Role of Large Single Dishes in VLBI

Tapasi Ghosh

Outline:
• Interferometry 101 - Basic Concepts
• Very Long Baseline Interferometry (VLBI)
• Large Single Dish perspective
• Some Scientific Results
Basic Concepts

Young’s double slit experiment:
Wave-front splitting at the two slits generates Huygens wavelets that produces interference fringes. Constructive interference occurs when path difference is an integer number of wavelengths.

Constructive interference: \( d \sin \theta = n \lambda \)
Destructive interference: \( d \sin \theta = (n+1/2) \lambda \)
Fringe Spacing = \( \lambda/d \)
Fringe Visibility = \( (I_{\text{max}} - I_{\text{min}})/(I_{\text{max}} + I_{\text{min}}) \)

Two Element (Radio) Interferometer:

- \( b \): baseline vector.
- \( s \): unit vector pointing to the source.
- \( \tau_g \): geometric delay.
- The correlator

\[ R(\tau_g) = C_1 C_2 \cos[2\pi \nu \tau_g] \]
As the source moves across the sky due to Earth’s rotation, the baseline vector traces part of an ellipse in the \((u,v)\) plane.

We obtain data for both \((u,v)\) and \((-u,-v)\) simultaneously, since the two antennas are interchangeable. So the ellipse completed in 12h, not 24!
Basic Concept - contd. : Visibility $\rightarrow$ Brightness distribution

For an extended source, each point in the source contributes to the fringe visibility

\[
V = \int_{-\infty}^{+\infty} d\sigma \cdot I(\sigma) \cdot \exp\{i2\pi b \cdot \sigma\}
\]

$V = $ Visibility function = Fourier transformation of source’s brightness distribution

$I(\sigma) = F^{-1} \ V(b)$
Some 2D FT pairs
From a “Dirty” to “CLEAN” image,

Dirty Image

Dirty Beam

Deconvolve

Clean Image
Examples of Arrays

VLÀ- The Very Large Array
27 antennas, d=25 m

GMRT-Giant Meterwave Radio Telescope
30 antennas, d=45 m

ALMA, 66 antennas, d=16 km
What is VLBI?

- Radio interferometry with distant, *physically unconnected* antennas
  - High resolution – milliarcsecond (mas) or better
  - Baselines up to an Earth diameter for ground-based VLBI
  - Can extend to space (HALCA, RadioAstron)
- Traditionally uses no IF/LO link between antennas
  - Atomic clocks for time and frequency – usually H-masers
  - Disc-based recorders for temporary data storage & transport
  - Delayed correlation after shipment of disc packs
  - Real time over the internet (eVLBI) is an option
- Can use available single-dish antennas
- No fundamental difference between linked interferometers & VLBI arrays
The Very Long Baseline Array (VLBA)

- Ten 25 m identical antennas.
- Distributed across the US.
- Range of Baselines: 236 to 8611 km.
- Frequency range: 0.3 to 86 GHz.
- Resolution: ~0.1 mas at 86 GHz.
- Operations center in Socorro, NM.
Arrays around the World

VLBA

EVN

HSA = VLBA + Y27 + GBT + AR + EB

LBA in Australia, KVN – S.Korea

CMVA - mm-range VLBI
VLBI with Antennas in Space

VSOP/HALCA had an orbit with apogee ~2 Earth diameters

RadioAstron has an orbit with apogee ~30 Earth diameter

From 1999 to 2001, VLBA & Ar co-observed with this Japanese 8-m orbiting antenna.

From 2012, GBT & Arecibo have co-observed with this Russian 10-m antenna, finding a new component of our ISM, and unexpected phenomena in quasars.
A Few Relevant Parameters

VLBI: Resolution

\[ \theta \sim \frac{\lambda}{b_{\text{max}}} \]

- At 1.4 GHz, VLBA’s maximum resolution is 5 mas.
- At 86 GHz, VLBA’s resolution is ~0.1 mas.

VLBI: Image Sensitivity

\[ \Delta I (\text{Jy/beam}) \approx \frac{\text{SEFD}}{\sqrt{N(N-1) \times \Delta \nu \times t_{\text{int}}}} \]

For 10 hr observing, dual polarization, \( \Delta\nu = 16 \text{ MHz} \), the rms noise of the VLBA is \(~40 \mu \text{ Jy/beam}.\)

VLBI: Baseline Sensitivity

\[ \Delta I_{12} \approx \sqrt{\text{SEFD}_1 \cdot \text{SEFD}_2 / \Delta \nu \Delta t} \]

Ar-VLBA baseline is 10 times more sensitive than an intra-VLBA baseline.

VLBI: Nominal Field of View

Determined by the bandwidth, the primary beam of the individual antenna in the array, and the basic integration time. Ignoring the last two factors, \( \theta_f \approx \lambda / b \times (\nu / \Delta \nu) \). For \( 10^4 \text{ km baseline, and 50-MHz bandwidth at 6cm, (with a resolution of 1mas)} \), the FOV is 120 mas.
### EVN Calculator

<table>
<thead>
<tr>
<th>Observing band &amp; data rate [Mbit/s]</th>
<th>On-source integration time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ef, Nt, My, Pv, Pa, Hn</td>
<td>150</td>
</tr>
<tr>
<td>Mc, Sh, Km, Ro70, Ho, Nl</td>
<td></td>
</tr>
<tr>
<td>On, Tm65, Sv, Ro34, Cd, Fd</td>
<td></td>
</tr>
<tr>
<td>Tr, Ur, Zc, Pb, Ap, La</td>
<td></td>
</tr>
<tr>
<td>Jb1, Mh, Bd, Ku, Go, Kp</td>
<td></td>
</tr>
<tr>
<td>Jb2, Ys, Wz, Ky, Gb, Pt</td>
<td></td>
</tr>
<tr>
<td>Cm, Sr, Ka, Kt, Y1, Ov</td>
<td></td>
</tr>
<tr>
<td>Wb, Ar, Ir, At, Y27, Br</td>
<td></td>
</tr>
<tr>
<td>W1, Hh, ALMA, Mp, Sc, Mk</td>
<td></td>
</tr>
</tbody>
</table>

The image thermal noise is estimated to be 31.18 uJy/beam (1 sigma) using natural weighting.

Number of spectral channels per subband, integration time [s], and maximum baseline length

| 16 ch | 2 s | 10000 km (Full EVN) |

The field of view limited by bandwidth-smearing is 4.95 arcseconds (assuming 10000.0 km for the maximum baseline).

The field of view limited by time-smearing is 16.70 arcseconds. These values are calculated for 10% loss in the response of a point source, and they give the FoV radius from the pointing center.

The resulting FITS file size will be about 427.24 MBytes.

This combination of channels and polarizations results in an aggregate bit rate of 1024 Mbps, assuming 2 bit sampling.

http://www.evlbi.org/cgi-bin/EVNcalc
Why add a Big Dish to VLBI Arrays

- A continuum observation, $\lambda=18$-cm, data-rate=512 Mbps, i.e. 128 MHz of RF bandwidth, dual-polarization, $\tau=120$ minutes on source:

<table>
<thead>
<tr>
<th>Configuration</th>
<th>1$\sigma$ Image noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSA (VLBA+Y27+EF+GB+Ar)</td>
<td>3.3 $\mu$Jy/beam</td>
</tr>
<tr>
<td>-Ar</td>
<td>7.1 $\mu$Jy/beam</td>
</tr>
<tr>
<td>EVN+Ar</td>
<td>3.8 $\mu$Jy/beam</td>
</tr>
<tr>
<td>-Ar</td>
<td>9 $\mu$Jy/beam</td>
</tr>
<tr>
<td>Global (EVN+VLBA+Y27+Gb)+Ar</td>
<td>2.5 $\mu$Jy/beam</td>
</tr>
<tr>
<td>-Ar</td>
<td>4.7 $\mu$Jy/beam</td>
</tr>
</tbody>
</table>

- A spectral-line observation, $\lambda=18$-cm, 64 channels over 1-MHz, 2 pol, 120mins.

<table>
<thead>
<tr>
<th>Observation</th>
<th>EVN</th>
<th>EVN+AR</th>
<th>VLBA</th>
<th>VLBA+Y27+GB</th>
<th>VLBA+Y27+Gb+AR</th>
</tr>
</thead>
<tbody>
<tr>
<td>mJy/beam/ch</td>
<td>0.9</td>
<td>0.31</td>
<td>3.0</td>
<td>0.62</td>
<td>0.25 mJy/beam/ch</td>
</tr>
</tbody>
</table>

GBO Remote Observer Training, Oct. 2020
For a heterogeneous array, the primary beam is determined by the largest dish’s voltage polar diagram.

The primary beam is >> the synthesized beam (~1 mas) and usually, the P.I.s do not image the whole primary beam.

The field of view for each imaged field is instead limited by the averaging time and the bandwidth, and is typically a few arcsec.

- The sky is almost entirely empty at VLBI resolution
  - “full beam” imaging not needed; rather, many small “fields” (phase centers)
  - DiFX allows many phase centers in one correlator pass

- 200 phase centers require only 20% more correlator time than 2 phase centers.

Middelberg et al., 2011
Special Considerations for Large Single dishes

- Slew times will be longer for large single-dish telescopes
- Breaks in the schedule will be required for pointing and focus calibrations
- Special considerations for weather, e.g. temperature limits on GBT
- Higher sensitivity opens up the possibility of self-cal for fainter targets
Using the GBT in a VLBI experiment

VLBA compatible back end, and Mark 6 recorder (RDBE, in both DDC and PFB mode with maximum recordable RF bandwidth of ~1.0 GHz)

HSA (high sensitivity array)
  can include GBT, Effelsberg, Arecibo, VLA

GMVA (global 3mm VLBI array)
  can include IRAM Pico Valeta, IRAM Plateau de Bure, Yebes, Metsahovi, Effelsberg, GBT, also ALMA

GBT can be included in EVN experiments.

Refer to http://www.gb.nrao.edu/~gbvlbi/vlbinfo.html
Creating a schedule

User writes "Key" file

Sched program

Station schedules, (deposited on server in Socorro):
  e.g.  Bb240z.vex

Astrid scheduling blocks:
  BB240Z.GB.py
  .....
Recent Important Results:

VLBI Resolves the Pleiades Distance Controversy

The Pleiades, or “Seven Sisters”, is a star cluster that is critical to our understanding of all objects throughout the universe. For decades, there has been debate over the exact distance from us to the Pleiades. Radio VLBI has now provided a "gold standard" distance measurement – Melis et al, 2014. Distance measurements of these weak stellar radio emitters would have been impossible without the presence of the Arecibo telescope in the VLBI Array.
On 2016 September 20, we detected four individual bursts in the Arecibo single-dish PUPPI data that overlap with EVN data acquisition (Table 1). No bursts were detected in the Arecibo PUPPI (1.7 GHz) or Mock (5 GHz) data from other sessions in which there are simultaneous EVN observations that can be used for imaging the bursts. We formed images from the calibrated visibility data for each burst and measured their positions with respect to the persistent radio source. Figure 1 shows these positions together with the persistent source at 1.7 and 5.0 GHz. The nominal positions measured for the four bursts are spread ≤15 mas around the position of the persistent source, and we discuss this scatter in Section 3.2.
The Seyfert-2 NGC 7674
Summary and Future

• VLBI provides extremely high angular resolution.

• Recent trends are to move to ultra-wide bandwidth data recording and wide-field mapping.

• Use of large single-dishes (e.g. GBT and Arecibo) with VLBA provides significant boost in sensitivity and u-v coverage.

• Large single-dish telescopes with VLBA are invaluable for spectral line and transient source studies where bandwidths and integration times have natural limits.
Future

GMVA & EHT

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

ngVLA

Long Baseline Options

- ngVLA integrated into a global scale array: eVLBI, phasing of core are 'given'
- Replace existing VLBA antennas/infrastructure with ngVLA technology, new stations?
- Operation: HSA/GMVA ('campaign-mode'), or dedicated array?
- Design and implementation depend on primary science drivers: astrometry vs. imaging vs. time domain...

The picture: Shadow of the Black Hole in M 87