Array Configuration

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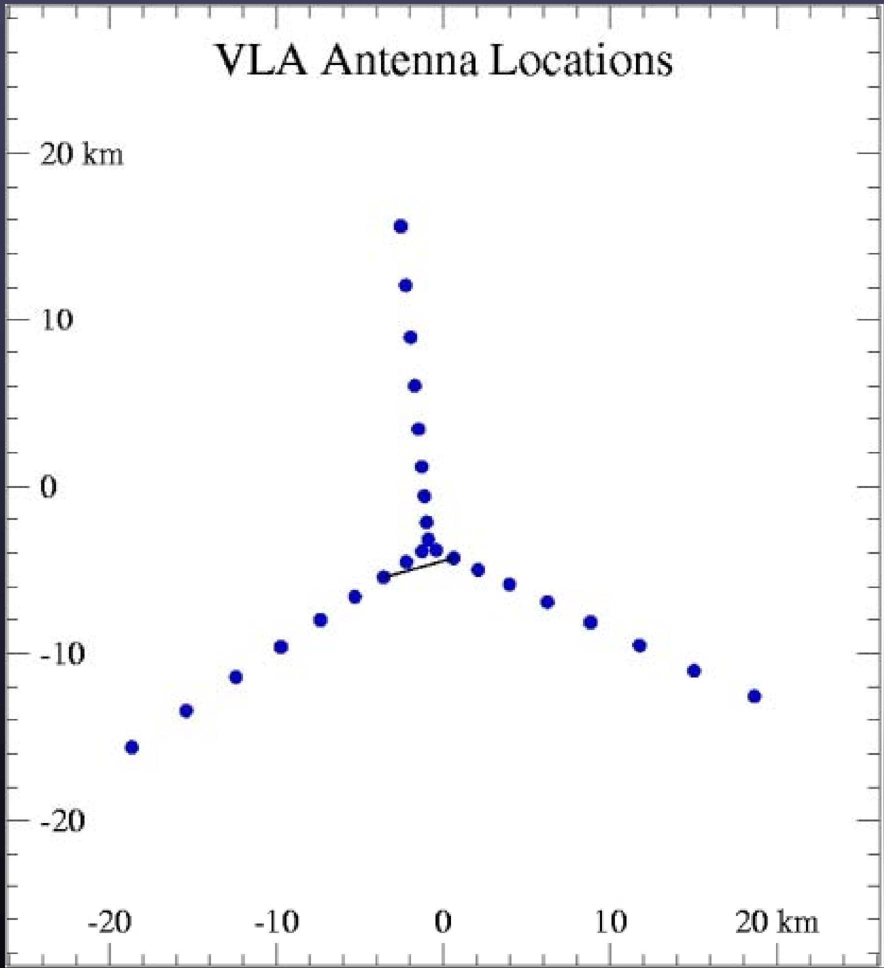
(based Aaron Cohen's lecture at NRAO's 2008 Synthesis Imaging Workshop)

Outline of Talk

- Quick Review of How Interferometry Works
- Overview of a few Interferometric Arrays
  - VLA, WSRT, GMRT, VLBA, MeerKAT
- Parameters of Array Design
  - min/max baseline lengths, number of elements, etc.
- Figures of Merit for Arrays Designs
  - resolution, angular scale, sidelobe levels, etc.
- Optimizing Array Configurations
  - continuous example
  - discrete example (LWIA)
- Large N, Small D concept

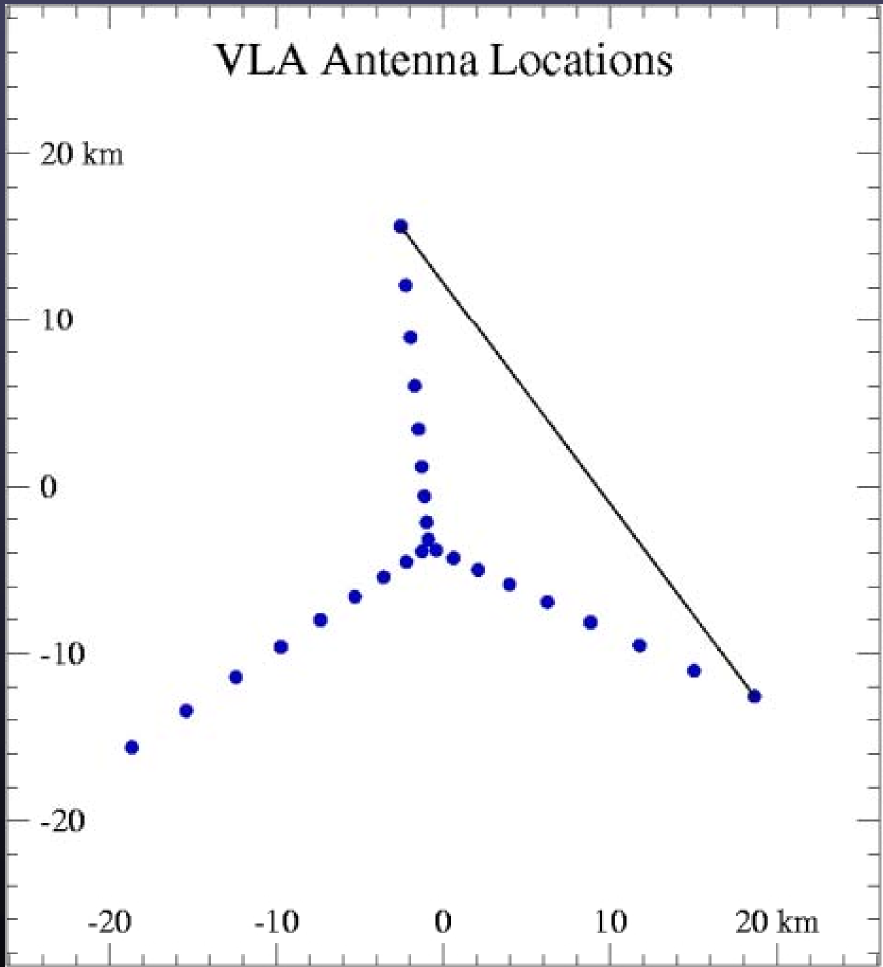
Single Baseline Interferometry

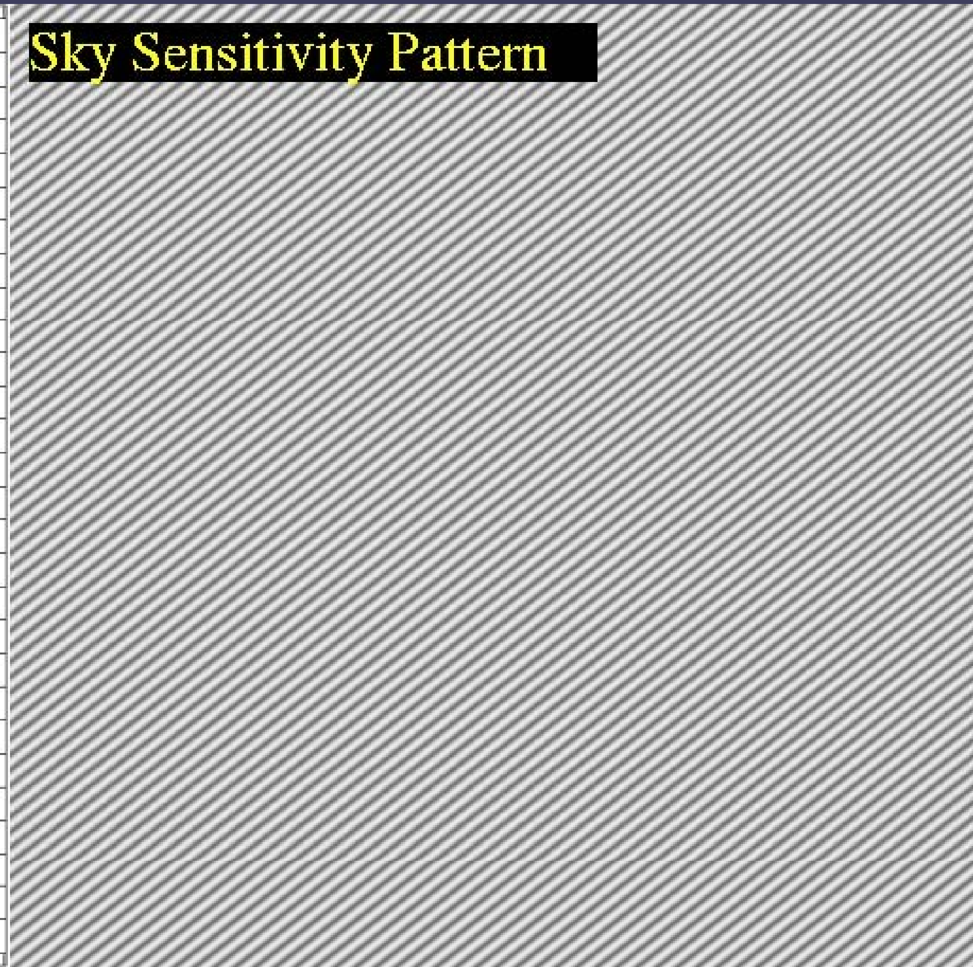
A single baseline has a sinusoidal sensitivity pattern across the sky, oscillating between constructive and destructive interference.



Single Baseline Interferometry

The oscillations in the sensitivity pattern have the same direction as the baseline, with a period determined by the baseline length in wavelengths

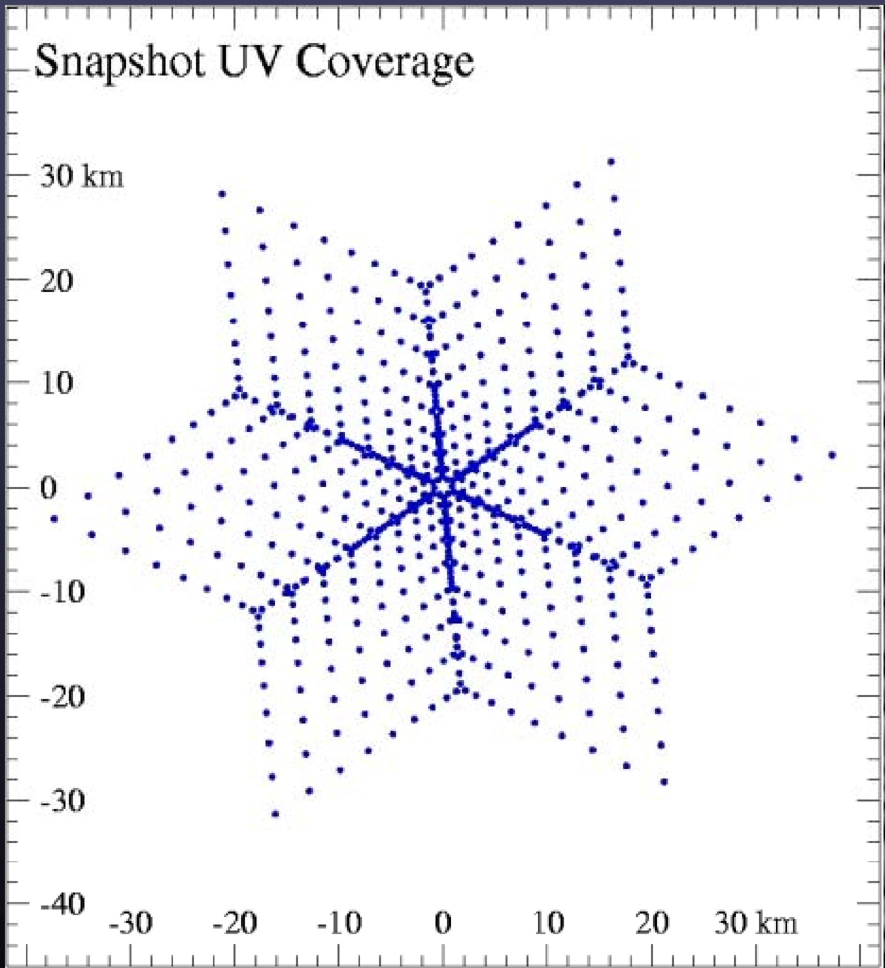


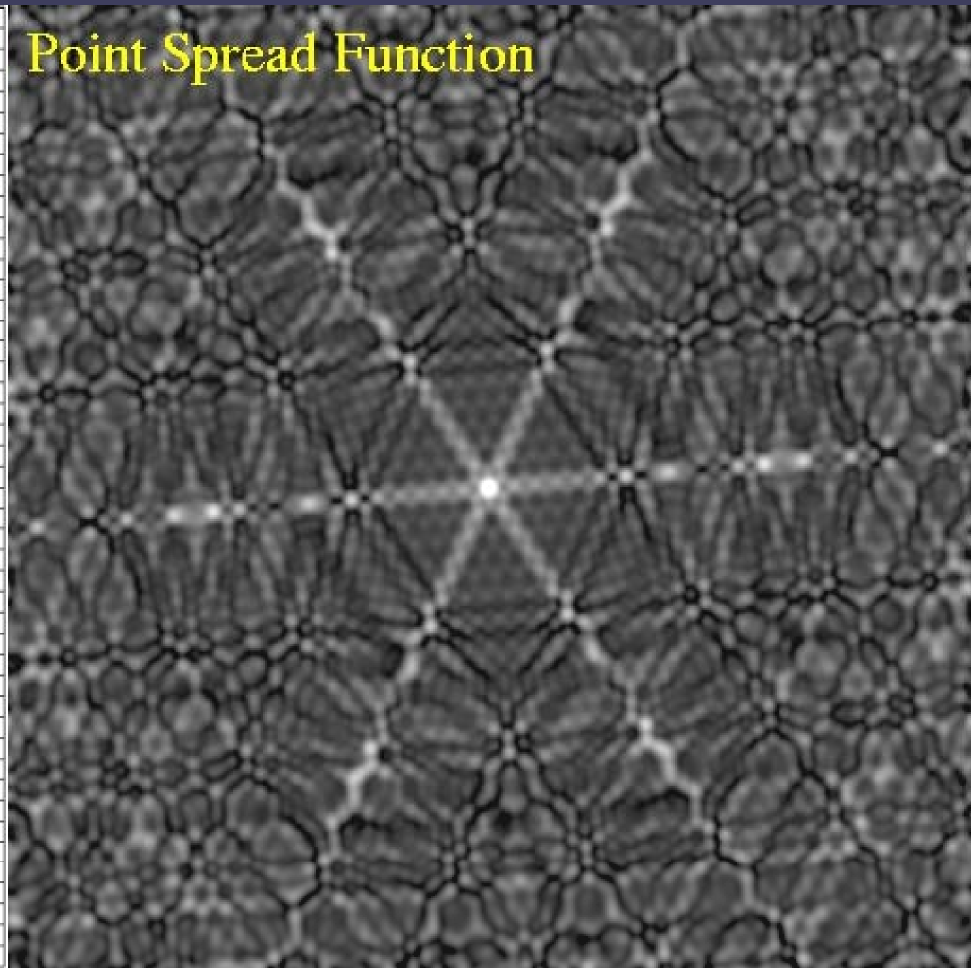


Point Spread Function for the VLA

The uv-coverage is the set of all baseline vectors.

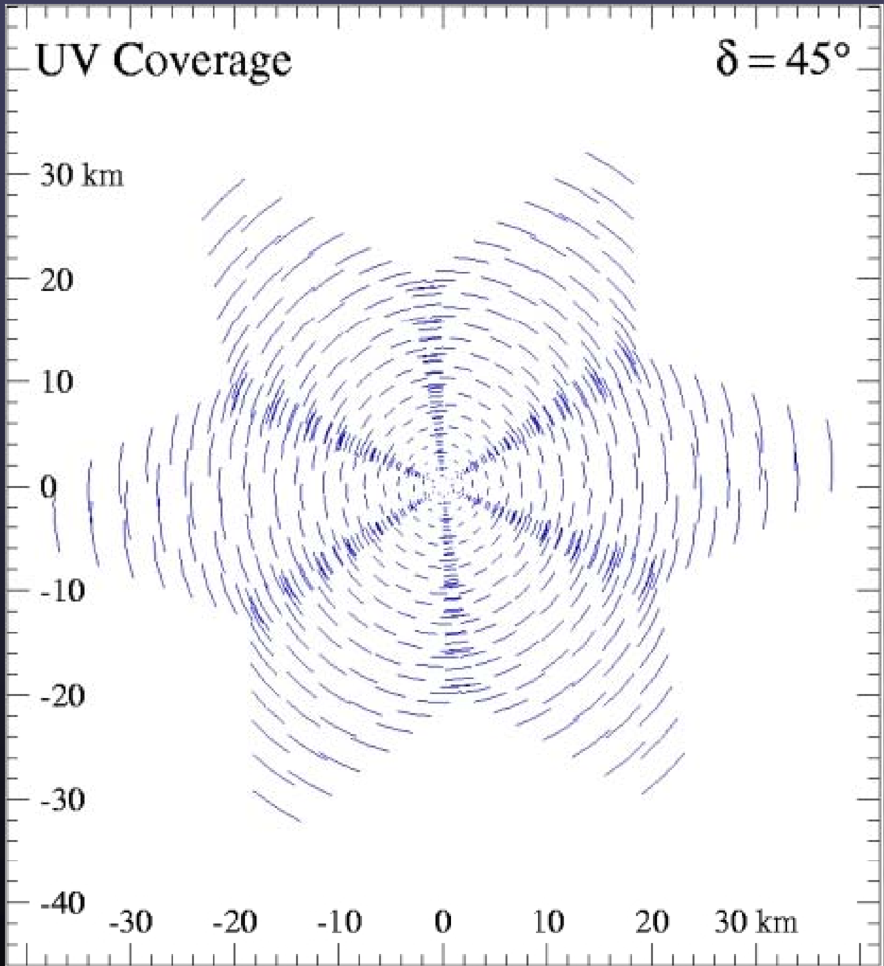
The synthesized beam (PSF) is the sensitivity pattern of all baselines.

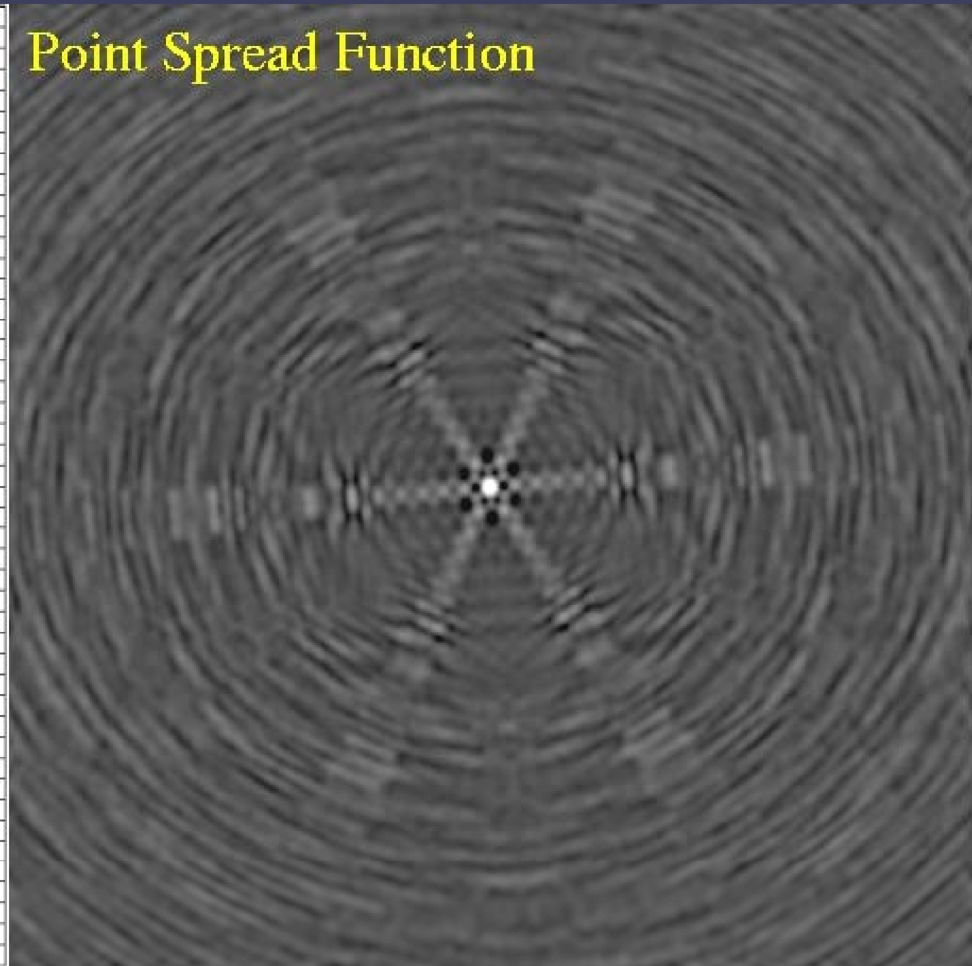




Point Spread Function for the VLA

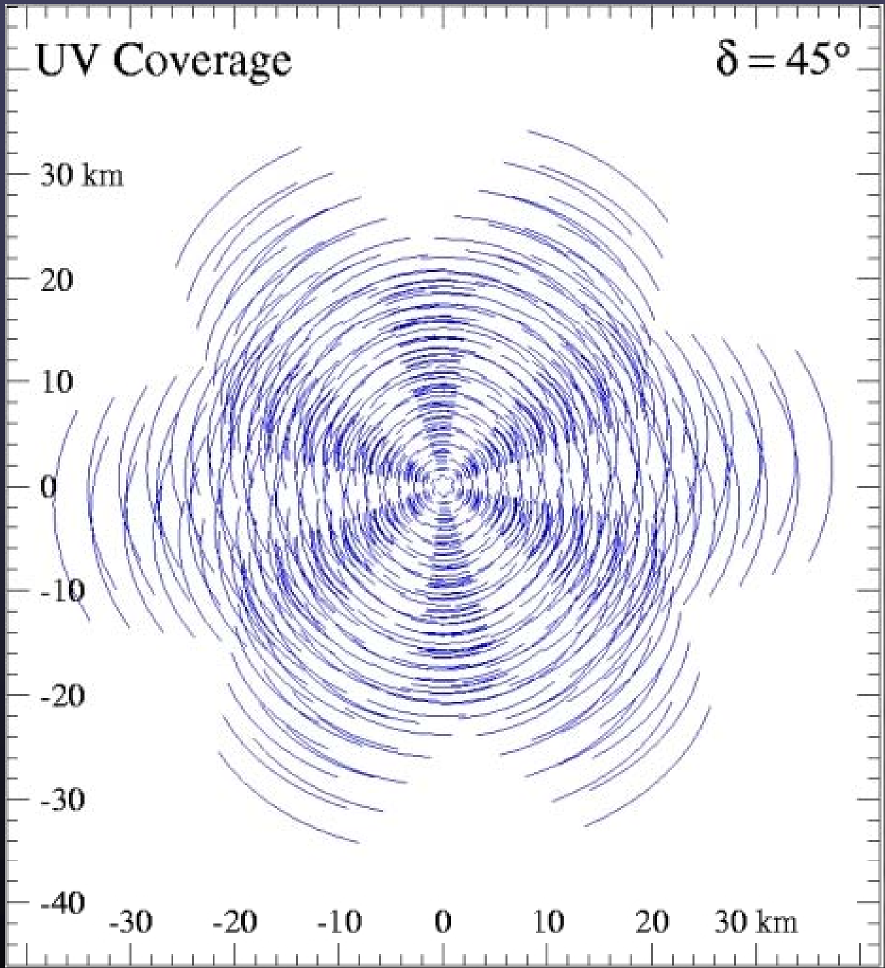
1 Hour Synthesis Observation

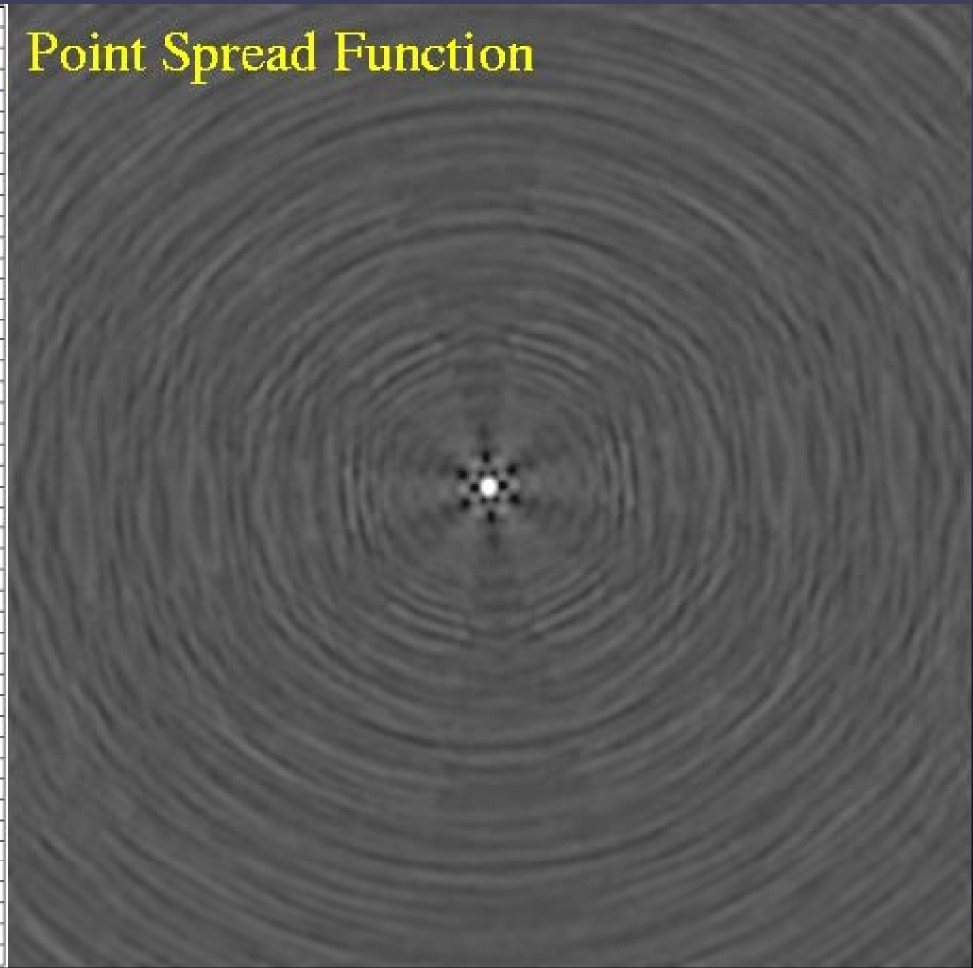




Point Spread Function for the VLA

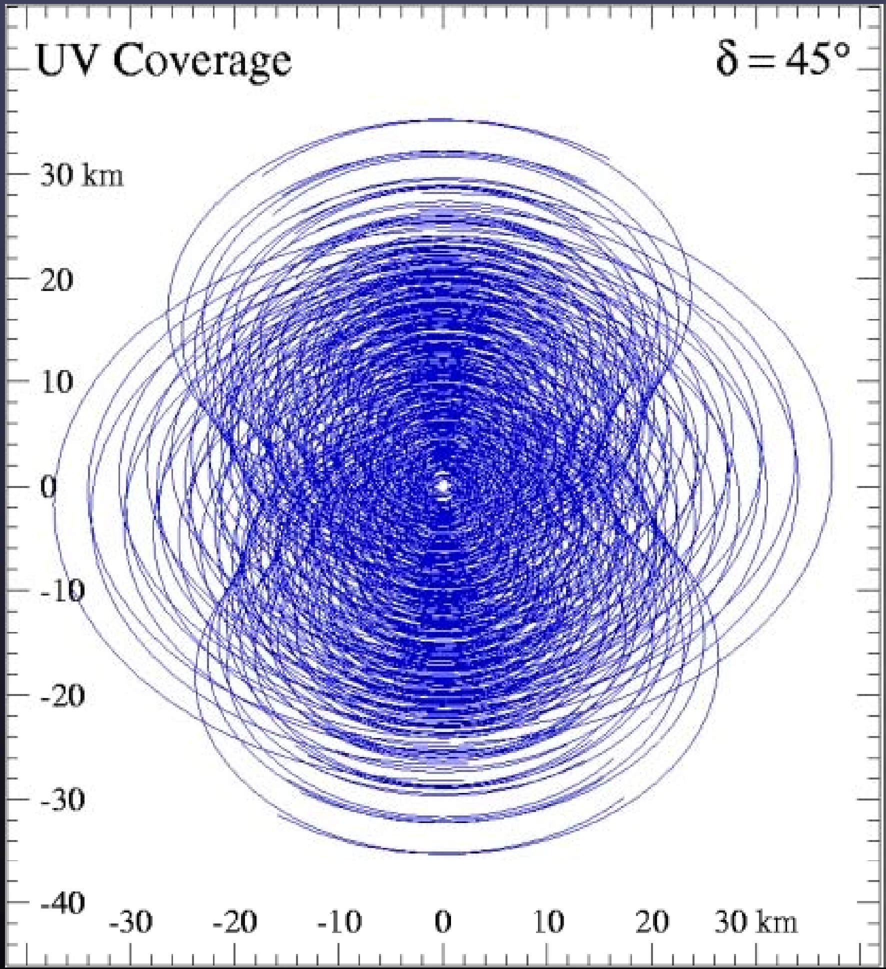
3 Hour Synthesis Observation

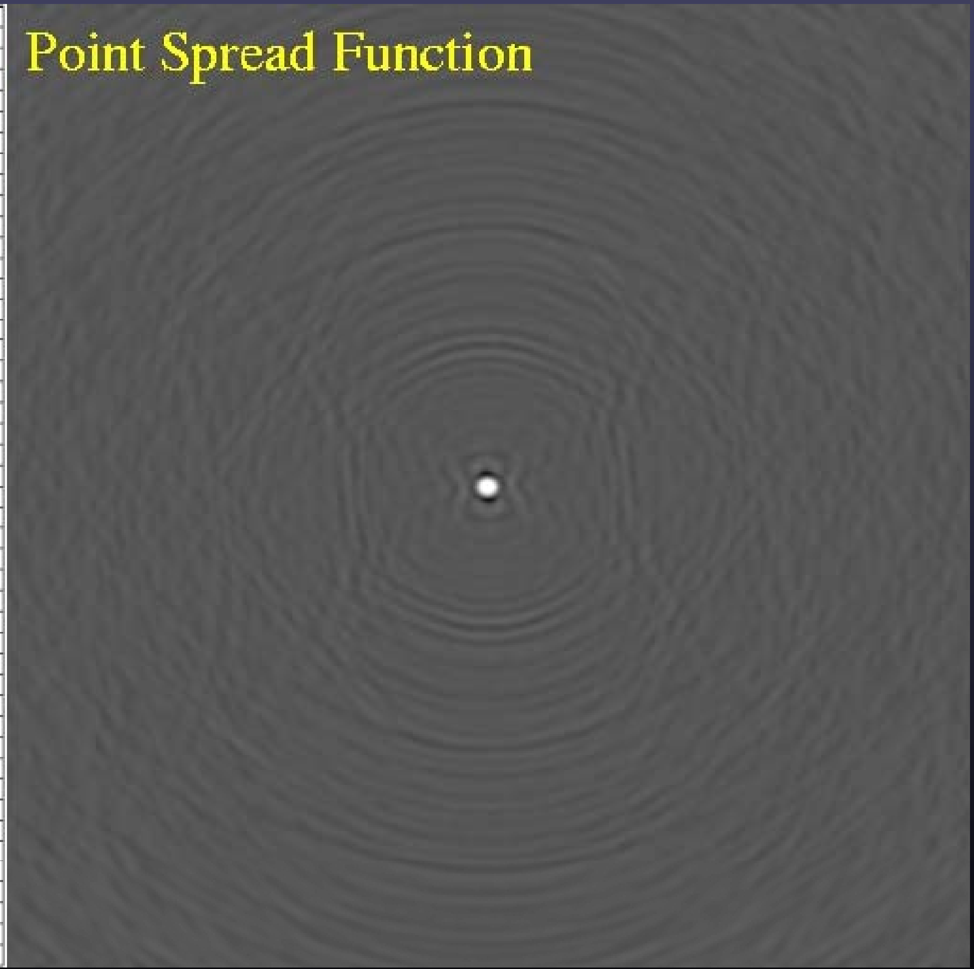




Point Spread Function for the VLA

12 Hour Synthesis Observation





Compensating for Incomplete uv-Coverage

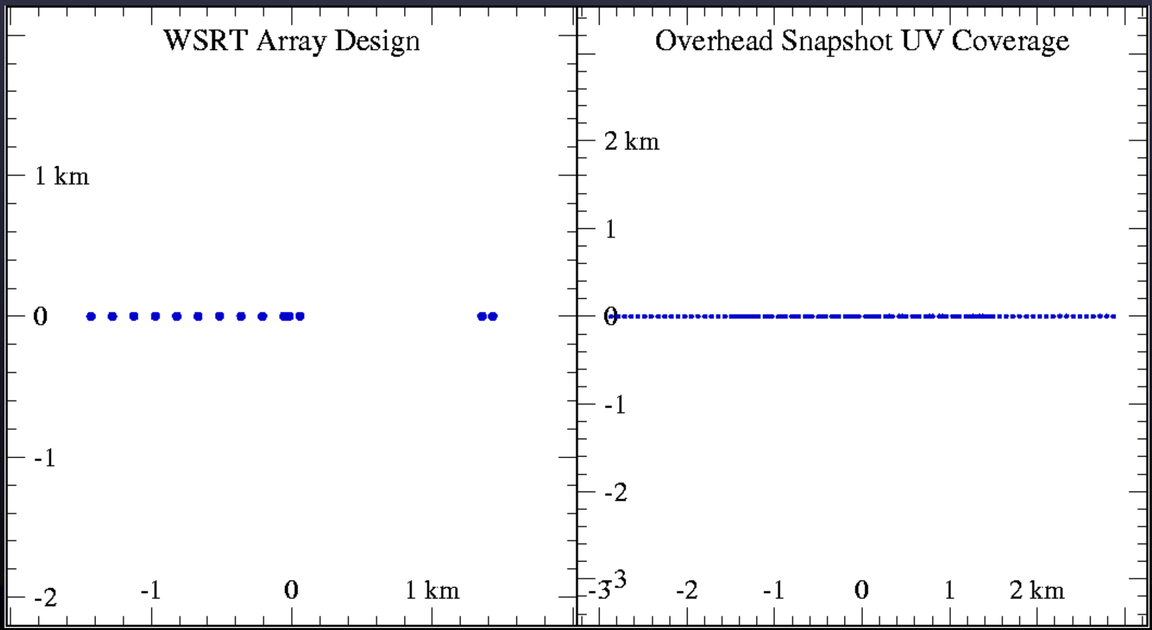
- Deconvolution
  - works well for simple sources
  - breaks down for large complex sources
- Multi-Frequency Synthesis
  - combine data from a wide range of frequencies in the uv-plane
  - greatly increases uv-coverage
  - need to deal with spectral variations

Importance of uv-coverage

- Resolution
  - determined by the longest baselines in the array
- Sensitivity to large scale structure
  - determined by the shortest baselines in the array
- Image fidelity
  - ability to reconstruct complex source structure
  - gaps in uv-coverage will limit this
- Image Dynamic Range
  - can be limited by side-lobes in the beam

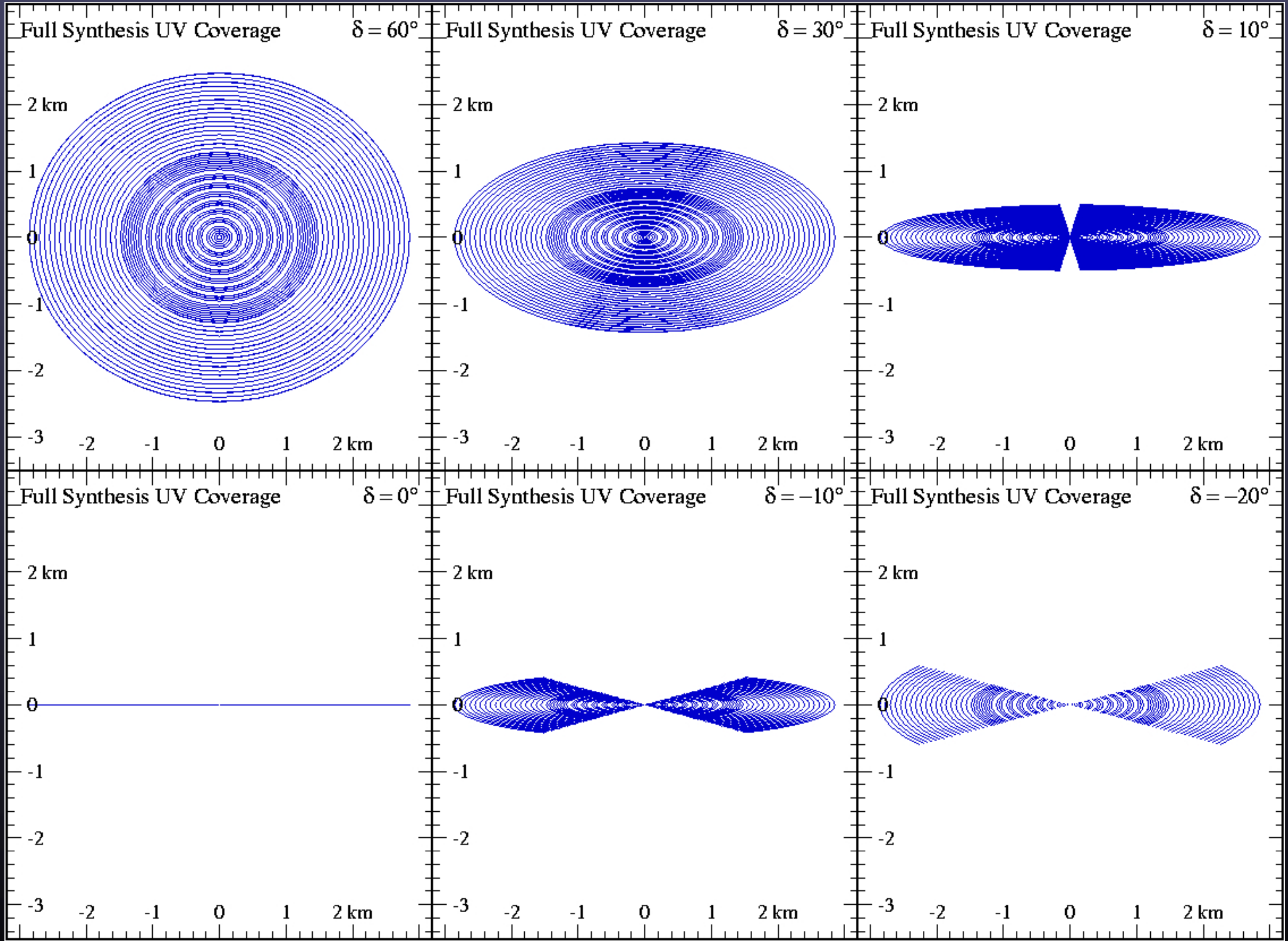
Westerbork Synthesis Radio Telescope

- Located in Westerbork, Holland
- Has 14 antennas, 25m diameter
- East-West Array
- Requires Earth Rotation Synthesis for all imaging
- Dedicated in 1970: one of the earliest major interferometric arrays



Westerbork Synthesis Radio Telescope

WSRT uv-coverage at various declinations

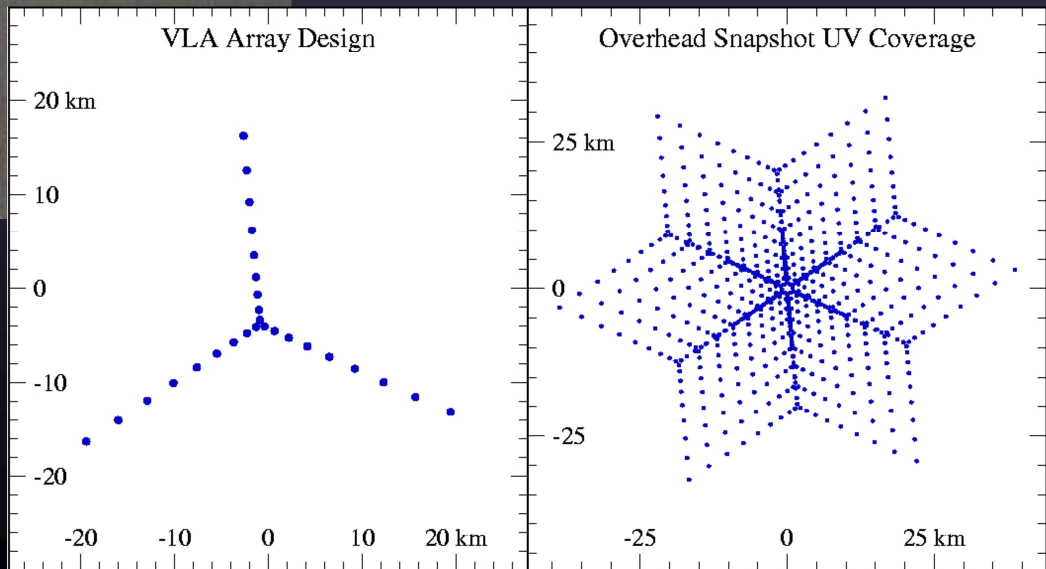


Tracks: elevation > 10 degrees

Expanded Very Large Array (EVLA)

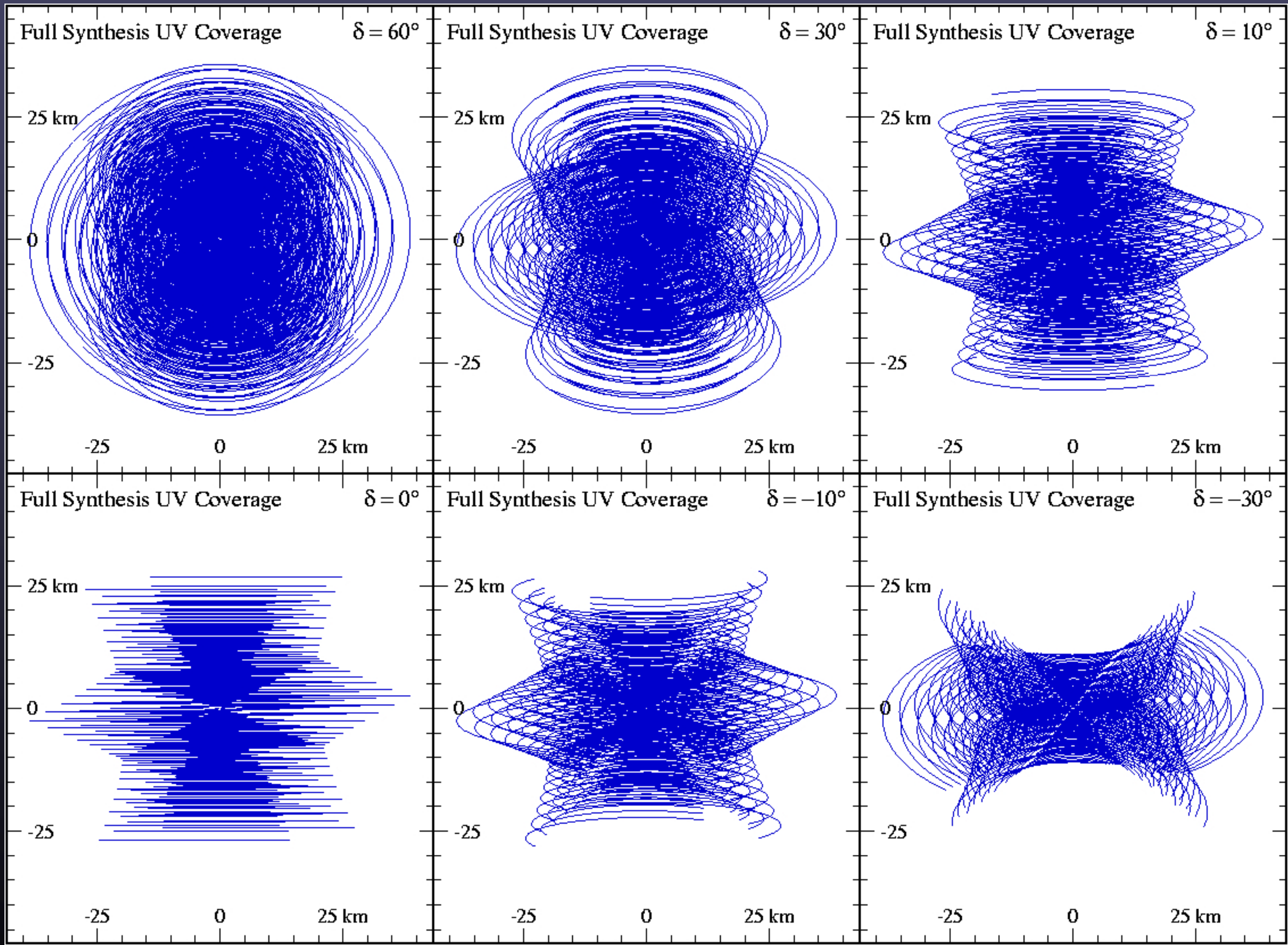
- Y-shaped Array
- Re-configurable

Config.	B_{max} (km)	B_{min} (km)
A	36	0.68
B	11	0.24
C	3.4	0.045
D	1.0	0.035



Very Large Array (VLA)

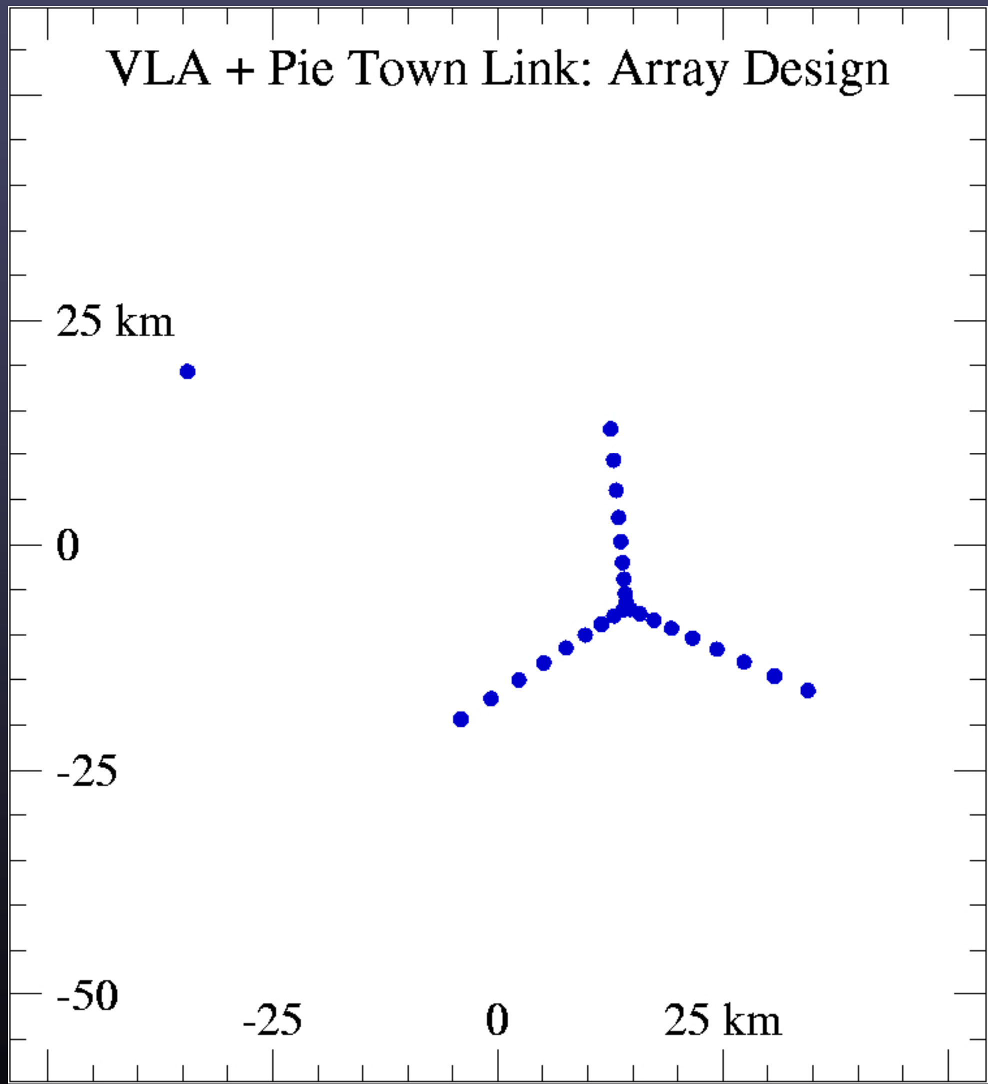
VLA uv-coverage at various declinations



Tracks: elevation > 10 degrees

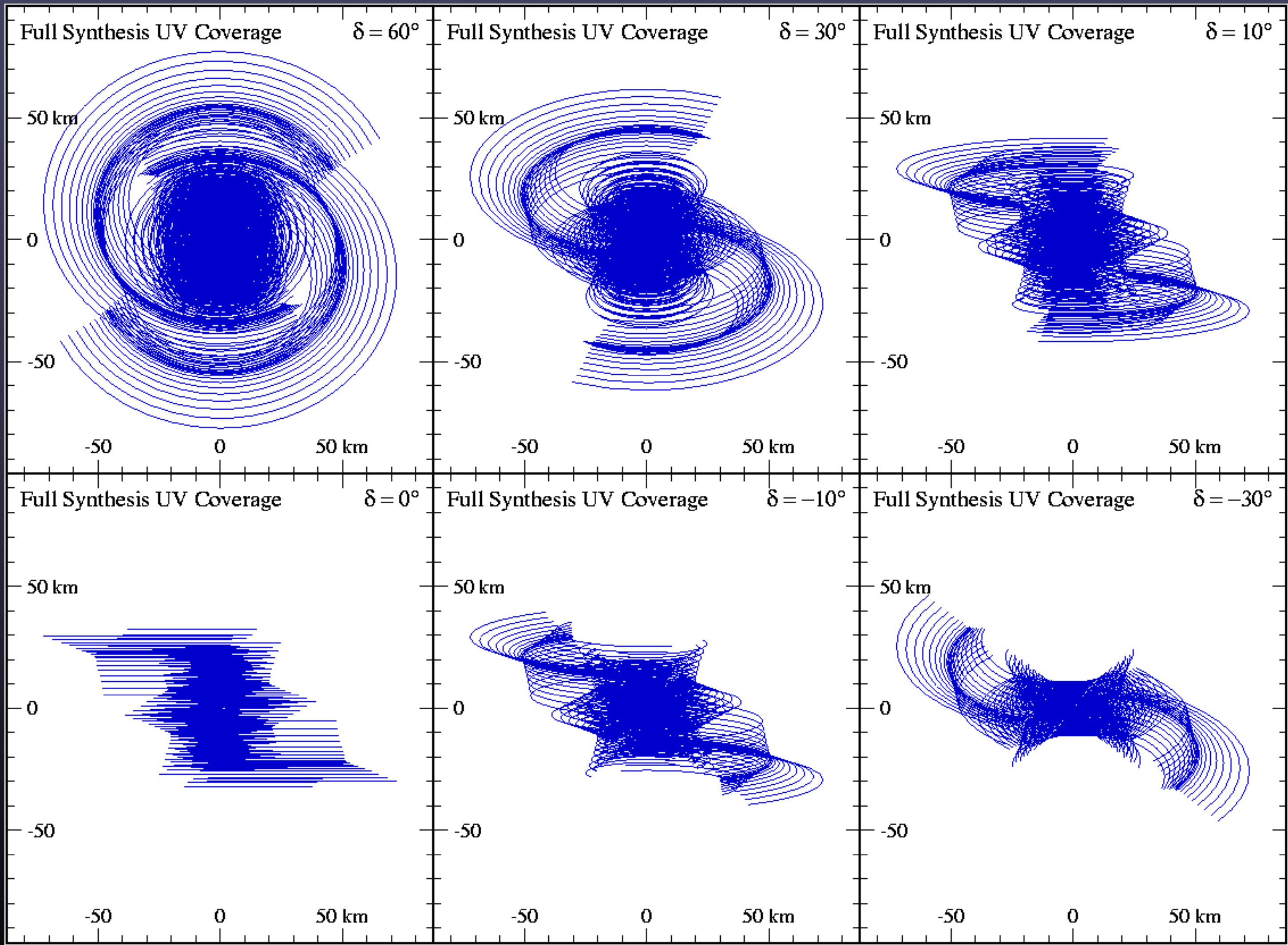
VLA – Pie Town Link

- Links (by fiber-optic cable) the VLBA antenna at Pie Town to the VLA
- Increases longest baseline from 35 to 73 km
- Best at high declinations
- Best with long uv-tracks



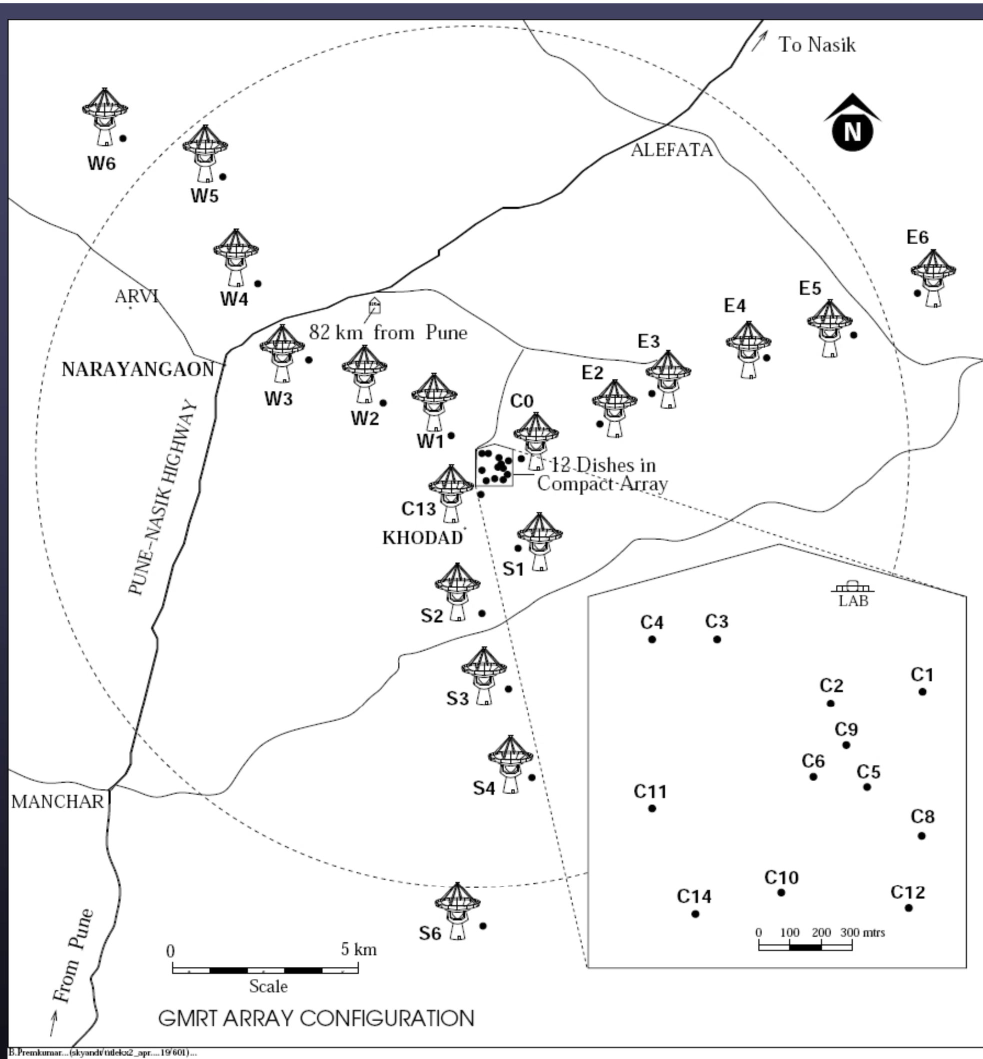
VLA – Pie Town Link

VLA+PT uv-coverage at various declinations



Tracks: elevation > 10 degrees

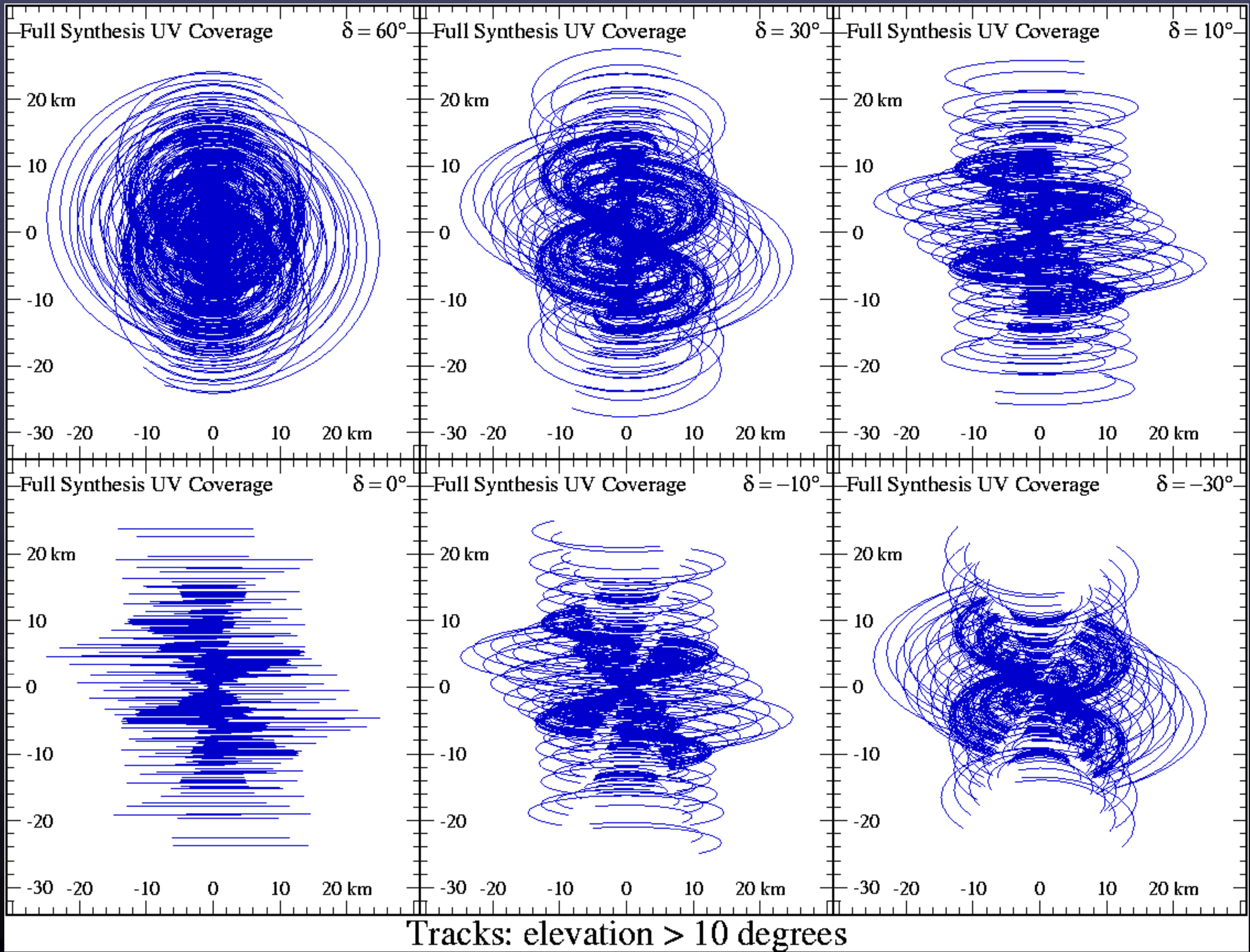
Giant Metrewave Radio Telescope (GMRT)



- Located near Khodad, India
- Contains 30 antennas each with 45m diameter

Giant Metrewave Radio Telescope (GMRT)

GMRT uv-coverage at various declinations

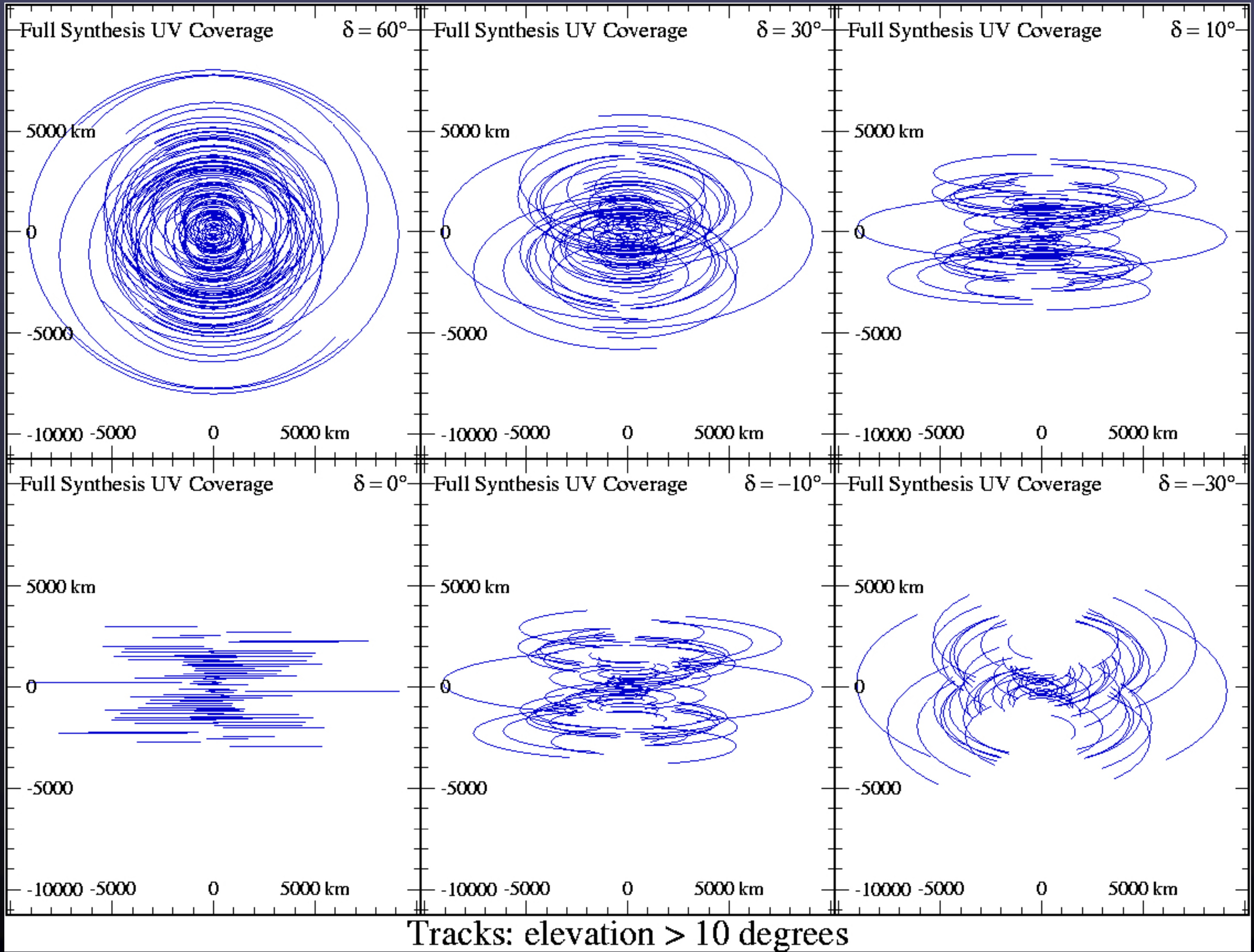


Very Long Baseline Array (VLBA)

- Built in 1995
- 10 VLA-type antennas
- Spread throughout continental US plus Hawaii and St. Croix
- Maximum baseline over 8,000 km
- Elements not electronically connected
  – must bring recorded data to central correlator
- Can achieve resolution of milli-arcseconds

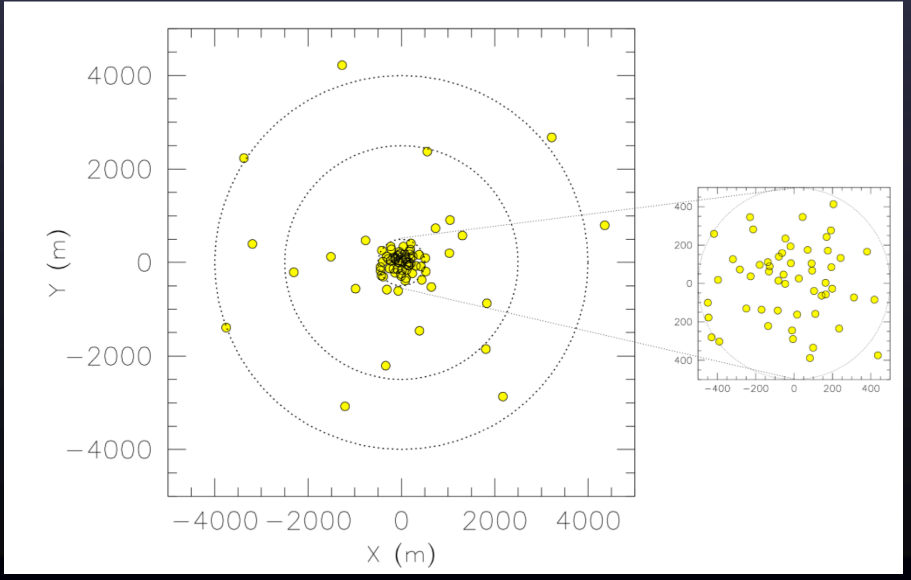
Very Long Baseline Array (VLBA)

VLBA uv-coverage at various declinations



MeerKAT

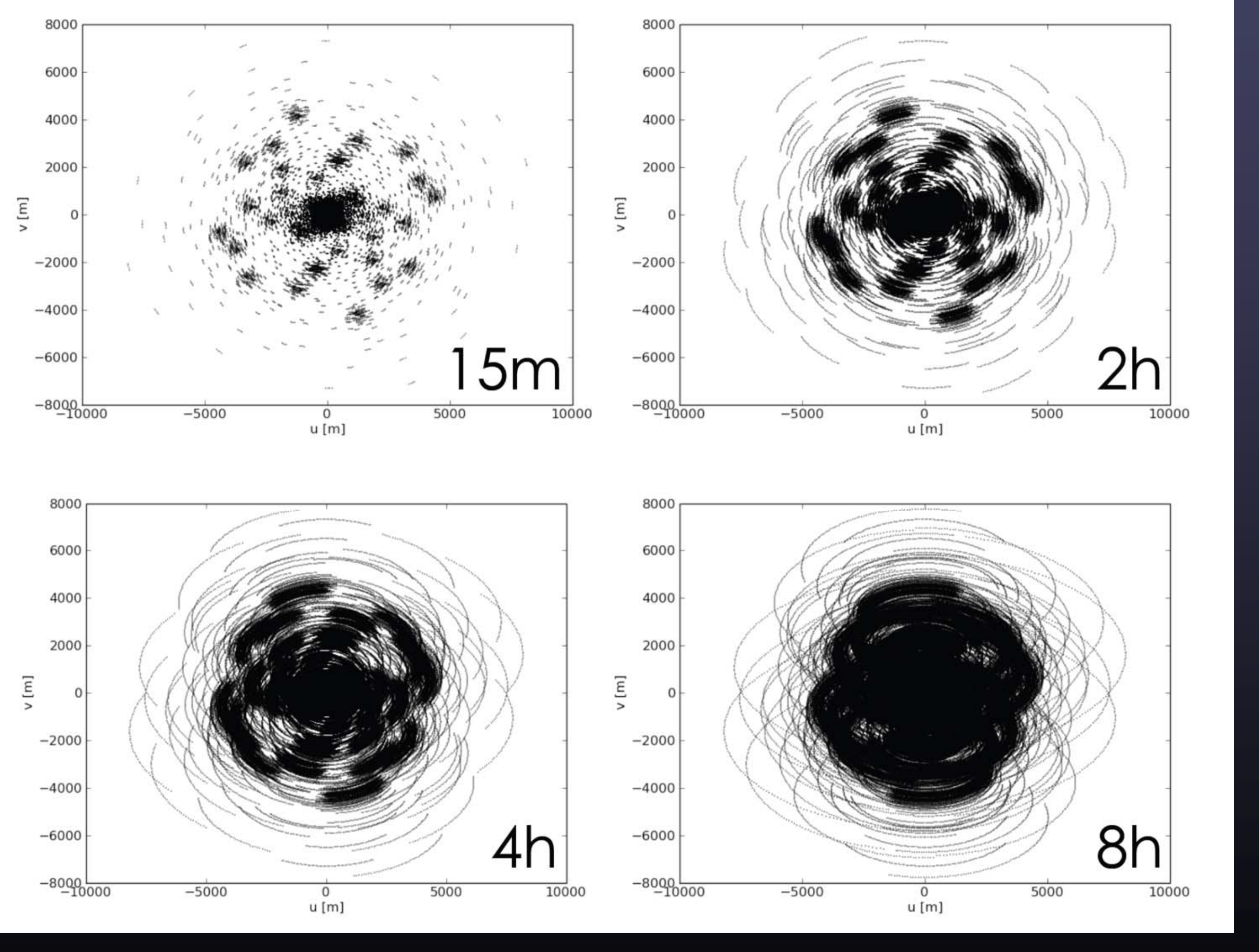
- Central Array
  - 80 x 12 meter antennas
  - Baselines from 20 m to 8 km
- Spur
  - 7 antennas, designed to give long east-west baselines
  - baselines up to 60 km



Tentative configuration of *Central Array* (Booth et al. 2010)

MeerKAT

MeerKAT uv-coverage at various integrations for a source with a declination of -30°



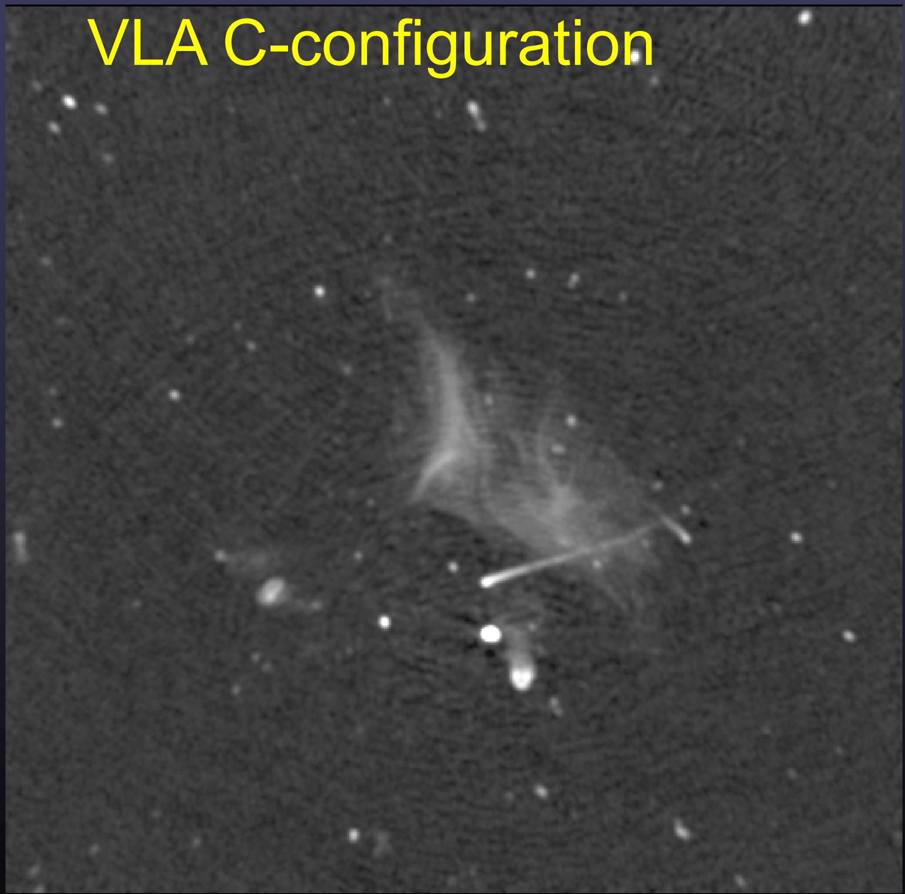
Main Parameters of Array Configuration

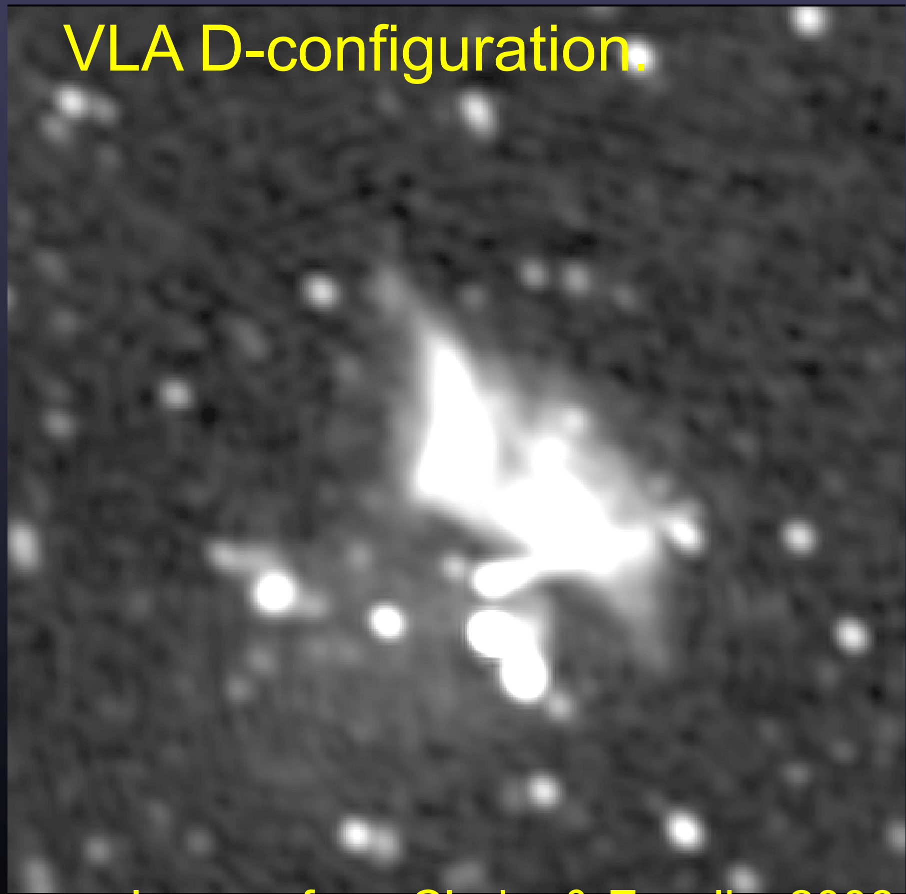
- Maximum Baseline Length
  - Determines the resolution
- Minimum Baseline Length
  - Determines the sensitivity to large scale features
- Number of Elements (N)
  - Limiting factor in how low sidelobes can be
  - This will affect the ultimate dynamic range achievable
- Array shape
  - This determines uv-coverage and distribution

Main Parameters of Array Configuration

- Long Baselines: Determine resolution
- Short Baselines: Detect large scale features

Abell 2256 at 1369 MHz



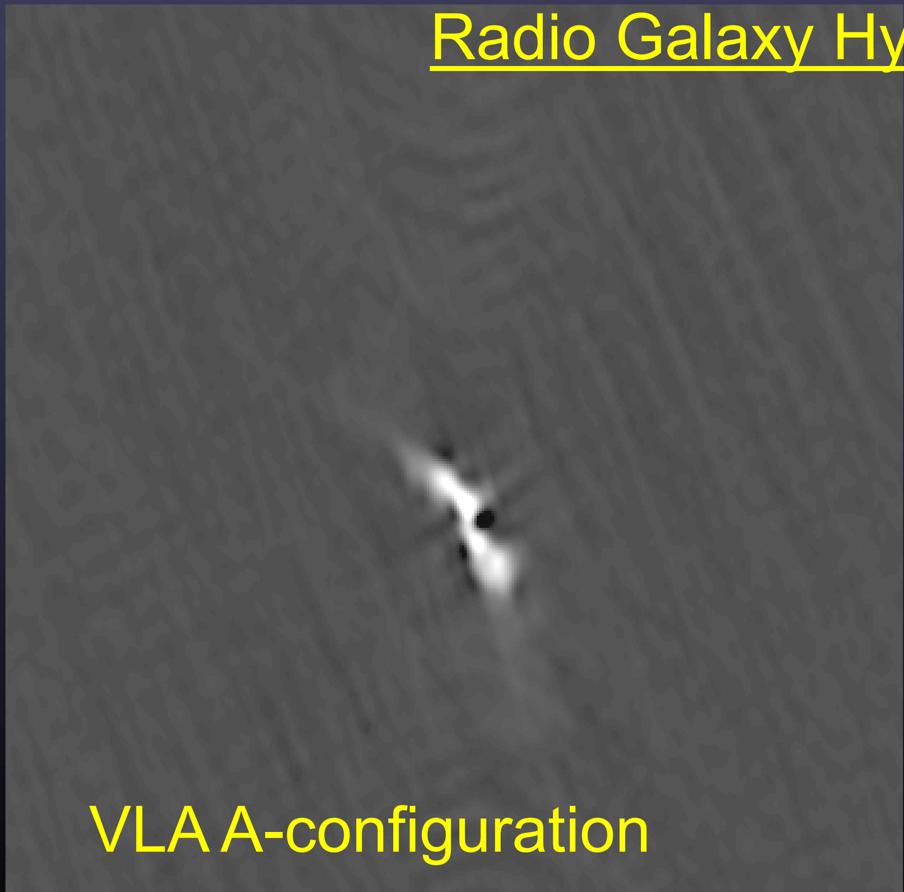


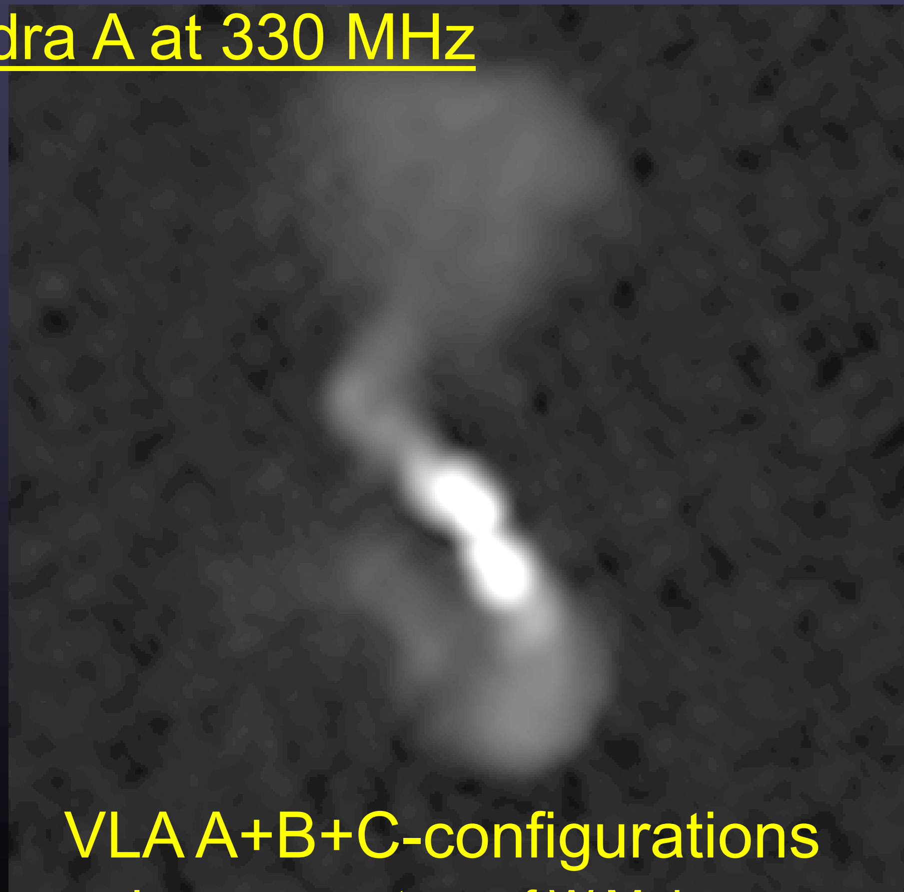
Images from Clarke & Ensslin, 2006

Effect of the range of baseline lengths

- The dynamic range between the longest and shortest baselines must be sufficient for the ratio of source size to the desired resolution.

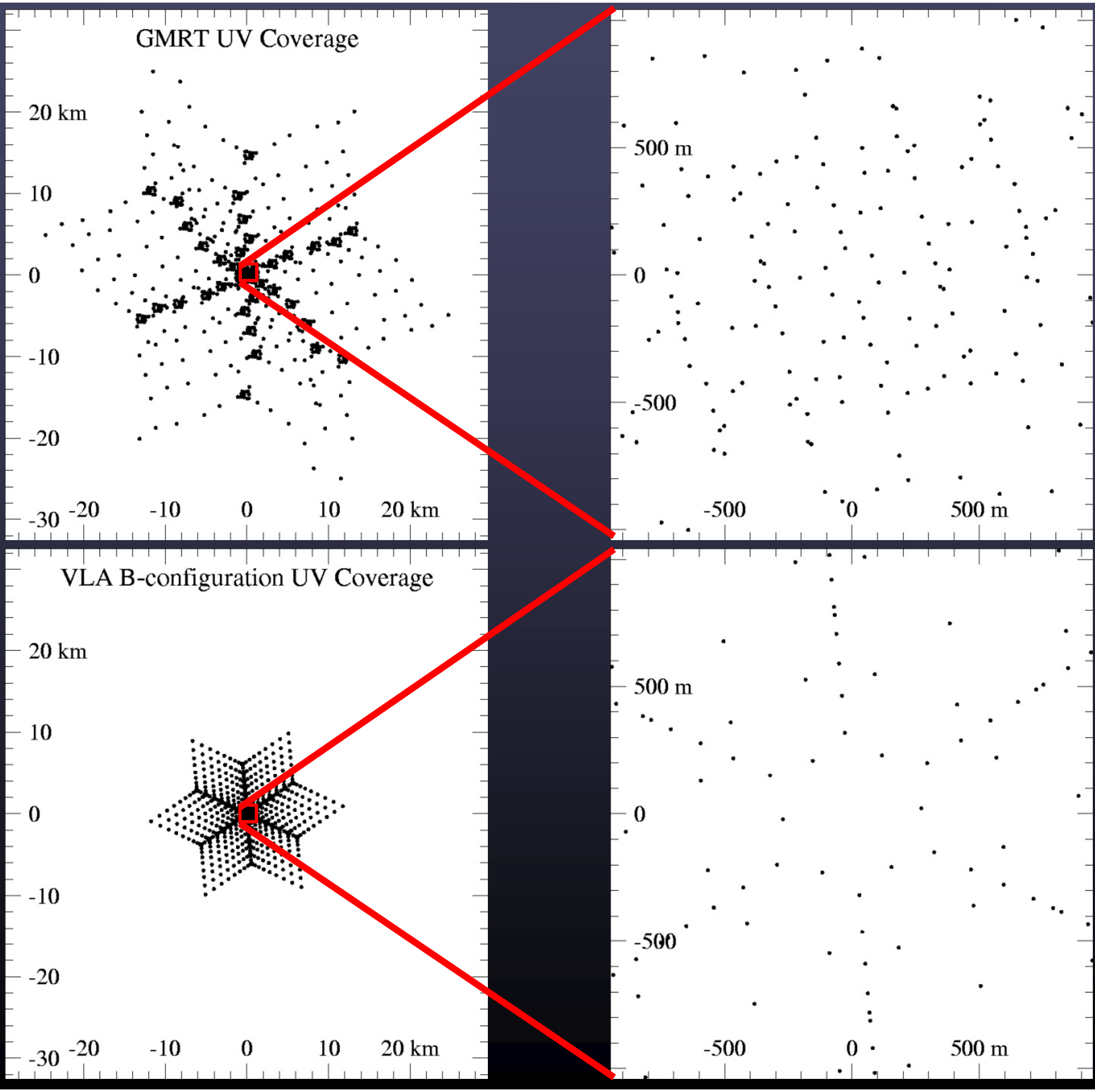
Radio Galaxy Hydra A at 330 MHz





Images courtesy of W.M. Lane

Effect of a central core

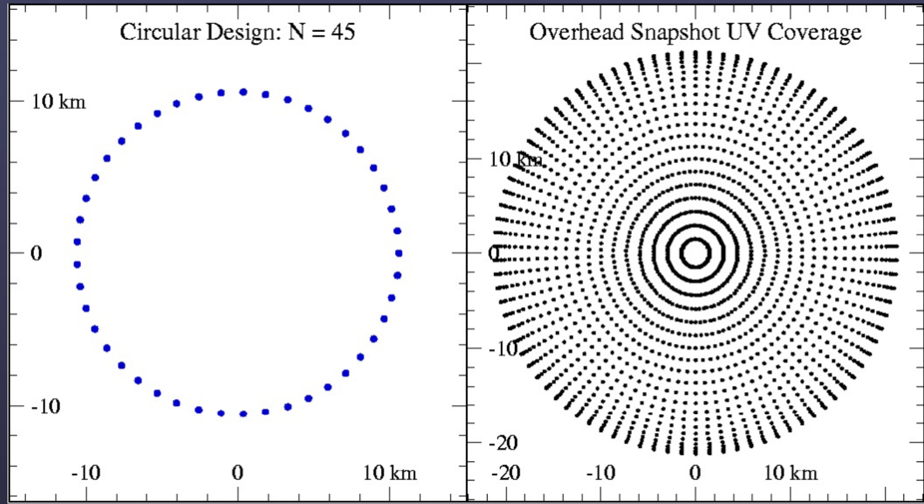


- Including a compact core can increase the baseline length dynamic range
- A core will also introduce non-uniformity in the uv-coverage
- This can be corrected with more antennas

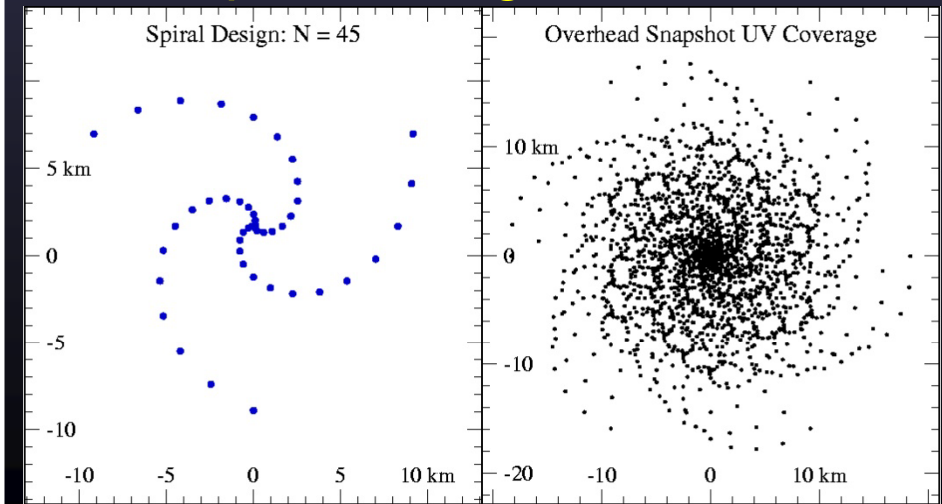
Various Array Designs

- Circular
  - maximizes number of long baselines
- Spiral
  - has more short baselines
- Random
  - has little redundancy or patterns

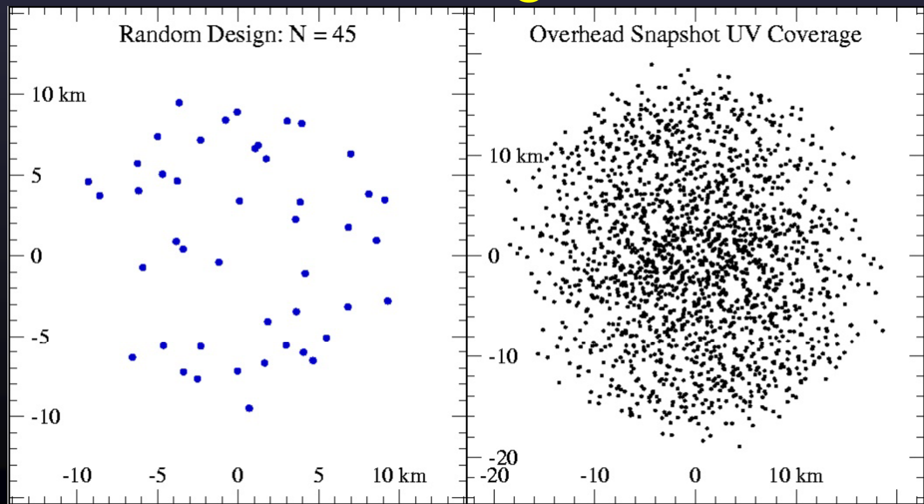
Circular Design: N = 45



Spiral Design: N = 45



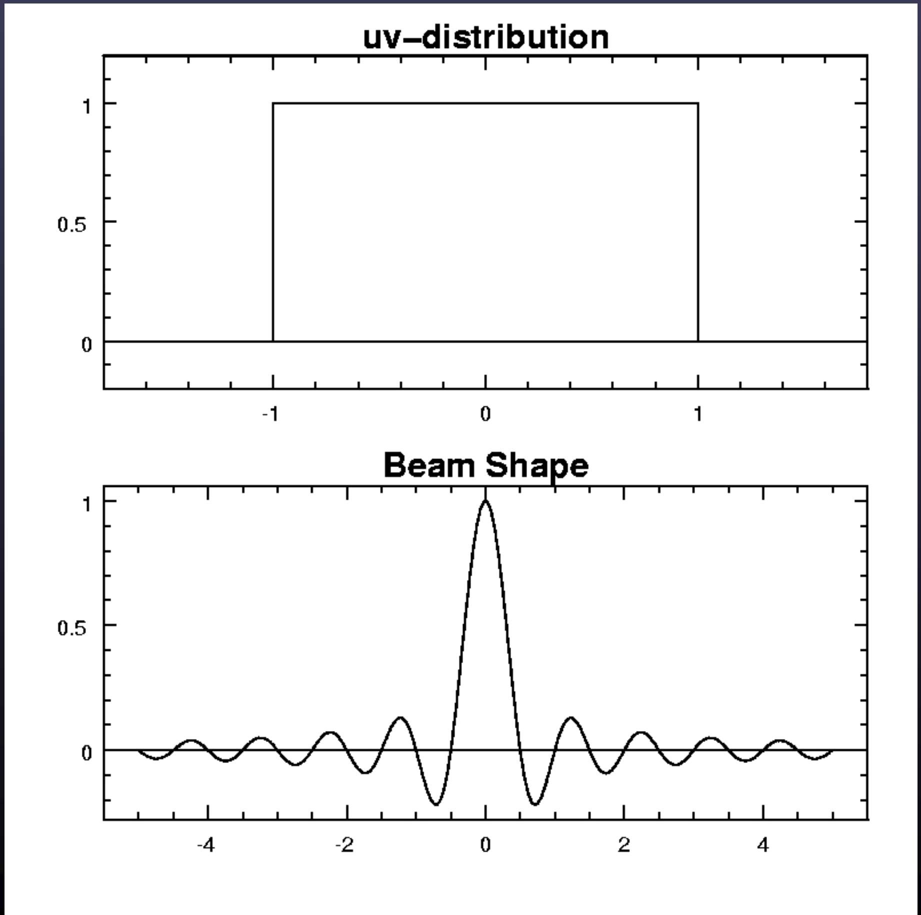
Random Design: N = 45



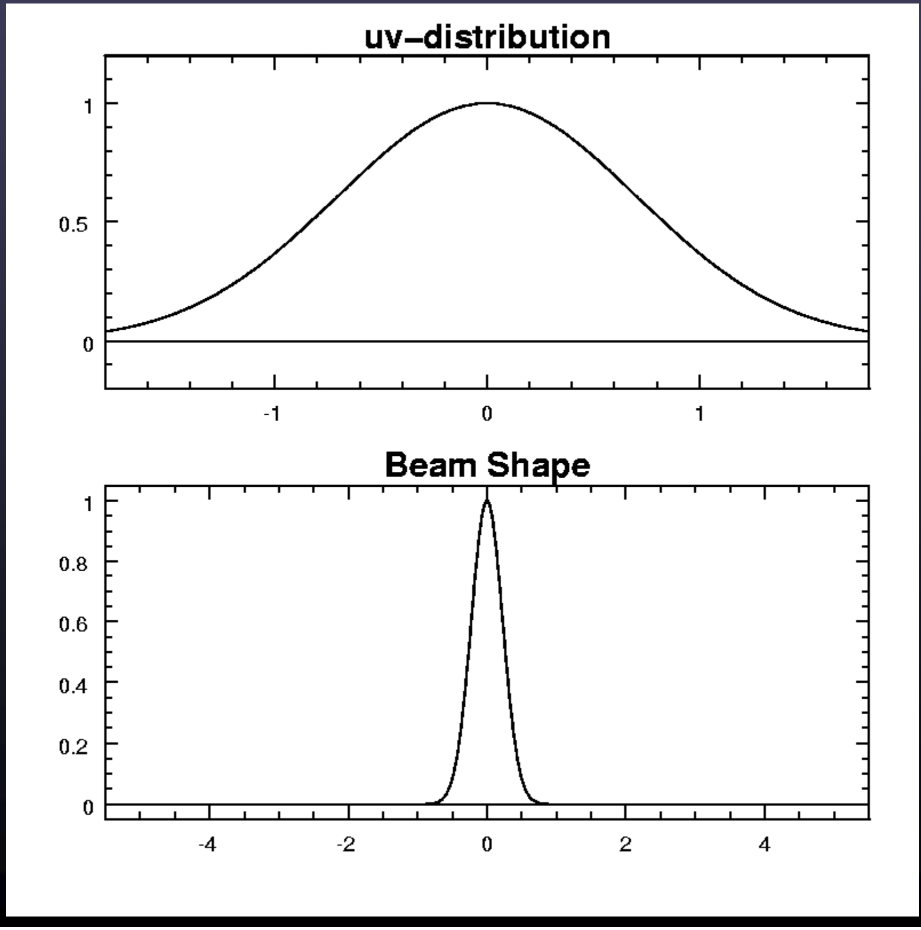
Nearby Side-lobes: dominated by uv-distribution

- Even with perfect uv-coverage the distribution or weighting can cause sidelobes:

Uniform distribution



Gaussian Distribution



Distant Side-lobes: Dependence on N

- Distant side-lobes are caused by gaps in the uv-coverage.
- RMS value of distant side-lobes is proportional to the square root of the number of uv-data points (assuming a random distribution)
- For a randomly distributed array, this means that the side-lobes will have an RMS value of ~1/N
- This can be much higher for non-random distributions
  - repetitions from patterns will result in much higher side-lobes
- Optimization can reduce this somewhat for a small region

Metrics for Optimization

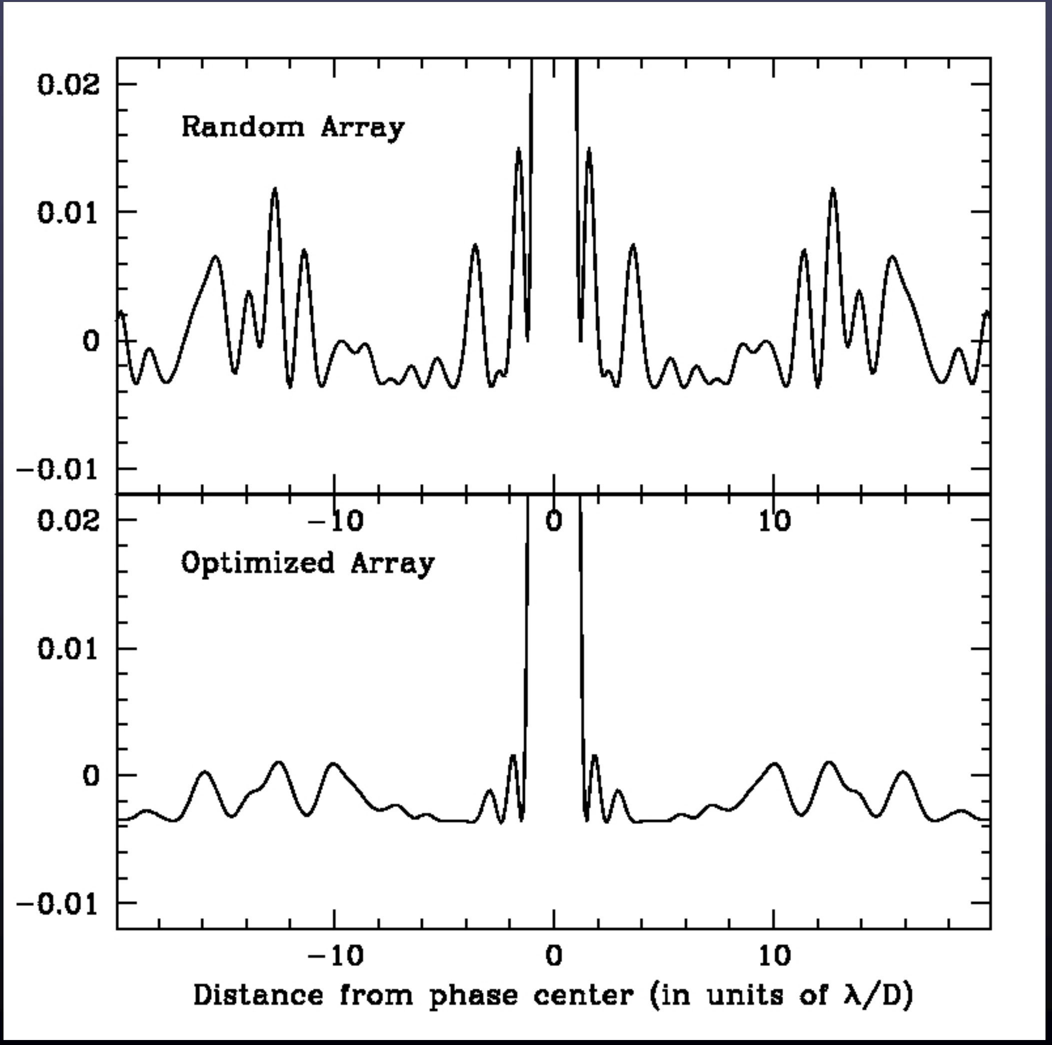
- Side-lobe levels
  – Useful for image dynamic range
- Range of baseline lengths
  – Useful for large complex sources
- Largest gaps in uv-coverage
  – Image fidelity
- Baseline length distribution
  – So that uv-weighting, which reduces sensitivity, is not needed

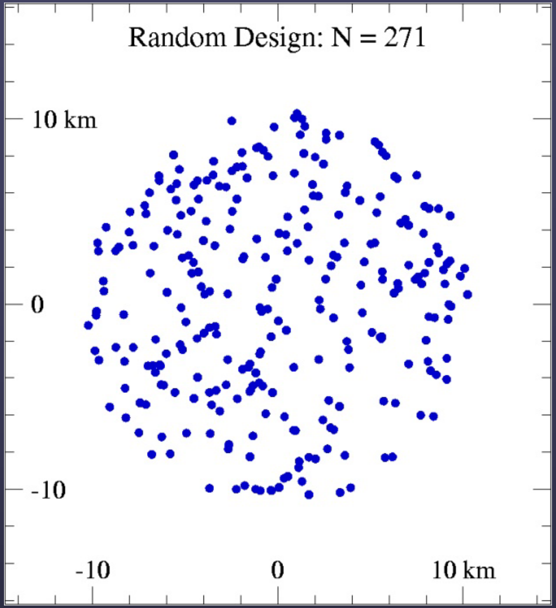
Array Optimization

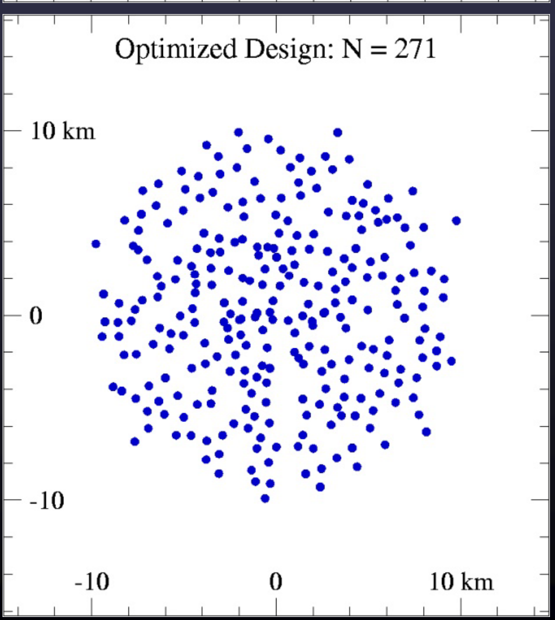
- Trial and Error
  - devise configurations and calculate metrics (works OK for small N)
- Random Distribution
  - Lack of geometric pattern reduces redundancy
  - Works surprisingly well for large N
- Simulated Annealing (Cornwell)
  - Define uv 'energy' function to minimize – log of mean uv distance
- UV-Density & pressure (Boone)
  - Steepest descent gradient search to minimize uv density differences with ideal uv density (e.g., Gaussian)
- Genetic algorithm (e.g., Cohanim et al.,2004)
  - Pick start configurations, breed new generation using crossover and mutation, select, repeat
- PSF optimization (L. Kogan)
  - Minimize biggest sidelobe using derivatives of beam with respect to antenna locations (iterative process)

Iterative minimization of sidelobes: Kogan Method

Comparing random versus optimized arrays for N = 271



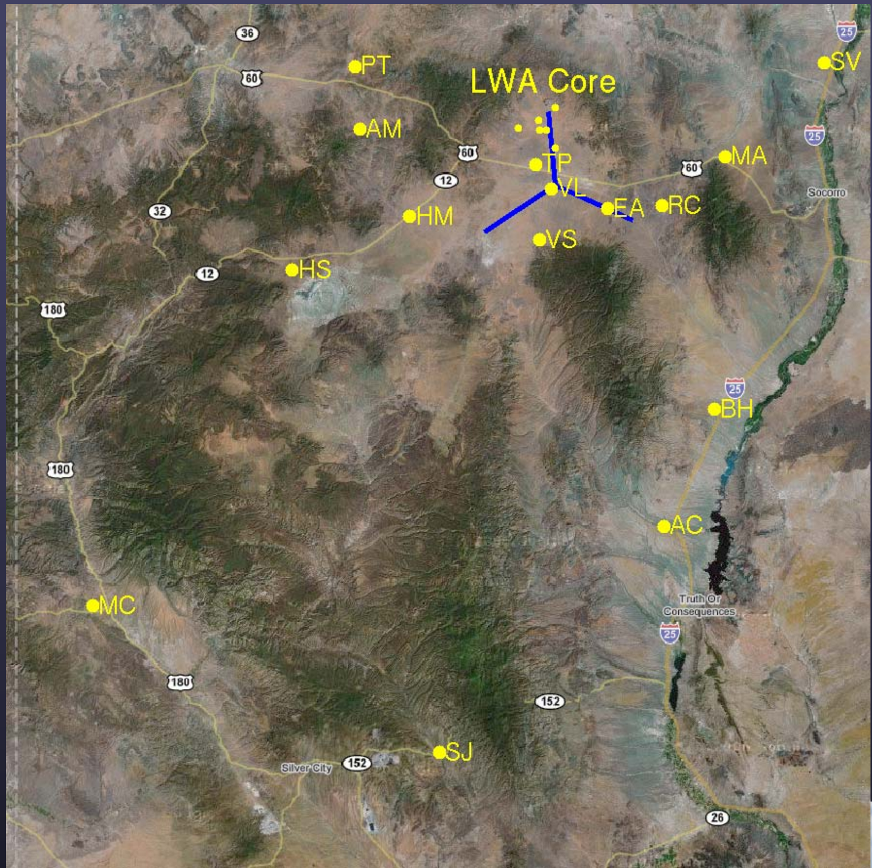




Simulations

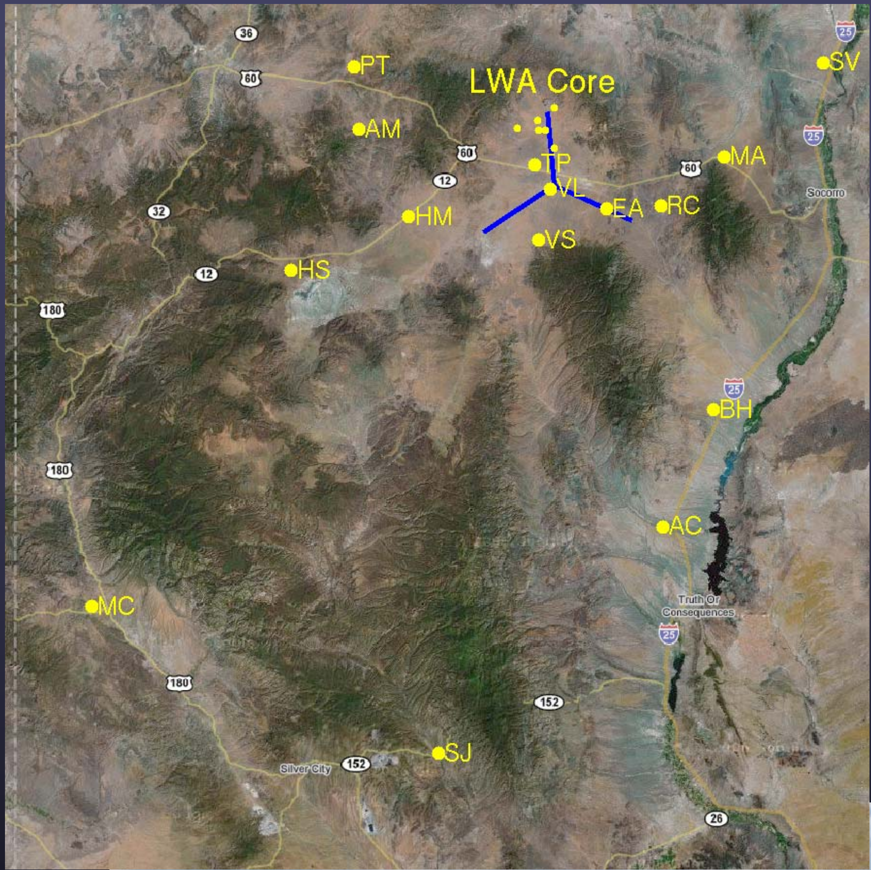
- Simulations are the ultimate test of array design
  - see how well the uv-coverage performs in practice
- Consider likely target objects
  - Generate realistic models of sky
  - Simulate data, adding in increasing levels of reality
    - Atmosphere, pointing errors, dish surface rms etc.
  - Process simulated data & compare final images for different configurations – relative comparison
  - Compare final images with input model
    - Image fidelity – absolute measure of goodness of fit
    - Compare with specifications for dynamic range and fidelity

Real World Example: Long Wavelength Array (LWA)



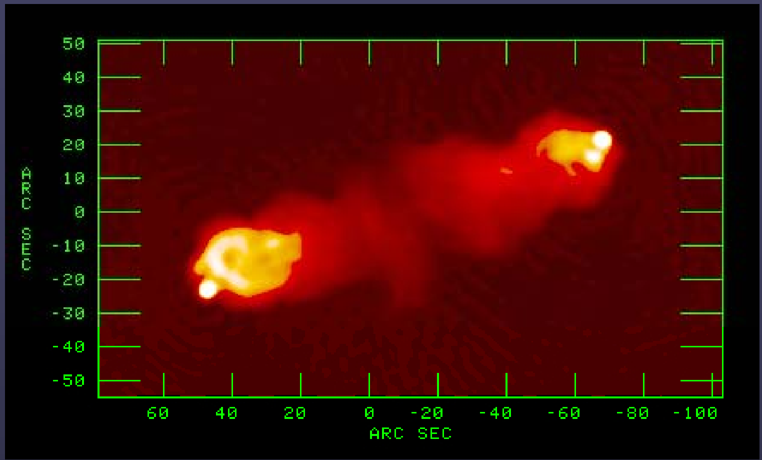
- Long Wavelength Array (LWA)
  - New low-frequency telescope (10-88 MHz) in New Mexico
  - 52 stations of 256 phased dipoles serve as 'antennas'
  - Intermediate array will have core plus 10 outlier sites
  - Need to find best 10 outlier sites

Real World Example: Long Wavelength Array (LWA)

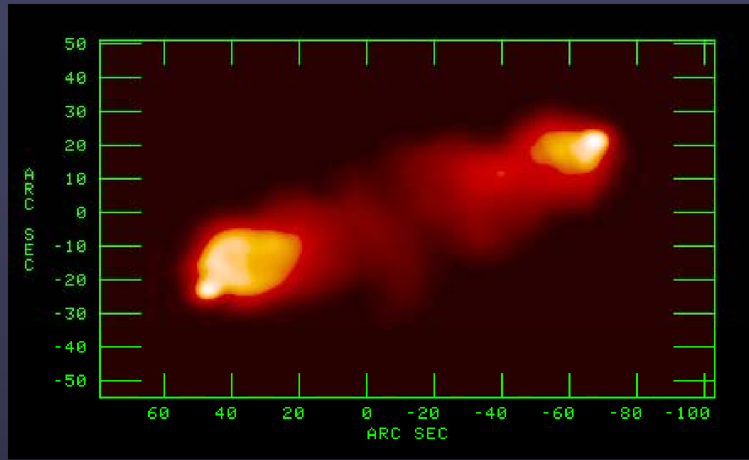


- Designing the LWA
  - 10 sites are needed
  - 15 sites found to be suitable based on topography and access to roads, fiber and power lines.
  - 4 sites are "fixed":
    - MC, SJ and AC for resolution
    - VL is already used for prototypes
  - Need to choose best 6 of remaining 11
  - 462 different options!

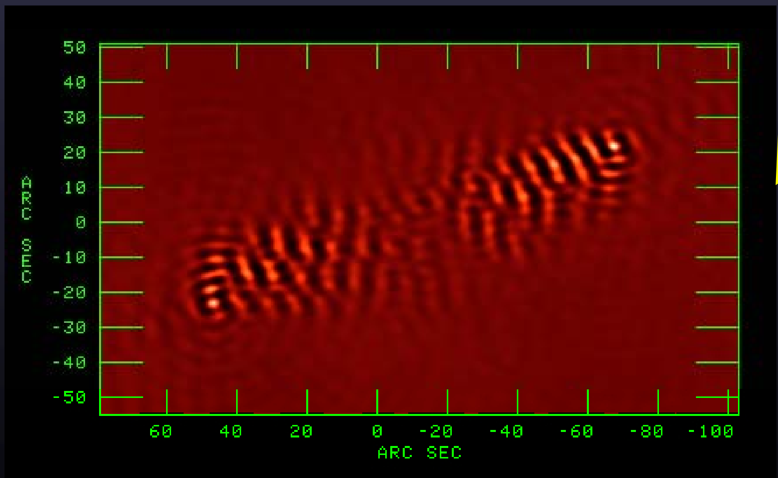
Simulating the Long Wavelength Array (LWA)



Cygnus A at 325 MHz with VLA A-configuration + PT



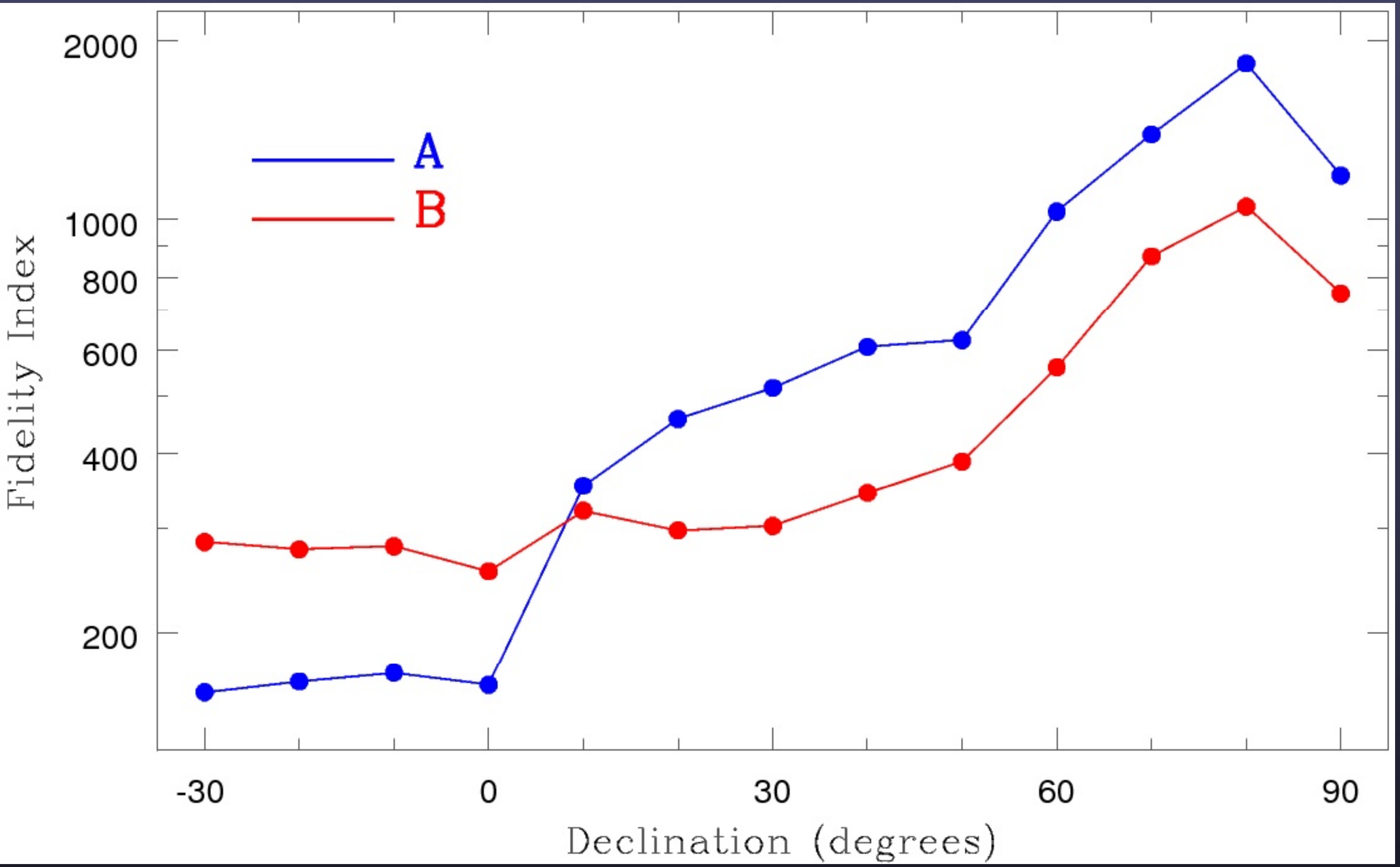
Simulated LWIA Image (74 MHz)



Residual Map (model subtracted)

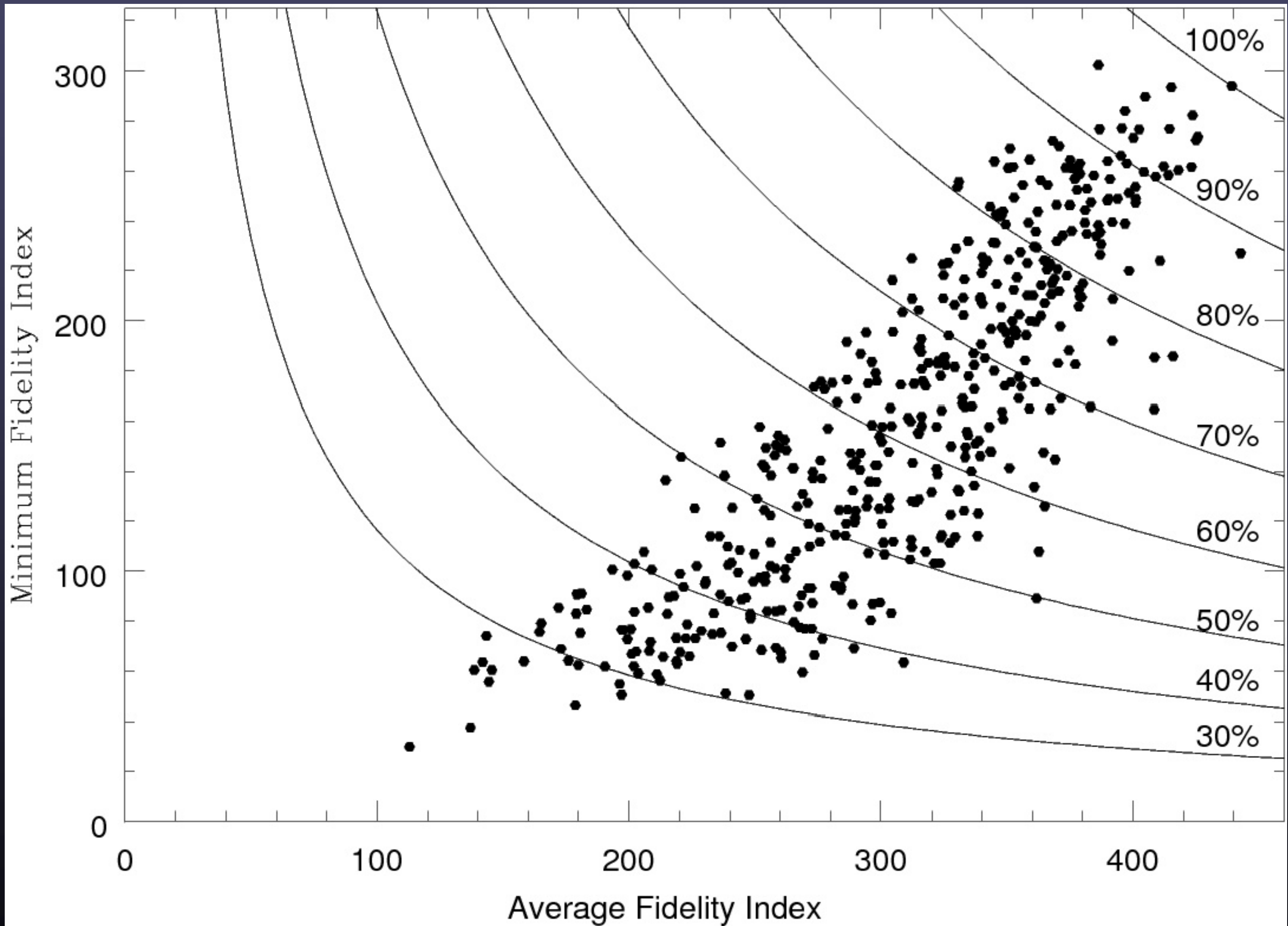
- Simulating Image Fidelity
  - Project model image to simulated uv-coverage and image in normal way
  - Subtract model to examine residual image errors
  - Can define: Fidelity Index = (peak intensity)/(residual rms)

Fidelity Index vs Declination



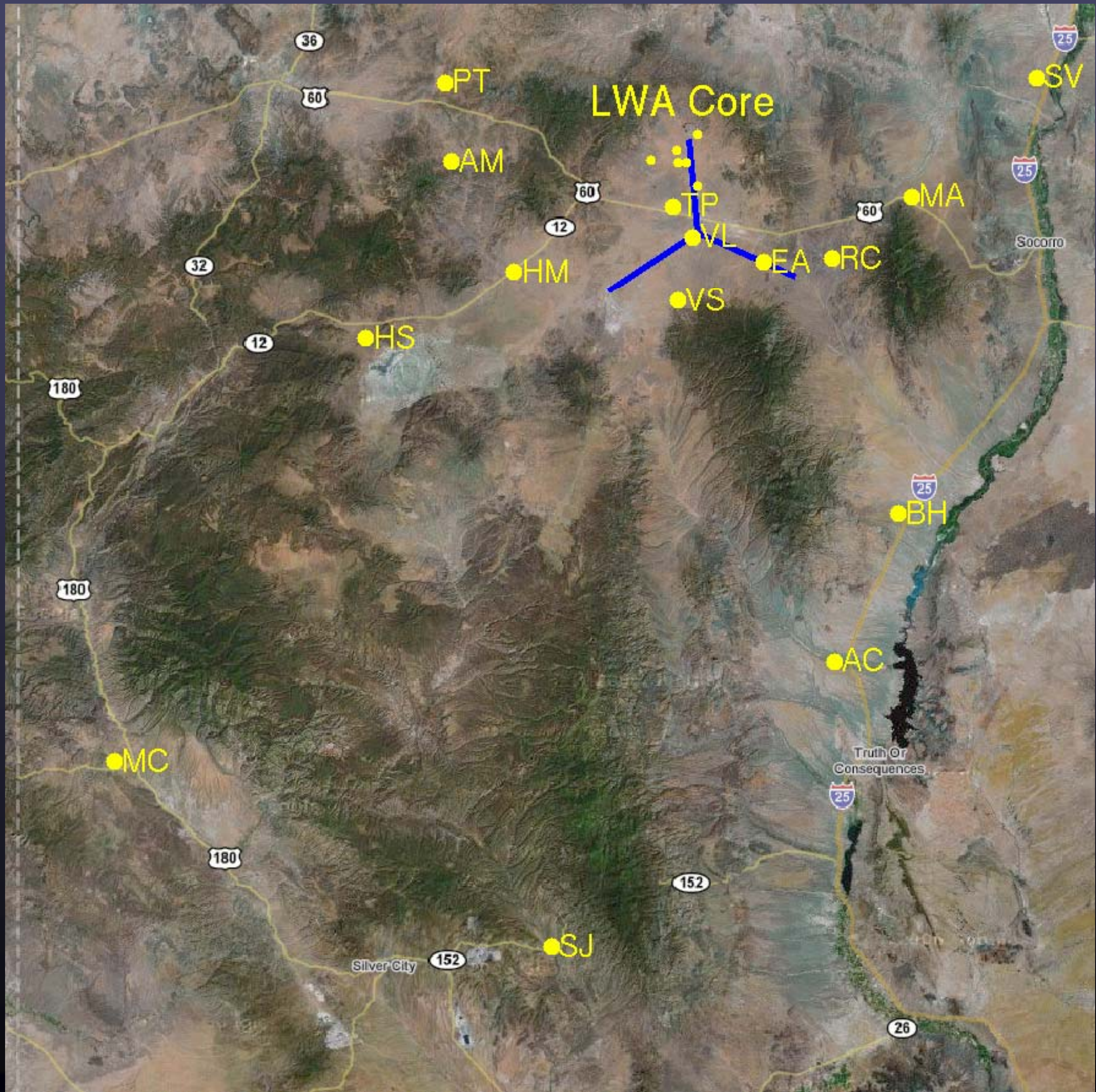
- Fidelity Index for two possible array configurations
  - Full time synthesis
  - Various source declinations

Determining the Relevant Figure of Merit



Fidelity Index based Figures of Merit for all possible array configurations

Rating of Possible Station Sites



- Fixed Sites:
  - VL, MC, SJ, AC
- “Optional” Sites Rated by frequency within “top 10” configurations:
  - HS → 10/10
  - SV → 9/10
  - BH → 8/10
  - HM → 7/10
  - MA → 7/10
  - EA → 6/10
  - PT → 6/10
  - RC → 4/10
  - VS → 3/10
  - AM → 0/10
  - TP → 0/10

Large-N / Small-D Concept

- N = number of antennas in array
- D = diameter of antennas in array
- Collecting Area (ND^2) kept constant
- uv-coverage is drastically improved while the point-source sensitivity is unchanged
- This can also be the most cost effective way to achieve the desired collecting area

Large-N / Small-D Concept

Advantages of higher N (at constant ND^2)

- Synthesized beam sidelobes decrease as ~1/N
- Field of view increases as ~N (for dishes)
- Redundancy of calibration increases as N
- uv-tracks crossings increase as N^4

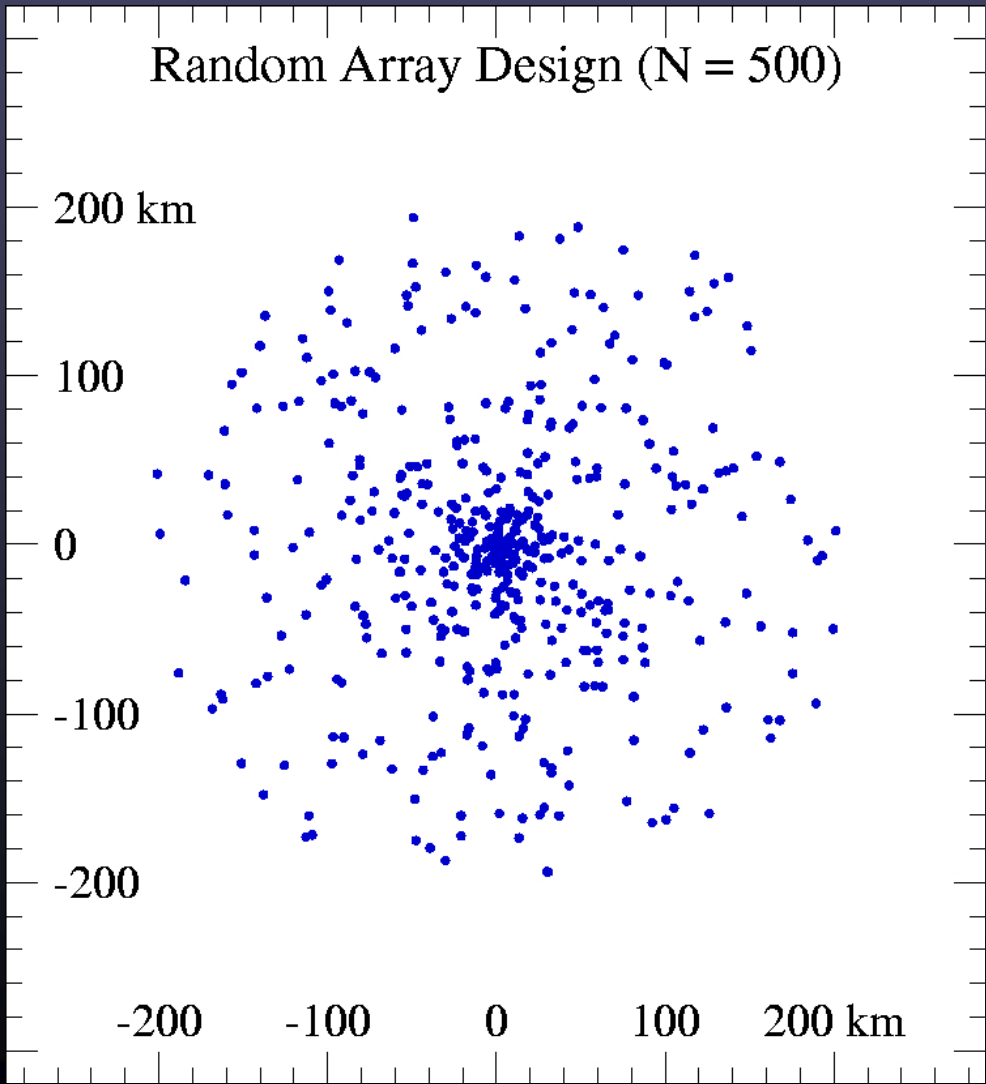
Disadvantages of higher N (at constant ND^2)

- Computation times can increase by up to N^4 !!!
  - N^2 times more baselines
  - N times as many pixels in the FOV
  - $N^{1/2}$ times as much channel resolution needed
  - $N^{1/2}$ times as much time resolution needed
- Need correlator with more capacity
- Higher data rate

Large-N / Small-D Concept

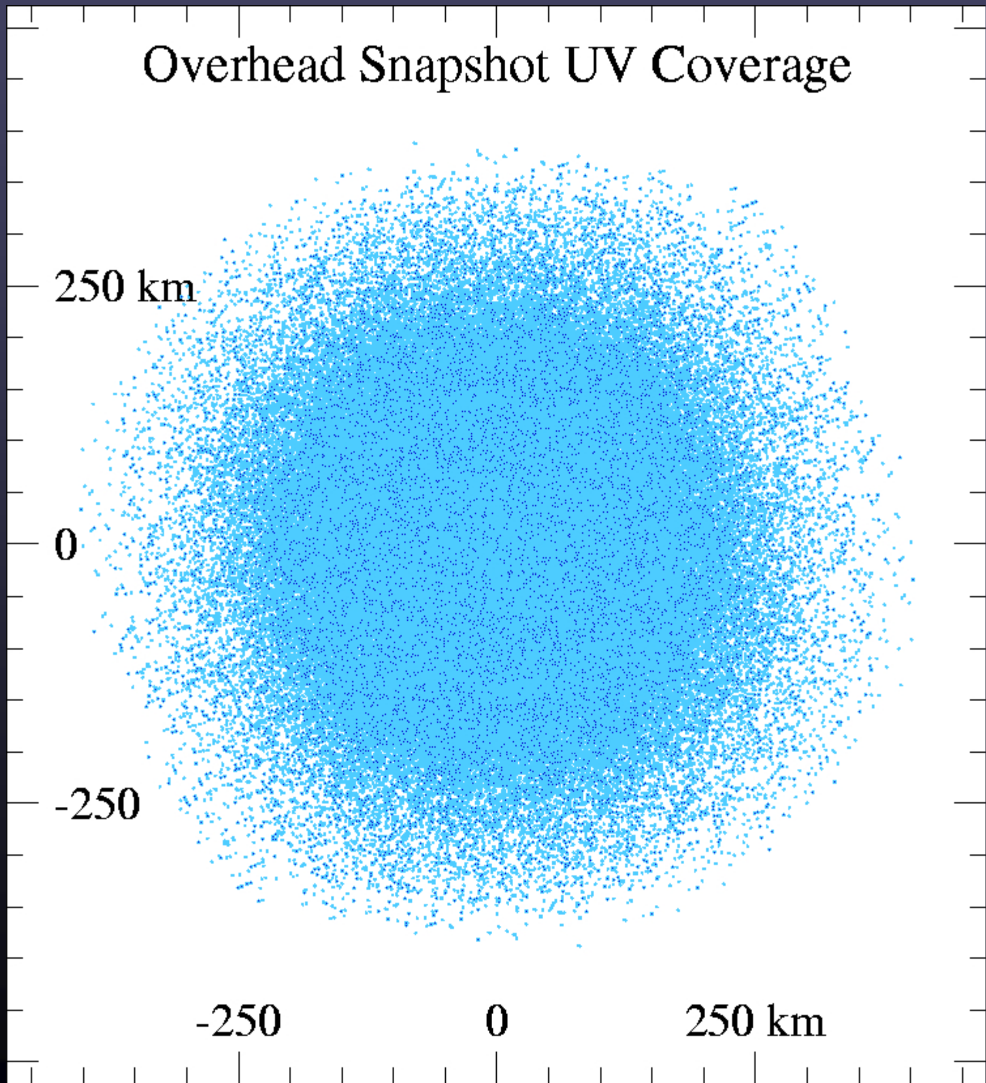
N = 500 Random Array

- N = 500
- Elements placed randomly within 200 km radius
- Random placement “biased” towards array center for more shorter baselines



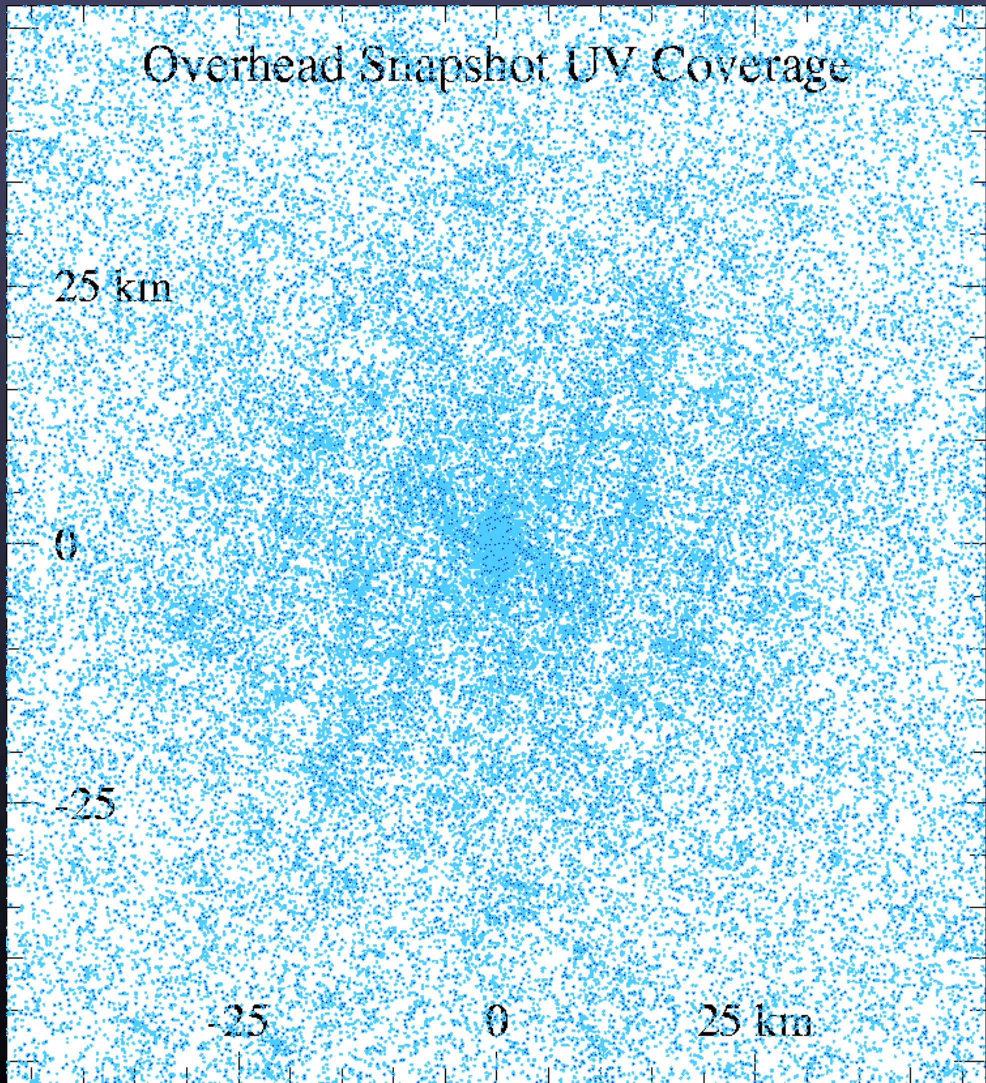
Large-N / Small-D Concept

N = 500 Random Array



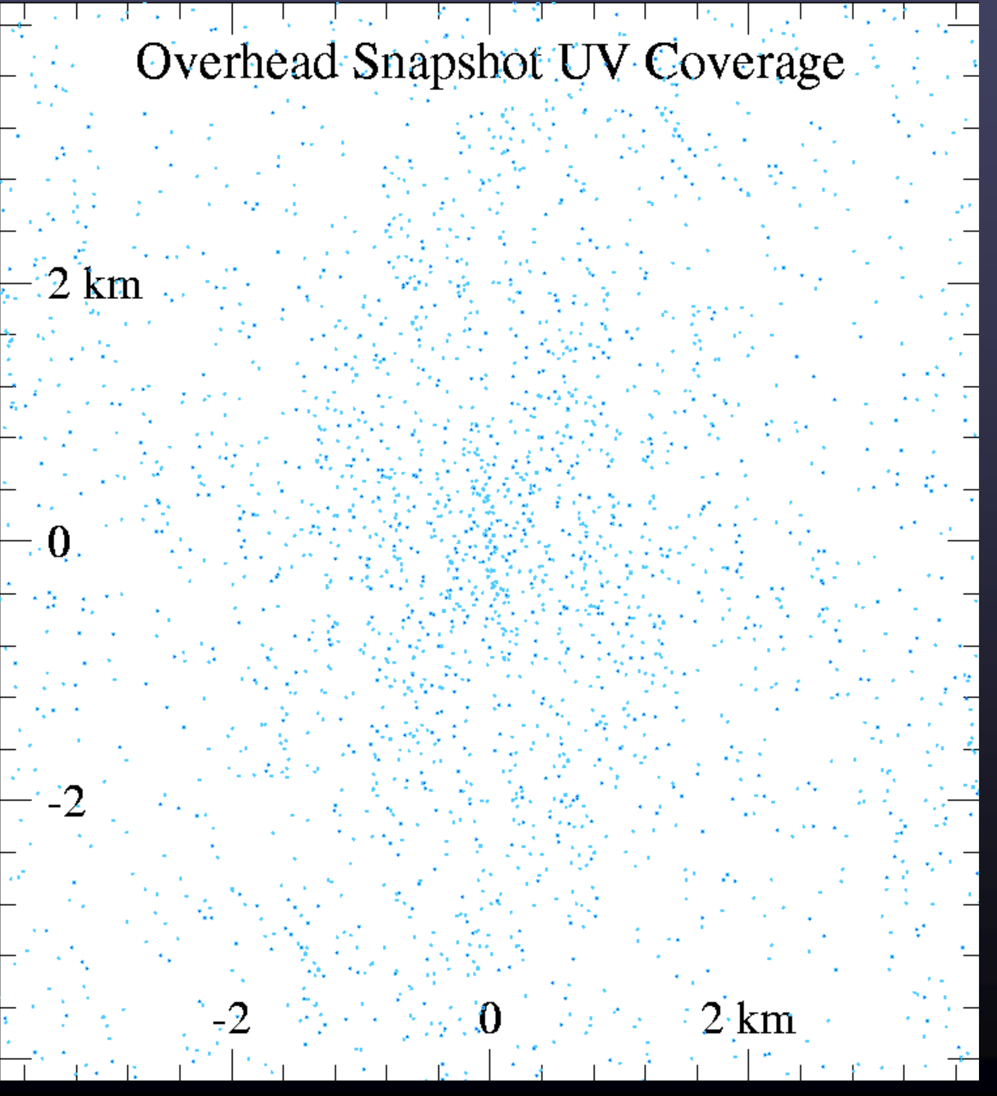
Large-N / Small-D Concept

N = 500 Random Array (magnified 10X)



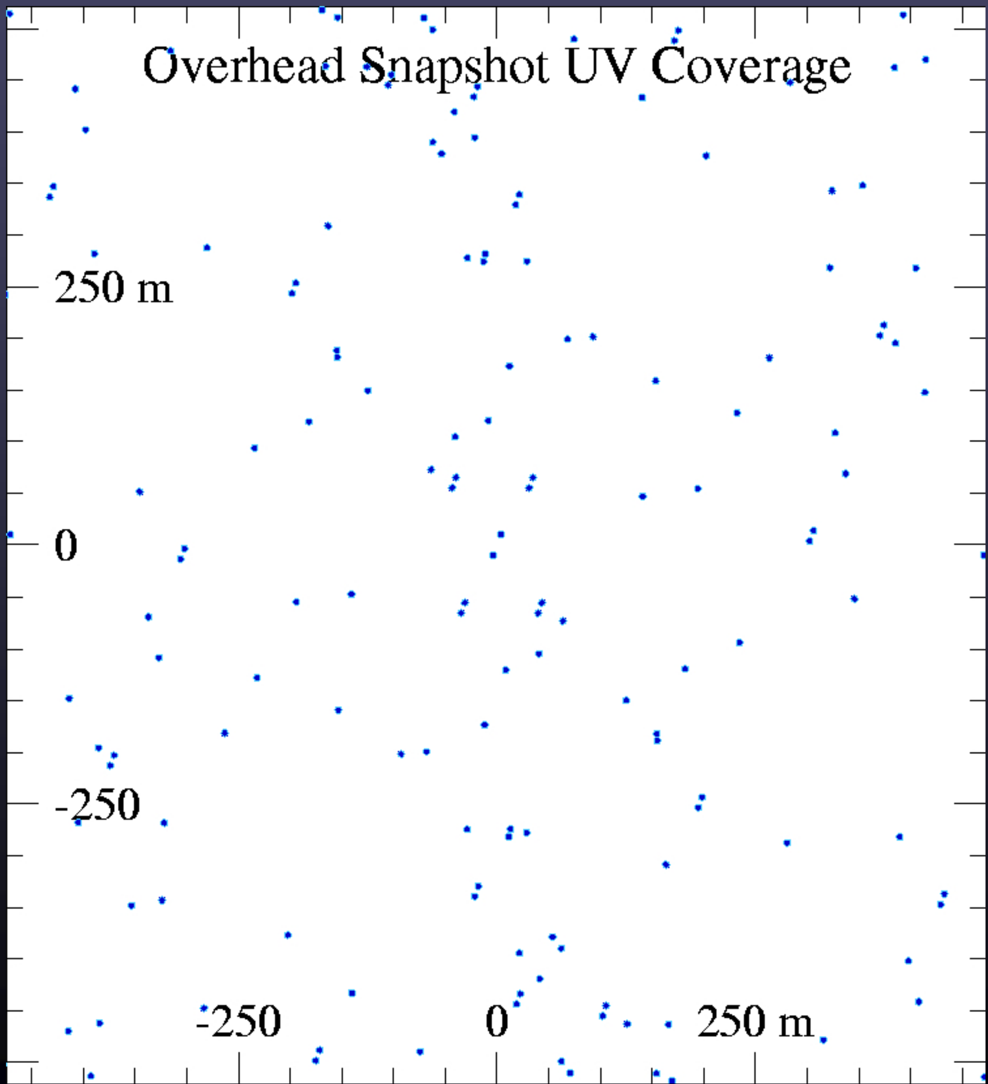
Large-N / Small-D Concept

N = 500 Random Array (magnified 100X)



Large-N / Small-D Concept

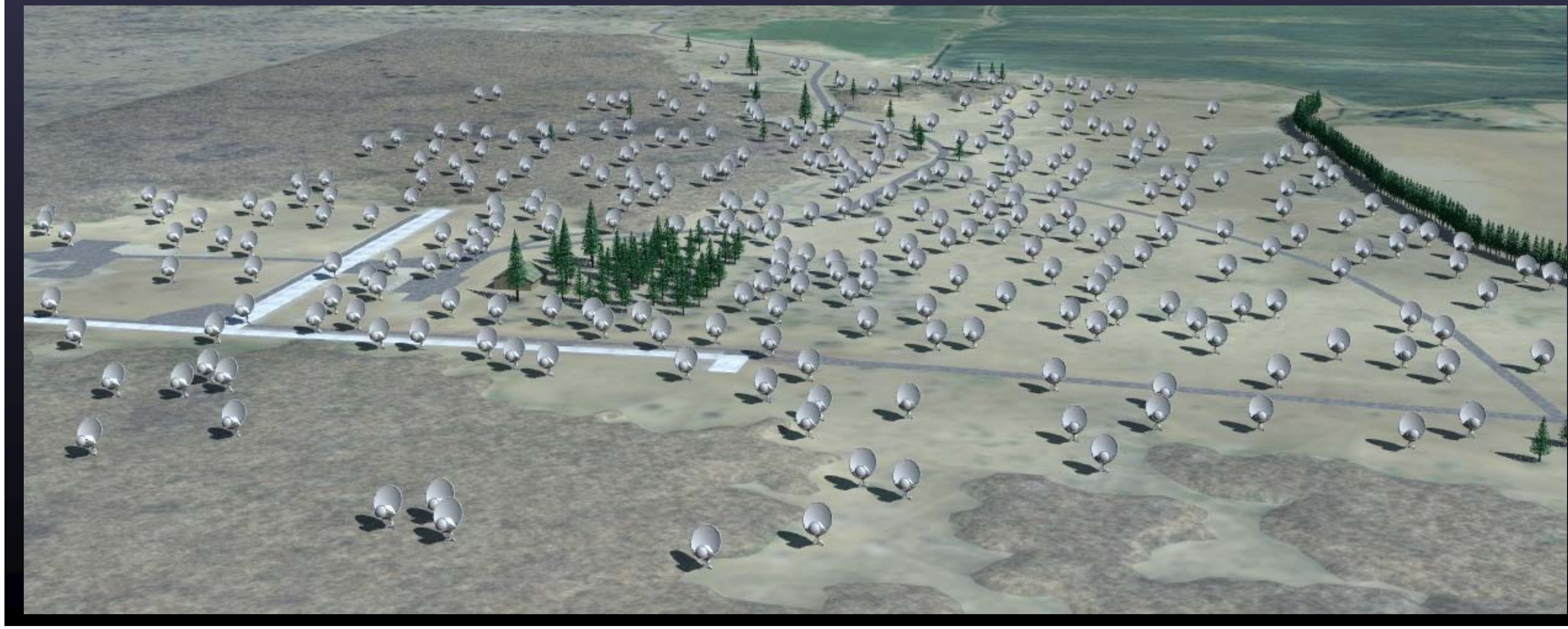
N = 500 Random Array (magnified 1000X)



Large-N / Small-D Concept

- ALMA: $\geq$ 50 antennas (re-configurable)
- LOFAR, LWA: $\geq$ 50 stations
- Allen Telescope Array: N = 350
- Square Kilometer Array: N ~1000

Allen Telescope Array (Artist Rendition)



Conclusion: Determining Array Parameters

- Longest Baseline
  - resolution needed: determined by science requirements, physical constraints
- Shortest Baseline
  - largest angular scale needed: determined by science requirements
- Number of Antennas (elements): N
  - Determined by budget constraints (higher N is nearly always better)
- Configuration of N elements
  - Determine figure of merit for the anticipated science goals
  - Maximize the figure of merit within the given “practical” constraints on element placement.

Hands on session

Please download the data from:

- www.hartrao.ac.za/~nadeem/Sythesis_school

Please pick up handouts outside (tomorrow):

- Appendix E (Special considerations for EVLA data) from the AIPS cookbook
- Log of the observation we will be looking at