ROLE OF LARGE SINGLE DISHES IN VERY LONG BASELINE INTERFEROMETRY

Sravani Vaddi
Post-doctoral Fellow
Arecibo Observatory

GBT
Effelsberg
Lowell

GBO/AO single dish school 13-17 Sep 2021
NEED FOR AN INTERFEROMETER

- Angular Resolution

\[ \theta \propto \frac{\lambda}{D} \]

where D is the diameter of the telescope

Hubble space telescope with D=2.4 m, wavelength=500 nm, Resolution \( \sim 0.05 \) arcsec.

For cm observations, one would need \( \sim 800 \) km diameter antenna (Not practical!)

Instead we use arrays of small telescopes and measure the interference pattern from the telescopes (like a double-slit experiment) \( \rightarrow \) This is interferometry.

**Synthesize** a single telescope of large aperture from a number of small telescopes.
Radio interferometry consists of two or more radio telescopes that are separated by a distance, known as **baseline**.

**Examples:**
- VLA has 27 antennas with baseline of 1-36 km; operating frequency: 1-40 GHz
- ALMA has 66 antennas; 35-950 GHz.
- GMRT has 30 antennas with baseline of 100 m-26 km; operates from 100-1200 MHz.
- LOFAR has ~20,000 dipoles; operates from 10-240 MHz.
NEED FOR VLBI

HIGH RESOLUTION

• An array of max baseline of 6000 km gives a resolution of
  • 7 milli arcsec at 1.4 GHz (21 cm)
  • 30 micro arcsec at 230 GHz (1 mm)
WHAT IS VLBI?

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

These fall into three main categories:

Continental – Baselines of 100s to 1000s of km

- VLBA
- EVN+Ar (12m)
- HSA - VLBA+ (Ar, Ef, GBT, VLA)

Global – Baselines of tens of 1000s of km

- Global mm-VLBI (EVN+VLBA)
- Space VLBI – involves the use radio dish on board satellite
  - VSOP using 8 m dish,
  - Radioastron using 10m dish.
CURRENT VLBI NETWORKS – VERY LONG BASELINE ARRAY (VLBA)

- 10 x 25m antennas distributed across the US
- 0.3 - 86 GHz
- Maximum baseline ~8,000 km
- Resolution of ~ 0.1 mas at 86 GHz.
CURRENT VLBI NETWORKS – EUROPEAN VLBI NETWORK (EVN)

- ~23 stations, 10m -> 100m diameter
- 0.3 - 43 GHz
- maximum baseline ~ 9000 km
- EVN+Ar gives a baseline of ~ 11,000 km
CURRENT VLBI NETWORKS – HIGH SENSITIVE ARRAY (HSA)
EAST ASIAN VLBI NETWORK

Chinese (CVN): 4 ants
Korean (KVN): 3 ants., simultaneous 22, 43, 86, 129 GHz
VERA: 4 dual-beam ants., maser astrometry 22-49 GHz
From 1999 to 2001, VLBA & Ar co-observed with this antenna.

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

8m radio telescope
Operating freq: 1.6, 5 GHz

RadioAstron has an orbit with apogee ~30 Earth diameter

From 2012, GBT & Arecibo have co-observed with this Russian 10-m antenna, finding a new component of our ISM, unexpected phenomena in quasars, probing innermost regions of AGN jets and B fields.
BASIC ELEMENTS OF VLBI

• Antennas
• Receivers
• Analog stages

• Recorders and data transport
• Correlation, post-processing
VLBI RECORDING SYSTEM AT AO

Consists of

- Roach Digital BackEnd (RDBE), digital processing unit
- Mark 6 recorder, records the data from the RDBE
- Field System, software unit communicates with RDBE and Mark6

The system was upgraded in 2019.

Offers:

- 512 MHz BW in PFB and DDC mode --> total of 2 GHz
- 4 Gbps recording speed
- 32 TB disk capacity
- E-shipping to JIVE
CORRELATOR

- Performs cross-correlation of two signals

\[ C_{ij}(\tau) = \int V_i(t)V_j(t + \tau)dt \]

where i,j are the stations.

The output of the correlator is called a ‘fringe’.

DiFX software correlators

Credit: IVSSC NASA GSFC Kingham lectures
ROLE OF LARGE SINGLE DISHES IN VLBI
IMPROVEMENT IN SENSITIVITY

VLBI Sensitivity of an array:

For identical antennas:

\[
\Delta I \ (Jy/beam) \approx \frac{T_{sys}/G}{\sqrt{(N(N-1)\Delta \nu \tau)}}
\]

For non-identical antennas, \( T_{sys}/G = \sqrt{(T_{sys}/G_1 \cdot T_{sys}/G_2)} \ldots \)

Bigger antenna —> larger gain —> low noise & high sensitivity

For example, for continuum observations at L-18cm, data rate=1024 Mbps, 2 hours of observing time,

<table>
<thead>
<tr>
<th>Array Configuration</th>
<th>Sensitivity (Jy/beam)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVN</td>
<td>13 ( \mu )Jy/beam</td>
</tr>
<tr>
<td>EVN+GBT</td>
<td>6.5 ( \mu )Jy/beam</td>
</tr>
<tr>
<td>Global (VLBA+EVN)</td>
<td>9 ( \mu )Jy/beam</td>
</tr>
<tr>
<td>VLBA+EVN+GBT</td>
<td>5.3 ( \mu )Jy/beam</td>
</tr>
</tbody>
</table>
SPECIAL CONSIDERATIONS

Slew rate     Field of View
LONGER SLEW TIME & POINTING CALIBRATION

- Larger dishes have longer slew times and can lead to loss of time in phase-referencing VLBI.

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Azimuth (deg/min)</th>
<th>Elevation (deg/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GBT</td>
<td>36</td>
<td>18</td>
</tr>
<tr>
<td>Arecibo305m</td>
<td>24</td>
<td>2.4</td>
</tr>
<tr>
<td>20-m</td>
<td>120</td>
<td>120</td>
</tr>
</tbody>
</table>

- Sufficient setup time and breaks in schedule are required for better pointing and focus.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Telescope</th>
<th>Break time</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-10 GHz</td>
<td>GBT</td>
<td>6 min every 4-5 hr</td>
</tr>
<tr>
<td></td>
<td>Effelsberg</td>
<td>8 min every 4 hr</td>
</tr>
<tr>
<td>40 - 90 GHz</td>
<td>GBT</td>
<td>8 min every 30-60 min</td>
</tr>
<tr>
<td></td>
<td>Effelsberg</td>
<td>8 min every 2 hr</td>
</tr>
</tbody>
</table>

- Use a small antenna to track the calibrator continuously while the large dish tracks only the target with occasional visits to the calibrator.
**FIELD OF VIEW**

FoV in an interferometry is determined by the primary beam of the largest antenna —> **Bigger dishes have smaller FoV**

VLBI FoV is limited by bandwidth and time smearing —> **FoV \sim 10^{-4} \times \text{primary beam}**

VLBI field is usually empty, full beam imaging not useful —> **target small fields**

*Multiple phase center technique*
FIELD OF VIEW

FoV in an interferometry is determined by the primary beam of the largest antenna —> **Bigger dishes have smaller FoV**

VLBI FoV is limited by bandwidth and time smearing —> FoV $\sim 10^{-4}$ x primary beam

VLBI field is usually empty, full beam imaging not useful —> **target small fields**

*Multiple phase center technique*
FIELD OF VIEW

FoV in an interferometry is determined by the primary beam of the largest antenna

—> Bigger dishes have smaller FoV

VLBI FoV is limited by bandwidth and time smearing —> FoV \sim 10^{-4} \times \text{primary beam}

VLBI field is usually empty, full beam imaging not useful —> target small fields

Multiple phase center technique

Repeat for many phase centers
A VLBI resolution of the Pleiades distance controversy

RadioAstron Observations of the Quasar 3C273: A Challenge to the Brightness Temperature Limit

Localization of repeating FRB

For FRB121102, three out of the four e-EVN detected pulses could not have been found without Arecibo.

Marcote +2017
SUMMARY

➤ VLBI offers high resolutions

➤ Addition of large single dishes (e.g. GBT, Effelsberg, FAST) to VLBI arrays
  ➤ provide significant boost in sensitivity.
  ➤ Are invaluable for spectral line and transient source studies where bandwidth and integration times have natural limits.

➤ Specials considerations such as slew rate and FoV