Array Design

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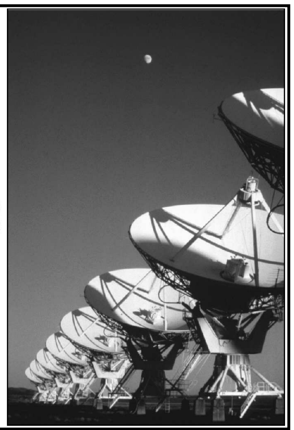

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Introduction

- Normally we use arrays the way they are..
  - Just decide on observing parameters and best configuration for particular experiment
- Now turn it around
  - try to design array that can best deal with expected wide range of experiments thrown at it
- Sometimes design array for particular experiment
  - Solar observations
  - Microwave background observations
- Major concern of array design is uv-coverage

How does an array affect your science?

- Layout of array determines:
  - Max resolution (can you see/resolve what you need to?)
  - Largest structure easily imaged (FOV and spatial sensitivity)
  - Side lobe levels in image – can you reach required DR?
  - Surface brightness sensitivity – is your object visible?
  - Robustness against failures in instrument
- Primary elements also important for most of these items
  - Size – field of view (FOV) [focal plane array? – boost FOV]
  - Shape – dish, cylinder, dipole array
  - Number – more is better (in general)

Telescope Design

- Suppose you are told to design the next mm or cm radio array
  - How do you decide on the basic parameters of the array?
  - Size of elements (often dishes) – D
  - Number of elements – n
  - Reconfigurable? – number of stations/configurations
  - Other (receivers, correlator,… not considered here)
- You'd find that science (e.g., key science programs) determines some of these, but only in combination with financial and political constraints

Things to consider when designing an array

- u-v coverage
  - always the main concern as it directly affects imaging speed and quality
- Flexibility
  - should the array be reconfigurable to be able to deal with all science requirements? If so, need to devise a set of configurations
- Constraints
  - Terrain ("fit on this plateau", "fit on this continent")
  - Money: number of antennas limited (tradeoffs with rest of instrument cost)
  - Politics – does it need to be located in a particular country/state to get enough money
- Robustness
  - Insensitive to limited failures (makes maintenance crew less stressed)

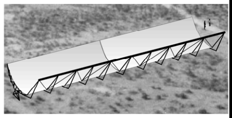
Telescope Design

- Science optimizations:
  - Point source sensitivity – $n D^2$, e.g., maximize total area for a given cost
    - large D – expensive antennas
    - large n - cost of (many) receivers
    - Example cost function: cost = $n*(c1 + c2*D^3)$
  - Imaging sensitivity – n D, optimize for large area surveys
    - FOV ~ $1/D^2$, so number of pointings to cover a given area in a given time increases with D^2, with time per pointing $t \sim 1/D^2$.
    - Sensitivity ~ $\sqrt{t}$ * area ~ $1/D * n D^2 = n D$
  - UV coverage – n D : simplified analysis – best coverage
    - Image primary beam λ/D, uv cell ~ D/λ, uv size Bmax/ λ
      - Need to fill $(Bmax/D)^2$ cells, with $n(n-1)/2$ baselines
      - Fraction filled: ~ $(nD)^2/Bmax^2$, i.e., maximizing nD gives best filling factor.

[with above cost function: n twice as big, D 1.6xsmaller for nD, 80% area]

Telescope Design

- Other option for primary element changes things
  - Parabolic cylindrical reflector – width D1, length D2
    - FOV ~ 2/D1 (generate beams over 2 radians along cylinder)
    - Imaging sensitivity ~ n $D_1^{1/2}D_2$, cost dominated by D_1 and line feed
    - Low cost option for fast survey instrument (option for SKA)
  - Dipole array – station size D, FOV fixed (4-5 sr)
    - Imaging sensitivity ~ n D^2 , cost dominated by LNAs and beam-forming electronics (good option at low freq - LOFAR)


Bunton


Astron

How Science impacts on design

- Small sources
  - High resolution - need long baselines – VLBI
  - no need for dense coverage – deconvolution works well
  - VLBI often sensitivity limited (short coherence time), large extra cost per station for recorders, tapes & correlator size
    - Favor large, sensitive antennas
- Large sources
  - Need multiple pointings - mosaicing
  - Need dense, nearly full coverage – reconfigure or close pack
  - Fill central hole in uv plane
    - Large dish – combine SD pointings with interferometer data
    - Very short spacings, possibly with smaller dishes; total power

How Science impacts on design

- Pulsar astronomy
  - Collecting area / sensitivity very important – large dishes popular
  - Array would need to be very condensed, only use inner part
    - Phase up central array to give single sensitive output stream
  - Use RFI mitigation – adaptive nulling to reduce interference
  - Would like large FOV or multiple targets
    - Electronic beam steering – multiple targets within FOV
    - Grand plan: gravitational wave detector using pulsar timing – sensitive to gravitational wave background from big bang (GWB vs. CMB)
  - SETI likes similar arrays to pulsar astronomy
    - Time series analysis/High Freq resolution

Existing Array Designs

- East-West Arrays – e.g., WSRT, ATCA, DRAO
  - Advantage in wide field imaging (no w-term, straightforward 2D FT relation between image and sky)
  - Need 12h synthesis for good image (or at least 4-5 cuts spaced by 2h)
  - Able to achieve filled uv-coverage with multiple configurations (except for central hole) – first sidelobe outside prim. beam
  - Poor resolution near equator
  - Not very robust (single antenna failure leaves large gap in coverage)


DRAO/NRC


WSRT / ASTRON

Existing Array Designs

- 2 dimensional arrays: e.g., VLA, GMRT, ATCA-mm, PdBI
  - Advantage in snapshot/short observations: better instantaneous coverage – make image with 1min data.(VLA), few hours (ATCA/PdBI)
  - w-term no problem for small field/high freq imaging, but major computation hurdle at low freq/wide field
- Fixed arrays – not reconfigurable: GMRT, SKA (planned)
  - may limit science, unless reduced sensitivity accepted (SKA ~ 50% eff)
- Partly fixed – WSRT/DRAO: main use of moving antennas is filling u-v plane
- Fully reconfigurable: VLA, ATCA, etc
  - More flexible instrument: variable resolution & surface brightness sensitivity


ATCA/CSIRO


PdBI/IRAM

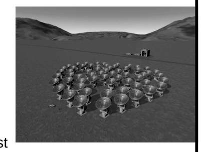
Multiple Configurations

- Two main reasons:
  - Improve uv-coverage
    - Especially for arrays with few antennas or regular spacings
  - Coverage good, but limited range of spacings
    - move antennas to optimize for different resolution
    - Tapering (reduce resolution) & uniform weighting (increase resolution) are inefficient ways to adjust resolution by large amount (i.e., more than factor of ~2)
- Ideal is a scale-free set of configurations
  - array has statistically the same layout on different scales
    - e.g., VLA-A,B,C,D zoom arrays, ALMA spiral
    - On smallest scales this fails:
      - shadowing constraints: minimum separation
      - maximize surface brightness: close packed array

Multiple Configurations

- How many configurations?
  - Each observation has its own optimum resolution
    - Reconfigure for each experiment?
      - Time wasted in reconfiguring & very costly in stations
    - Could move 1-2 antennas at a time – variable resolution array (ALMA)
  - Minimize down-weighting of data for wide range of resolutions
    - Need to find balance between acceptable sensitivity loss and cost of extra stations/time lost moving antennas
  - Design configurations to be self-sufficient to some degree
    - i.e., have some coverage on short scales for large arrays
    - Reduces need for multi-config. observations
- Combining data with different resolution
  - Very different integration time ($\sim\theta^{-2}$)needed at high & low res.
    - Easy to fill in central hole, hard to improve resolution – at same sensitivity (uv density)

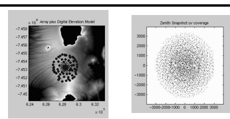
Case studies: ALMA



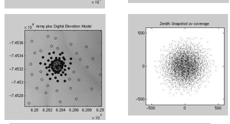
- Wide range of conflicting requirements
  - Compact configurations for wide field mosaicing of molecular clouds
  - High resolution observations of distant universe
  - Good instantaneous uv coverage
    - good mm weather may not last long
    - low elevation to be avoided
  - Minimize number of antennas, stations, cabling cost
- Configuration contenders:
  - circular arrays, (log)spirals, various optimized arrays (minimum sidelobe/uniform coverage)
  - Converging towards design that configures smoothly from close packed to spiral with gaussian uv distribution (no tapering needed!) to ring-like array with maximum baselines & resolution.
  - Simulations show that the gaussian uv distribution gives superior deconvolution (less work to do..) [Conway]
    - Related to fact that CLEAN interpolates quite well, but extrapolates poorly

Case studies: ALMA

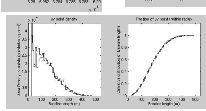
- ALMA – largest configuration



- ALMA – intermediate config

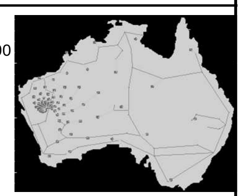


- Intermediate config – uv distribution (blue)



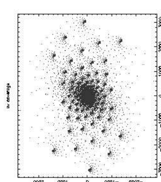
(spiral zoom arrays by Conway)

Case Studies: SKA

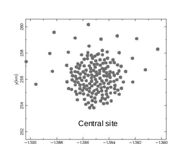


- Square Kilometer Array – specs:
  - 1 km^2 collecting area (actually A/T=20000 at 20cm, T~50K)
  - Collecting area: 20% within 2km, 50% < 5km, 75% < 150km, shortest baseline 20m, longest >3000km
  - DR > 10^6, Image fidelity > 10^4 (over full FOV, not central source only)
  - 1 sq degree FOV at 20cm
- Designs:
  - tiles/dipoles, 6m luneberg lenses, 12m dishes, 100m cylindrical reflectors, 200m dishes with feed on aerostat, holes in the ground (Arecibo like)

Case Studies: SKA



- Basic configuration choice
  - large N/small D or small N/large D (with multi-feed)
- Basic element choice
  - 0D, 1D, 2D concentrator: dipole array, cylinder with line feed, dish with feed(array)
- Extreme central concentration of array
  - one super station correlating with more distant stations
  - uv coverage dominated by central site
  - Can make array layout asymmetric and use uv plane conjugate to fill other half
  - Move array center to one side of continent to maximize long baselines
- My attempt at a 300 station design:
  - Asymmetric 7-armed logarithmic spiral + random close packed central disk with tapered edge (each station also tapered disk)
  - fans out over 180 degrees at each scale
  - Fits on edge of continent, providing long baselines

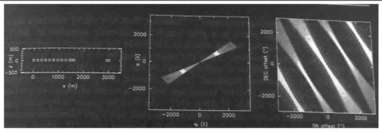


Optimizing

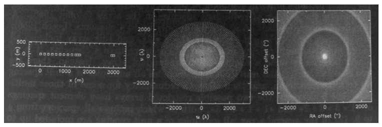
- Hardest question: what should we optimize?
  - uv-coverage (snapshot/long observation) – Surface Brightness sensitivity - PSF sidelobe level - Cable length – Cost
    - Really want to optimize scientific output of array for given cost – too vague
- Next hardest question: what is optimal?
  - E.g., uv-coverage – uniform, power law, gaussian
    - Depends on experiment – need to find compromise that can do all
- Problem is never fully described
  - Hand-waving decisions remain until the end
  - "Premature optimization is the root of all evil"
- Optimizing often teaches you basic facts about configurations
  - E.g., most uniform coverage has antennas in ring-like array, but results in poor sidelobes due to sharp long baseline cutoff
  - Often combine multiple optimization goals with "flexible" weighting
- Useful once specs and designs close to completion
  - Good at optimizing last 10% - e.g., minimize sidelobes taking terrain & preferred station positions into account

A look at some uv-coverages

- E-W short obs

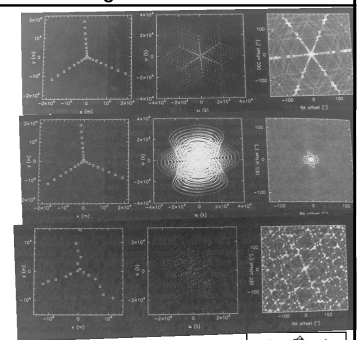


- E-W long obs



U-V coverages

- VLA snapshot
- VLA long track
- GMRT snapshot



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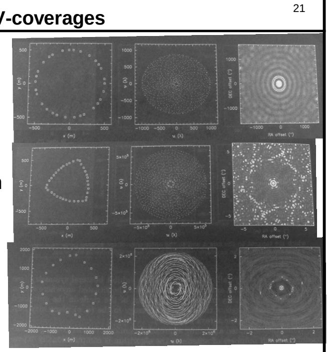
U-V-coverages

- Ring, optimized for uniform coverage
- Keto, Reuleaux triangle (best uniform coverage with radius cutoff)
- Long track Keto optimization for uniform coverage



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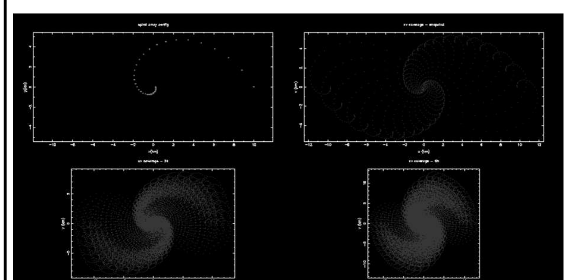
U-V coverage for spirals – 1 arm



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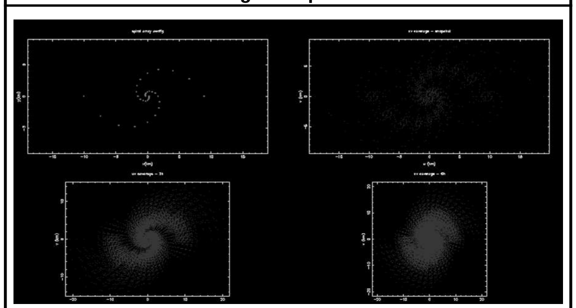
U-V coverage for spirals – 2 arm



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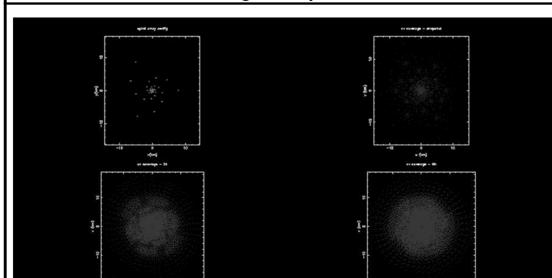
U-V coverage for spirals – 3 arm



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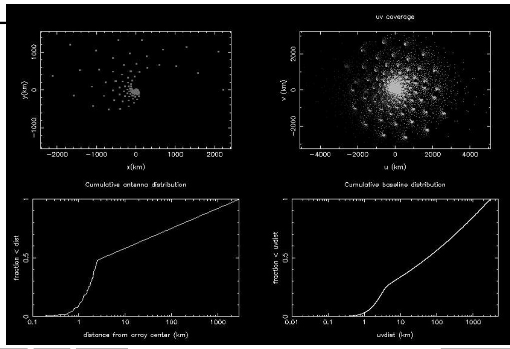
UV coverage analysis



Optimization techniques

- 'trial and measure'
  - i.e., devise config with variable parameters and compute metrics (uv coverage %, sidelobe levels) or use 'brute force' exhaustive search (may work for small n)
- Simulated annealing (Cornwell)
  - Define uv 'energy' function to minimize – log of mean uv distance
- Neural/Elastic net (Keto)
  - pick random point, move nearest uv sample closer by moving antennas – repeat until each sample close to random point – uniform
  - Can match other distributions by adjusting random picks
- UV-Density & pressure (Boone)
  - Steepest descent gradient search to minimize uv density differences with ideal uv density (e.g., gaussian)
  - Can handle long tracks & pos. constraints

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Optimization techniques

- PSF optimization (Kogan)
  - Minimize biggest sidelobe using derivatives of beam wrt antenna locations
  - good for fine tuning specific arrays: e.g., max brightness sensitivity array (close packed disk)
- Genetic algorithm (e.g., Cohanim et al.,2004)
  - Pick start configs, breed new generation using crossover and mutation, select, repeat
  - Can also use multiple objectives & constraints (weed out illegal configs)
- Constraints can dominate result
  - e.g., max. radius results in ring arrays with bad inner sidelobes
- Optimization space tends to be very flat
  - Large number of possible arrays with indistinguishable characteristics
  - many local minima – some algorithms better at avoiding these

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Simulations

- Final test of array design
  - see how well your uv-coverage performs in practice
- Take set of key experiments
  - 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

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Constraints on configurations

- Real life adds complications
  - Terrain: mountain, slopes, creeks, flood areas, roads
  - Add terrain mask to specify no go areas
  - Track/transporter location
    - Railtrack – a few straight sections (E-W, T, Y)
  - Shadowing, low elevation coverage
    - Ideally want a range of compact configs (stretched)
  - Cope with range of declinations & hour angles
  - Cope with wide range of required resolutions
    - Reconfigurable array avoids sensitivity loss
    - Fixed, scale free array can be ~50% eff at all resolutions

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Fixes for existing arrays

- Deconvolution
  - deal with large sidelobes due to poor uv coverage
  - Works well for simple fields, breaks down for complex fields
- Weighting schemes
  - Trade sensitivity for better dynamic range
  - Uniform weight + taper to give desired beamshape
  - Briggs weighting
    - Good compromise between natural & uniform
- Fix poor configurations
  - Devise different configurations using existing stations
  - Add a few well chosen stations (e.g. to fix short spacing problems)
    - E.g., VLA-E config + updates to other configs to add shorter baselines
- Multi-frequency synthesis
  - For continuum observations using one or two bands, processed in channels, can give a huge increase in uv-coverage
  - Deconvolution may need to take spectral features into account for high DR

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Hardware & Software Solutions

- Often there are two ways to solve a problem
  - Use array/telecope design that minimizes the problem
  - Fix the problem using more advanced algorithms
- Examples:
  - Deconvolution versus filled uv-coverage
  - Mosaicing versus very small dishes
  - Wide field imaging (w-term) versus E-W array
- Software solution is often preferred
  - Cheaper and/or increased array speed/flexibility/sky coverage
- If s/w solution not feasible – may need to resort to h/w
  - E.g., SKA wide field processing for small D (<12m) and large B (>30km)
    - Cost of computing may be more than cost of array (T Cornwell EVLA memo)
    - Favours larger dish size or combining antennas into stations (but that limits FOV)
    - E-W config? (Limits sky coverage)
    - Restrict long baselines to E-W band we can handle at reasonable cost (increase width of band over time) – I.e., trade observing time for computing time
    - Implement imaging algorithm in hardware?

Conclusions & Advice

- Try to meet specifications, but keep array as flexible as possible (future science not predictable)
- If problems can be solved effectively in s/w, don't fix them in h/w (often limits flexibility of instrument)
- More antennas is (often) better
- Optimize late, be wary of giving up flexibility
- Explore unusual designs
  - E.g., cylinders (50's technology) with latest feed designs can be very competitive at cm wavelenghts