Array Configuration

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Outline of Talk

- Quick Review of How Interferometry Works
- Overview of Existing Interferometric Arrays
  - VLA, WSRT, GMRT, VLBA
- 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
- Large N, Small D concept

Single Baseline Interferometry

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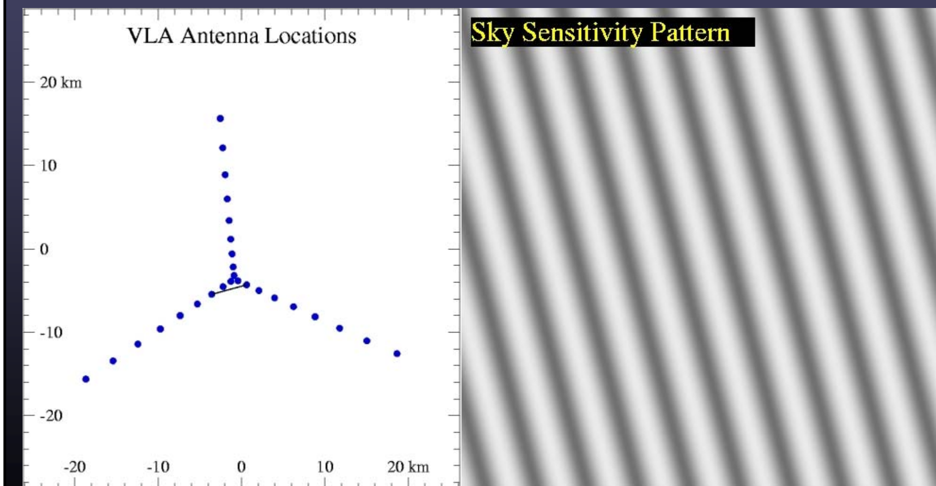
Sky Sensitivity of a short VLA baseline



Single Baseline Interferometry

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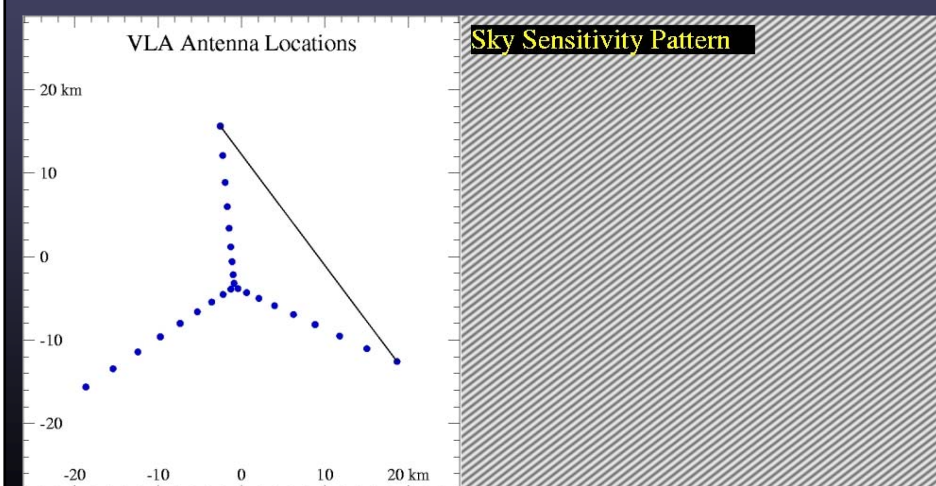
Sky sensitivity of a long VLA baseline



Point Spread Function for the VLA

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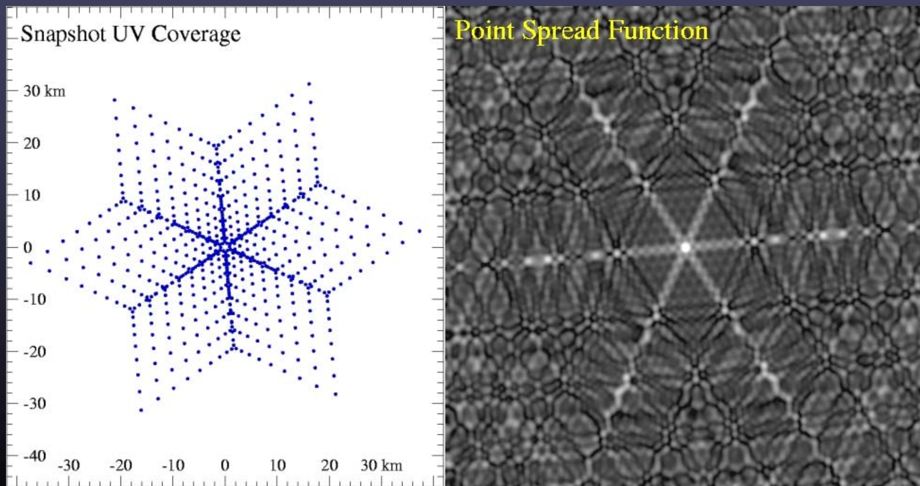
Snapshot Observation



Point Spread Function for the VLA

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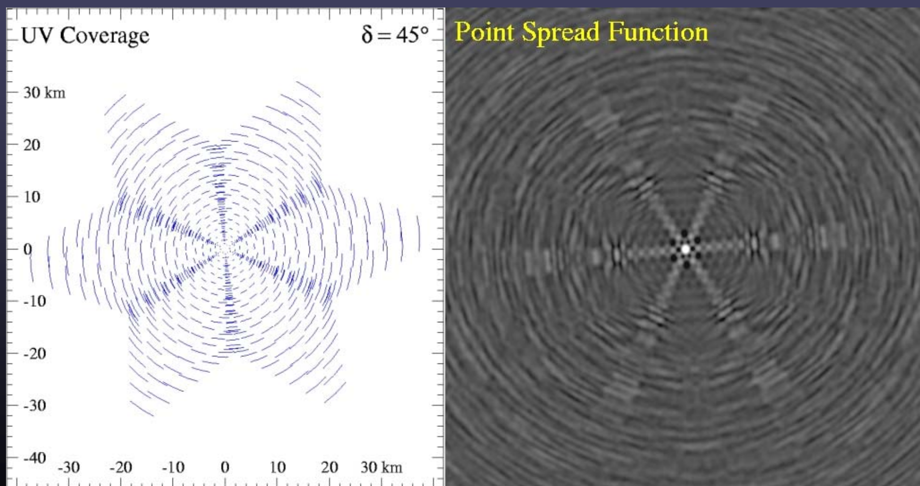
1 Hour Synthesis Observation



Point Spread Function for the VLA

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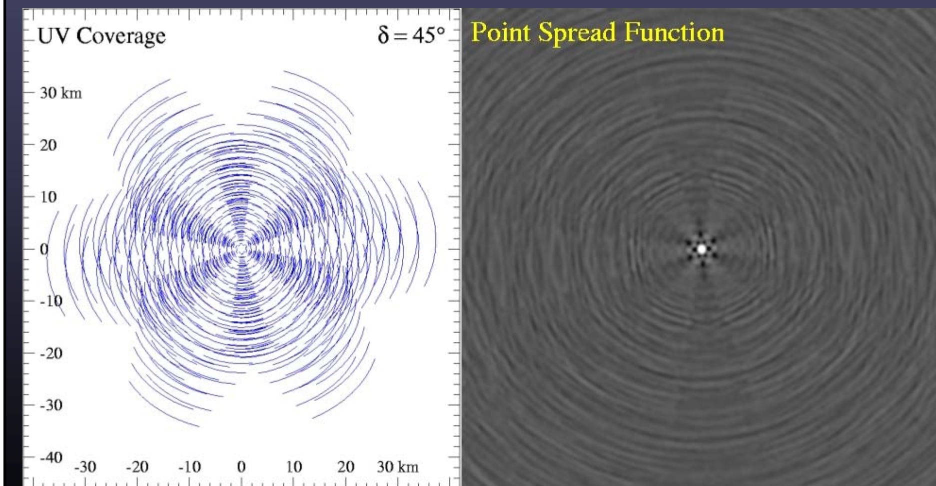
3 Hour Synthesis Observation



Point Spread Function for the VLA

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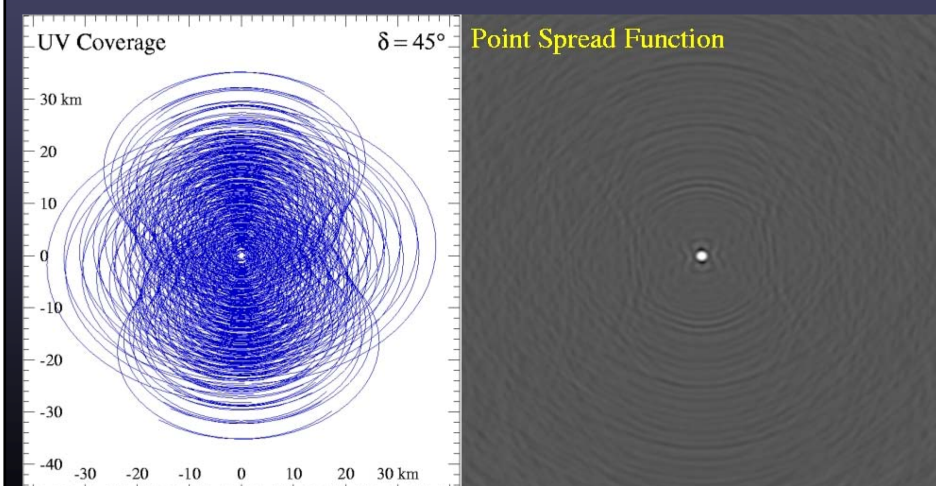
12 Hour Synthesis Observation



Compensating for Incomplete uv-Coverage

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- Deconvolution
  - works well for simple sources
  - breaks down for large complex sources
- Re-Weighting
  - uniform weighting plus taper can lower sidelobes
  - reduces sensitivity but may increase dynamic range
- 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

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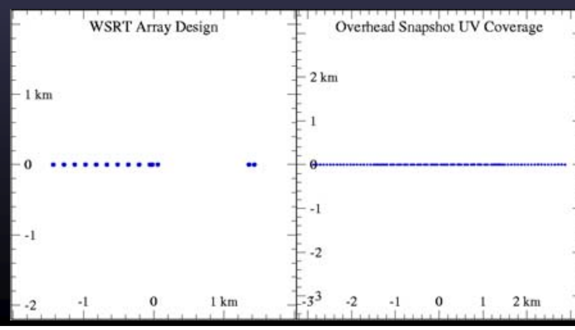
- Image Dynamic Range
  - Limited by sidelobes in the beam
- Image fidelity
  - ability to reconstruct complex source structure
  - gaps in uv-coverage will limit this
- Resolution
  - Determined by the longest baselines in the array
- Sensitivity to large scale structure
  - Determined by the shortest baselines in the array

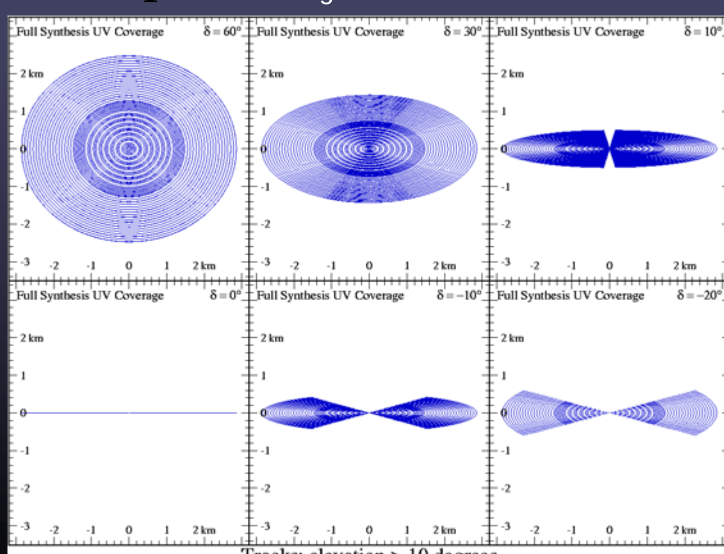
Westerbork Synthesis Radio Telescope

- 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

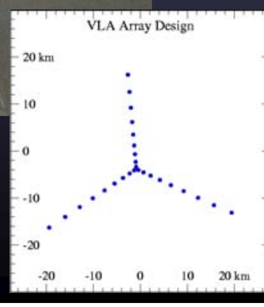
WSRT uv-coverage at various declinations

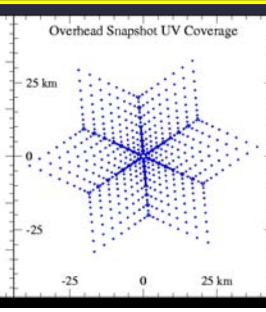


Very Large Array (VLA)

- Y-shaped Array
- Re-configurable

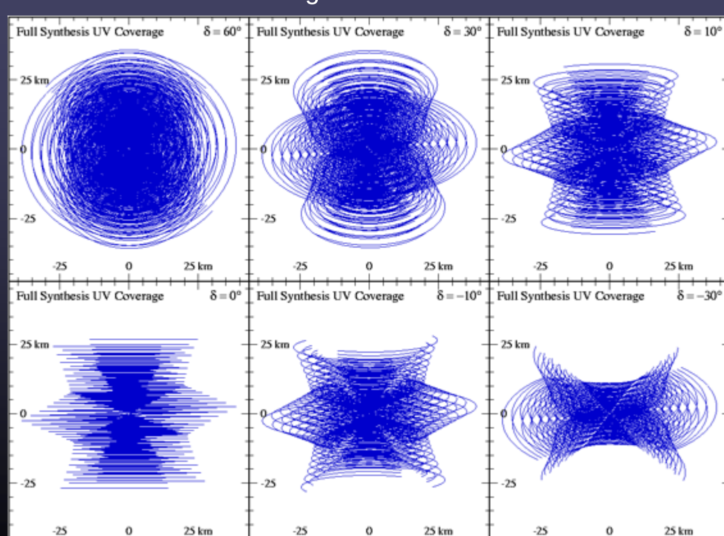
Config.	B_{max} (km)	B_{min} (km)
A	36	0.68
B	11	0.24
C	3.4	0.045
D	1.0	0.035





Very Large Array (VLA)

VLA uv-coverage at various declinations



Tracks: elevation > 10 degrees

VLA – Pie Town Link

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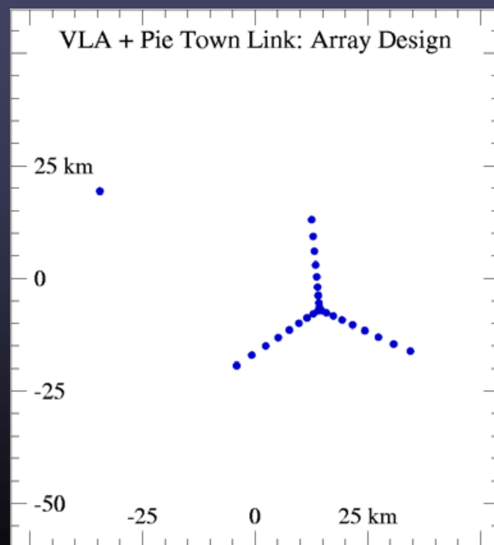
- Links (by fiber-optic cable) the VLBA antenna at Pie Town to the VLA
- Increases longest baseline from 35 to 73 km
- Best at high declinations
- Best with long uv-tracks



VLA – Pie Town Link

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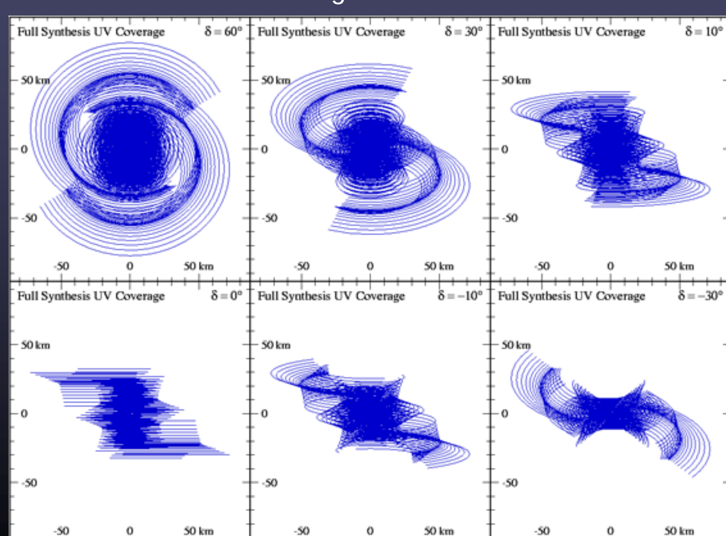
VLA+PT uv-coverage at various declinations



Tracks: elevation > 10 degrees

Giant Metrewave Radio Telescope (GMRT)

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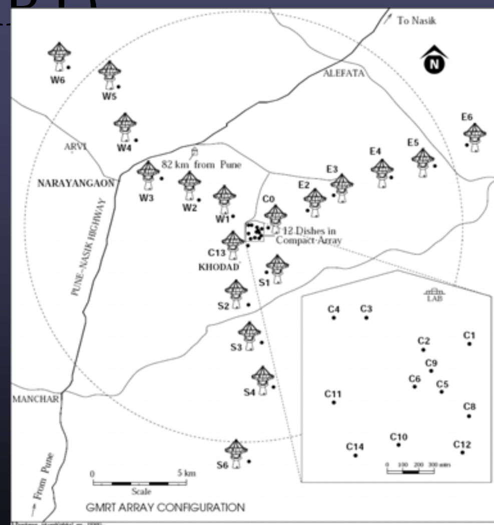

- Located near Khodad, India
- Contains 30 antennas each with 45m diameter

Giant Metrewave Radio Telescope (GMRT)

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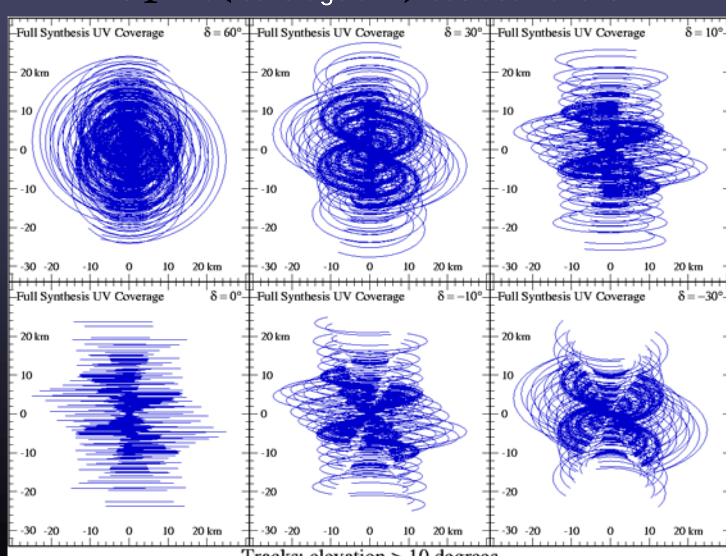
GMRT uv-coverage at various declinations



Very Long Baseline Array (VLBA)

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- 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)

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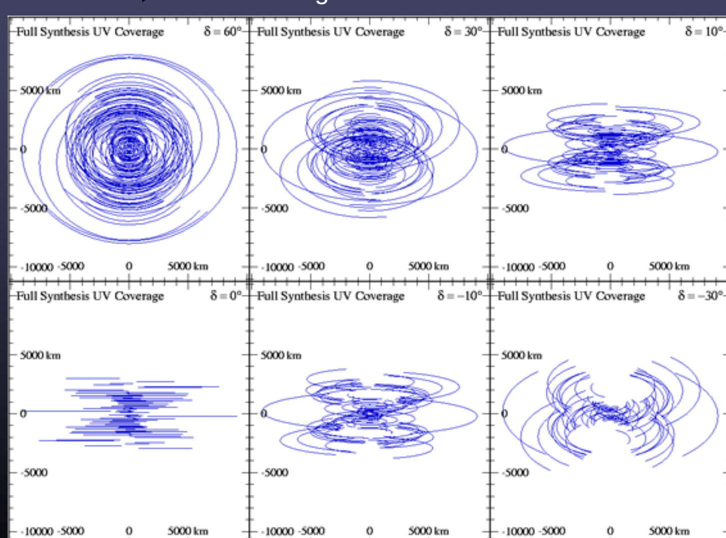
VLBA uv-coverage at various declinations



Tracks: elevation > 10 degrees

Main Parameters of Array Configuration

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- 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

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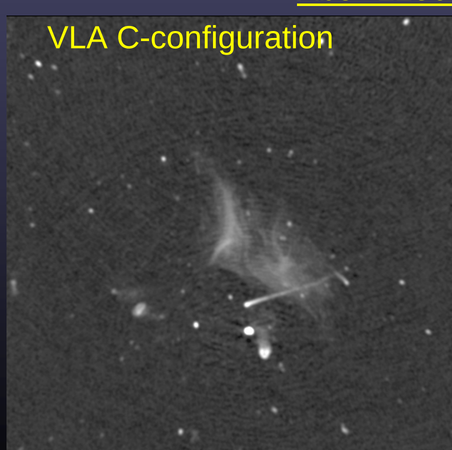
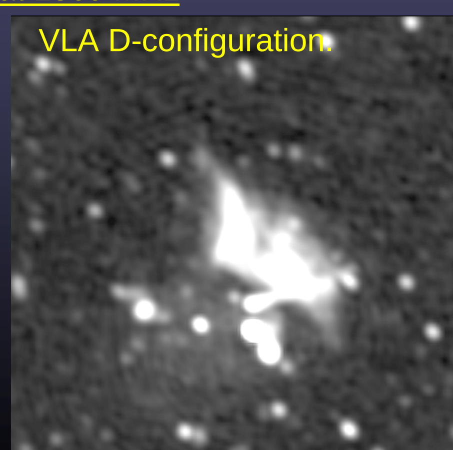
- Long Baselines: Determine resolution
- Short Baselines: Detect large scale features

Abell 2256 at 1369 MHz





Images from Clarke & Ensslin, 2006

Effect of the range of baseline lengths

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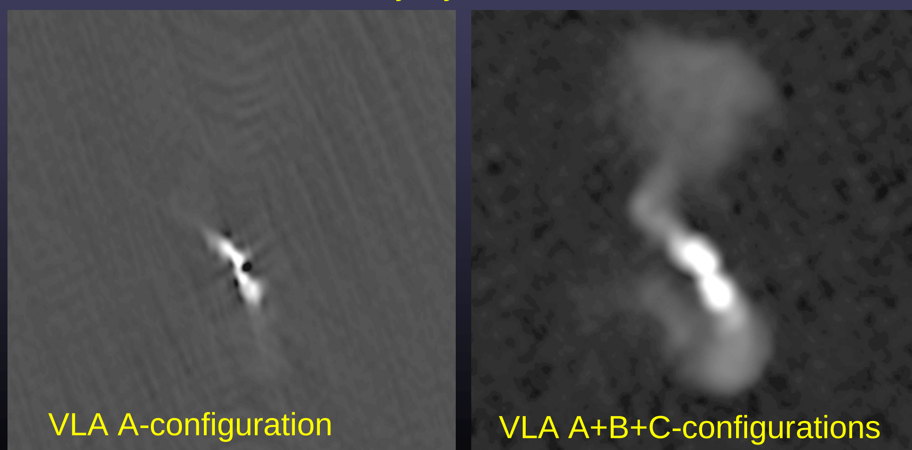
- For very complex sources, a large dynamic range between the longest and shortest baselines is needed

Radio Galaxy Hydra A at 330 MHz



VLA A-configuration

VLA A+B+C-configurations

Images courtesy of W.M. Lane

Effect of a central core

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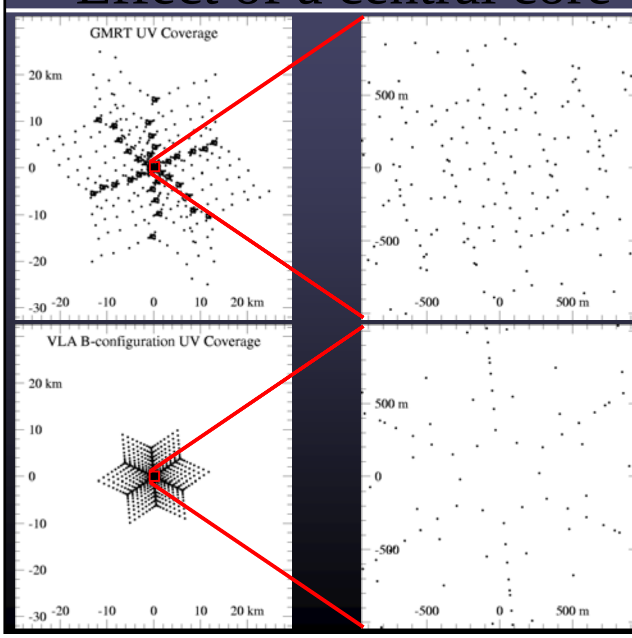
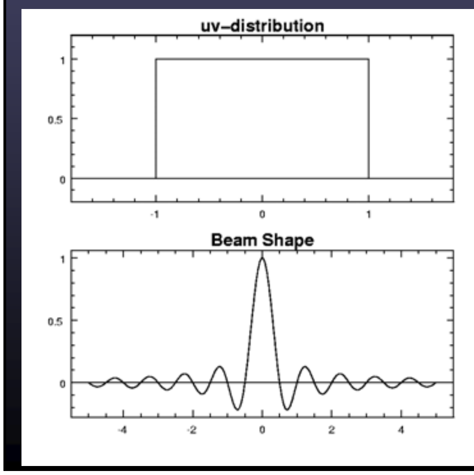


- Including a compact core can increase the baseline length dynamic range
- A core will also introduce non-uniformity in the uv-coverage
- This can be corrected with more antennas

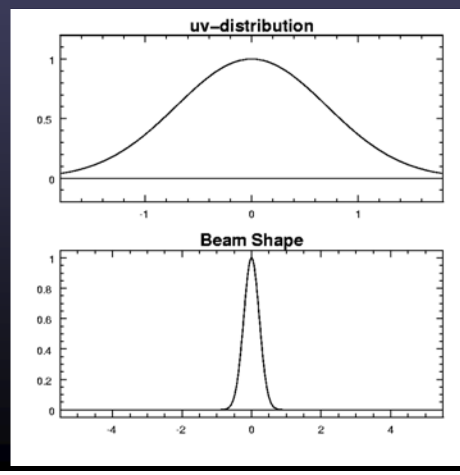
Baseline length distribution

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

Uniform distribution



Gaussian Distribution



Sidelobe Levels: Dependence on N

- RMS value of sidelobes 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 sidelobes 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 sidelobes
- Optimization can reduce this somewhat for a small region

Various Array Designs

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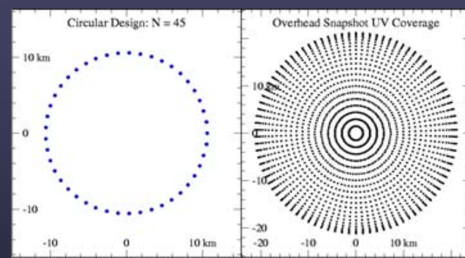
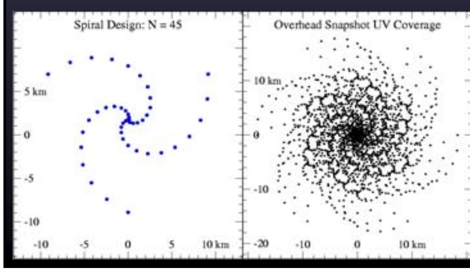
- Circular
  - maximizes number of long baselines
- Spiral
  - has more short baselines
- Random
  - has little redundancy or patterns

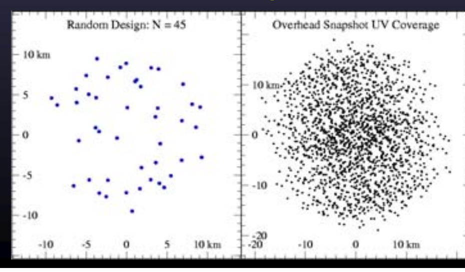
Circular Design: N = 45



Spiral Design: N = 45



Random Design: N = 45



Array Optimization

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- 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 configs, breed new generation using crossover and mutation, select, repeat
- PSF optimization (Kogan)
  - Minimize biggest sidelobe using derivatives of beam wrt antenna locations (iterative process)

Metrics for Optimization

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- Sidelobe 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: Kogan Method

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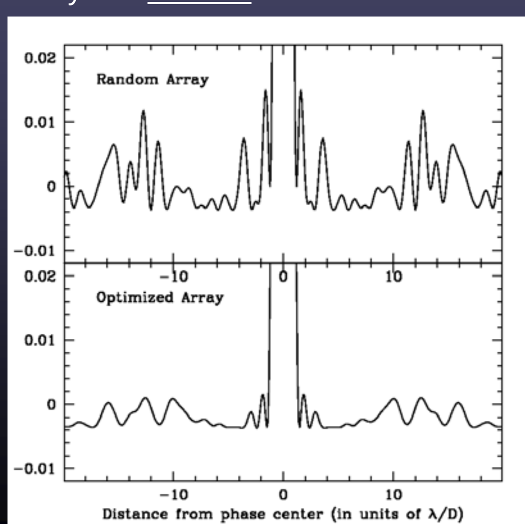
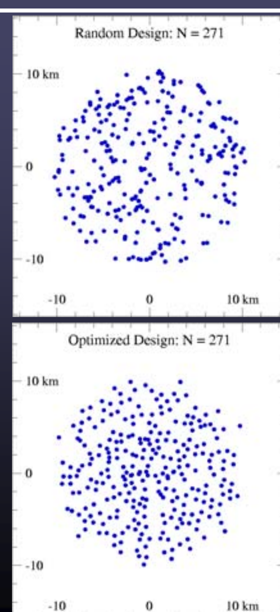
Comparing random versus optimized arrays for N = 271





Simulations

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- 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 DR and fidelity

Large-N / Small-D Concept

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- 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

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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^5 !!!
  - N^2 times more baselines
  - N times as many pixels in the FOV
  - N times as much channel resolution
  - N times as much time resolution
- Need correlator with more capacity
- Higher data rate

Large-N / Small-D Concept

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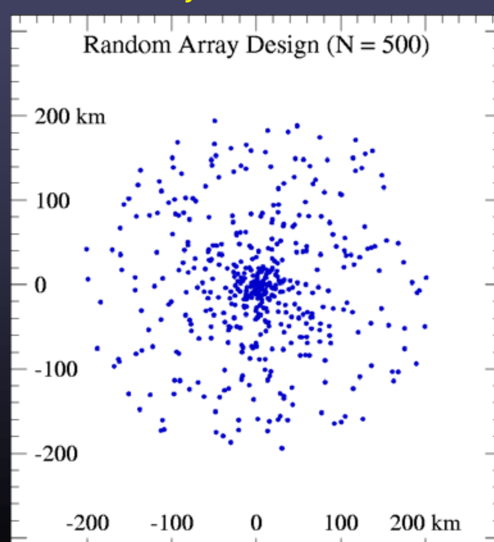
N = 500 Random Array

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



Large-N / Small-D Concept

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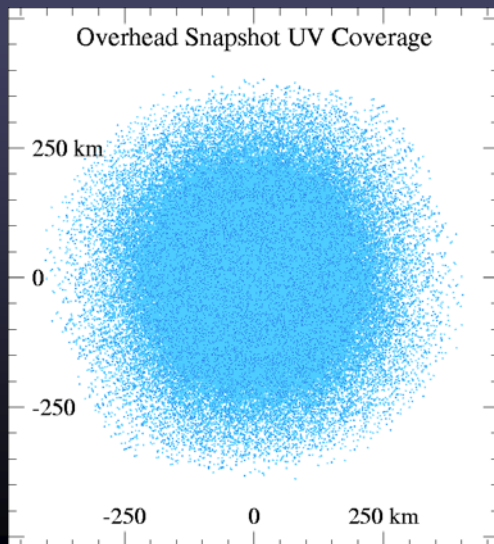

Large-N / Small-D Concept

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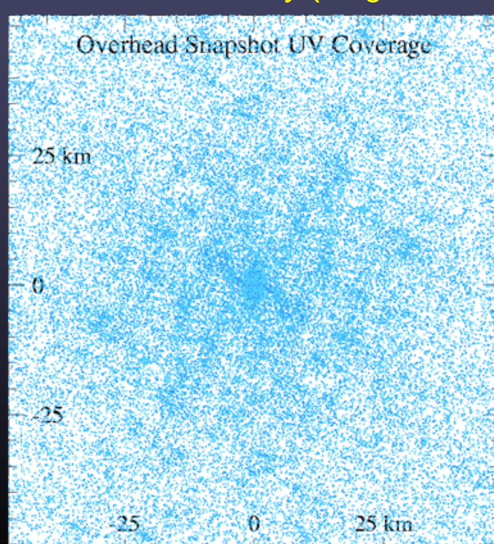
N = 500 Random Array (magnified 10X)



Large-N / Small-D Concept

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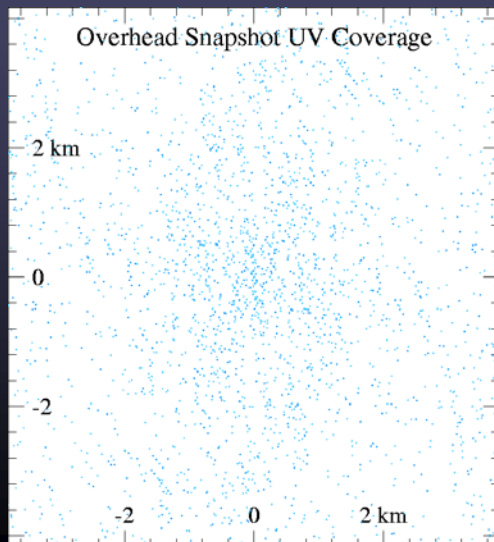
N = 500 Random Array (magnified 100X)



Large-N / Small-D Concept

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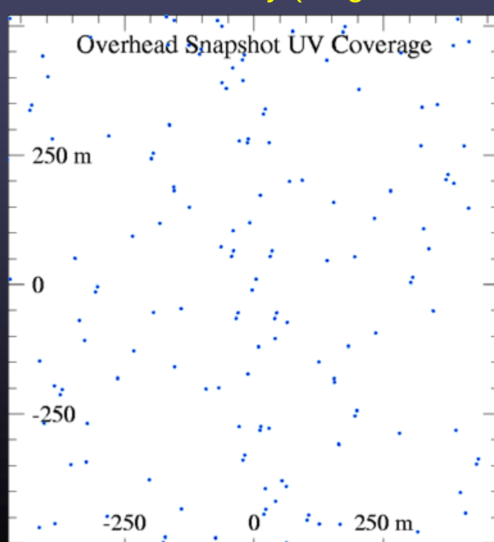
N = 500 Random Array (magnified 1000X)



Large-N / Small-D Concept

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- ALMA: 64 antennas (re-configurable)
- LOFAR, LWA: >~50 stations
- Allen Telescope Array: N = 350
- Square Kilometer Array: N ~1000

Possible SKA Design

Allen Telescope Array (Artist Rendition)

Determining Array Parameters

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- 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
  - Maximize image fidelity

Various Array Designs

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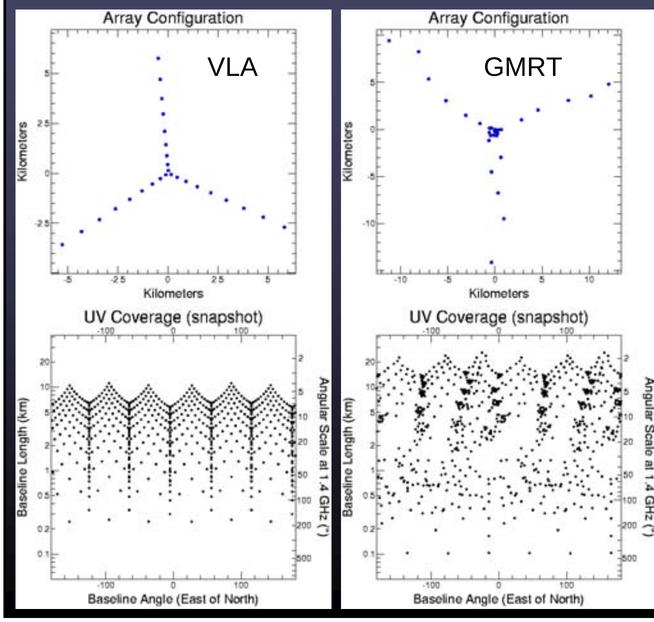

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