-wave” propagation detected by KaVA
Burns et al. (2019) accepted to nature astronomy

Rapidly expanding maser emission region. Heat-wave generated in the central star is propagating through the maser emission region.
EAVN

(CVN+KVN+VERA/JVN+\alpha)
The East Asia VLBI Network (EAVN)

• Situation in and around East Asia
  • Regular operation of VLBI facilities in each EA country (VERA/JVN (JP); KVN (KR); CVN (CN))

• A small task force, ‘the EAVN Tiger Team’ was organized on June 2013 to handle various issues related to EAVN
  • To promote VLBI test observations
  • To proceed data reduction of test observations
  • To clarify the problems for future regular operation and open-use observations with EAVN

To construct a VLBI network in East Asia
The East Asian VLBI Network (EAVN)

- VERA/JVN (Japan), KVN (Korea), CVN (China)
- Collaborative effort to form a large VLBI network in East Asia
More results on EAVN-M87-2017 (22/43, spectra, kinematics, jet base)
EAVN MoU @ EAVN WS Sep/2018, Pyeongchang

Signing Ceremony of the MOU Among KASI, NAOJ, SHAO, and XAO
Date: September 6, 2018
Venue: YongPyong Resort Grand Ball Room
EAVN open-use has just started

- First EAVN open-use observations starting from Oct/2018
- Available stations: 10 (KaVA, Tianma, Nobeyama, Urumqi)
- Bands: 22GHz (13mm), 43GHz (7mm)
- Angular resolution: 0.5 mas
- Good sensitivity at 22/43GHz
Array sensitivity of EAVN

• EAVN: “high-sensitivity” + “regular monitoring capability” at 6.7-43GHz
  • Complementary to other VLBI facilities
<table>
<thead>
<tr>
<th>Subarray</th>
<th>Telescope name</th>
<th>Diameter of telescopes (m)</th>
<th>Frequency bands (GHz)</th>
</tr>
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<tbody>
<tr>
<td>CVN</td>
<td>FAST</td>
<td>500</td>
<td>0.07-3</td>
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<td></td>
<td>Kunming</td>
<td>40</td>
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<td></td>
<td>Miyun</td>
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<td>Tianma</td>
<td>65</td>
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<td>Urumqi</td>
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<td>JVN</td>
<td>Gifu</td>
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<td>Ogasawara</td>
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<td>NRO</td>
<td>Nobeyama</td>
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<td>KVN, NGII</td>
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<td>Ulsan</td>
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<td>6.4-9</td>
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<tr>
<td></td>
<td>Yonsei</td>
<td>21</td>
<td></td>
</tr>
</tbody>
</table>

The operational frequency bands are marked with solid dots. The available frequency coverage in the early science phase of FAST is 0.07-3 GHz. The frequency coverage of the Tianma telescope is continuous from 1.25 up to 50 GHz. The Ulsan telescope has a broadband receiver at the 6.4-9 GHz frequency range.
UV coverage of major VLBI arrays

Target: M87, Frequency: 22 GHz
EAVN (+ Italy) AGN Campaign

Main purpose
To obtain scientific results with EAVN
To conduct VLBI monitoring quasi-simultaneously with EHT + ALMA campaign
(To evaluate system performance of EAVN)
(To check up on the array operation and availability of KEY/VEX files at each station)

Brief summary of the Campaign
Main target: Sgr A* (43 GHz), M87 (22 and 43 GHz)
Total observing time: 186 hours/18 epochs (83 hours/9 epochs at 22 GHz; 103 hours/12 epochs at 43 GHz)
cf. EAVN campaign in 2017: 40 hours/5 epochs at 22 GHz; 100 hours/12 epochs at 43 GHz
Number of participating telescopes: 14 (Italy: 2, China: 2, Korea: 3, Japan: 7)

Correlation and data reduction ongoing
More results on EAVN-M87-2017 (22/43, spectra, kinematics, jet base)
Intensive monitoring of M87/SgrA

- EHT will see the first horizon-scale images of SMBHs (SgrA/M87)
- Centimeter-VLBI plays key roles in many aspects:
  - Connect the horizon scales to large-scales (accretion flows, jet collimation)
  - Subsequent evolution/propagation of ejected jet (jet acceleration, shock)
  - Spectral information of synchrotron plasma (B-field, $U_e/U_B$)
  - Scattering screen towards SgrA
- EAVN is a suitable facility to complement EHT
• EAVN: Very dense uv-coverage for SgrA
• First 300Mλ detection at 43GHz (Tianma - Ogasawara)
• Non-gaussianity?
• Contemporaneous 22GHz data => scattering properties
• Millimeter-regime core-shift with KVN
More results are coming from EA-VLBI

SgrA* (Zhao+; Cho+; Johnson+2018)

High-z quasars (Zhang+2018; Furuya+)

NLSy1 (Wajima+)

And more!
Future expansion of EAVN

- More stations
  - E-KVN
  - QTT 110m
  - Thai 40m
  - Malaysia
  - Indonesia

- EAVN with FAST (<3GHz)
  - Sensitivity comparable to SKA1, but 30 times higher angular resolution

- “World Array” with EAVN+EVN+VLBA
Expanding observing frequency to Lower and Higher EA stations with 1-2GHz receivers

Ultra-high-sensitivity VLBI in EA
To collaborate with SKA
Expanding observing frequency to Lower and Higher
NRO 45m Triple band observation

• System change/upgrade
  • Kunming 40 m: 6.7 GHz receiver available
  • Nanshan 26 m: 43 GHz cooled receiver
  • Nobeyama 45 m: New quasi-optics at 22/43/(86) GHz simultaneous reception (HINOTORI Project)

• Triple-band simultaneous observing system “HINOTORI” (2016-now)
  • Kagoshima Univ., Osaka Pref. Univ., Yamaguchi Univ., Ibaraki Univ., + NAOJ

Extragalactic formaldehyde using T70
 preparation for ALMA Band-2
Black hole Shadow
EHT observations in 2017

- 5 nights on April 5-11, 2017
- 8 stations at 6 sites participated
- Maximum baseline ~ 10000 km
- Wavelength ~ 1.3 mm
- Nominal beam ~ 25 uas

The shadow of M87’s super-massive black hole

Ring-size: 0.01 ly (4 light day)
Mass: 6.5 x10^9 Solar mass
A new station to EHT
Balloon-borne VLBI?

• EHT collaborations seriously consider the future array extension with space station

• Better images, some more sources with shadow

• See Astro2020 paper (will be opened)
Future Plan of VLBI astronomy in Japan

• Under discussion in various layers
  • VLBI consortium
  • Working groups (in Mizusawa, VLBI consortium, JVN)
  • Mizusawa VLBI User’s Meeting
  • VLBI Science Advisory committee in NAOJ

• Short term
  • From VERA to EAVN, JVN
  • Just started good collaboration. We plan to keep and expand the activity under the international collaboration.

• Long term
  • Large international project (SKA, ngVLA, ...), New Satellite VLBI, New telescope led by Universities
New VLBI technologies developed by NAOJ

- High speed sampler, Digital filter
- Optical fiber data transmission
- High precision phase-referencing / astrometry
- (Space-VLBI, 2-beam receiver, ...)

**OCTAVE system**
VSI based VLBI terminal, 32 Gbps (max) recording capacity
World compatibility, suitable to the East-Asian Correlator
NAOJ’s expected role in VLBI

- A research base is expected to be in NAOJ
  - Cutting edge development research is expected to be lead/backed up by NAOJ
  - University’s research strongly depends on personality of each researcher (unstable). NAOJ is the stable core of VLBI.
- A key: Cooperation of Nobeyama and Mizusawa

**Triple-band simultaneous observing system “HINOTORI” (2016-now)**
- Kagoshima Univ., Osaka Pref. Univ., Yamaguchi Univ., Ibaraki Univ., + NAOJ

- "HINOTORI" exclusive to 45-m!
- 86GHz (TZ)
- 22GHz (H22)
- 43GHz (H40)

Extragalactic formaldehyde using T70 ➔ preparation for ALMA Band-2

Implication of EAVN

• Background
  • Simple ‘Expansion’ model is difficult in Japan now
    • Demographics, Social security expenses, Economical recession...
  • Still, the achievements of Japanese astronomical society is respected by communities of east Asian countries
  • Construction of new VLBI telescopes in east Asia
  • ‘Collaboration’ strengthen the performance of VLBI

EAVN construction

• Let the owls of Minerva fly as messengers
• To construct a new network of knowledge and research