Role of Large Single Dishes in VLBI

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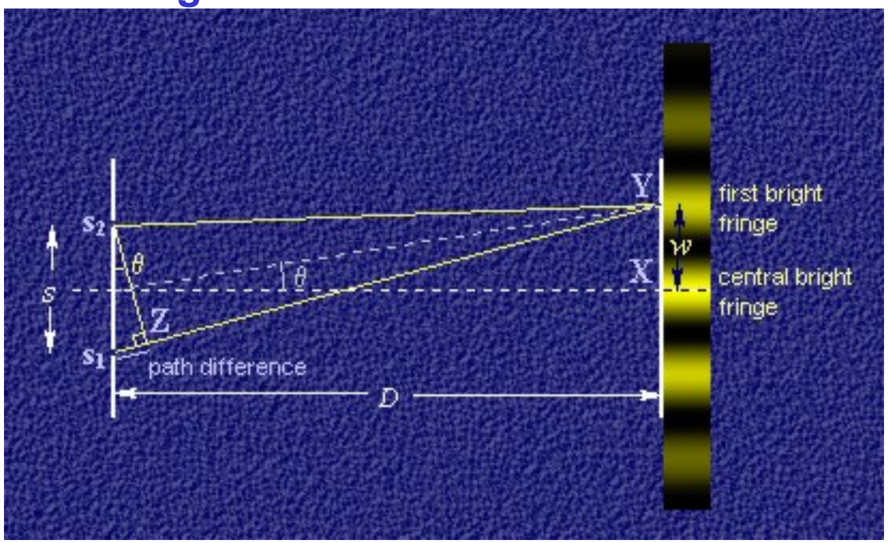
Outline:

- 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.



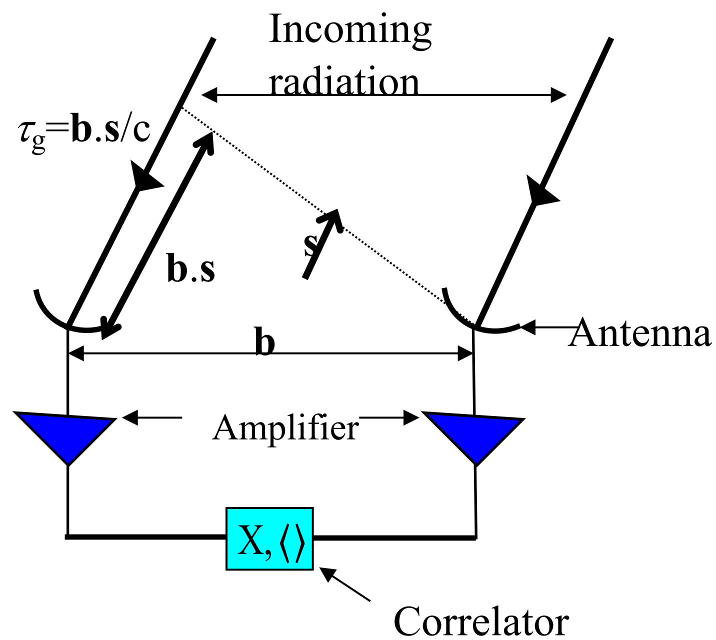
Constructive interference: d $\sin\theta = n\,\lambda$

Destructive interference: d $\sin\theta=(n+1/2)\,\lambda$

Fringe Spacing = λ/d

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

Two Element (Radio) Interferometer:



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

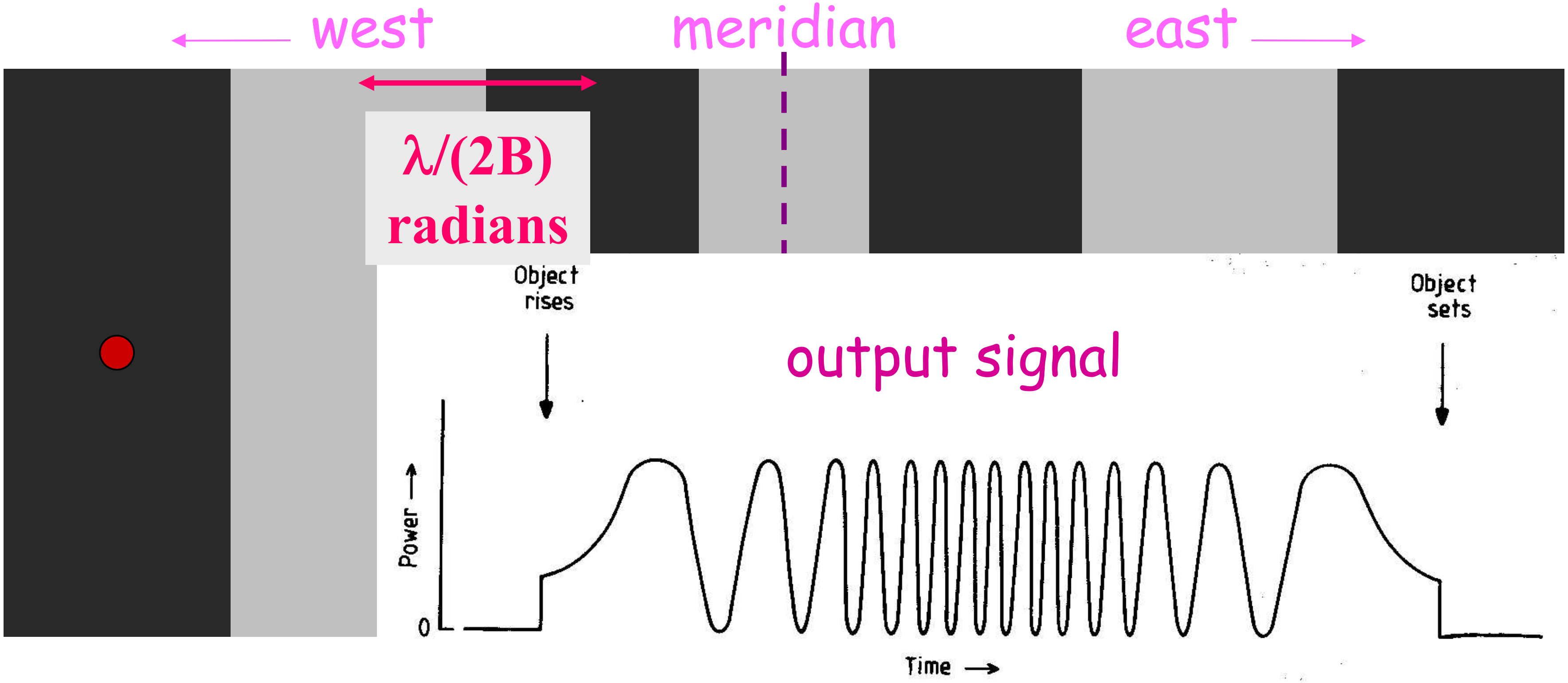
$$\mathcal{R}(\ _g) = C_1C_2\cos[2\qquad _g]$$

Basic Concepts

By analogy to the double slit experiment, regions which would cause constructive and destructive interference can be considered "stripes" in the sky. As the source moves through it, it produces oscillating output signal.

The angular resolution is now given by the fringe half-spacing $\lambda/2B$ (in radian).

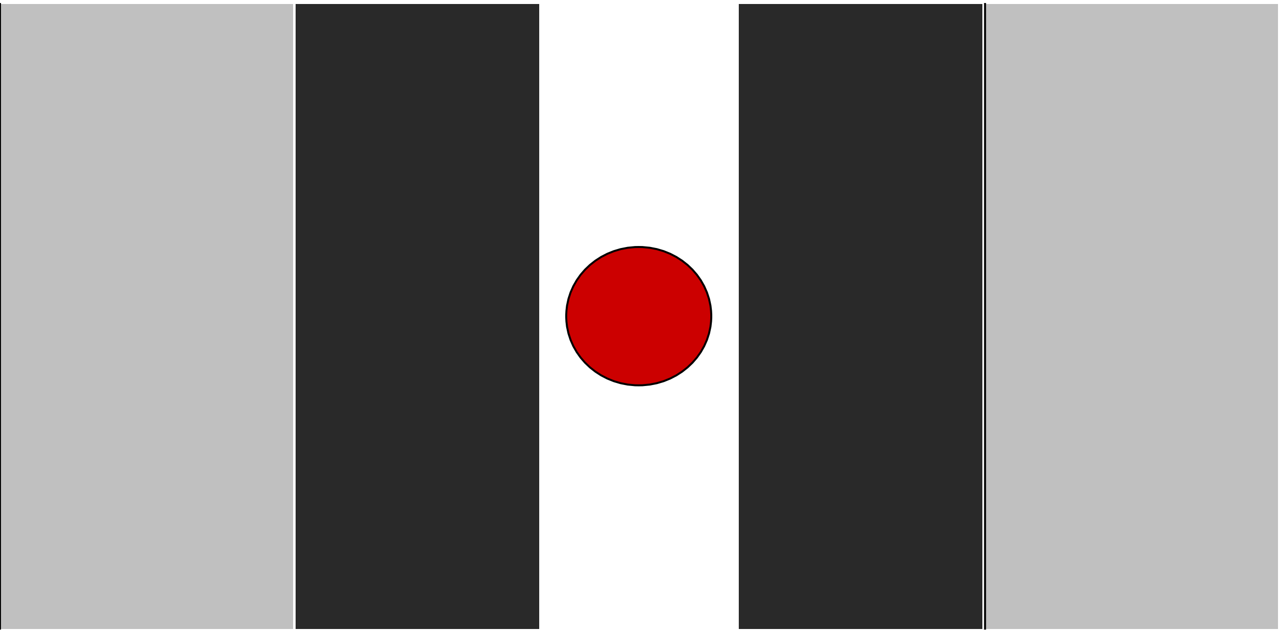
If the source is very small compared to the fringe half-spacing $\lambda/(2B)$, we say it is unresolved. The output signal is then just the fringe pattern.



Basic Concept-contd. : Delay tracking

- If the source size is comparable to, or greater than, the fringe spacing, there will be little change In the output signal -- the source is then said to be “resolved out”.

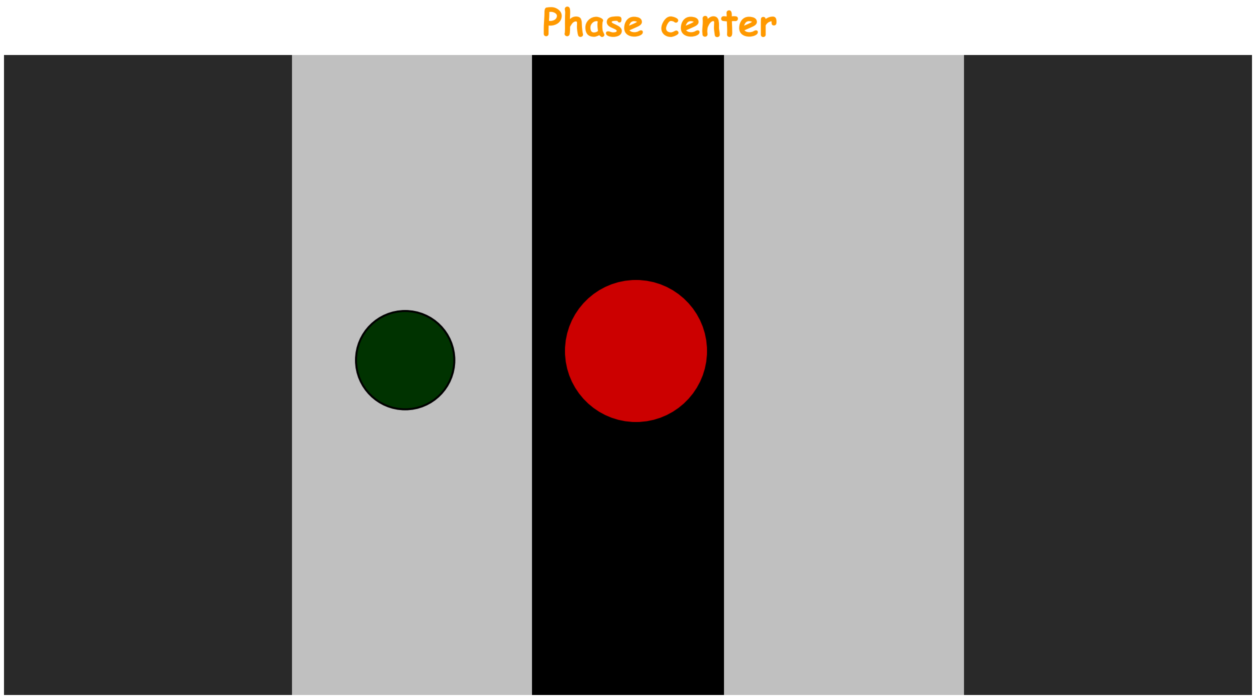
- Since the fringe spacing is proportional to wavelength, different frequencies in the observing band will have slightly different fringe patterns. To counter this, a variable delay is added to the signal from one dish, causing the white light fringe to follow the source across the sky.



Basic Concept-contd. : Delay tracking

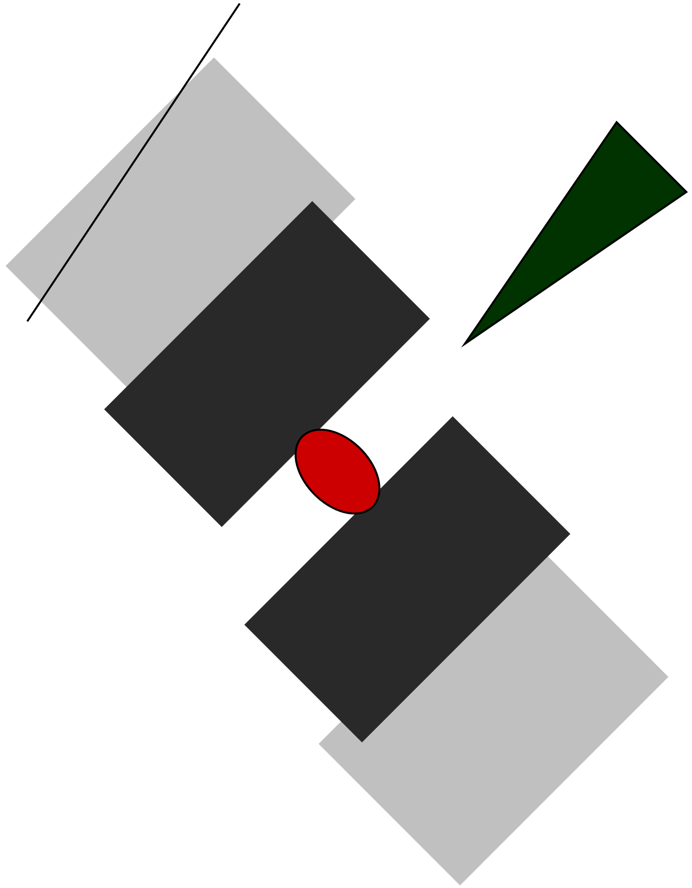
▪ However, by having the fringes move with the source, less information is available at a time about the source structure.

So a phase shift of $\pi/2$ is inserted in parallel to effectively shift the fringe pattern. This is done automatically by using a complex correlator, and we measure a quantity called the complex fringe visibility of the source, V(b) where, V_amp= Sqrt(Rcos ^{2} + Rsin ^{2}) & V_phase= tan $^{-1}$ (Rsin/Rcos)..



Basic Concept-contd. : Fringe rotation

The changing baseline geometry causes the fringes to change orientation with time!

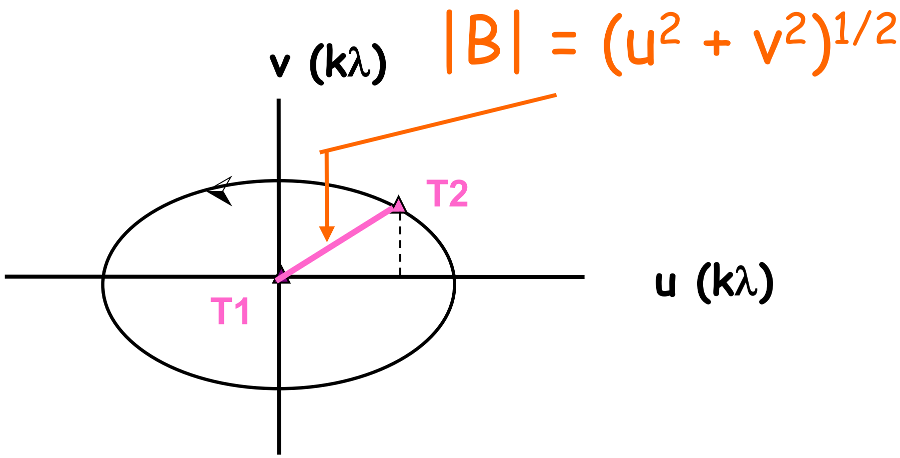


Basic Concept - contd. : Visibility (u-v) plane

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.

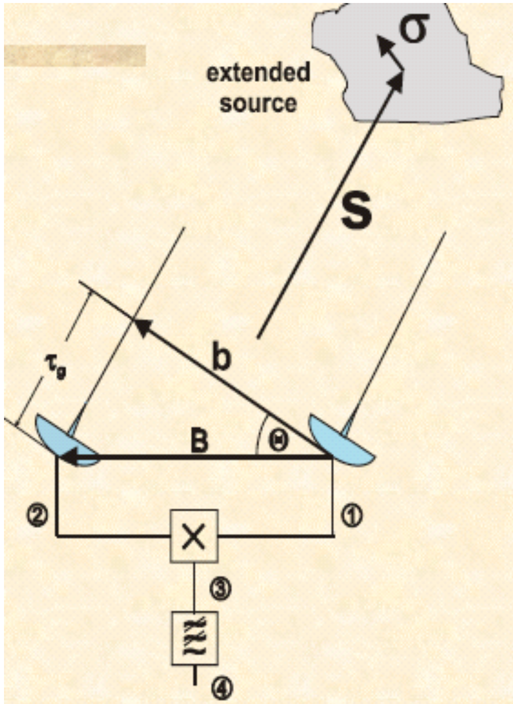
One way to formalize this is to adopt the "view" of the baseline from the source.

- **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 → Brightness distribution



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

$$V = \int_{-\infty}^{+\infty} d\boldsymbol{\sigma} \cdot I(\boldsymbol{\sigma}) \cdot \exp\{i 2\pi \mathbf{b} \cdot \boldsymbol{\sigma}\}$$

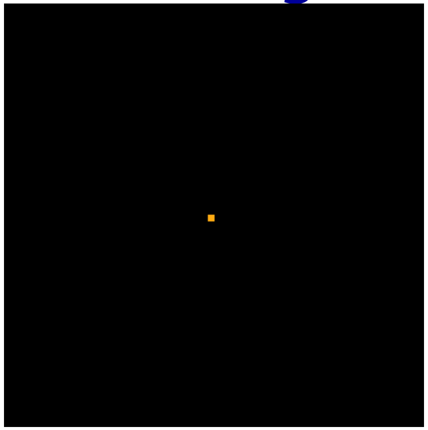
V = Visibility function = **Fourier transformation of source's brightness distribution**

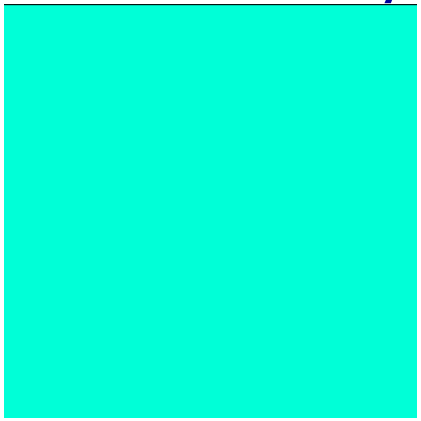
$$I(\sigma) = F^{-1}\ V(b)$$

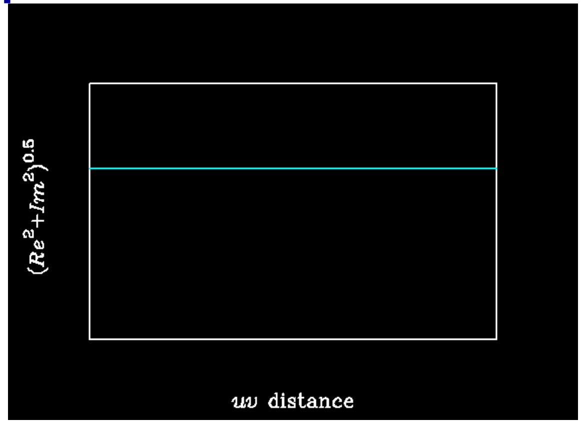
Some 2D FT pairs

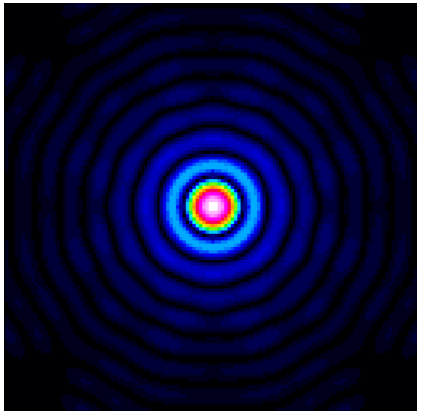
Image

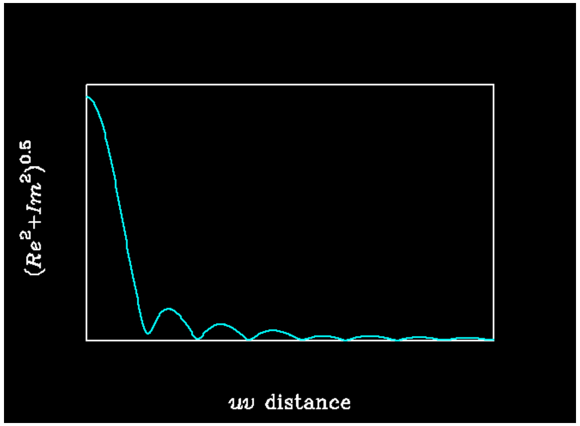
Visibility amp





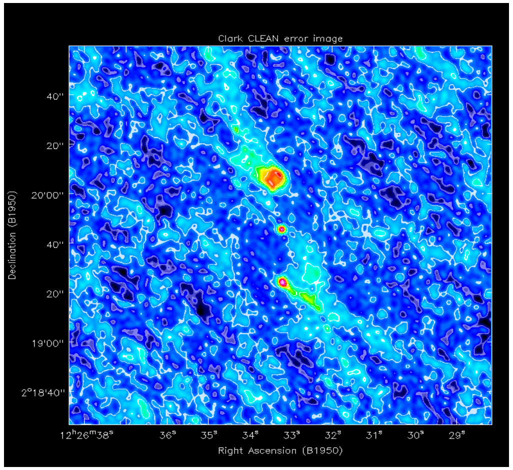






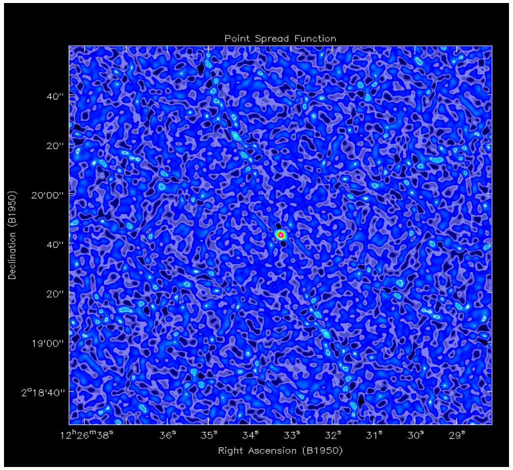
From a "Dirty" to "CLEAN" image,

Dirty Image

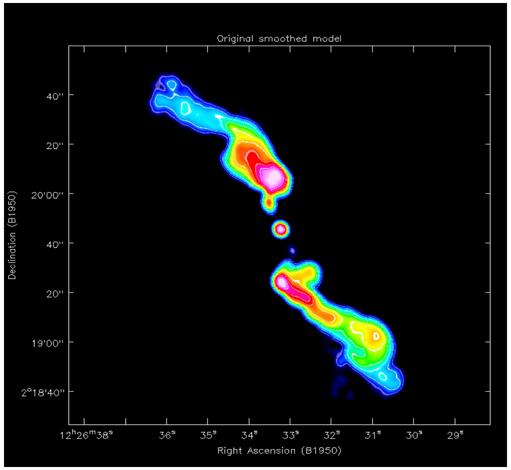


Deconvolve

Dirty Beam



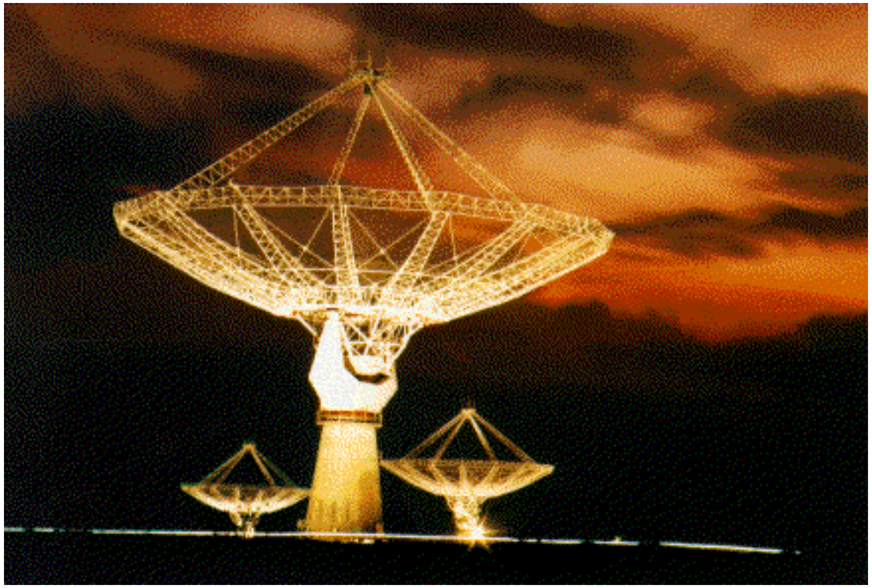
Clean Image

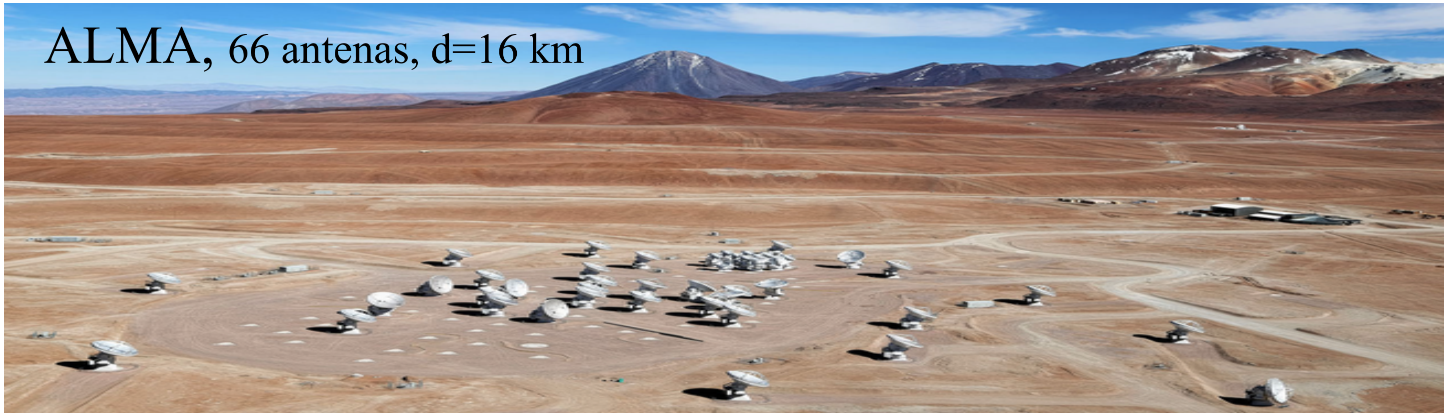


Examples of Arrays

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

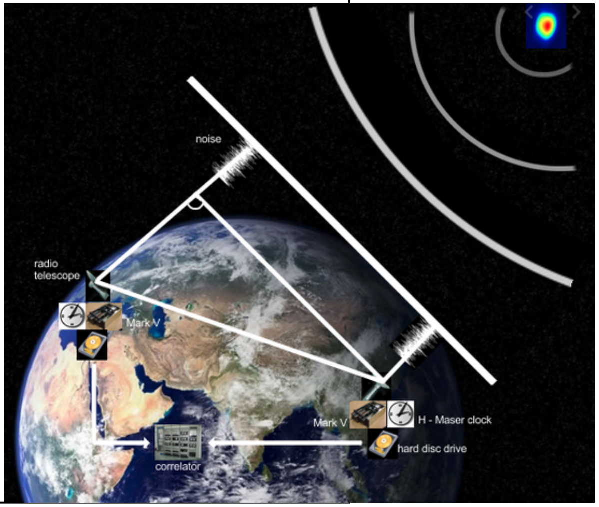
GMRT-Giant Meterwave Radio Telescope
30 antennas, d=45 m





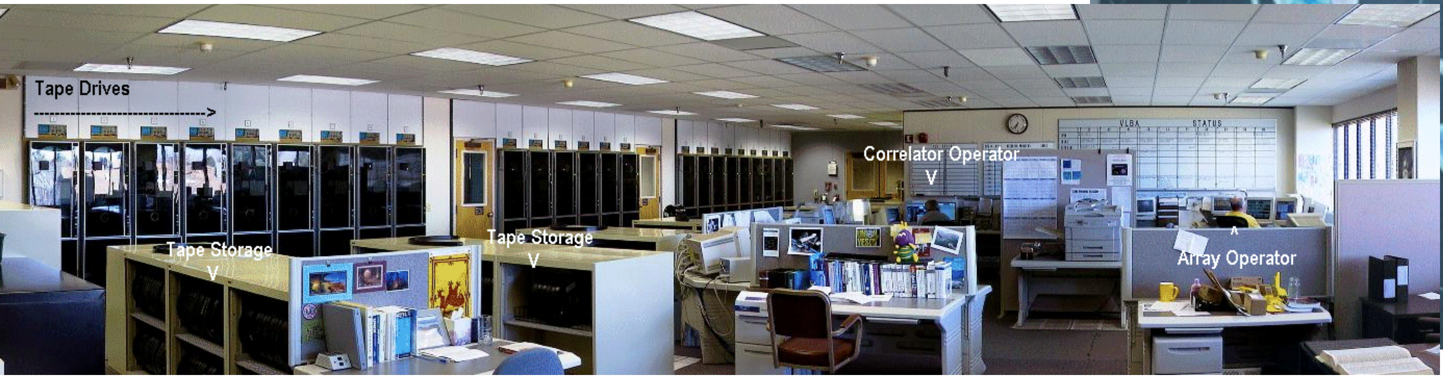
What is VLBI?

- 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



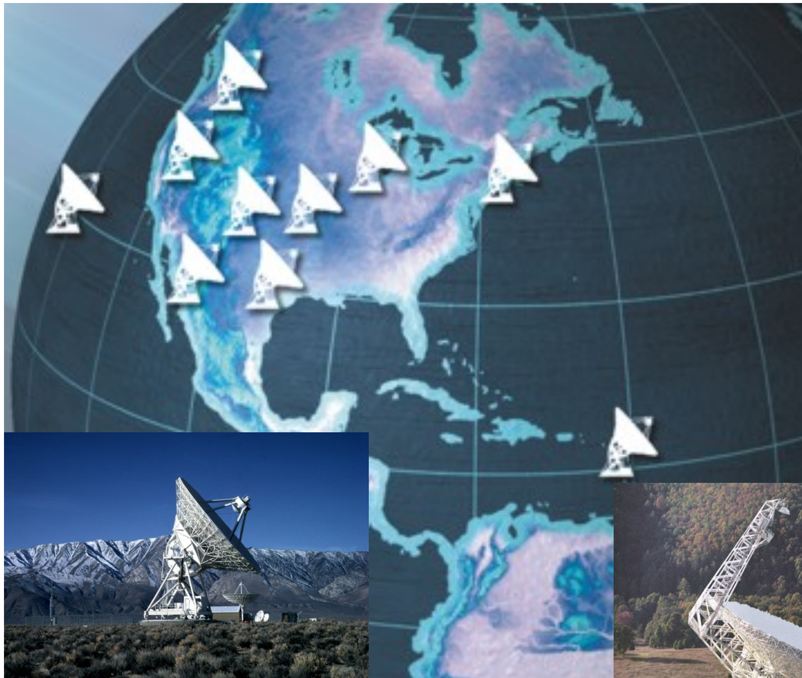
The Very Long Baseline Array (VLBA)

- Ten 25 m identical antennas.
- Distributed across the US.
- 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

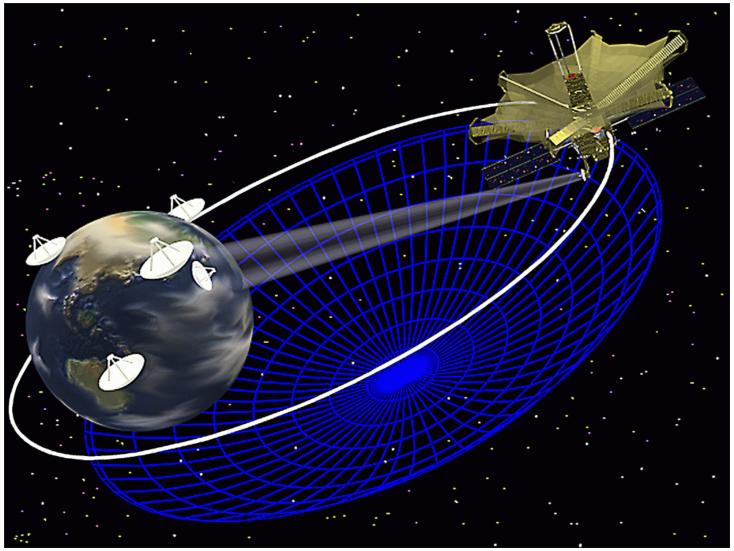
HSA=VLBA+Y27+GBT+AR+EB

LBA in Australia, KVN – S.Korea

CMVA - mm-range VLBI

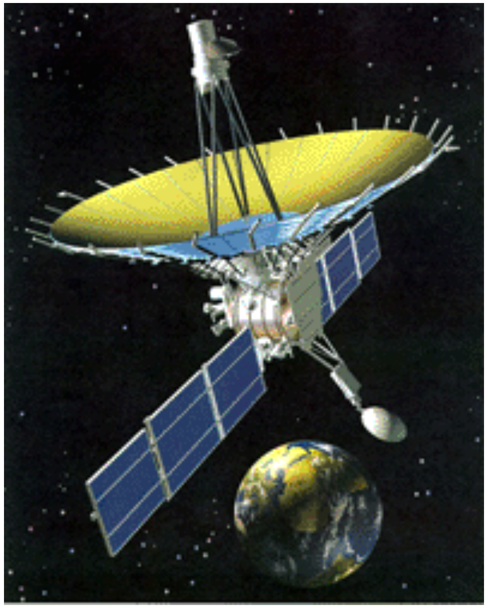
VLBI with Antennas in Space

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

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

For 10 hr observing, dual polarization, $\Delta\nu$= 16 MHz, the rms noise of the VLBA is ~40 μ Jy/beam.

VLBI: Baseline Sensitivity

$$\Delta I_{12} \approx \sqrt{[SEFD_1 \,.\, SEFD_2/\Delta\nu\Delta t]}$$

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 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]: L - 18cm | 1024

On-source integration time [min]: 150

☐ Ef	☐ Nt	☐ My	☐ Pv	☐ Pa	☑ Hn
☐ Mc	☐ Sh	☐ Km	☐ Ro70	☐ Ho	☑ Nl
☐ On	☐ Tm65	☐ Sv	☐ Ro34	☐ Cd	☑ Fd
☐ Tr	☐ Ur	☐ Zc	☐ Pb	☐ Ap	☑ La
☐ Jb1	☐ Mh	☐ Bd	☐ Ku	☐ Go	☑ Kp
☐ Jb2	☐ Ys	☐ Wz	☐ Ky	☐ Gb	☑ Pt
☐ Cm	☐ Sr	☐ Ka	☐ Kt	☐ Y1	☑ Ov
☐ Wb	☐ Ar	☐ Ir	☐ At	☐ Y27	☑ Br
☐ W1	☐ Hh	☐ ALMA	☐ Mp	☑ Sc	☑ Mk

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)

Number of polarizations, subbands per polarizations, and bandwidth of a subband [MHz]: 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/cgi-bin/EVNcalc

Why add a Big Dish to VLBI Arrays

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

HSA (VLBA+Y27+EF+GB+Ar) *-Ar*	*1σ Image noise = 3.3 μJy/beam* *7.1 μJy/beam*
EVN+Ar *-Ar*	*1σ Image noise = 3.8 μJy/beam* *9 μJy/beam*
Global (EVN+VLBA+Y27+Gb)+Ar *-Ar*	*1σ Image noise = 2.5 μJy/beam* *4.7 μJy/beam*

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

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

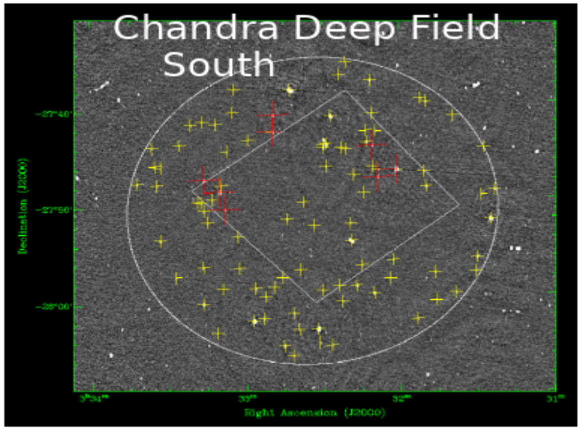
VLBI Field-Of-View

- 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 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 a connected element array for VLBI

Single element (Y1)

- Improves uv coverage but probably has minimal impact on sensitivity.

Full array (Y27)

- Can vastly improve sensitivity
- Requires additional calibration observations, "phasing up", to make the array synthesize a single VLBI element

VLBI Phase Referencing

- **Technique**:
  - Observe a strong phase calibrator near the target on the sky
  - Measure phase using calibrator and apply to the target source

- **Advantages**:
  - Allows imaging of faint sources
  - Preserves absolute sky position (essential for astrometry)

- **Disdavantages:**
  - More overhead involved in calibrator observations
  - Suitable nearby calibrator(s) not always available

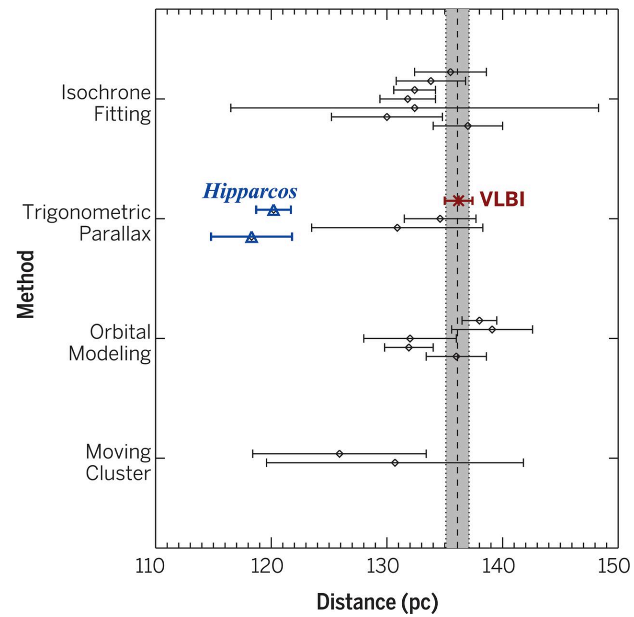
Some Practical Considerations

- Proposals requesting out-of network single-dish telescopes are either submitted through VLBA system or handled in an ad hoc manner.
- Most telescopes participating in VLBI use standard backends and recorders (RDBE and Mark 5C/Mark6 recorder)
- Schedules are prepared with SCHED, a standard, text-based software package for VLBI scheduling
- Observations and correlations are run by staff – some pipeline processing can also be done by staff, then regular synthesis data processing is done by P.Is in AIPS or CASA.

Arecibo VLBI system
Courtesy: Luis. Quintero

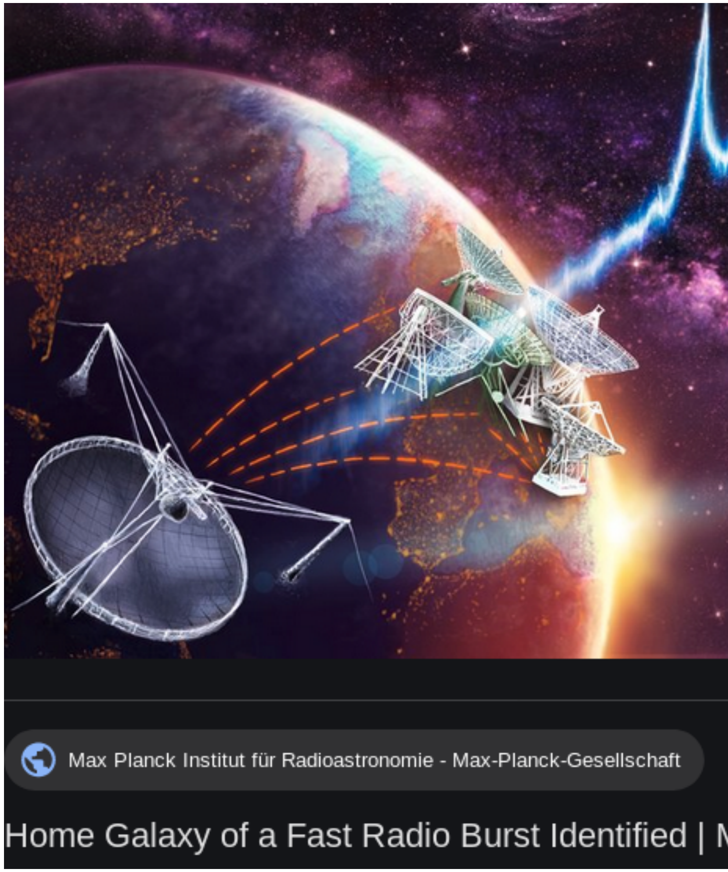
Recent Important Results:

VLBI Resolves the Pleiades Distance Controversy

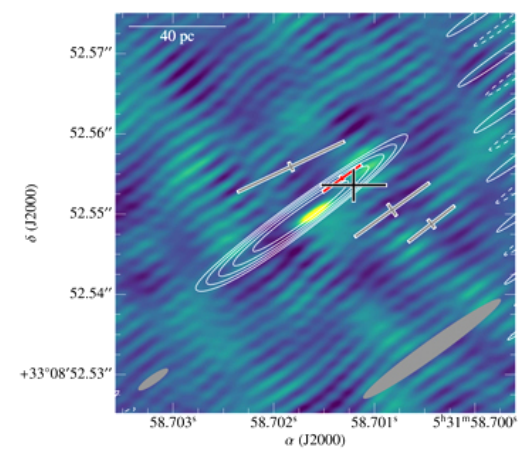


The Pleiades, or “Seven Sisters”, is a star cluster that is critical to our understanding of all objects throughout the universe. For decades, there has been debate over the exact distance from us to the Pleiades. Radio VLBI has now provided a "gold standard" distance measurement – Melis et al, 2014. Distance measurements of these weak stellar radio emitters would have been impossible without the presence of the Arecibo telescope in the VLBI Array.

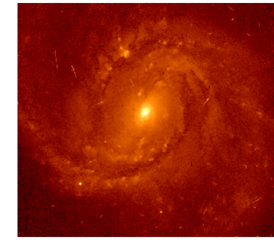
Repeating FRB host

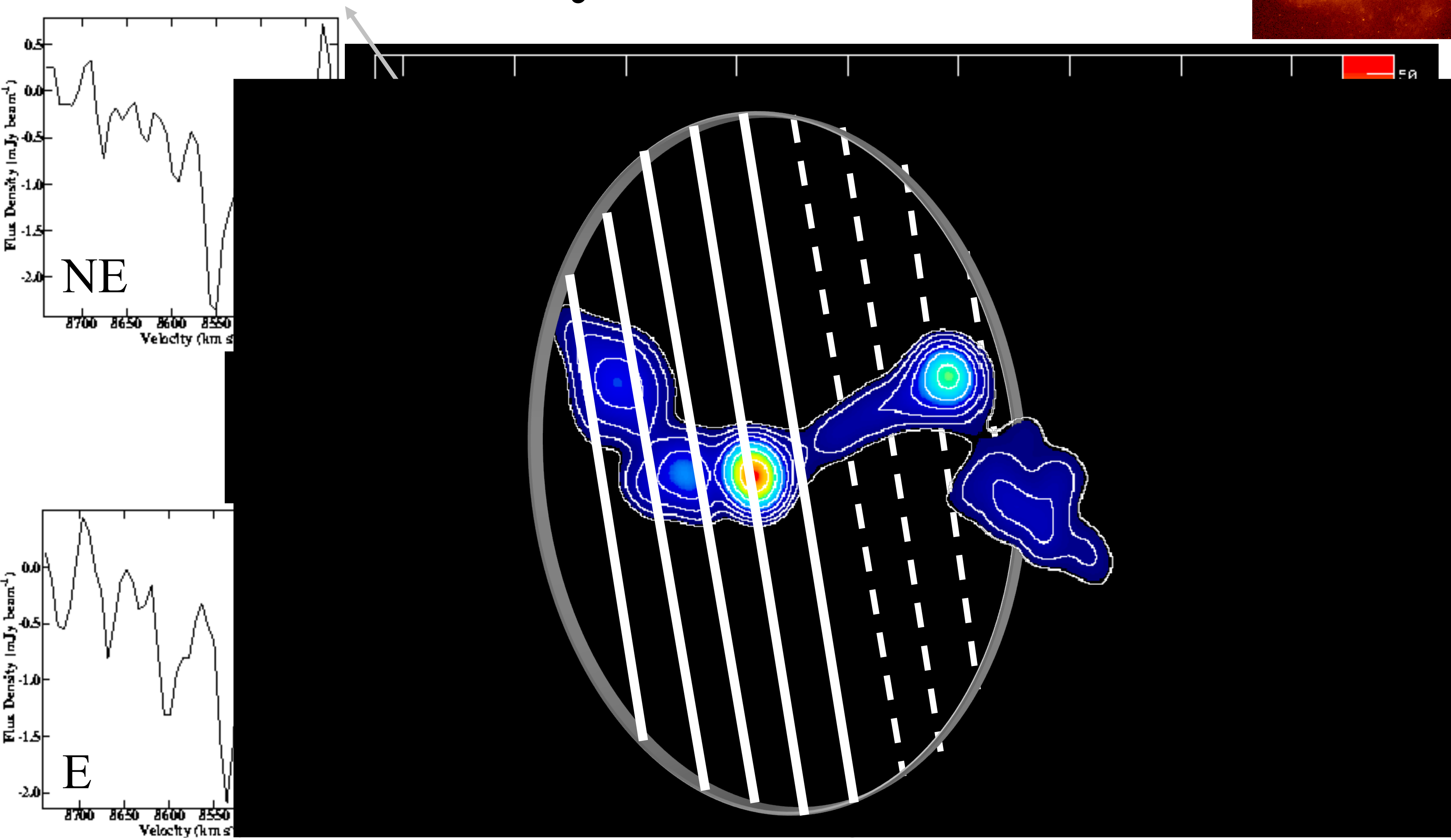


On 2016 September 20, we detected four individual bursts in the Arecibo single-dish PUPPI data that overlap with EVN data acquisition (Table 1). No bursts were detected in the Arecibo PUPPI (1.7 GHz) or Mock (5 GHz) data from other sessions in which there are simultaneous EVN observations that can be 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 $\lesssim 15$ mas around the position of the persistent source, and we discuss this scatter in Section 3.2.



The Seyfert-2 NGC 7674



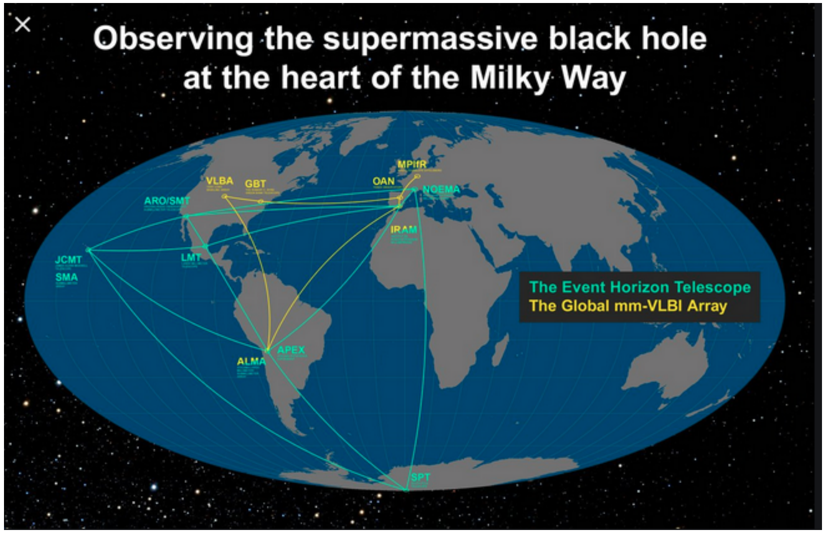


Summary …. a n d ...

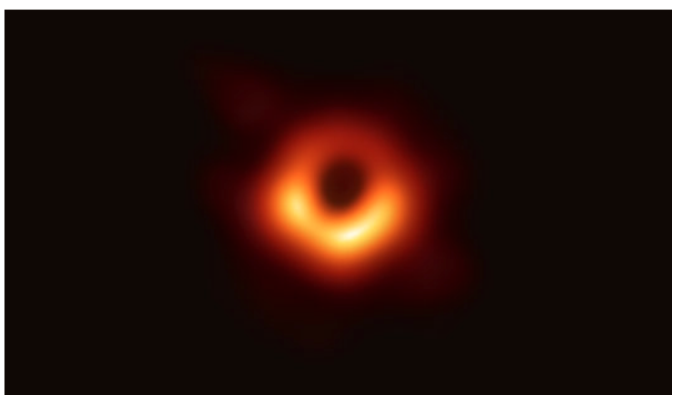
- VLBI provides extremely high angular resolution.
- Recent trends are to move to ultra-wide bandwidth data recording and wide-field mapping.
- Use of large single-dishes (e.g. GBT and Arecibo) with VLBA provides significant boost in sensitivity and u-v coverage.
- Large single-dish telescopes with VLBA are invaluable for spectral line and transient source studies where bandwidths and integration times have natural limits.

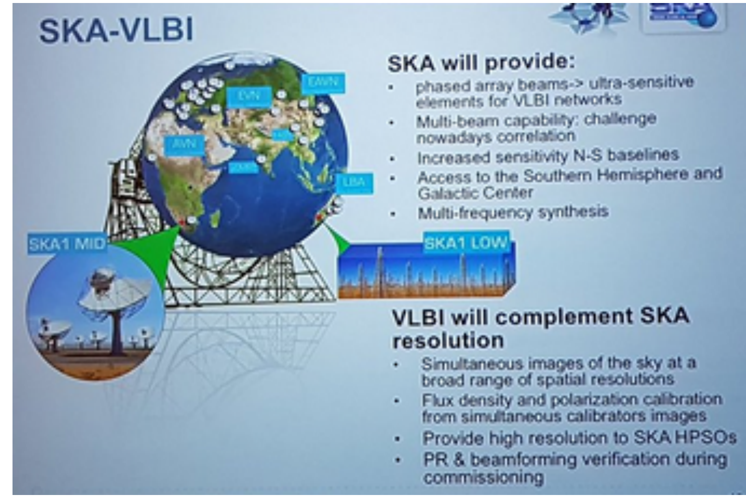
Future

GMVA & EHT



The picture: Shadow of the Black Hole in M 87





ngVLA