Radio follow-up with
Japanese VLBI Network &
East Asia VLBI Network

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  - Capability of VLBI

- VLBI array in the EA: JVN/VERA/EAVN
  - Brief introduction of each array

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Angular resolution
\[ \theta \sim \frac{\lambda}{D} \] (波長/基線長)
- \( D \sim 2000 \text{ km} \) (〜日本列島)
- \( \lambda \sim 1 \text{ cm} \) (23 GHz)
\[ \rightarrow \theta \sim 1 \text{ milli-arcsec (mas)} \]
Very Long Baseline Interferometry

Angular resolution $\theta \sim \frac{\lambda}{D}$

- $D \approx 2000$ km (~Japan islands)
- $\lambda \approx 1$ cm (23 GHz)

$\theta \sim 1$ milli-arcsec (mas)

Acciari+09
Very Long Baseline Interferometry

Capabilities of radio interferometer

- **Sensitivity**
  \[ \propto \text{No. of antenna (Effective aperture), bandwidth, system noise} \]

- **Angular resolution**
  \[ \propto \text{Longest baseline length} \]

- **Image quality**
  \[ \propto \text{No. of various baselines} \]
  - spatial frequency \( \leftrightarrow \) FT \( \rightarrow \) point spread function
Very Long Baseline Interferometry

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- \( D \approx 2000 \) km (~日本列島)
- \( \lambda \approx 1 \) cm (23 GHz)
- \( \theta \approx 1 \) ミリ秒⾓

Summary of VLBI

- Extremely good “eye”
  - \( \theta < 1 \) mas even with Japanese baselines

- (sub)-pc-scale structure of distant object
  - Structural changes (jet kinematics, specifying high-energy emission site, localization...)

- High \( T_b \) object (> ~10^6 K) is a main target
  - e.g., blazars, other AGN jets, astronomical masers (GRB afterglow, GW-170817, ... -> long integration time is required)
World’s VLBI array

**Very Long Baseline Array (VLBA)**
- Baseline length: < ~8,000 km
- Frequency: 330 MHz - 86 GHz
- Operation: NRAO

**Korea-Japan VLBI Network (KVN and VERA Array: KaVA)**
- Baseline length: < ~2,300 km
- Frequency: 22/43 GHz
- Operation: NAOJ, KASI
World’s VLBI array

- VLBA, KaVA, VERA: dedicated VLBI array
  - running throughout the year except for the period of maintenance

- e.g., EHT, GMVA, EVN, JVN: coordinated by multi-purpose telescopes
  - limited sessions/year

- Basically, proposal based ToO is acceptable
  - NEED to reserve the slot of ToO observation of expected event
  - For (actually) unexpected or urgent event, the slot of DDT is prepared

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Target of opportunity

From the announcement of KaVE/EAVN call for proposal

KaVA/EAVN accepts target of opportunity (ToO) proposals. Although proposers can request the participation of Tianma and Nanshan as well as KaVA for ToO observations, both Tianma and Nanshan will join only on a best effort basis. Note that Nobeyama cannot be included for ToO proposals.

It is strongly recommended that ToO proposals (especially expected ToO) are submitted during the regular CfP. Unexpected or urgent ToO can be submitted as Director’s Discretionary Time (DDT) proposals at any time. ToO proposals must include clear triggering criteria to initiate an observation. ToOs are valid for one year after it is approved. ToO proposals for DDT should follow the same format of regular call and should be sent to eavnprop(at)kasi.re.kr.
World’s VLBI array

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- A few “weeks” are required by data distribution
  - Data shipping from each antenna, correlation procedure of all baselines, ...
  - NOT suitable for alerting to other EM facilities
Japanese VLBI Network: JVN
VLBI Exploration of Radio Astrometry: VERA
East Asia VLBI Network: EAVN
VLBI array in the East Asia Region
**JAPANESE VLBI NETWORK: JVN**

- **Network**
  - 6 Univ. (Tsukuba, Ibaraki, Gifu, Osaka Pref., Yamaguchi, Kagoshima) and NAOJ, JAXA/ISAS, NICT, GSI
  - 12 radio telescopes (10 stations)
    - 1 x 11m, 4 x 20m, 6 x ~30m, 1 x 64m
    - Ibaraki and Yamaguchi: two 30m-class
  - Baseline length: 80 km - 2270 km
    - Angular resolution of 3 mas is achieved at 8GHz
  - 3 observing frequencies: 6/8/22 GHz
    - $\Delta B = 32$MHz until 2014, 512MHz since 2015
  - Operation: Each university & NAOJ independently

- **Purpose:**
  - A new, characteristic VLBI array
  - A base of East Asian VLBI

- **EAVN test observations (JVN + Shanghai26m)**
  - 6.7 GHz Methanol masers project led by Fujisawa-san+
VLBI EXPLORATION of RADIO ASTROMETRY: VERA

- **Sub-array of the JVN**
  - Baseline length: 1,000 - 2,270 km
  - Operated by NAOJ for revealing Galactic dynamics
  - ~100hrs/yr open-sky is prepared

- **Specializing “Astrometry”**
  - Good angular resolution & poor imaging capability
  - Suitable for the detection of compact structure and its change
    - E.g., detection of the newly ejected compact jet

- **Array specification**
  - Frequency: 22GHz / 43GHz
  - Angular resolution: 1.2 mas (22GHz), 0.6 mas (43GHz)
  - 2-beam simultaneous receiving system

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Fig. Consisting of 4 radio telescopes located at Iwate-Oshu, Tokyo-Ogasawara, Kagoshima-Satsumasendai, Okinawa-Ishigakijima
VERA observation of TXS 0506+056

We started intensive follow-up of TXS0506+056 since 8 days after the detection of IceCube-170922A (based on proposed ToO)
- Date: 2017 Sep 30, Oct 13, Nov 1, and Nov 13

No significant structural change in the pc-scale

Quick follow-up with VERA@23GHz
(Niinuma+ in prep.)
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Quick follow-up with VERA@23GHz
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Transverse structure can be seen in the jet
(Niinuma+ in prep.)
EAST ASIA VLBI NETWORK: New Array!
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- Consisting of dedicated array (KaVA: 7-telescopes) & multi-purpose telescopes (e.g., Nobeyama 45m, Shanghai 65m, Nanshan 26m)
  - Baseline length: 300km – 5500km

- Regular operation at high radio frequency (22/43GHz) since 2018
  - Now, call for proposal for 2019B semester
  - At 43GHz, one of the highest sensitivity array in the world
  - Good imaging capability comparable to VLBA

- Still under the extension!
  - In one or two years, JVN will join to EAVN at low radio frequency part
  - Image quality will be improved
Follow-up of TXS0506+056 by EAVN

EAVN clearly reproduce the jet structure compared to VERA.

VLBI flux is still increasing: $\sim$400 mJy/b (2017 Sep) $\rightarrow$ $\sim$800 mJy/b (2018 Nov)
Radio follow-up with VLBI

Toward multi-messenger astronomy
Imaging observation of “VLBI scale”

- Basically, VLBI imaging is time-consuming observation
  - At least a few hours are required per object (depending on no. of baselines, sensitivity)

- Searching for plausible candidates within a few deg$^2$ by VLBI?
  - ~100 radio sources were located within the error of IceCube-170922A
  - Unrealistic: extremely narrow FoV and time-consuming for each pointing
IceCube-170922A & TXS 0506+056
Radio catalog (NVSS@1.4 GHz) and IceCube positional error

1mas \approx 0.0000003 \text{ deg}
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- Follow-up of a few plausible candidates: realistic (so far)
  - EM observation with large FoV performs survey
  - VLBI investigates the details
    - e.g., gamma-ray flaring blazars PKS B1424-418, TXS 0506+056
Non-Imaging Radio Follow-up

- Snap-shot observation by “one baseline” VLBI
  - Only light-curve study BUT in VLBI scale
  - University’s baseline (Ibaraki Univ., Yamaguchi Univ.)
    - Operation, correlation done by both University
    - Survey, quick follow-up with high-sensitivity \((5 \text{mJy@10}\sigma, 6\text{min integ.})\) and relatively good resolution \((\theta\sim9\text{ mas, } = 40\text{pc@z~0.3})\)

- Yamaguchi Interferometer (YI)
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| **Observing Band**             | 6 GHz / 512 MHz  
|                                | 8 GHz / 512 MHz  |
| **Baseline**                   | 110 m |
| **Beam size**                  | 6 GHz: 1’.4  
|                                | 8 GHz: 1’.1 |
| **Data rate**                  | 2 Gbps/Antenna |
| **Integration time**           | 3 hours |
| **1σ sensitivity**             | 0.1 mJy |
| **Observing Time**             | 3000 hours/yr |

YI will be used for...
- Daily monitoring of compact object/AGN/YSO
- Deep survey of weak radio source (〜1 mJy)
Summary

VLBI is an unique instrument to investigate the detailed structure and to see the vicinity of the SMBH
- But the target is quite limited (high $T_b$ objects)

Follow-up of a few plausible target: VLBI imaging

Search for plausible target or quick follow-up: non-imaging VLBI or YI