ARRAY DESIGN

Craig Walker NRAO

Sixteenth Synthesis Imaging Workshop

16-23 May 2018

Based in part on a 2008 lecture by Aaron Cohen

STEPS TO DESIGN AN ARRAY

- Why build a new array? The science case
- Define the capabilities required for the science
  - Frequency range, field of view, sensitivity, survey speed, resolution …
- Set the technical specifications to provide the capabilities
  - Antenna number, size, type, and performance
  - Electronics (receivers, data transmission system, correlator …)
  - Site and configuration characteristics
- Design the hardware to meet the specs
  - Antennas, receivers electronics etc.
  - Estimate the cost
  - See earlier talks by McKinnon and Deller
- Select a location for the array
- Design and optimize the configuration
- Show what the array can do. Simulations

SCIENCE REQUIREMENTS

- Specify the key science goals
  - Exciting topics with broad appeal
  - Concentrate on a small number
  - Represent the full range of desired capabilities
  - Document the goals in a compelling and convincing manner
    - White papers, books, talks
- Use the goals to sell the array to astronomers and the public
  - Required for funding
- Use the goals to specify the technical characteristics
- Show the goals can be met with a feasible and affordable array

CASE STUDY: SKA KEY SCIENCE DRIVERS (circa 2007)

SKA project identified 5 key science drivers:

1. Cradle of Life
   - Astrobiology, planet detection, SETI
2. Probing the Dark Ages
   - Epoch of reionization, redshifted CO, first AGNs
3. The origin and evolution of Cosmic Magnetism
4. Strong field tests of gravity using pulsars and black holes
5. Galaxy evolution, cosmology and dark ages
6. (Exploration of the Unknown)

(Schilizzi et al, 2007, SKA Memo 100)

CASE STUDY: SKA KEY SCIENCE REQUIRED ARRAY CHARACTERISTICS

- Frequency Range
- Field of View
- Sensitivity
- Survey Speed
- Resolution
- Max Baseline
- Dynamic range driver?
- Polarization driver?

Table 4. Desired specifications for the SKA

KSP ID	KSP Description	Frequency Range GHz	FoV	Sens-itivity	Survey Speed	Resn.	Base-line	Dyn. Range Driver	Poln. Driver
		0.1 0.3 1.0 3.0 10 30	deg^2	m^2/K	$deg^2 m^4 K^{-2}$	mas	Km		
1	**The Dark Ages**								
1a†	EoR				$>\sim 3\times10^7$		1	*	**
1b	First Metals		0.003	15,000		50	125		
1c	First Galaxies & BHs			20,000		10	4500	*	**
2	**Galaxy Evolution, Cosmology & Dark Energy**								
2a†	Dark Energy				6×10^8		5		
2b†	Galaxy Evolution			20,000	1×10^9		10		
2c	Local Cosmic Web				2×10^7		0.5		
3	**Cosmic Magnetism**								
3a†	Rotation Measure Sky				2×10^8		10-30		**
3b	Cosmic Web				1×10^8		5		**
4	**GR using Pulsars & Black Holes**								
	Search				1×10^8		< 1		
4a†	Gravitational Waves		-	>15,000		1	200		**
4b	BH Spin		1	10,000			-		**
4c†	Theories of Gravity			>15,000		1	200		**
5	**Cradle of Life**								
5a†	Proto-planetary Disks		0.003	10,000		2	1000		
5b	Prebiotic Molecules		0.5-1	10,000		100	60		
5c	SETI		1						
6	**Exploration of the Unknown**		Large	Large	Large				

† Headline science, see Section 3.2
* See Section 5.1.8 for explanation of Dynamic Range drivers
** See Section 5.1.6 for explanation of Polarisation Purity drivers

Schilizzi et al. 2007, SKA Memo 100

DEVELOP THE TECHNICAL SPECS

- From the required array characteristics, set the technical specs
  - Frequency range: antenna accuracy, receivers, site
  - Field of view: antenna size, multi-beam feeds, frequency resolution
  - Sensitivity: total collecting area (antenna size and number) receiver quality, bandwidth
  - Resolution: maximum baseline length, frequency, site
  - Dynamic range: number of antennas, calibration style
  - Polarization: feeds, receiver, antenna
  - Spectral resolution: correlator

FREQUENCY RANGE: ANTENNA DESIGN

- The frequency range strongly influences the type and cost of the antennas and receivers
  - Low frequencies (< 3 GHz very roughly)
    - Less demanding for accuracy
    - Can get large collecting area at low cost
    - Can use aperture arrays of fixed elements at $\lesssim$ 1.5 GHz
  - High frequencies (> 3 GHz very roughly)
    - Will use dishes and cryogenic receivers
    - High surface accuracy
    - High pointing accuracy
    - Offset feed designs provide low Tsys and high efficiency

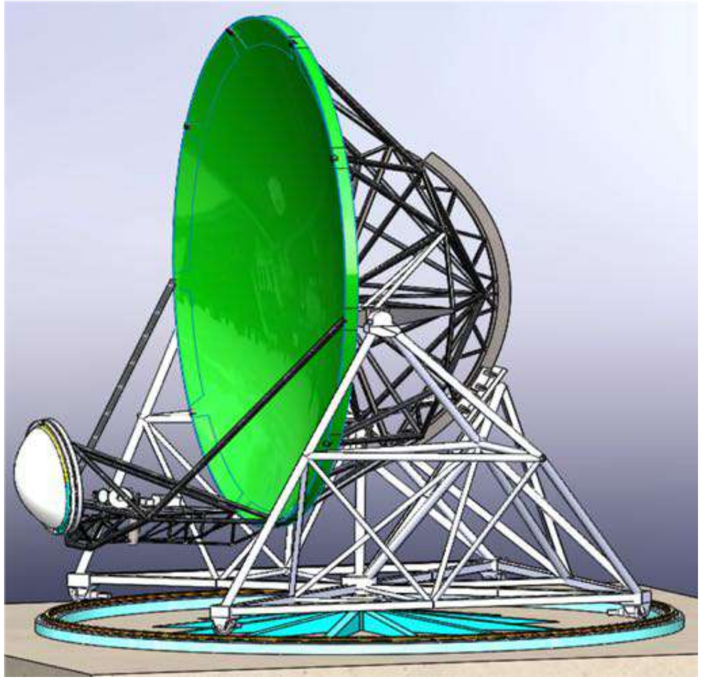
ANTENNA TECHNOLOGIES

Lowest frequencies – dipole arrays

MWA 80-300 MHz.

Steered by phasing fixed elements

High frequencies – dishes



NRC concept for ngVLA antenna

Offset low feed

ngVLA 1.2 to 116 GHz

COST VS ANTENNA DIAMETER

- Need realistic model of cost vs N_{ant} and D
- Traditional dish antenna cost scales as $D^{2.7}$
- Number of antennas scales as D^{-2} for constant area
- Total cost for all antennas scales as $D^{0.7}$
  - Favors smaller antennas.
- But many items scale with N_{ant} and N_{beams}
  - Receiver electronics, LO/IF, data transmission, parts of correlator
- Other items scale with N_{ant}^{2}
  - Baseline sections of correlator scale, postprocessing
- Optimum has a broad minimum favoring 10 to 20 m antennas

FIELD OF VIEW

- Reasons for small fields of view:
  - Good for targeted observations of small sources
  - Less trouble with strong, confusing sources
  - May be able to afford better receivers, more bandwidth
  - Fewer, larger antennas simplify operations
  - Easier processing – fewer baselines, smaller data sets
  - But cost scales faster than area, so don't make antennas too big
- Reasons for large fields of view:
  - Surveys - want to cover large areas of sky
  - Large sources (e.g. galactic clouds, nearby galaxies)
- Options for large field of view:
  - Many small antennas with large beams
  - Multiple beam receiving systems – a lot of electronics

FIELD OF VIEW EXAMPLES

- EVLA: 25m antennas - primary beam 30' at 1.4 GHz.
  - Good for sensitivity and wide frequency coverage
  - Slow for surveys
- ALMA: 50 X 12m antennas + ACA (12 X 7m array + 4 X 12m for total power)
  - Compromise between sensitivity for extragalactic sources and ability to observe large galactic objects
  - The ACA is used for short baselines and wide fields
- VLBA: 10 X 25m antennas, but individual fields limited by delay and rate smearing to a few arcseconds. Not for blind surveys!
  - Can use multiple phase centers over primary beam
- LWA, MWA, LOFAR: Fixed aperture arrays. In principle, with enough electronics, could observe the whole sky.
- WSRT, ASKAP: Feed arrays on dish antennas for multiple beaming

SENSITIVITY AND SURVEY SPEED

- The sensitivity spec is the desired noise level in single fields
  - Important for detecting weak sources and for high dynamic range
  - Depends on collecting area (N_{ant} D^2), system temperature (Ts), integration time (t) and bandwidth ($\Delta\upsilon$)
    - Image noise $\sigma \propto Ts / (N_{ant}\, D^2\, (t\, \Delta\upsilon)^{0.5})$
  - Integration time to reach noise σ: $t_\sigma \propto Ts^2 / (N_{ant}^2\, D^4\, \Delta\upsilon\, \sigma^2)$
- A survey speed spec relates to time for surveys or mosaics
  - Integration time to reach noise σ over the full area depends on:
    - Single field sensitivity (as above)
    - Number of fields required $\propto$ (total area / beam area) $\propto (D/\lambda)^2$
    - Number of simultaneous beams (N_{beams})
    - Time to survey to noise σ: $t_s \propto t_\sigma\, (D/\lambda)^2 / N_{beams}$
  - Note a survey is faster with smaller antennas (D) for fixed sensitivity

RESOLUTION AND BRIGHTNESS TEMPERATURE

- Resolution $\theta \approx \lambda / B_{max}$
  - Highest resolutions use high frequencies and long baselines
  - High resolution good for hot or non-thermal sources (AGN, masers …)
  - High resolution best for astrometry
- Brightness temperature (Rayleigh-Jeans limit)
  - Flux density for brightness temperature T_B: $S = 2\,k\,T_B\,\Omega / \lambda^2$
  - For measured T_B, use the synthesized beam solid angle $\Omega_b \propto (\lambda / B_{max})^2$
  - Then: $S \propto T_B / B_{max}^2$ Depends only on baseline, not frequency
  - For low T_B sources, need short B_{max} for detection
  - Low T_B sources include radio lobes, molecular clouds, most thermal objects
- A general purpose instrument will need a wide range of resolutions

EXTREME BASELINE EXAMPLES

- ALMA ACA and most compact configuration
- Good for large, diffuse sources

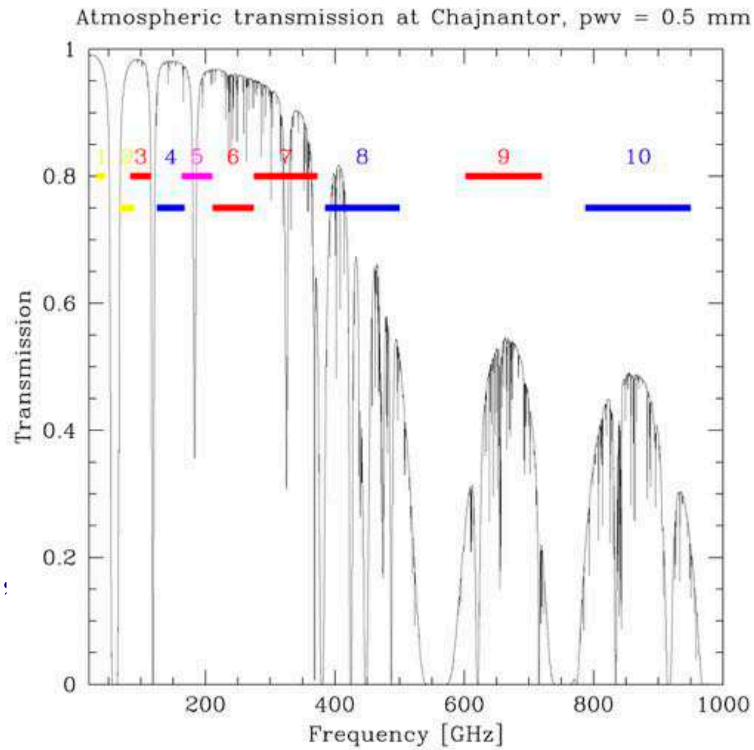
- VLBA - Continental or more in scale
- Good for very high brightness sources and astrometry
- Space VLBI is being done

LOCATION

- Location has large performance, operations, financial, and political impacts
- Latitude important for sky coverage, observing conditions and ionosphere
- At high frequencies, want high altitude site with a dry climate (ALMA)
- At low frequencies, want protection from RFI (SKA)
- At low frequencies, avoid regions with worst ionosphere (SKA etc)
- Site must be large enough to accommodate the array
- Need reasonable access and place to live for staff and their families
  - Not everyone can work remotely
- Need infrastructure: roads, power, communications
  - Expensive if need to provide own, especially to outer stations.

TROPOSPHERE

- At high frequencies, the troposphere is the main problem for calibration
- Phase: Water vapor dominates fluctuations
  - Highly variable and limits phase stability
  - The dry component has larger path length, but is stable
  - For a high frequency array, need a dry site
    - Want an arid location at high altitude
    - EVLA at 2114 m
    - ALMA at 5000 m in the Atacama Desert
- Sites can be tested with water vapor radiometers or small interferometers

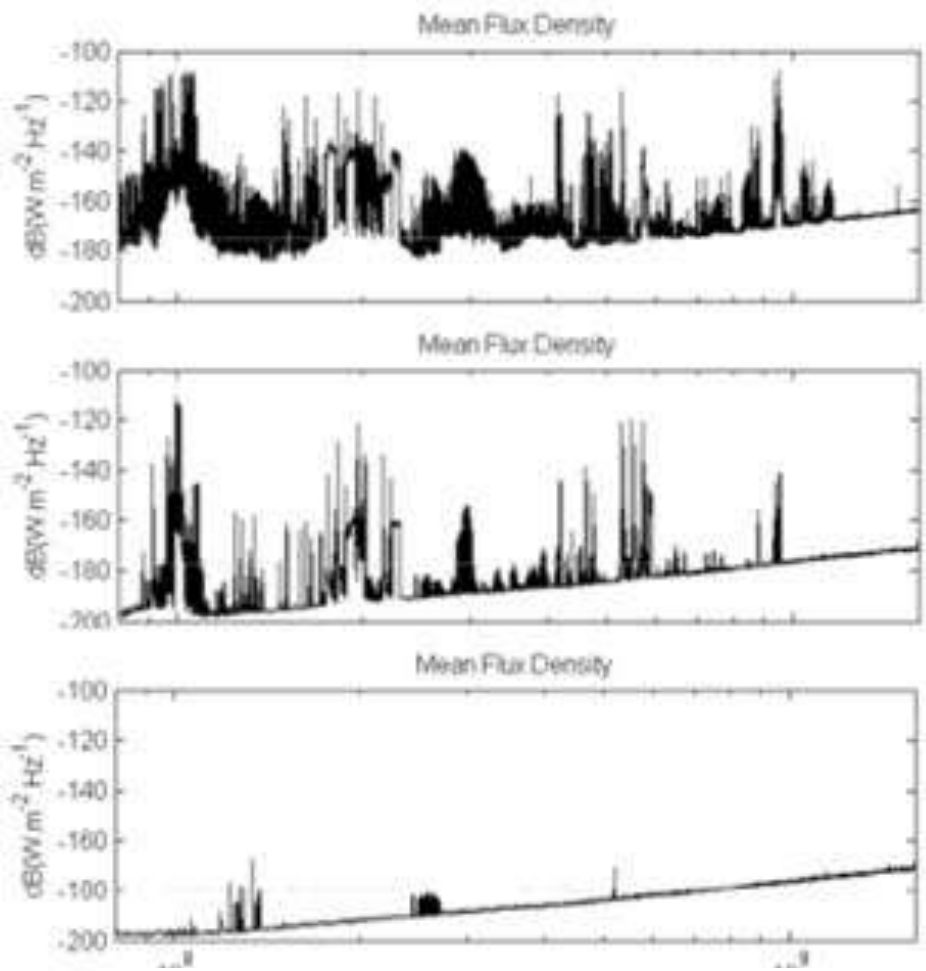


- Opacity:
  - Above is transparency at ALMA up to 1000 GHz
  - Limits high frequencies
  - Use windows between atmospheric lines
  - Varies with weather

RADIO FREQUENCY INTERFERENCE

- RFI is a big problem especially on short baselines at low frequencies.
  - Non-closing corruption of data
  - Time variable
  - Corruption of spectra
- It is becoming more of a problem at high frequencies
- Want isolation from civilization
- Want terrain shielding (surrounding mountains good)
  - Can't hide from satellites
- Problem is reduced for long baselines
  - Sources are different for each antenna – don't correlate
  - Attenuated by high fringe rates (differential Doppler shifts)
  - But can saturate receivers

RFI EXAMPLES



Large city
population: several million

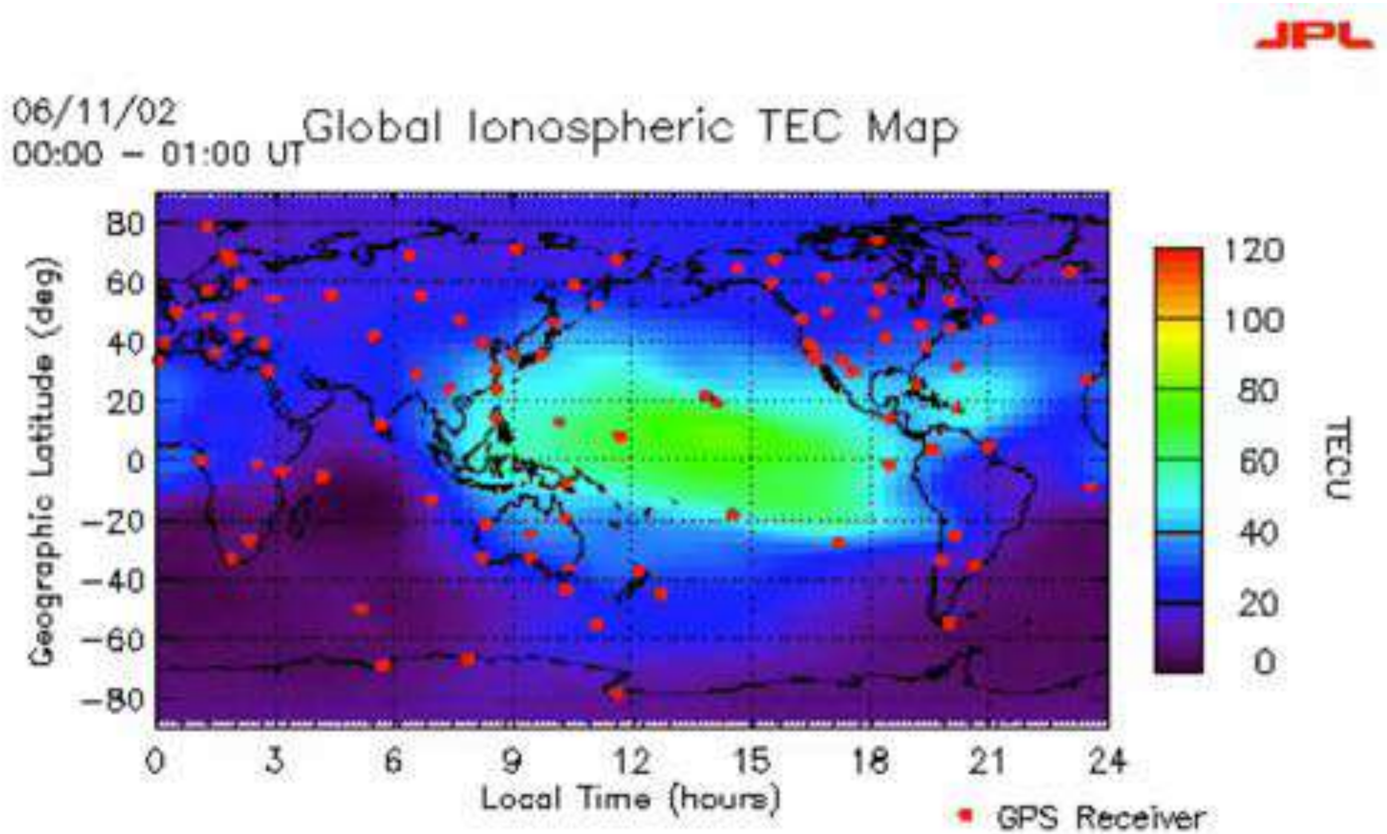
Town
population: several thousand

Candidate SKA core site
population: a few

100 MHz Frequency 1 GHz

IONOSPHERE

- Causes a propagation delay proportional to λ^2
- Can seriously complicate the calibration of low frequency data
- Concentrated near the subsolar point along the geomagnetic equator



CONFIGURATION

- Where to put the individual antennas within overall site
- Goals
  - Obtain adequate UV coverage to meet the scientific goals
  - Obtain the desired distribution of long and short baselines
  - Minimize cost of construction and maintenance
- Some top level decisions
  - Centrally condensed or more uniform distribution?
  - Use reconfiguration?
  - Optimize for snapshot coverage or only for full tracks?
  - Are some antennas in clusters, especially far from core?
- Once configuration is chosen, can't freely move individual antennas
  - UV coverage depends on relative antenna locations

ANTENNA SITE CONSTRAINTS

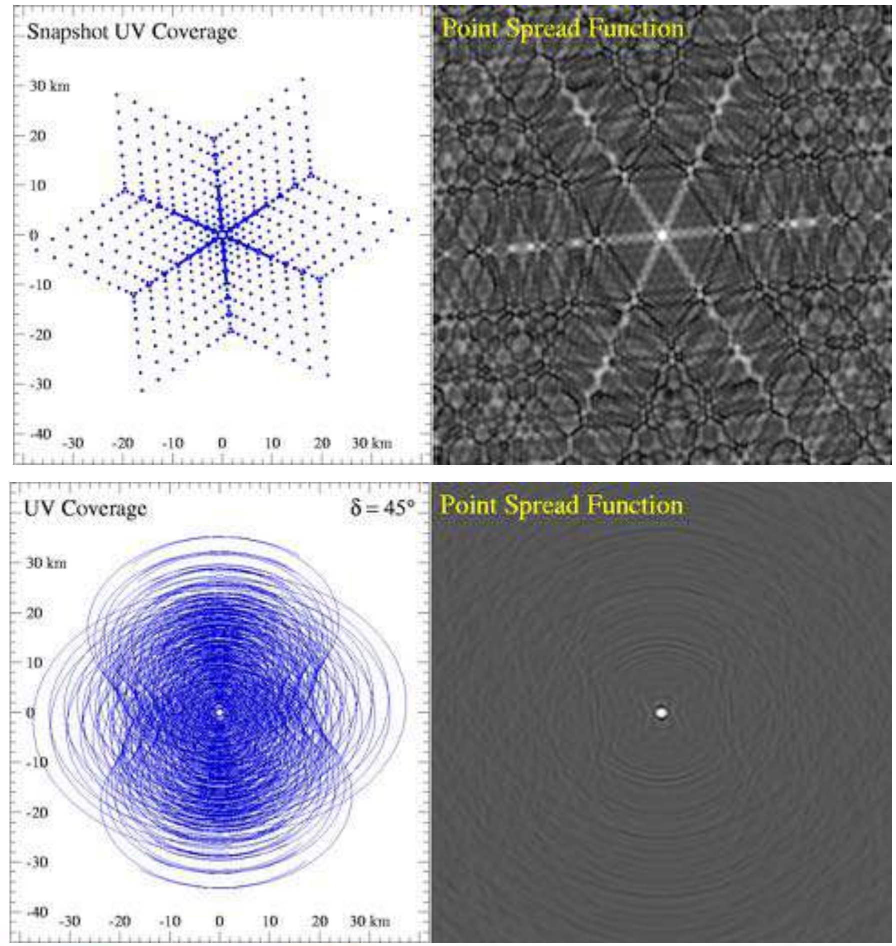
- Antenna location constraints vary on different scales
  - For short baselines (10s of km), want large flat area
    - Full freedom to position antennas as desired
  - For about 30 to 300 km, geography has big impact
    - Need individual sites
    - Need power, communication, and road access at reasonable cost
    - Need to avoid cities, wilderness areas, military bases etc.
    - Sites need to be close (few km) to the desired position
  - For baselines over about 300 km, precise site position not critical
    - Usually can find an acceptable site close enough to desired position
    - Main constraints are major geographic features like oceans and national boundaries

RECONFIGURE?

- Moving antennas allows wide baseline range with fewer antennas
  - Constrains observation dates
  - Requires transporter and roads/rails
  - Increased operations and maintenance complexity
- JVLA: 4 configurations
  - Scale by 3.28
- ALMA: 10 configurations + ACA
  - Variable scale < factor of 2
- SKA and ngVLA will not reconfigure
  - Weights and tapers for desired resolution with good imaging roughly cut sensitivity in half (1.5 – 2.4)

UVCOVERAGE: SNAPSHOT vs FULL TRACK

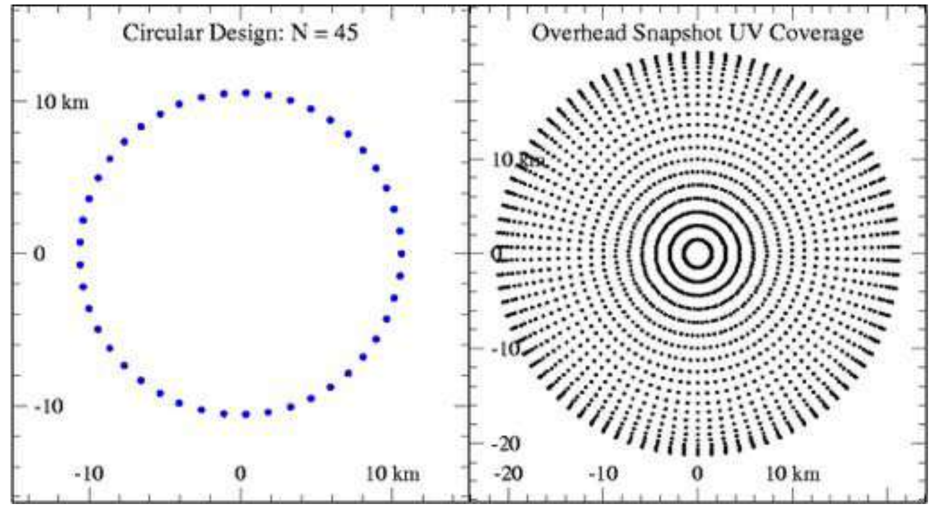
- Is good snapshot UV coverage required?
  - Surveys, large source lists etc.
- Snapshot UV coverage much worse
  - Higher sidelobes
  - Can highlight array weaknesses
    - Straight arms on JVLA
- If optimize for snapshots, long track coverage will be good.
  - Opposite not true
- Good snapshots require many antennas
- Probably best to optimize snapshots



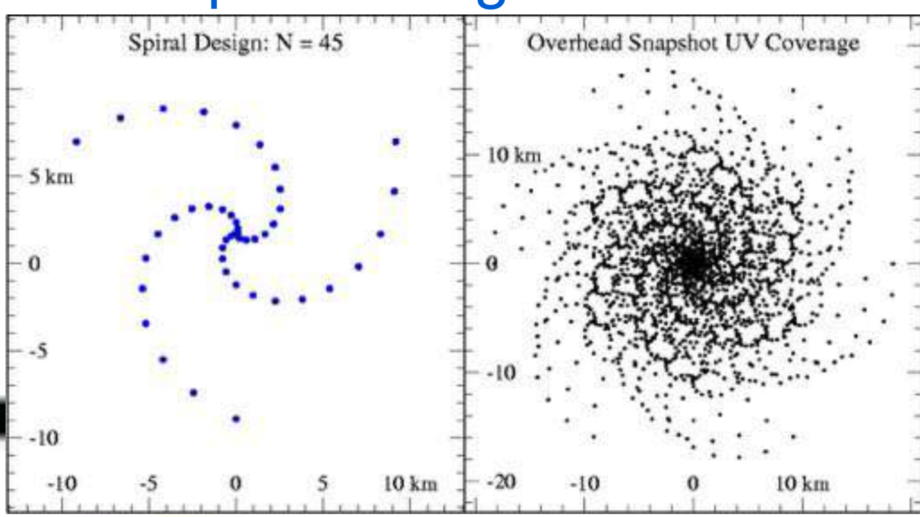
VARIOUS "IDEAL" ARRAY DESIGNS

- Circular
  - maximizes number of long baselines
  - high resolution, but big center hole
- Spiral
  - has more short baselines
  - Less total fiber and power line
- Random
  - Has little redundancy or patterns
  - Can be improved

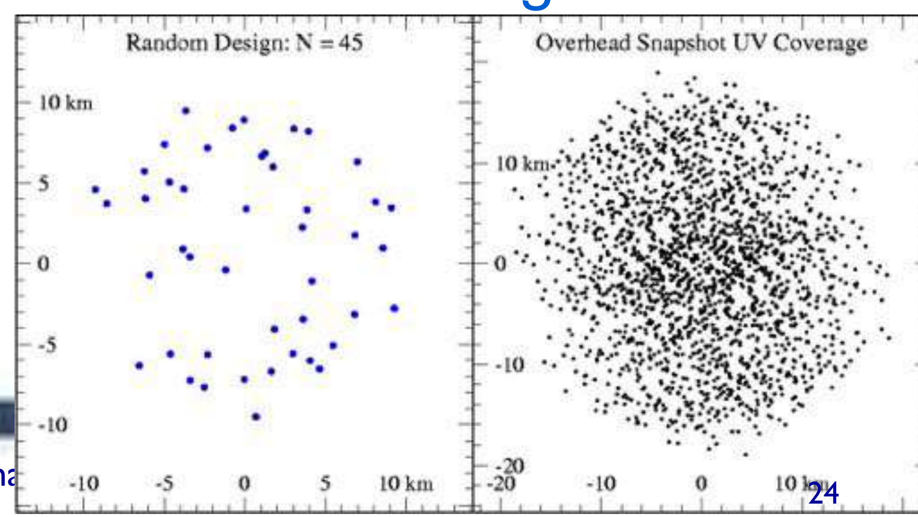
Circular Design: N = 45



Spiral Design: N = 45



Random Design: N = 45



Ima

METRICS FOR OPTIMIZATION

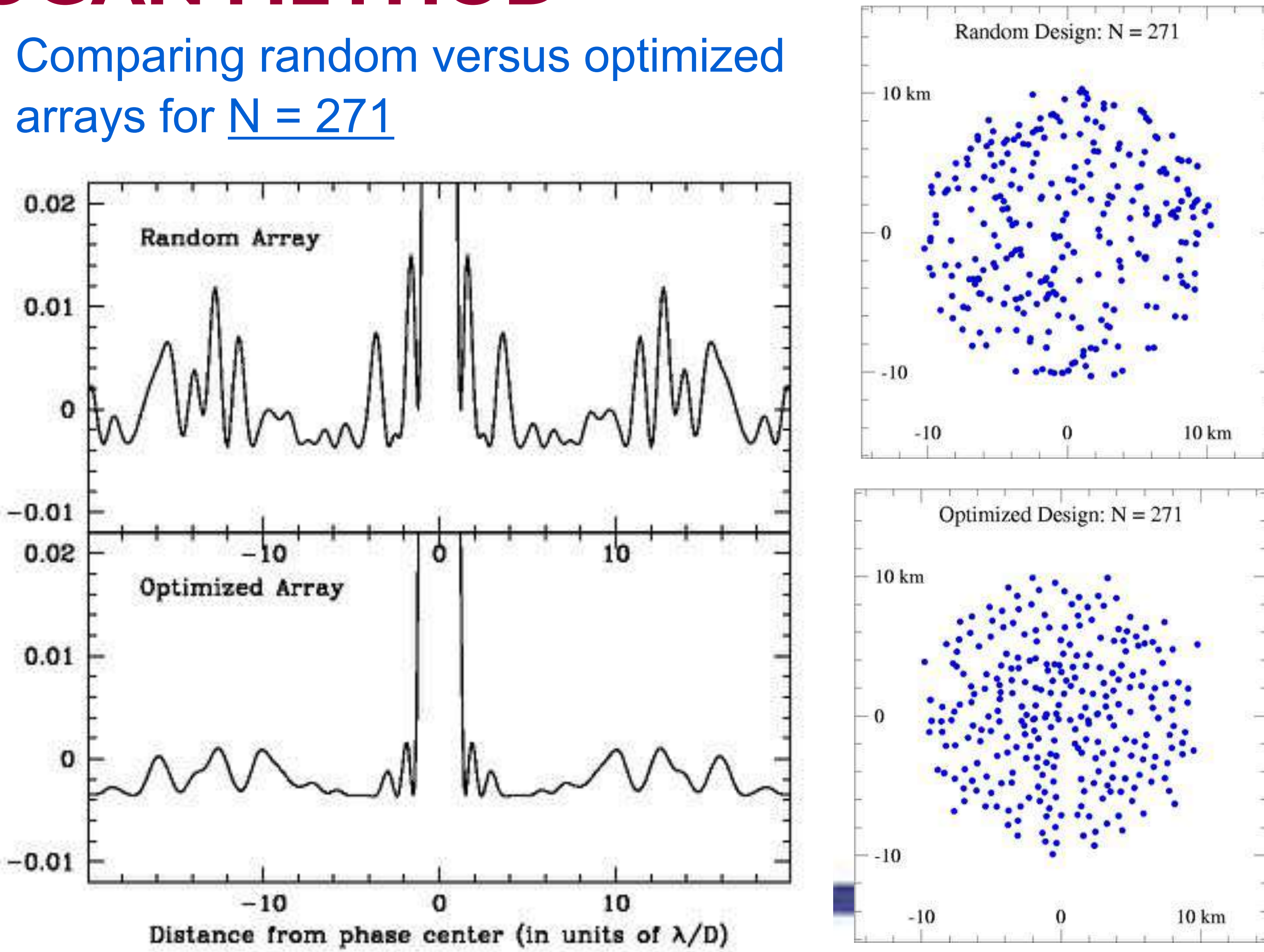
- Sidelobe levels
  - Low sidelobes help deconvolution and dynamic range
  - Measure peak or RMS sidelobe levels
  - Measure ratio of power in central lobe to total in dirty beam
- Largest gaps or uniformity in UV-coverage
- Image fidelity using simulations
  - But be wary of the many parameters to be adjusted
- Match to desired baseline length distribution
  - Important, but use something else to prevent UV holes
- Minimize infrastructure cost and adverse impacts
  - Fiber, power, road, access for maintenance, RFI, water vapor

ARRAY OPTIMIZATION METHODS

- Trial and Error
  - Devise configurations and calculate metrics (works OK for small N)
  - Drag and drop antenna position tool with maps useful
- Random Distribution
  - Works surprisingly well for large N, but not as well as optimized array
- Simulated Annealing (Cornwell)
  - Define uv 'energy' function to minimize – eg: 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 highest sidelobe using derivatives of beam with respect to antenna locations (iterative process)

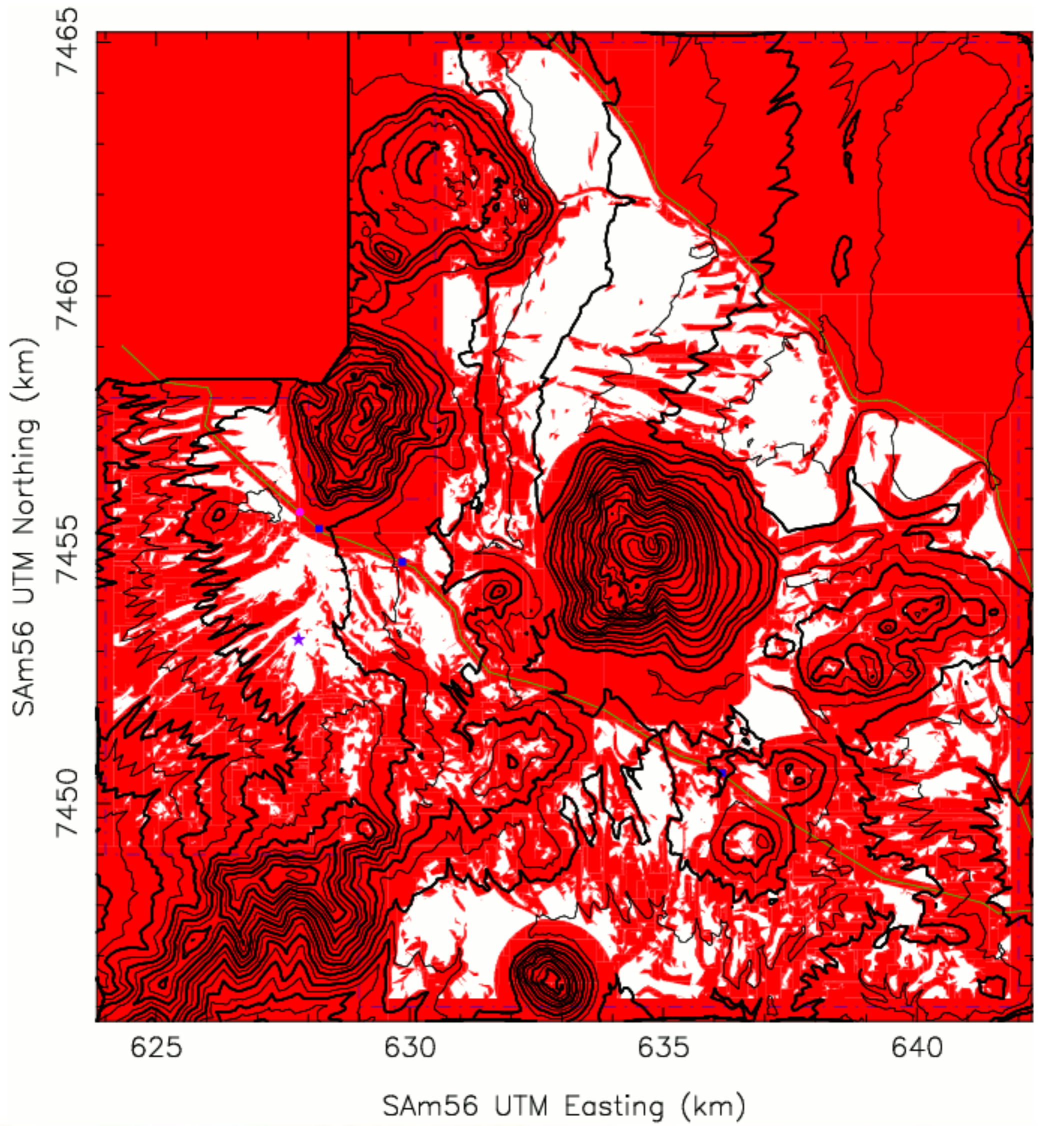
ITERATIVE SIDELOBE MINIMIZATION: KOGAN METHOD

Comparing random versus optimized arrays for N = 271



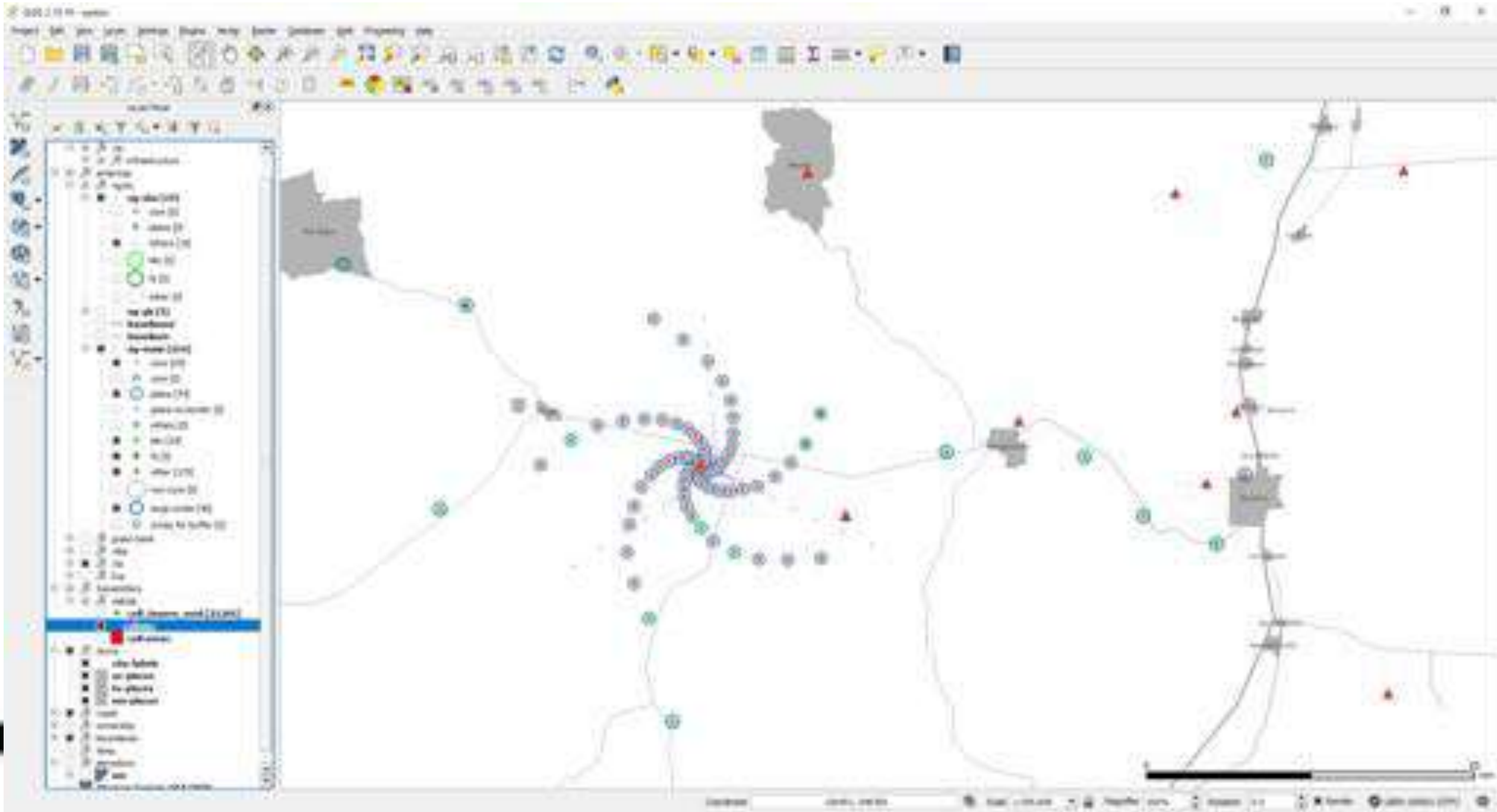
MASK

- In the optimization, a mask can be used to define acceptable places to put antennas
- Example is for ALMA
  - Based mainly on gradient
  - Pads can go in the white areas
- Preparation of a mask is an important step
  - Time consuming to get all the required data



USE OF GIS (Geographic Information Services)

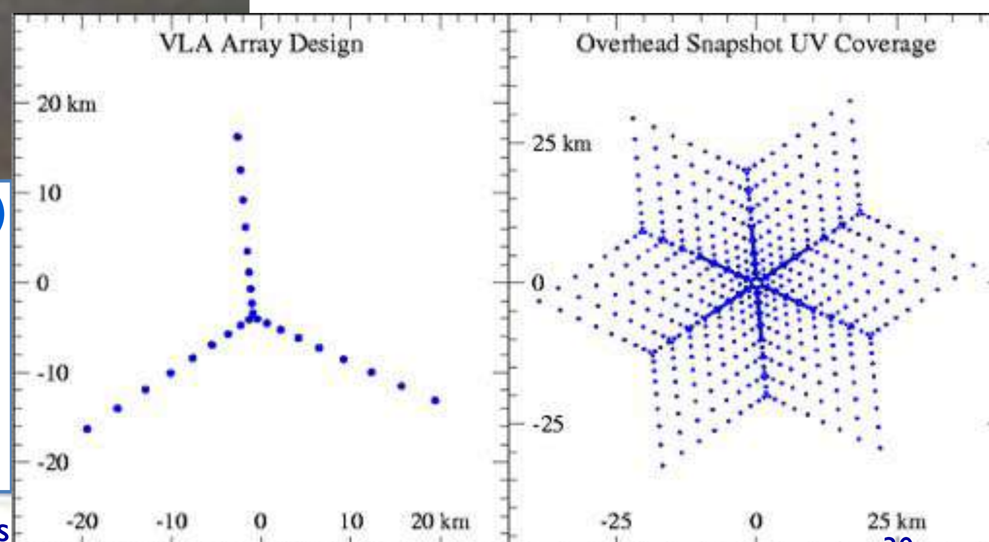
- Can use layers for many useful types of information relating to sites
  - Antenna locations, roads, cell towers, fiber, land ownership, towns….
  - Significant help in identifying good sites, especially for longer baselines
- Free program QGIS – ngVLA example below



EXAMPLES: JANSKY VERY LARGE ARRAY

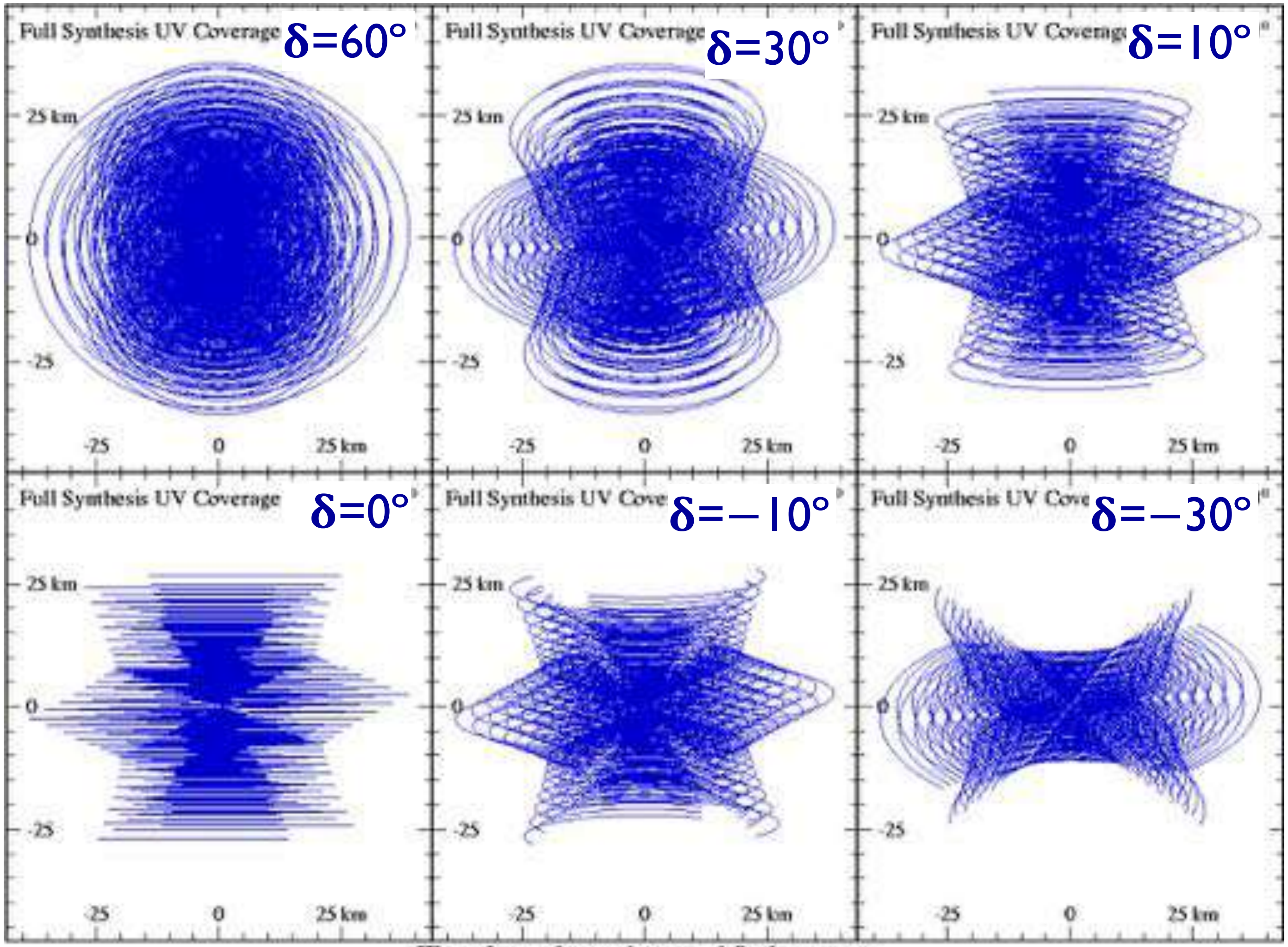
- Dedicated 1980
- Y-shaped Array
- 27 Antennas
- Re-configurable
- Centrally condensed

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



EXAMPLES: VLA LONG TRACK

VLA uv-coverage at various declinations

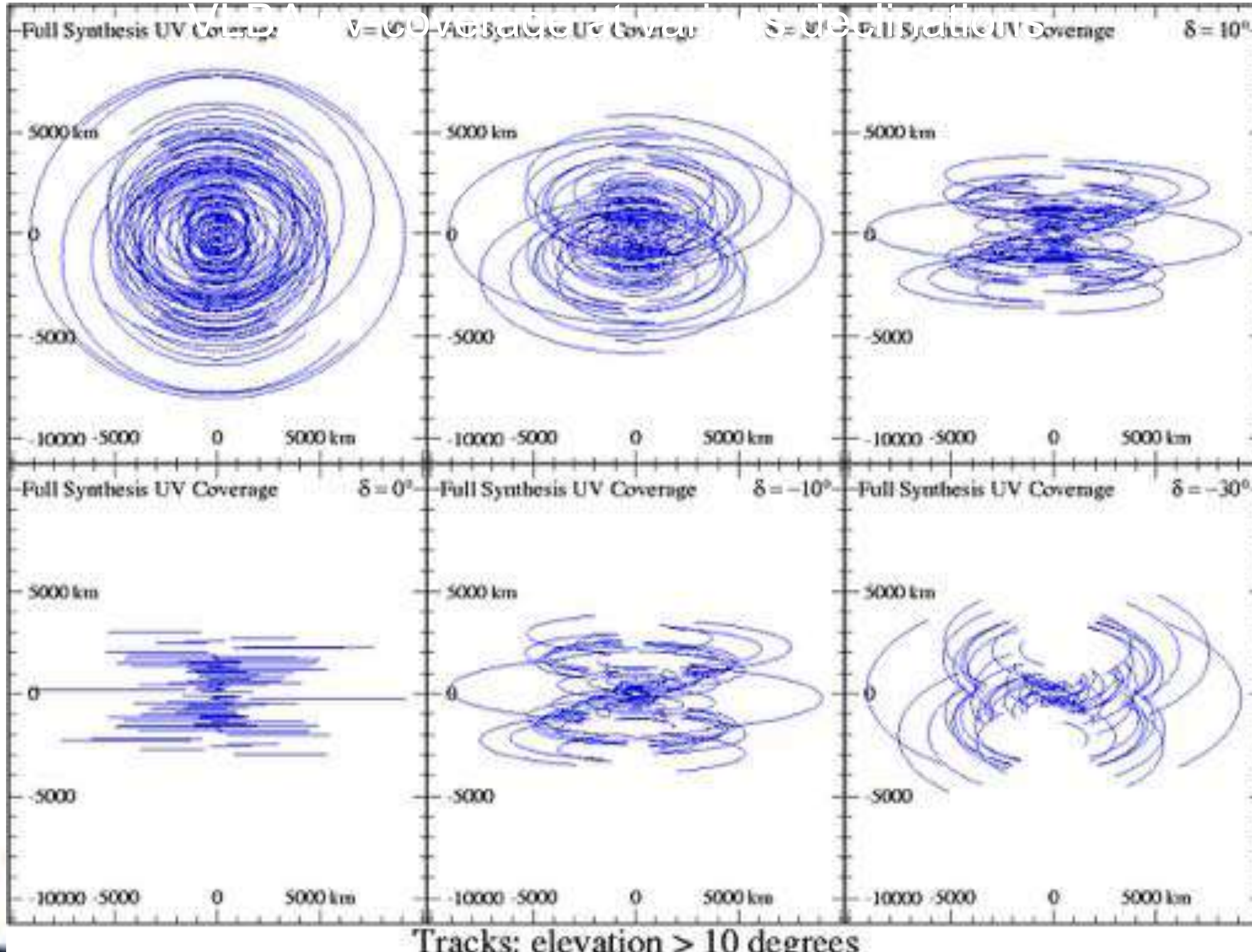


Tracks: elevation > 10 degrees

EXAMPLES: Very Long Baseline Array (VLBA)

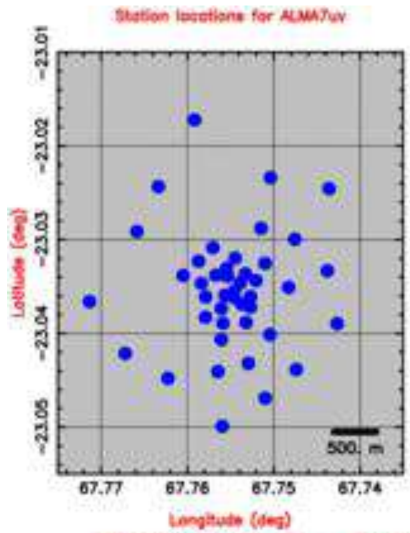
- Dedicated 1993
- Ten 25m antennas
- US Territory, Hawaii to St. Croix
- Baselines 200 to 8,600 km
  - 40:1 range
- Elements not connected
  - Separate clocks
  - Data recorded and shipped
- Resolution 0.”001 at 8 GHz
  - Frequencies 327 MHz – 90 GHz

EXAMPLES: VLBA

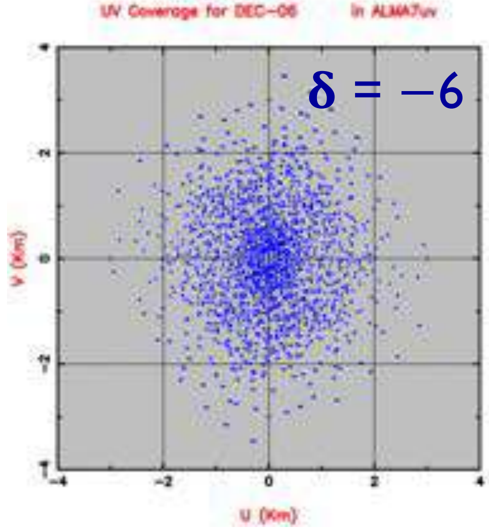


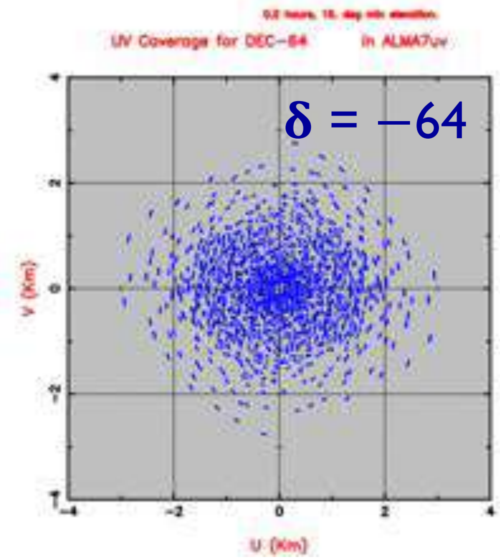
EXAMPLES: ALMA

- Dedicated 2013
- Premier mm array
- Main array: 50 antennas, 12m diameter
- 10 configurations
  - Shown are 43 antennas of array 7
  - Snapshot coverage
- Separate array of 12m and 7m antennas used for short baselines



Stephane Guisard/ESO.



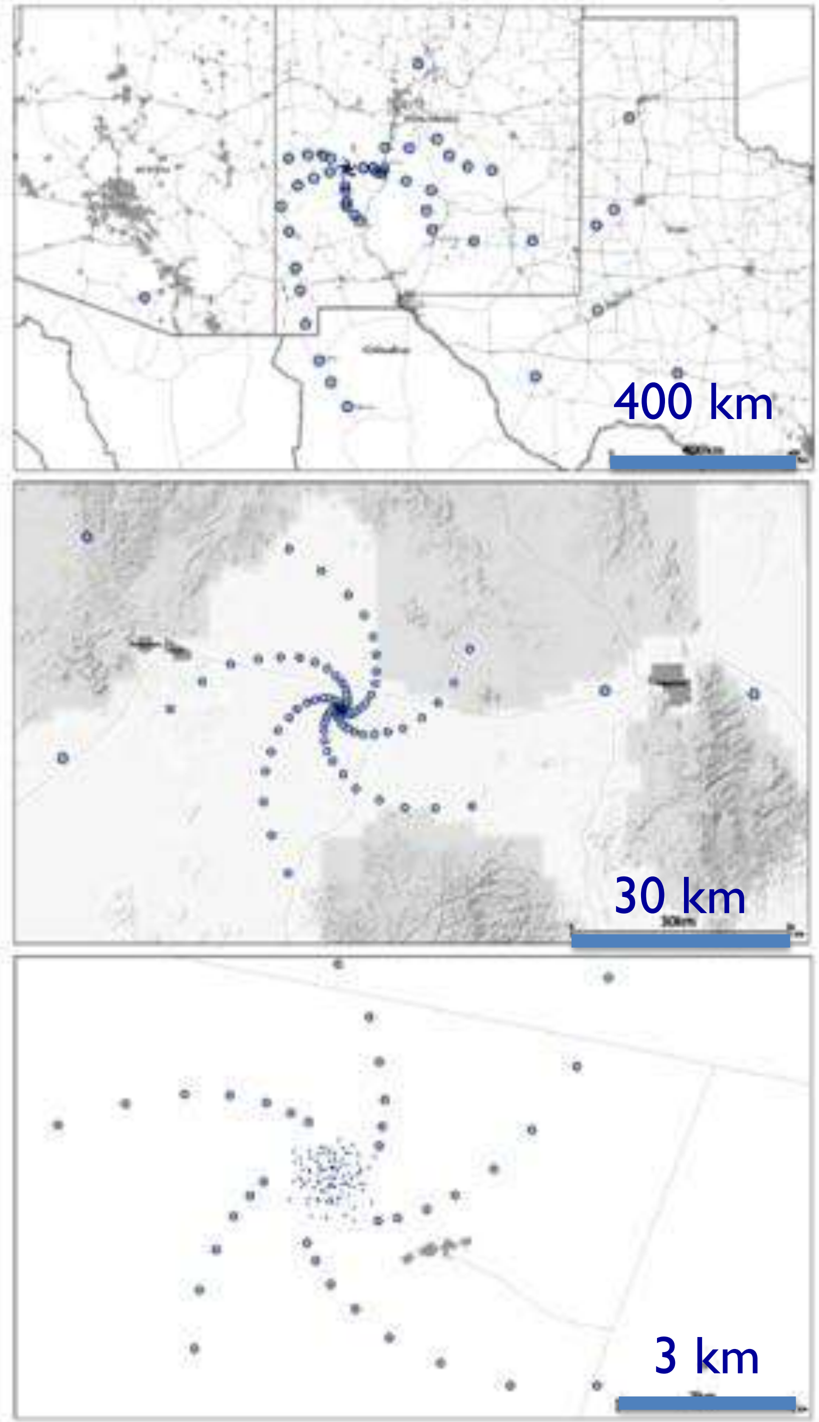


FUTURE DIRECTIONS: LARGE-N / SMALL-D CONCEPT

- Most arrays now being planned have many, relatively small antennas
  - For enhanced sensitivity and survey speed and lower cost
  - Optimum antenna size in the 10-20m range (See earlier slide)
- Most plans have a centrally condensed, fixed, configuration
  - Trading sensitivity for simplified operations and better flexibility
  - Many antennas needed for good UV coverage
- ATA explored the concept. Built N = 42, D = 6 m. Planned N = 350
- Current mid to high frequency array projects:
  - SKA1 Mid: N ~ 204, D = 15 m Including MeerKAT
  - ngVLA: N = 214, D = 18 m
  - SKA2 Mid: N ~2500, D = 15 m
- Aperture arrays at low frequency can be extreme large N / small D cases
  - SKA2 Low expected to have about 10^6 antennas
  - With enough electronics, these can observe the whole sky

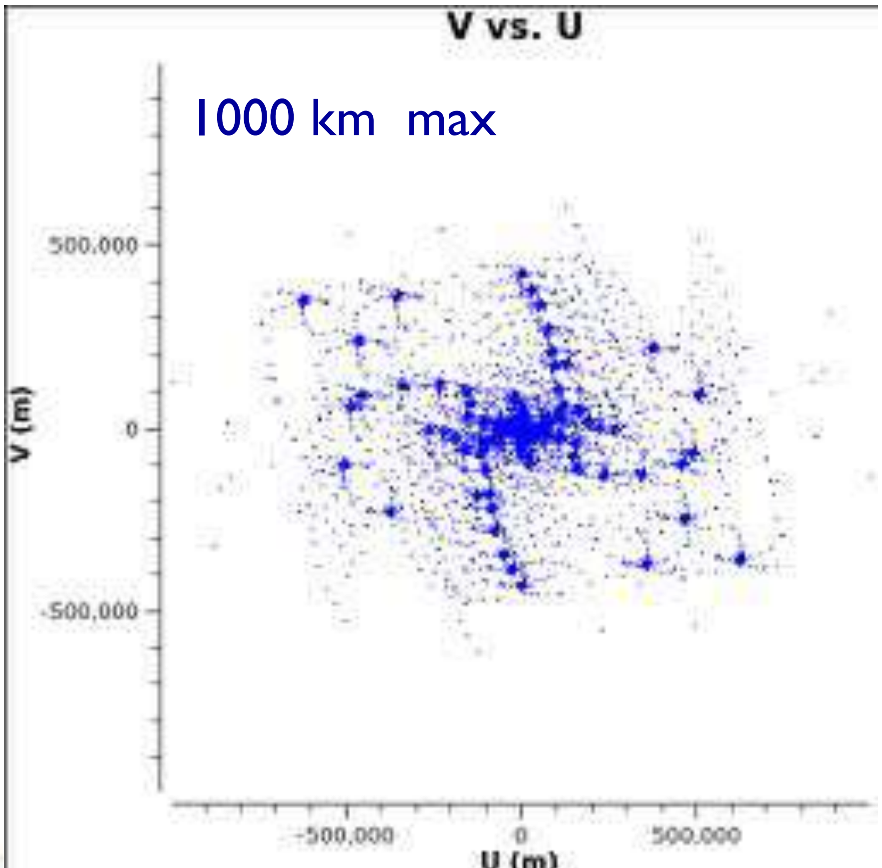
NGVLA: SPIRAL214 CONFIGURATION

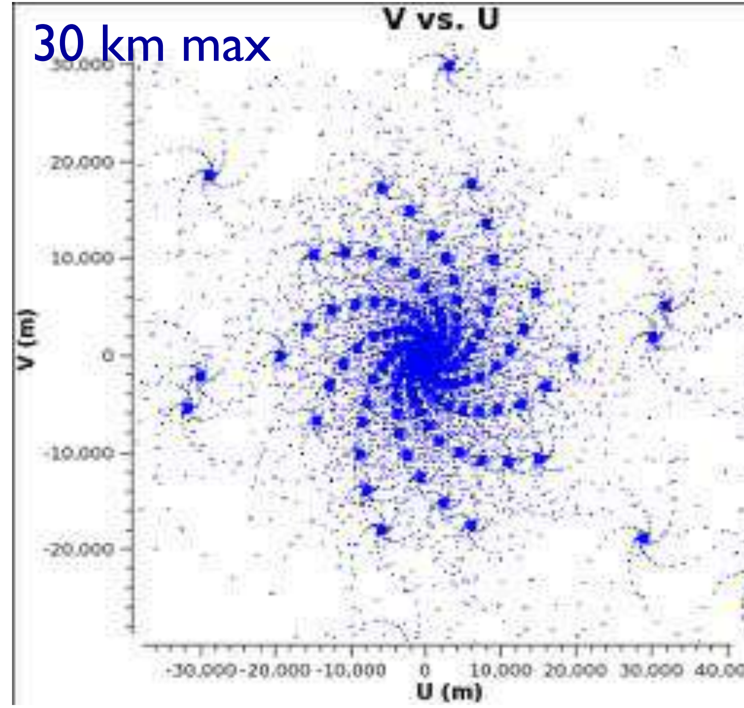
- Centrally condensed, fixed configuration
- Large N, Small D, but not extreme
  - N = 214, D = 18 m.
- Three scales:
  - Full (> 30 km): Approximate spiral
    - Conform to geographic and infrastructure constraints.
  - Plains (2 km to 30 km): 5 arm spiral
    - Plains of San Augustin – flat
  - Core (2 km): Optimized dense array.
    - For high brightness sensitivity

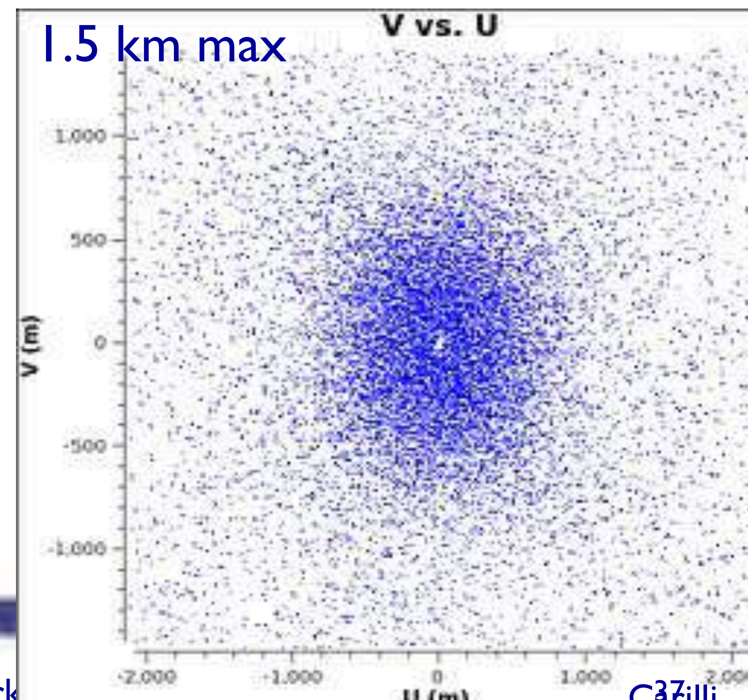


Carilli, Erickson ngVLA Memo 41

NGVLA SPIRAL214 UV COVERAGE

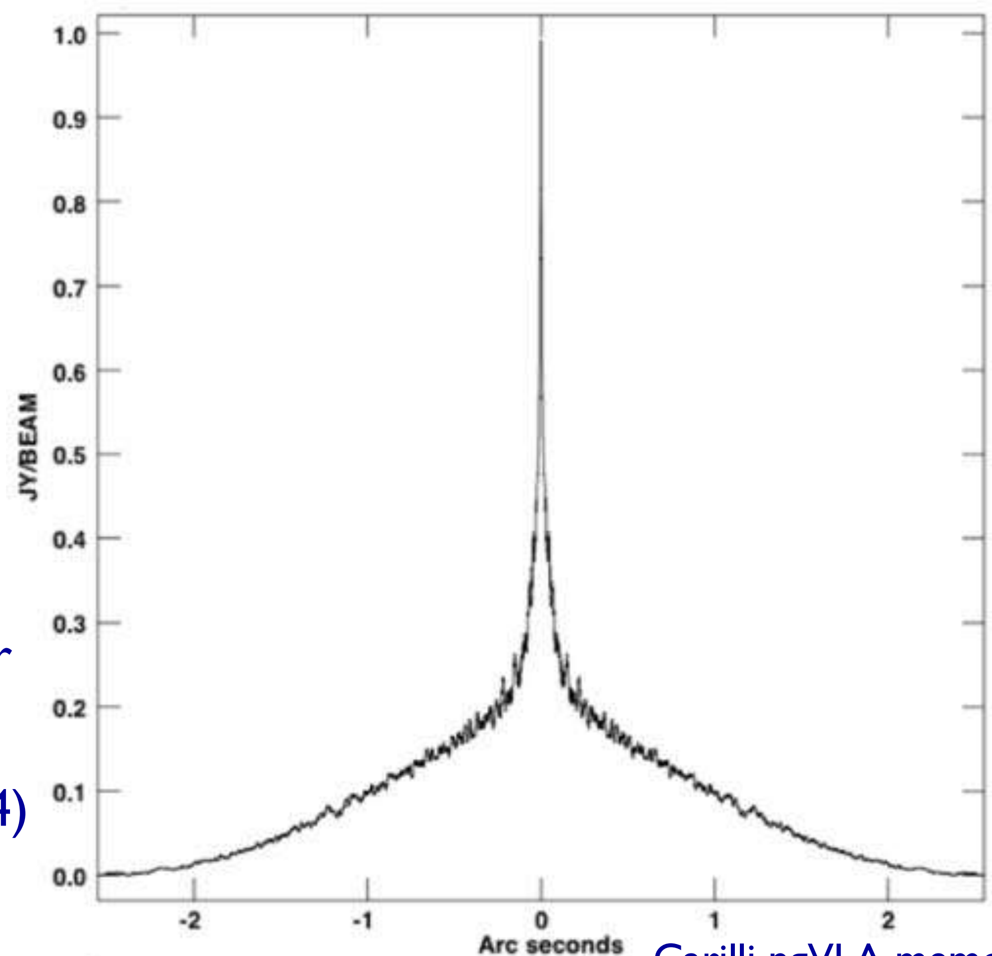






NGVLA: POINT SPREAD FUNCTION: CENTRALLY CONDENSED CONFIGURSATION

- Natural weight
- N-S beam cut 30 GHz
- Older Y based ngVLA config.
- Fit beam 13.0 X 17.0 mas
- Wide wings from dominant short baselines
- Noise 0.14 μJy/beam in 4 hr
- T_B Noise 0.85 K in 4 hr
- Adjust beam with weights and taper
  - Beams from 10 – 1400 mas
  - Some loss of sensitivity (1.5-2.4)



Carilli ngVLA memo 16

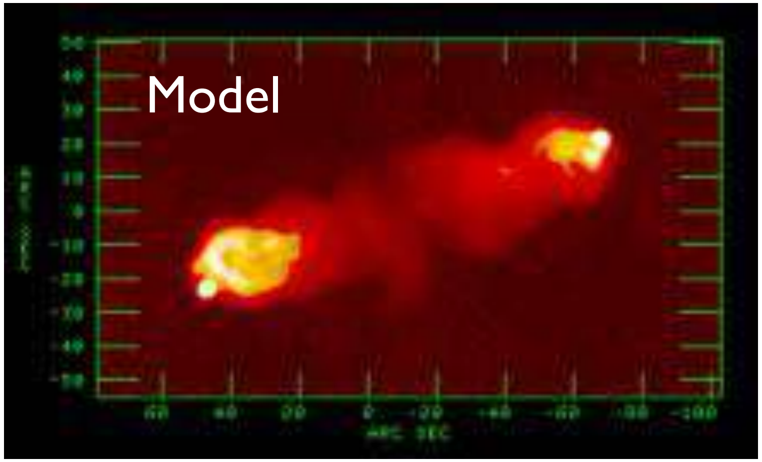
SIMULATIONS

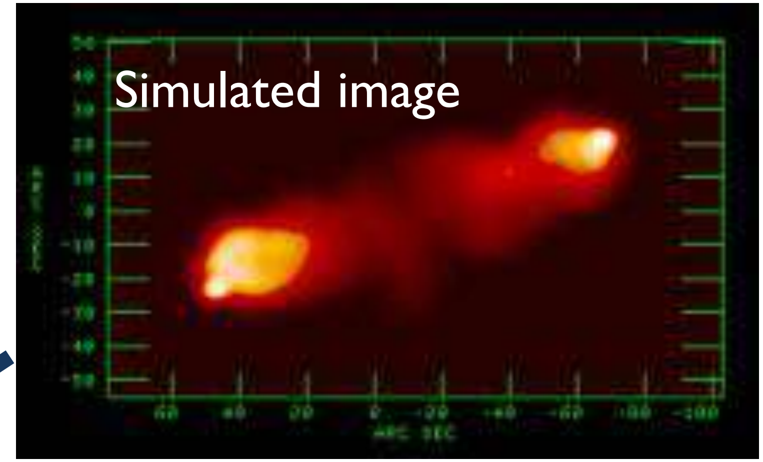
- Purpose of simulations:
  - Help set specifications needed by key science
  - Confirm that the key science can be done
  - Help build support for funding
  - My opinion: Do not use to optimize configuration – too many knobs
- Steps for a simulation:
  - Generate models of the sky representing realistic key science targets
  - Simulate data, adding increasing levels of reality
    - Receiver noise
    - Atmospheric and ionospheric phase fluctuations and absorption
    - Antenna pointing errors and efficiency
    - Instrumental bandpass and polarization variations
  - Process simulated data to make images or extract other science
    - Might use multiple methods
  - Compare results with known input model – tests image fidelity

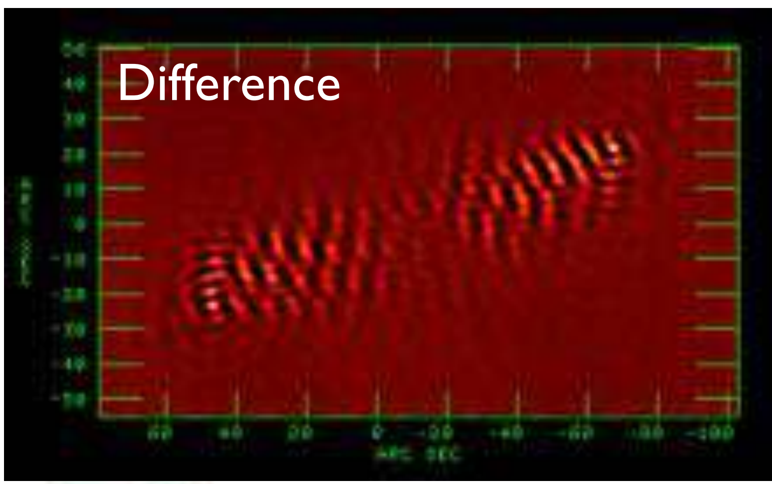
SOME QUESTIONS TO ADDRESS WITH SIMULATIONS

- Will the array do the key science specified?
  - Is there adequate sensitivity on the required scales?
  - Is there adequate brightness sensitivity on the required scales?
  - Is the array able to image large enough sources?
  - Is the array able to observe polarization adequately?
- What is the best distribution of long vs short baselines?
- What calibration strategies should be supported?
  - Are the slew rates and source switch times adequately fast?
  - Should antennas be paired?
  - Should an array of smaller calibration antennas be built?
  - Are water vapor radiometers needed?
  - Is a separate instrument needed to measure short spacings?
    - Single dish or array of smaller antennas?

SIMULATING IMAGING WITH THE LONG WAVELENGTH ARRAY



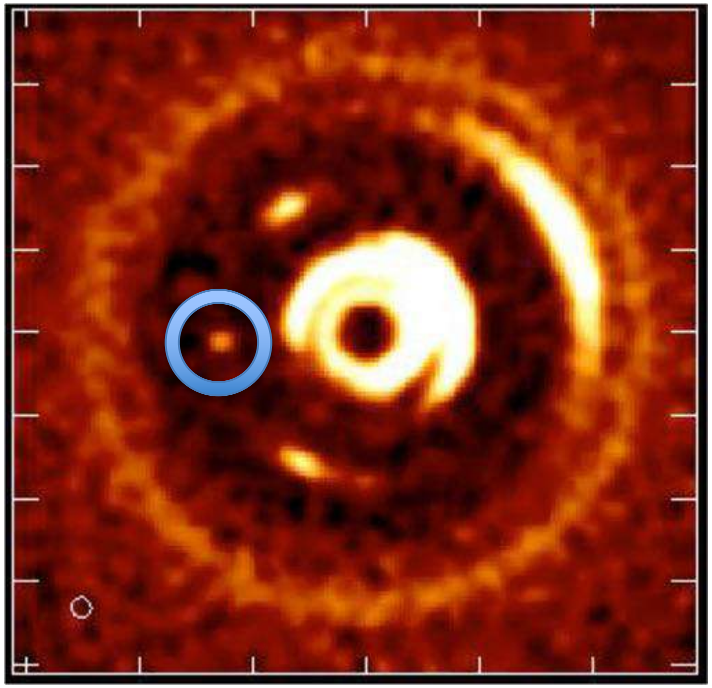




- Simulating image fidelity
  - Use model image to simulate UV data and image in normal way
  - Subtract model to examine residual image errors

SIMULATED MOVIE OF YOUNG PLANETARY SYSTEM WITH ngVLA

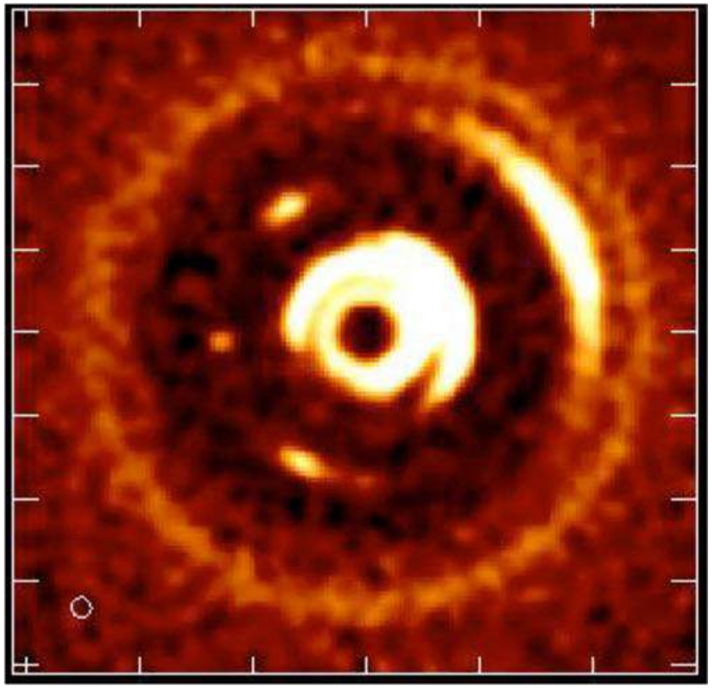
- A simulation to demonstrate exciting science
  - Based on physical model
  - Use to sell the array
- ngVLA observations at 100 GHz
- Jupiter analogue at 5 AU from solar type star
  - Dust at L1 points
  - Cleared out gap
- Time span ~10 years



Luca Ricci et al.

SIMULATED MOVIE OF YOUNG PLANETARY SYSTEM WITH ngVLA

- A simulation to demonstrate exciting science
  - Based on physical model
  - Use to sell the array
- ngVLA observations at 100 GHz
- Jupiter analogue at 5 AU from solar type star
  - Dust at L1 points
  - Cleared out gap
- Time span ~10 years



Luca Ricci et al.

SIMULATION SOFTWARE

- Simulation software creates model data sets
  - Use model image, array configuration, and observing style
  - Include effects of noise, troposphere, ionosphere
  - Mimic instrument properties (bandpass polarization etc).
- The imaging is generally done with standard software
- Most analysis packages have basic simulation capabilities. Examples:
  - AIPS - Basic fake data creation with full imaging and analysis
  - CASA - SIMOBSERVE can model many arrays
  - MeqTrees - Implements measurement equations (Mainly LOFAR)
  - ASKAPSoft - includes support for multi-beam systems
  - IRAM/GILDAS ALMA simulator

NRAO

THE END