## **Role of Large Single Dishes in VLBI**

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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 = (Imax - Imin)/(Imax + Imin)

#### Two Element (Radio) Interferometer:



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

$$\boldsymbol{R}(\tau_{g}) = C_{1}C_{2}\cos[2\pi\nu\tau_{g}]$$

## **Basic Concept - contd.** : Visibility (u-v) plane

Tracking a source across the sky provides more information than a "snapshot" observation, because the source is sampled with a variety of fringe spacings orientated at different angles to the source.

One way to formalize this is to adopt the "view" of the baseline from the source.



## 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

$$\mathsf{V} = \int_{-\infty}^{+\infty} \mathrm{d}\boldsymbol{\sigma} \cdot I(\boldsymbol{\sigma}) \cdot \exp\{i2\pi \mathbf{b} \cdot \boldsymbol{\sigma}\}$$

V = Visibility function = Fourier transformation of source's brightness distribution

$$I(\sigma) = F^{-1} V(b)$$

# Some 2D FT pairs



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NRÃO

# From a "Dirty" to "CLEAN" image,

# <figure>

#### Deconvolve

#### Clean Image



#### Dirty Beam





# **Examples of Arrays**

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



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





# 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.
- $\succ$  Distributed across the US.

ape Drives

- Range of Baselines:236 to 8611km.
- ► 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



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

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, and unexpected phenomena in quasars.

## **A Few Relevant Parameters**

#### **VLBI: Resolution**

$$\theta \sim \frac{\lambda}{b \max}$$

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

#### VLBI: Image Sensitivity

 $\Delta I$ (Jy/beam)  $\approx \frac{SEFD}{\sqrt{N(N-1) \times \Delta v \times t_{int}}}$ 

VLBI: Baseline Sensitivity  $\Delta I_{12} \approx \sqrt{[SEFD_1 \cdot SEFD_2/\Delta v \Delta t]}$  For 10 hr observing, dual polarization,  $\Delta v$ = 16 MHz, the rms noise of the VLBA is ~40  $\mu$  Jy/beam.

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,  $\theta_{\rm f} \approx \lambda/b \times (\nu/\Delta\nu)$ . For 10<sup>4</sup> km baseline, and 50-MHz bandwidth at 6cm, (with a resolution of 1mas), the FOV is 120 mas.

#### **EVN Calculator**

EVN e-EVN VLBA GLOBAL GMVA	RESET GO		
Observing band & data rate [Mbit/s]	On-source integration time [min]		
L - 18cm 🗘 1024 🗘	150		
Ef Nt My Pv Pa Hn			
Mc Sh Km Ro70 Ho NI			
On Tm65 Sv Ro34 Cd VFd			
Tr Ur Zc Pb Ap ZLa	The image thermal noise is estimated		
🗆 Jb1 🗌 Mh 🔤 Bd 🔤 Ku 🔤 Go 🕑 Kp	to be 31.18 uJy/beam (1 sigma) using natural weighting.		
🗆 Jb2 🔍 Ys 🔍 Wz 🔷 Ky 🔷 Gb 🕑 Pt			
Cm Sr Ka Kt Y1 Ov			
□ Wb □ Ar □ Ir □ At □ Y27 ∨ Br			
□ W1 □ Hh □ ALMA □ Mp 🕑 Sc 🕑 Mk			
Number of spectral channels per subband, integration time [s], and maximum baseline length	Number of polarizations, subbands per polarizations, and bandwidth of a subband [MHz]		
16 ch ᅌ 2 s ᅌ 10000 km (Full EVN) ᅌ	2 pols 🗘 8 sb 🗘 16 MHz 🗘		
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.		
	RESET GO		

http://www.evlbi.org/cgibin/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:

HSA (VLBA+Y27+EF+GB+Ar)	1σ Image noise = <mark>3.3 μJy/b</mark> eam
-Ar	<b>7.1 µJy/beam</b>
<u>EVN+Ar</u>	1σ Image noise = <mark>3.8 μJy</mark> /beam
-Ar	<mark>9 μJy</mark> /beam
Global ( <u>EVN+VLBA</u> +Y27+ <u>Gb</u> )+ <u>Ar</u>	1σ Image noise = <mark>2.5 μJy</mark> /beam
- <u>Ar</u>	<mark>4.7 µЈу</mark> /beam

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

EVN	EVN+AR	<u>VLBA</u>	VLBA+Y27+GB	VLBA+Y27+Gb+AR
0.9	0.31	3.0	0.62	0.25 <u>mJy</u> /beam/ <u>ch</u>
mJy/beam/ch				



### **VLBI Field-Of-View**

- 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 <u>VLBI</u> resolution
    - "full beam" imaging not needed; rather, many small "fields" (phase centers)
    - DiFX allows many phase centers in one <u>correlator</u> 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



## **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.

# **Repeating FRB host**



#### Home Galaxy of a Fast Radio Burst Identified | N

On 2016 September 20, we detected four individual bursts in the Arecibo single-dish PUPPI data that overlap with EVN data acquisition (Table <u>1</u>). 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 <u>1</u> 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 <u>3.2</u>.





# **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





ngVLA

Long Baseline Options

The picture: Shadow of the Black Hole in M 87







- 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 constant

The Next Generation Very Large Array