VLBI Observations with ALMA

#FirstPictureOfBlackHole
Taking the first picture of a black hole

At the center of the Milky Way, there is a supermassive black hole known as Sagittarius A*.
It weighs 4 million times the mass of the Sun!

2 major international projects joined different telescopes from the south pole to Hawaii and Europe, passing by ALMA, to create virtual observatories the size of the Earth: The Event Horizon Telescope (EHT) and the Global mm-VLBI Array (GMVA).

ALMA and its 66 antennas are the most sensitive component of both projects, multiplying sensitivities 10 times.

In search of the impossible!

www.almaobservatory.org

Taehyun Jung
Korea Astronomy & Space Science Institute

2018 ALMA Special Lecture, March 07I, 2018 @ SNU
“Just checking.”
Amateur optical telescope
- Diameter : 10 cm
- Wavelength : 570 nm
- $\lambda/D \sim 0.0000057$

Radio Telescope
- Diameter : 21 m
- Wavelength : 21 cm
- $\lambda/D \sim 0.01$

Telescope Resolution

$$\theta_{rad} \approx \frac{\lambda}{D}$$

$$\theta_{arcsec} \approx \frac{2\lambda_{cm}}{D_{km}}$$
Single Dish
Interferometer

KVN 한국우주전파관측망
Korean VLBI Network

Free space
Guided

\[(\sum V_i)^2\]
Very Long Baseline Interferometer (VLBI)

Quasar

Noise

Radio Telescope

Hydrogen maser clock (accuracy 1 sec in 1 million years)

Data Acquisition
Very Long Baseline Interferometer (VLBI)

Wavefront with the same phase (which departed at the same time)

\[
\tau_g = \frac{\vec{b} \cdot \vec{s}}{c}
\]
KVN

Korean VLBI Network

KVN Yonsei Observatory

KVN Ulsan Observatory

KVN Tamna Observatory
1.3cm (22GHz 주파수 관측)

KVN 21m 단일경 ~ 120"
KVN VLBI 478km ~ 0.006"

20,000배 차이!!

$\theta_{rad} \approx \frac{\lambda}{D}$

KVN Yonsei Observatory

KVN Ulsan Observatory

KVN Tamna Observatory
전파간섭계  Connected interferometers

The Very Large Array (VLA)
- Wide frequency range up to 50 GHz
- 25-m diameter antennas on rails - Baseline 1 - 36 km
- Good sensitivity - 6σ/2y in 12 hrs (8.4 GHz)

see www.nrao.edu

SMA

ATCA
Very Long Baseline Interferometry
The Global VLBI - Array

- European VLBI Network (EVN)
- Very Long Baseline Array (VLBA)
- High Sensitivity Array (HSA)
East Asia VLBI Network: EAVN

First Open Call for Proposal
Starting from 2018 Sep.
\[ \theta_{rad} \approx \frac{\lambda}{D} \]
Russia’s RadioAstron space observatory

The RadioAstron observatory with an unprecedented high resolution capability will make it possible to observe remote objects in space.

- Highly elliptical orbit
  - Apogee: 330,000 kilometers
  - Perigee: 362,000 kilometers
  - Orbital period: 8.2 days

Parabolic antennas
- Diameter: 30 meters
- Comprises 27 carbon-plastic “petals”

Broad-beam antennas

Focal module

Navigator service module

High-capacity radio facility

This is the first Russian orbital radio telescope
It will study:
- Galaxy nuclei
- Black holes
- Neutron stars
- Interstellar plasma clouds
- The Earth’s gravitational field
- And many other objects and phenomena in the Universe

Ordered by: Federal Space Agency
Chief contractor: Lavochkin Research and Production Association
Scientific equipment developed by: Astro Space Center of the Russian Academy of Sciences’ Lebedev Physics Institute.
The RadioAstron observatory was launched on July 13, 2011.
Active service life: At least five years

RIANOVOSTI © 2011

The Highest Angular Resolution Ever !!
World Record

~ 10 μas (0.000 000 028 deg)

NGC 4258 Extragalactic maser
λ = 1.35 cm, Radioastron-Green Bank, B'y=19.5xED
Resolution: 11 μas!
Radio Interferometers: Frequency & Resolutions

(Credit: Savolainen. T.)
GMVA: Global Millimeter VLBI Array

Target Frequency: 86GHz (3.5mm)

(Credit: T. Krichbaum)
# ALMA vs GMVA

<table>
<thead>
<tr>
<th>ALMA</th>
<th>vs</th>
<th>GMVA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong># of Antenna</strong></td>
<td></td>
<td>20</td>
</tr>
<tr>
<td><strong>35 – 950GHz</strong></td>
<td></td>
<td>(43), 86GHz</td>
</tr>
<tr>
<td><strong>1cm-0.3mm</strong></td>
<td></td>
<td>7mm – 3.5mm</td>
</tr>
<tr>
<td><strong>15m - 16km</strong></td>
<td></td>
<td>~200km – 10,000km</td>
</tr>
<tr>
<td><strong>~<a href="mailto:5mas@0.3mm">5mas@0.3mm</a></strong></td>
<td></td>
<td>~0.05mas@3mm</td>
</tr>
<tr>
<td><strong>8GHz BW</strong></td>
<td></td>
<td>0.5GHz BW</td>
</tr>
<tr>
<td><strong>Full Stokes</strong></td>
<td></td>
<td>Full Stokes</td>
</tr>
</tbody>
</table>

**GMVA sensitivity**

- 0.90 mJy/hr (Europe+VLBA)
- 0.49 mJy/hr (Europe+VLBA+GBT)
- 0.22 mJy/hr (Europe+VLBA+GBT+ALMA)

**Angular Resolution**

- ALMA: 15km @86GHz $\rightarrow \theta \sim 100\mu as \times 666$
- ALMA: 15km @230GHz $\rightarrow \theta \sim 30\mu as \times 666$
- GMVA: 10000km @86GHz $\rightarrow \theta \sim 100\mu as$
- EHT: 10000km @230GHz $\rightarrow \theta \sim 30\mu as$

\[
\Delta S = \frac{\text{SEFD}}{\eta_s \cdot (2 \cdot \Delta \nu \cdot \tau_{ff})^{1/2}} \quad \text{(Jy)}
\]

**BW & Recording Rate**

- GMVA: 128MHz BW, 2Gbps
- EHT: 4GHz BW, 32Gbps
mm-VLBI (EHT/GMVA) with ALMA

Observing the supermassive black hole at the heart of the Milky Way

Telescopes contributing to the EHT and GMVA observations of Sagittarius A*: The connected telescopes simulate a telescope equivalent to the dimensions of the whole western hemisphere of the Earth. Credit: ESO/O. Furtak
Phasing ALMA for VLBI

- ALMA Phasing Project (APP) (2011~2016)
  - Phasing-up all ALMA telescopes for (sub)mm-VLBI as one single VLBI station
  - Large increase in Sensitivity (by x10) → improve image fidelity e.g., 64x12m → 96m eff. aperture
  - Increase resolution (by x2)

Image courtesy of MIT Haystack Observatory
Event Horizon Telescope
A Global Network of Radio Telescopes

Target Frequency: 230GHz (1.3mm)
Event Horizon Telescope
A Global Network of Radio Telescopes

Target Frequency: 230GHz (1.3mm)
mm-VLBI with ALMA

Fish et al. (2013)

Fig. 1.—The $(u,v)$ coverage of sources at $+20^\circ$ (left) and $-20^\circ$ (right) declination. The top row shows the global VLBI baseline coverage at 7 mm, and the bottom row shows the coverage at 3 mm. Baselines to ALMA are indicated in red. ALMA provides substantial improvement in the north-south coverage of global VLBI arrays, especially at 3 mm and for southern sources.
# Black Hole Size

<table>
<thead>
<tr>
<th>source</th>
<th>$M_{BH}/M_{\text{sun}}$</th>
<th>Distance</th>
<th>Angular radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sgr A*</td>
<td>$4 \times 10^6$</td>
<td>8 kpc</td>
<td>10$\mu$as</td>
</tr>
<tr>
<td>M87</td>
<td>$6 \times 10^9$</td>
<td>15 Mpc</td>
<td>7$\mu$as</td>
</tr>
<tr>
<td>M104</td>
<td>$1 \times 10^9$</td>
<td>10 Mpc</td>
<td>2$\mu$as</td>
</tr>
<tr>
<td>Cen A</td>
<td>$5 \times 10^7$</td>
<td>4 Mpc</td>
<td>0.25$\mu$as</td>
</tr>
</tbody>
</table>

$\mu$as = $10^{-6}$ arcsecond

Shadow diameter: 1~5 times Schwarzschild radius
For imaging shadow, ~ 10$\mu$as resolution is required

(Credit: M. Honma)
Black Hole and AGN Jets

Figure 2: Simulated images at 345 GHz of the black hole in the Galactic Centre using a VLBI array involving ALMA and other telescopes. The input model is based on general relativistic magneto-hydrodynamic simulations of plasma around a Kerr black hole from Mościbrodzka et al. (2009). Left: Face-on orientation; Right: Edge-on orientation. The black hole shadow and photon ring are much more difficult to detect, but still visible in the edge-on case. Figure updated from Faccke et al. (2011).
BH Shadow Seen by mm-VLBI with ALMA

Simulated Image

EHT without ALMA

EHT with ALMA

GRMHD

mm-VLBI data simulator

(Credit: Ciriaco Goddi)
VLBI Traction on Black Hole Orbit

Hot spot in accretion flow orbit BH at Innermost Stable Circular Orbit (ISCO)

Closure Phase vs Time

Orbit period ~30min

Many orbits observed during a single night → Extraction of orbit period gives an estimate of BH spin!!

(Credit: S. Doeleman)
SgrA* monitoring program on behalf of KaVA/EAVN Science WG
1\textsuperscript{st} VLBI Observations with ALMA

- 1\textsuperscript{st} observation: April 2-15 2017
  - April 2-4: GMVA (86GHz, 3mm)
  - April 5-11: EHT (230GHz, 1.3mm)
    ※ 8 telescopes (62 hrs ALMA time)
    4PB raw data
- 2\textsuperscript{nd} observation: April 15-27 2018
mm-VLBI with ALMA: General Science Cases

- Imaging EH of BH: SgrA*
- Testing GR
- Origin of AGN jets and jet formation
- Cosmological evolution of galaxies and BHs, AGN feedback
- Galactic masers (Star Formation, Evolved Star)
- Pulsars, neutron stars, and X-ray binaries
- Extragalactic emission lines
- Absorption lines in distant galaxies and study of their ISM
- Testing cosmology and fundamental physical constants
- Astro-chemistry

Reviewed by Fish et al. (2013) and Tilanus et al. (2014)
**Motivation:**

**AGN Study: mm-VLBI with ALMA**

What are the physical processes acting at the centers of Quasars and in other Active Galactic Nuclei? One needs to directly image the regions near the central Black Hole and study how the powerful radio-jets are launched and accelerated.

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**mm- and sub-mm VLBI with ALMA offers micro-arcsecond scale resolution and will help to answer the following questions:**

- **Assymetric emission around a rotating Black Hole?**
- **The Black Hole: A GR-MHD dynamo?**
- **Magnetic field lines?**
- **Jet rotation/precession due to frame dragging or binary BH?**
- **Origin of Gamma-rays in AGN jets?**

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*Image: A. Marscher*
Masers in Stars, SF regions

• New Probes of YSOs and AGBs

• New maser line detection with ALMA
  • H2O at 232GHz
  • H2O at 321GHz

• double-peaked profile similar to SiO
  → tracing hotter/dense gas than H2O at 22GHz?
  → mm/submm VLBI is essential to study dynamics & excitation
Movies of H2O & SiO masers of VY CMa at 22/43/86/129GHz, KVN

Position–velocity plot showing the observed 22 GHz water vapour emission from the oxygen-rich AGB star IK Tau (colour-coded by velocity), together with the predicted locations of water maser emission at 321 and 325 GHz from models by Malcolm Gray.

KVN KSP (Credit: Y.J. Yun)
AGN Torus from Absorption Lines with KVN

- HCN (1-0) associated with the AGN torus (Sawada-Satoh+ 16)
  - High opacity localized on the receding jet.
  - Ongoing infall of HCN clumps to SMBH.
  - Yielded physical properties of the torus.
    - $N(H_2) : 10^{24}-10^{25}$ cm$^{-2}$
    - Infall rate : $\sim 0.05-0.5$ M$_{\odot}$/yr

NGC 1052

(a) $V$ 1656 km s$^{-1}$
(b) $V$ 1719 km s$^{-1}$

[Imagery and diagrams illustrating the AGN torus and absorption lines]

(a) XDR
(b) Plasma region
(c) Western receding jet
(d) Eastern approaching jet
VLBI with ALMA: Proposal Preparation

Strategy

- ALMA participate in open-access VLBI networks
- ALMA-VLBI proposal is assessed in competition with other ALMA proposals
- ALMA-VLBI data products will become public after some proprietary period

Proposals

- ALMA bands 3 and 6 are available
  - GMVA 3mm, EHT 1.3mm
- ALMA+GMVA : PIs must submitted a proposal to the GMVA by 1st Feb. in addition to their ALMA VLBI proposal
  → stress why ALMA is essential !!
- Notes:
  - No Large Program and DDT proposals
  - At present, up to 37 12m antennas in the phased array
  - Usually ALMA-VLBI campaign will be carried out in April
  ※ proposal deadline issue btw GMVA and ALMA
EHT: Korea Participation
- EHT: Starting from early 2010
- Official participation of Korea from mid-2017 under the EAO - supporting JCMT VLBI operation and joining S&T WG

Current EHT-K activity
- Multi-Wavelength WG
- AGN WG
- Imaging WG
- Error & Calibration WG
Simultaneous MF receiving system is seriously considered as a MMtron’s Rx.

For even Higher Angular Resolution → VLBI+ALMA (EHT) + Millimetron (S-VLBI)

(Credit: S. T. Han)
Starting important step forward to make a synergies between connected interferometers and VLBI.

overcoming the boundaries of tools and experties

**Connected Array**
low ang. resolution
wider filed of view
dense, sensitive obs

**VLBI**
high ang. resolution
narrow/wide field imaging
high Tb dominated

Multi-band Fringe Fitting in CASA is now available!!

After “manual phase cal”

After “multi-band” fringe fitting
Useful Link & References

- **EHT**: [http://eventhorizontelescope.org/](http://eventhorizontelescope.org/)
- **GMVA**: [https://www3.mpifr-bonn.mpg.de/div/vlbi/globalmm/](https://www3.mpifr-bonn.mpg.de/div/vlbi/globalmm/)
- **ALMA-VLBI related**
  - Cycle 6 CfP: [https://almascience.nrao.edu/news/alma-cycle-6-pre-announcement](https://almascience.nrao.edu/news/alma-cycle-6-pre-announcement)
  - Cycle 5 CfP: [https://almascience.nrao.edu/proposing/proposers-guide](https://almascience.nrao.edu/proposing/proposers-guide)

- **Science Cases**
  - Fish et al., 2013 (arXiv:1309.3519)
    *High-Angular-Resolution and High-Sensitivity Science Enabled by Beamformed ALMA*
  - Tilanus et al., 2014 (arXiv:1406.4650)
    *Future mmVLBI Research with ALMA: A European vision*
  - Matthews et al., 2018
    *The ALMA Phasing System: A Beamforming Capability for Ultra-high-resolution Science at (Sub)Millimeter Wavelengths*

Thank you!