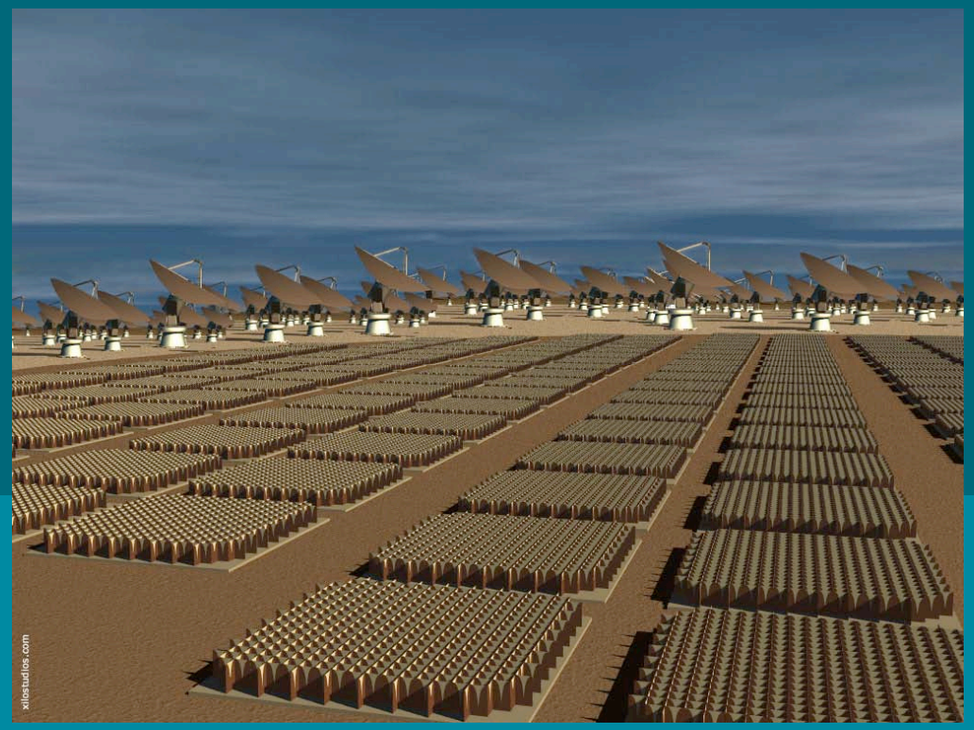
Calibration and imaging for the next generation of radio arrays



Tim Cornwell

Australia Telescope National Facility

CSIRO

What's next?

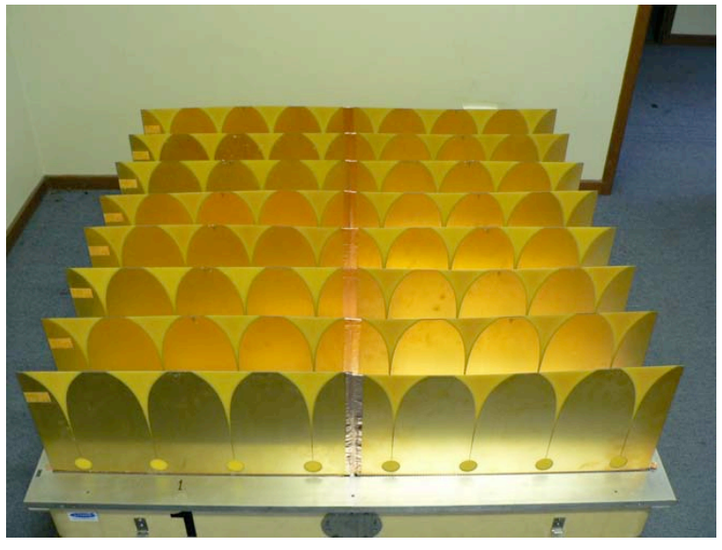
- "Next-generation" = Wide field of view, high sensitivity
- Digitize immediately after amplification
- Advantages
  - Accurate
  - Extensible
- Disadvantages
  - Major exercise in computing
  - FPGA's spreading from correlators upstream
  - Power consumption - antennas replaced by silicon

Measuring the electric field

- Use tiles of receptors
- Amplify, digitize, transmit
- Form beams by summing digitized voltages
- Can use either as-is or in focal plane of an antenna

Second digital revolution in radio astronomy

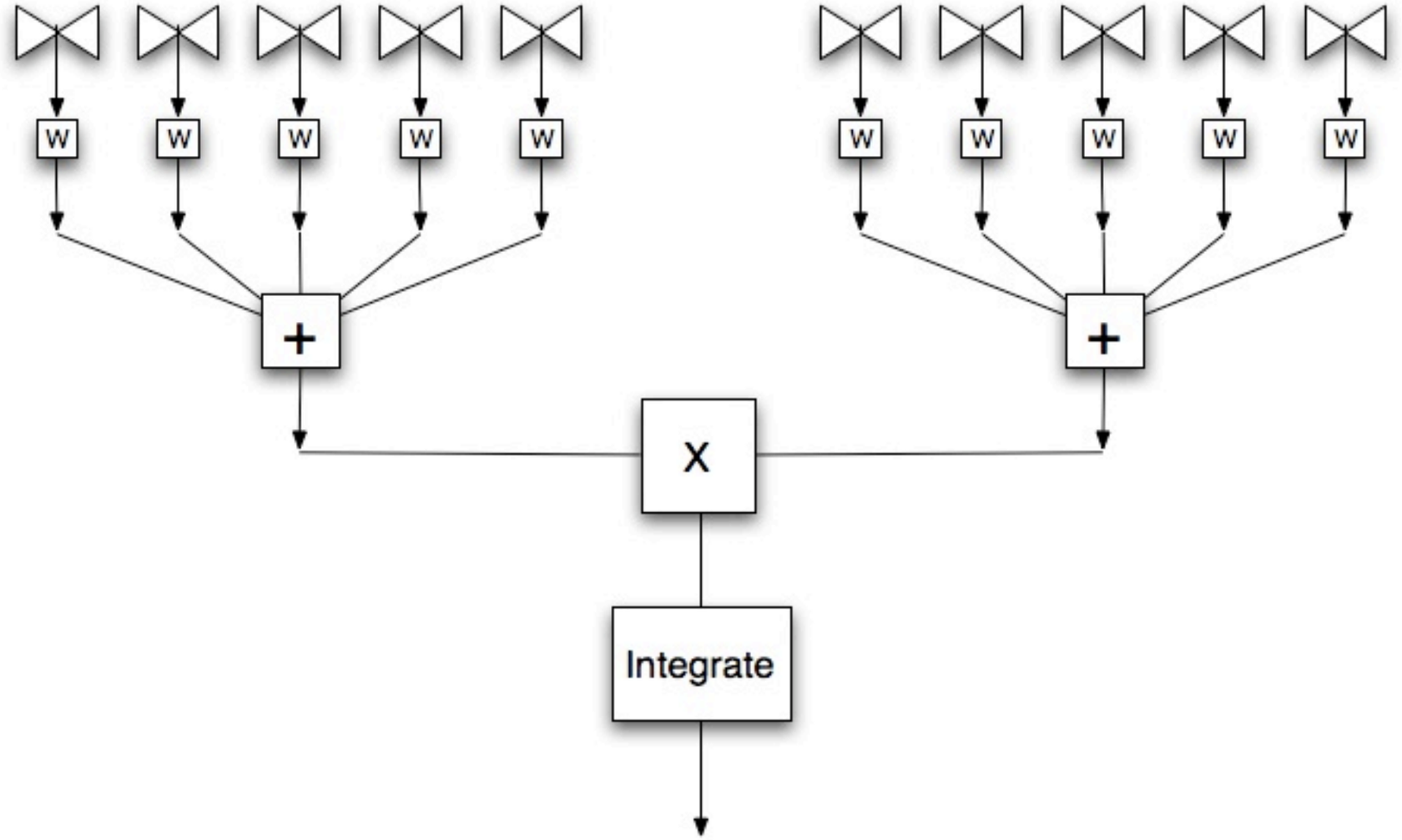
LFD tile

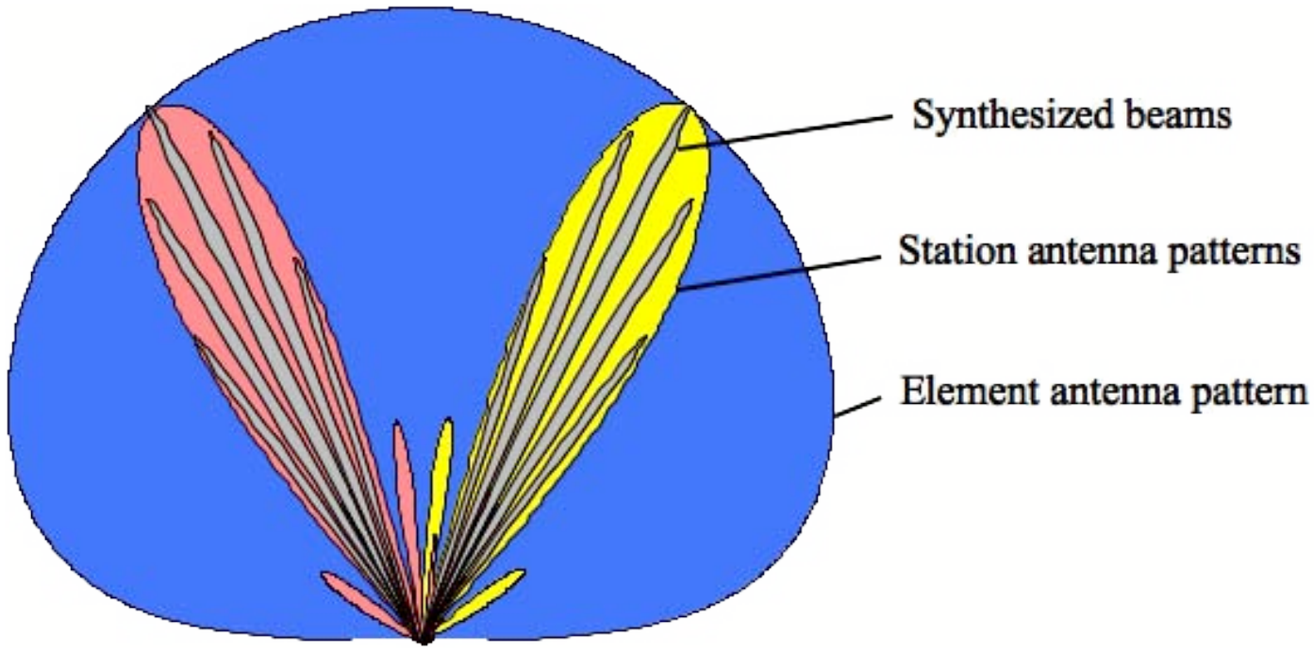


Vivaldi feeds

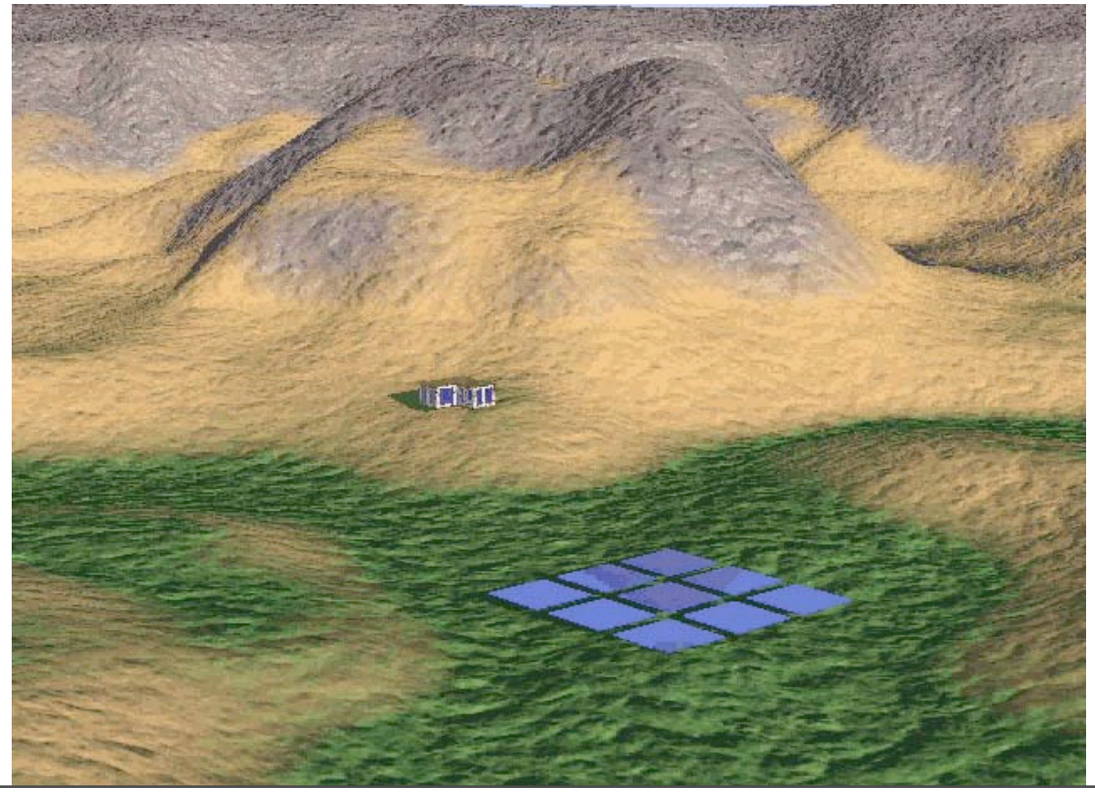
Aperture Array

- Form multiple beams on the sky
- Beamformers can be analog or digital
- Beams can be steered independently





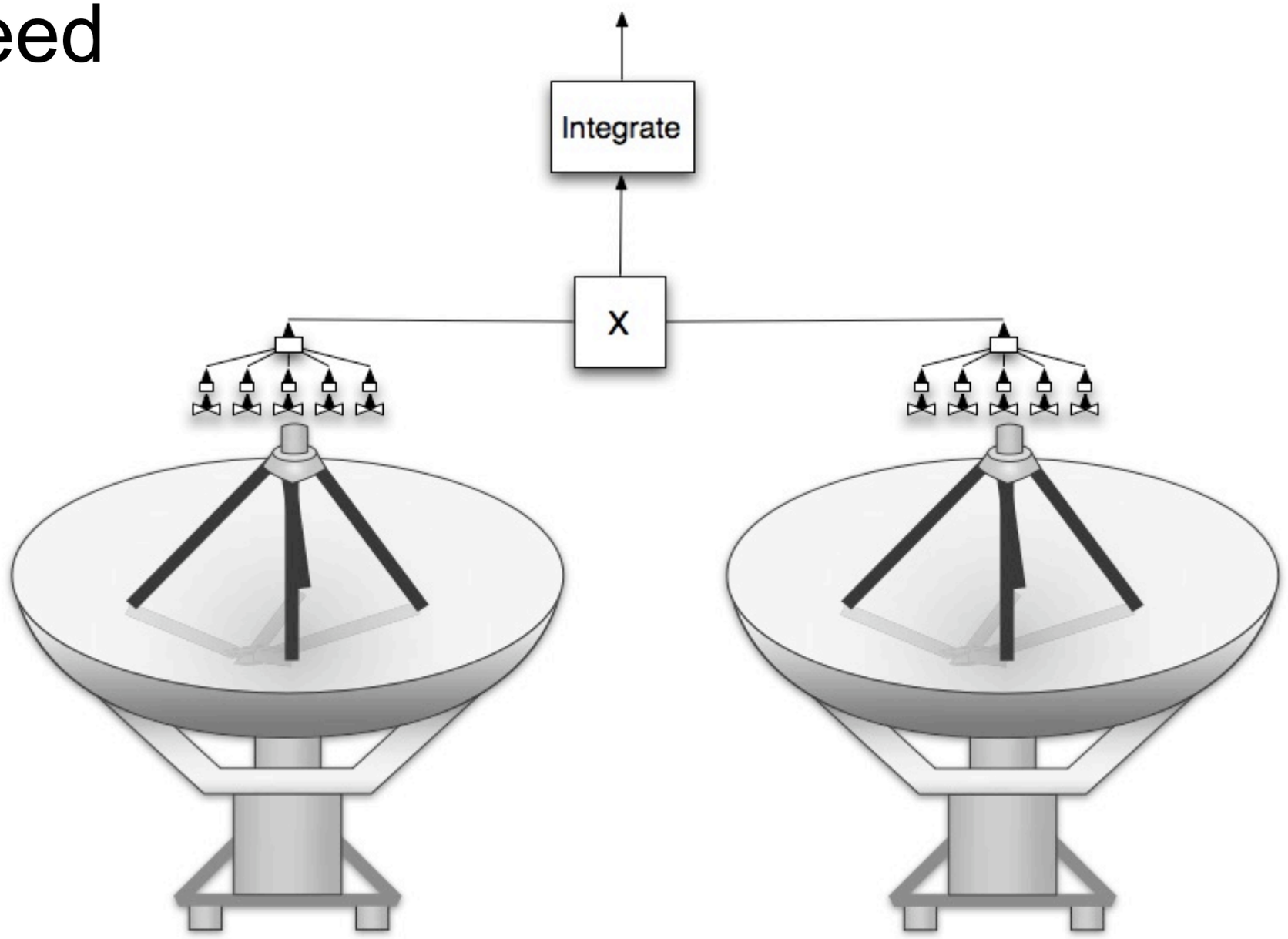
LOFAR, LWA, LFD

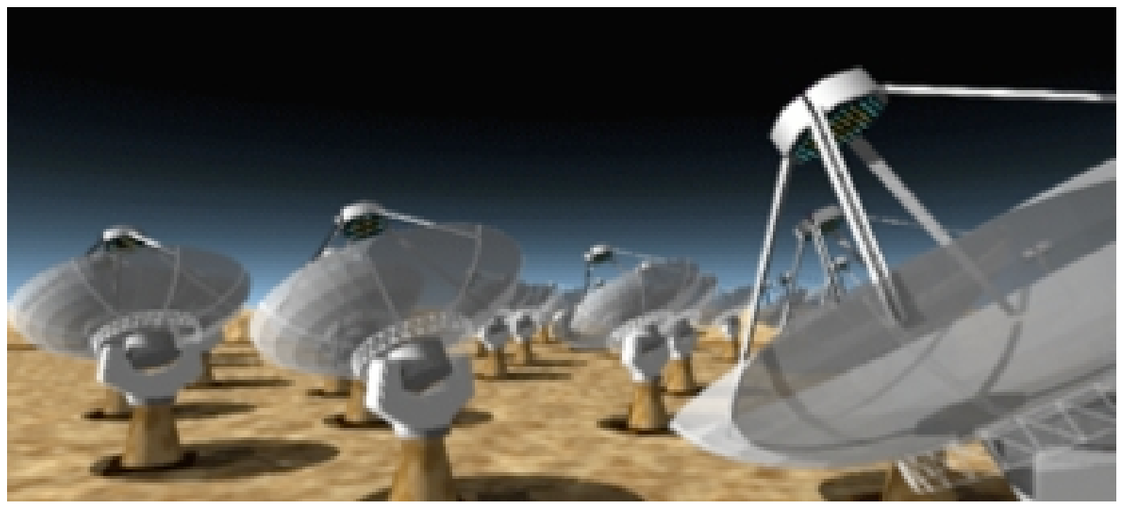


Phased Array Feed

- Put at focus of an antenna
  - Antenna acts as a concentrator
- Critically sampled or better
- Excellent upgrade for existing antennas
  - Apertif for WSRT
- Can control illumination of antennas
  - Optimize efficiency or sidelobes

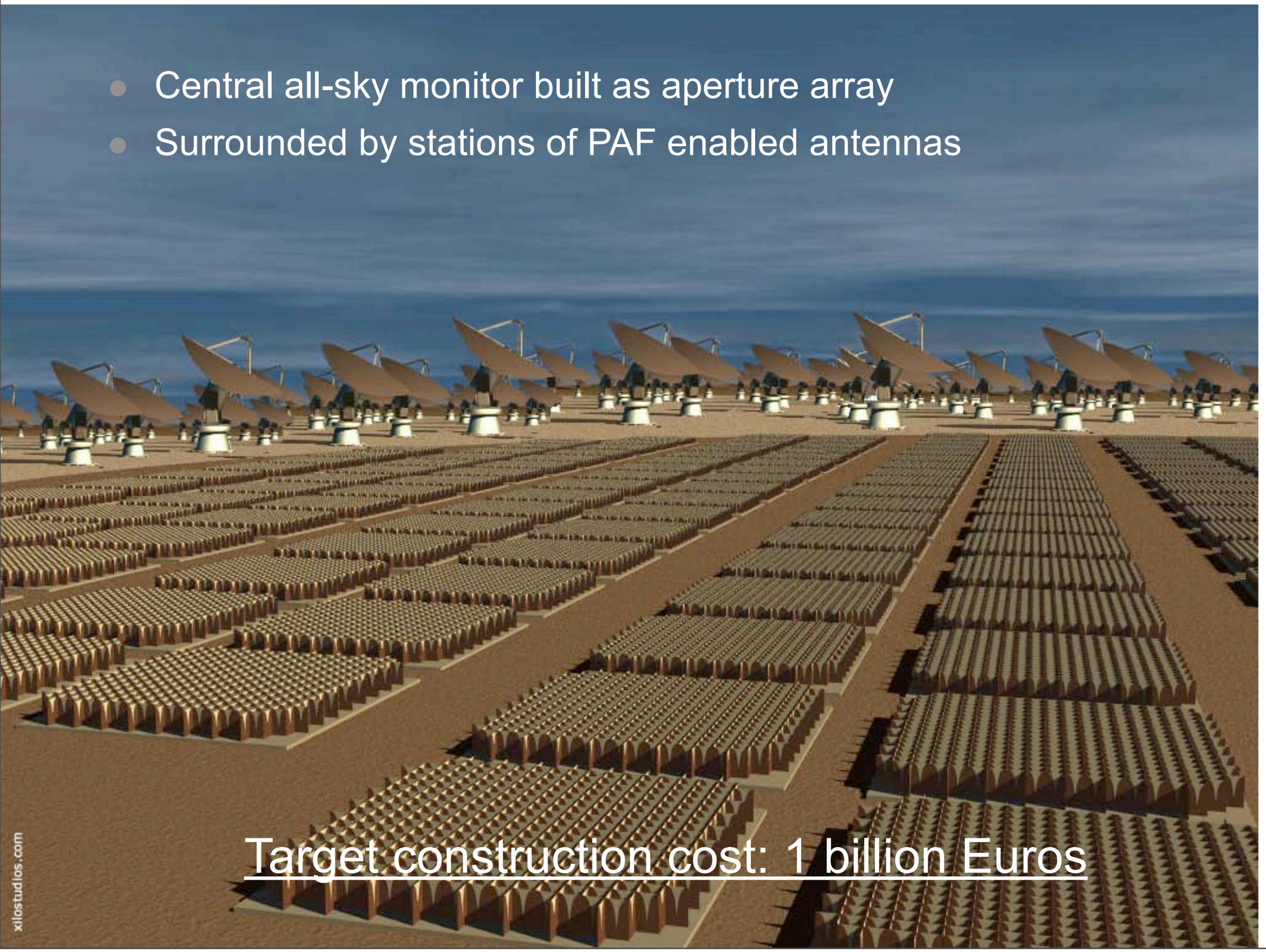
xNTD, Apertif





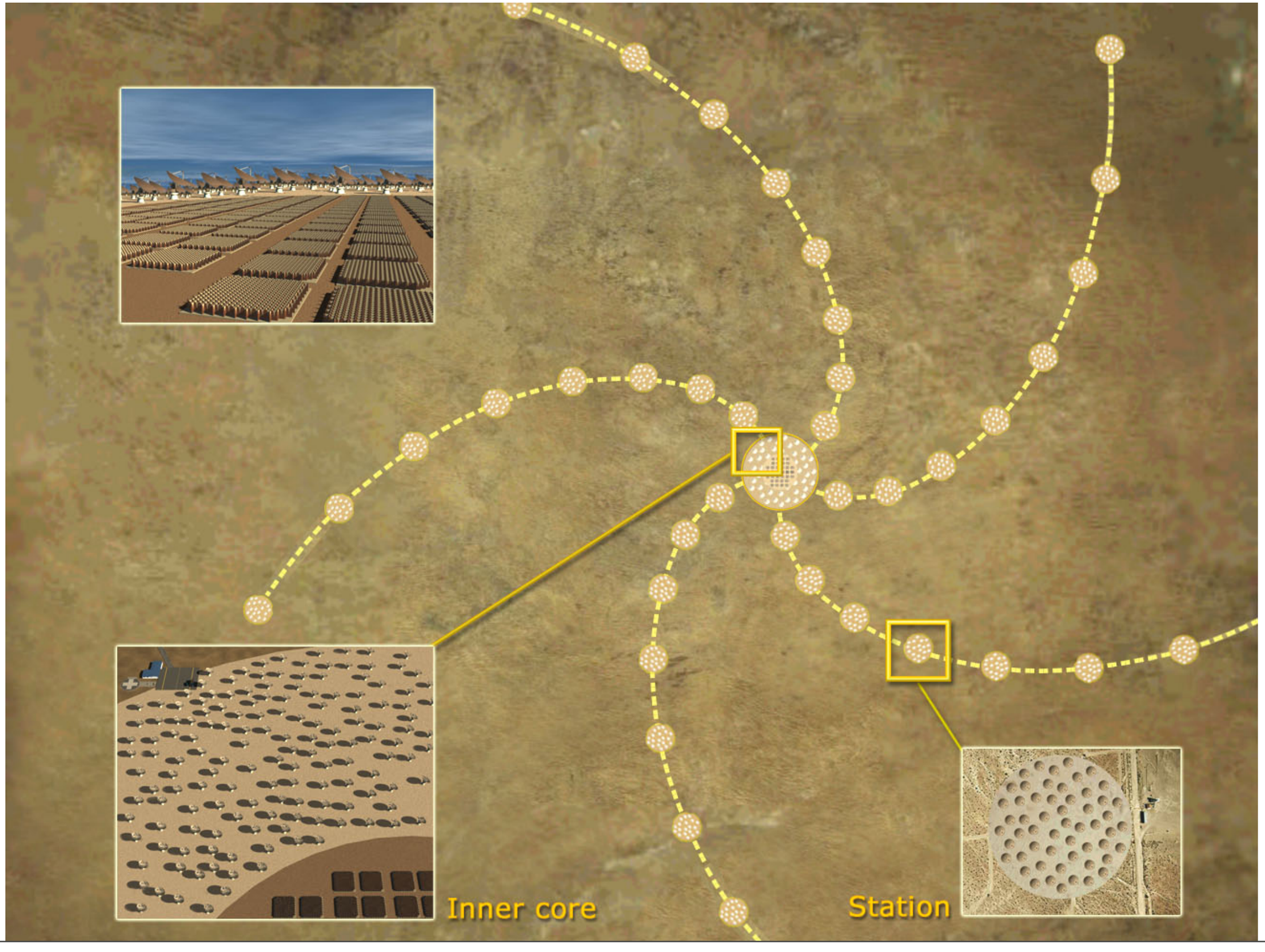
The Square Kilometre Array will have both...

- Central all-sky monitor built as aperture array
- Surrounded by stations of PAF enabled antennas

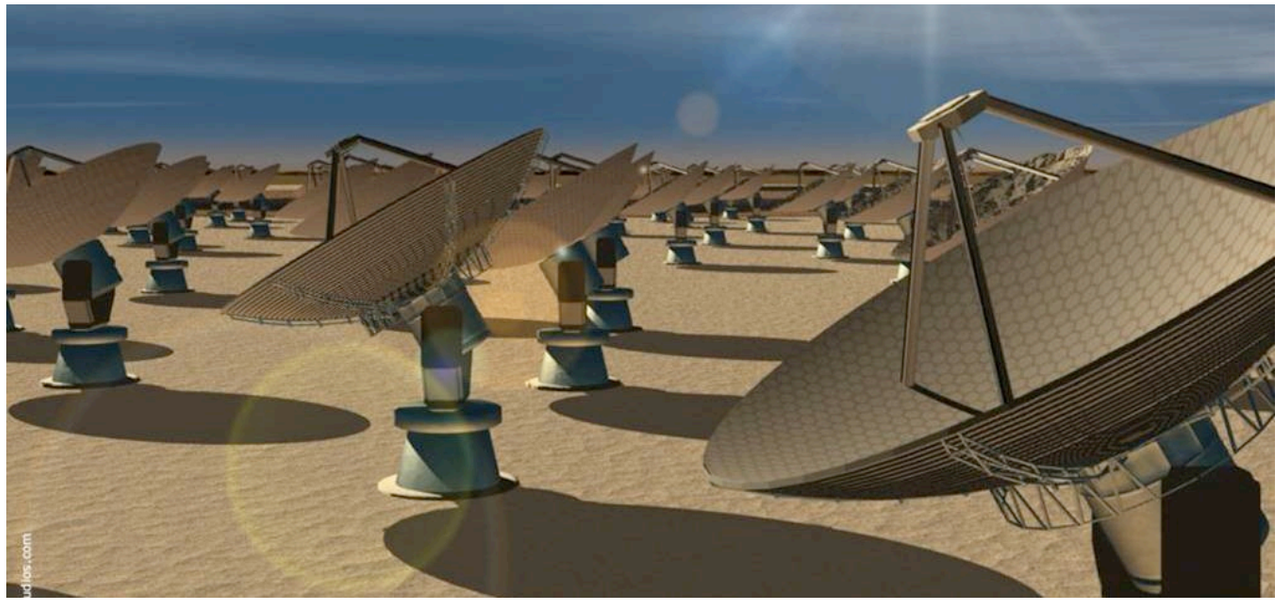


Target construction cost: 1 billion Euros

SKA - the reference design



Early demonstrators at Mileura, Western Australia



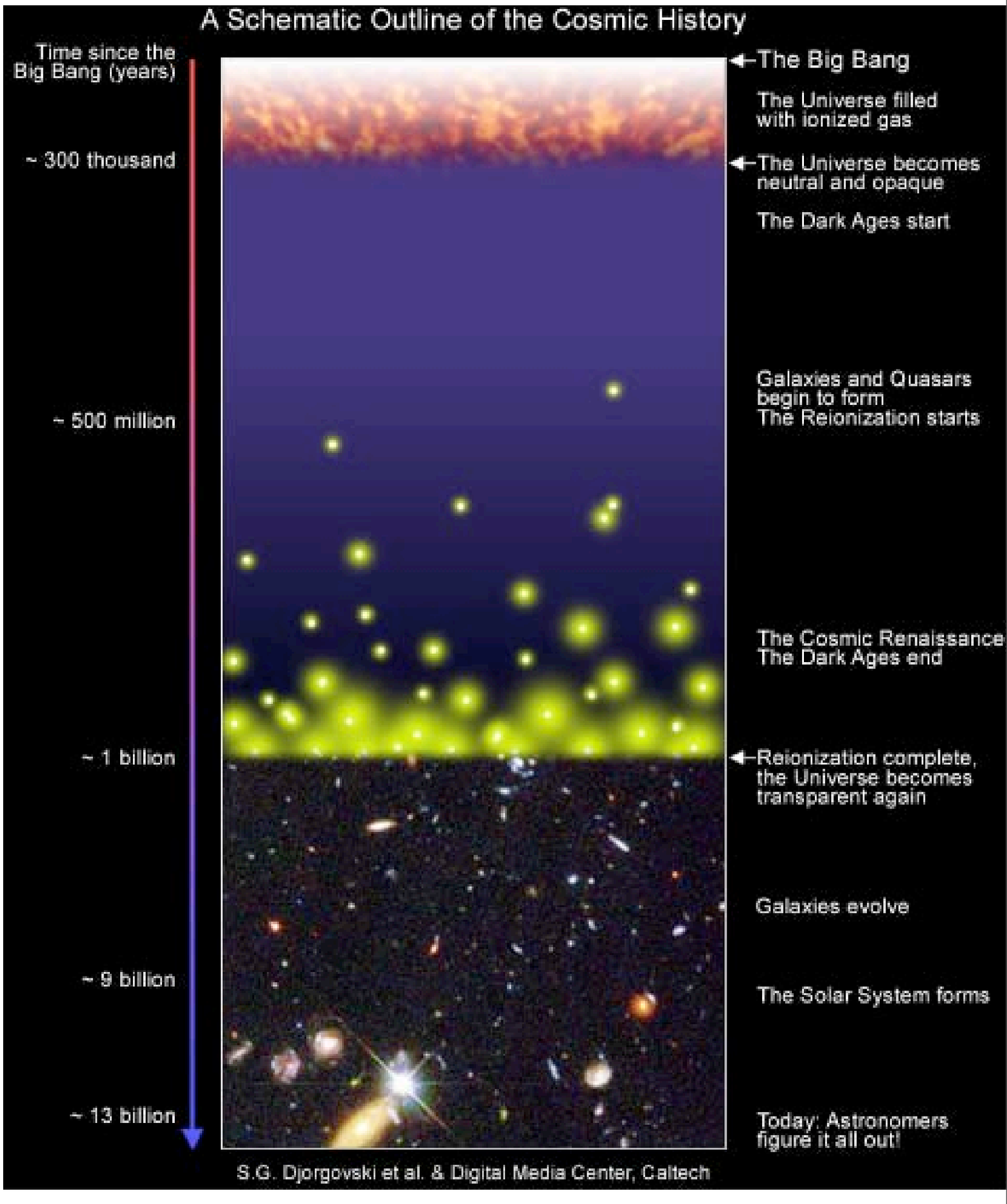
CSIRO xNTD @ Mileura
~700 MHz – 1.8 GHz

MIT LFD @ Mileura
4x4 crossed dipole array
80 – 300 MHz
NSF funding for 450 tiles USD 10M

xNTD + LFD ~ a prototype of the Present SKA ref design @ Mileura Shared backends, infrastructure, etc.

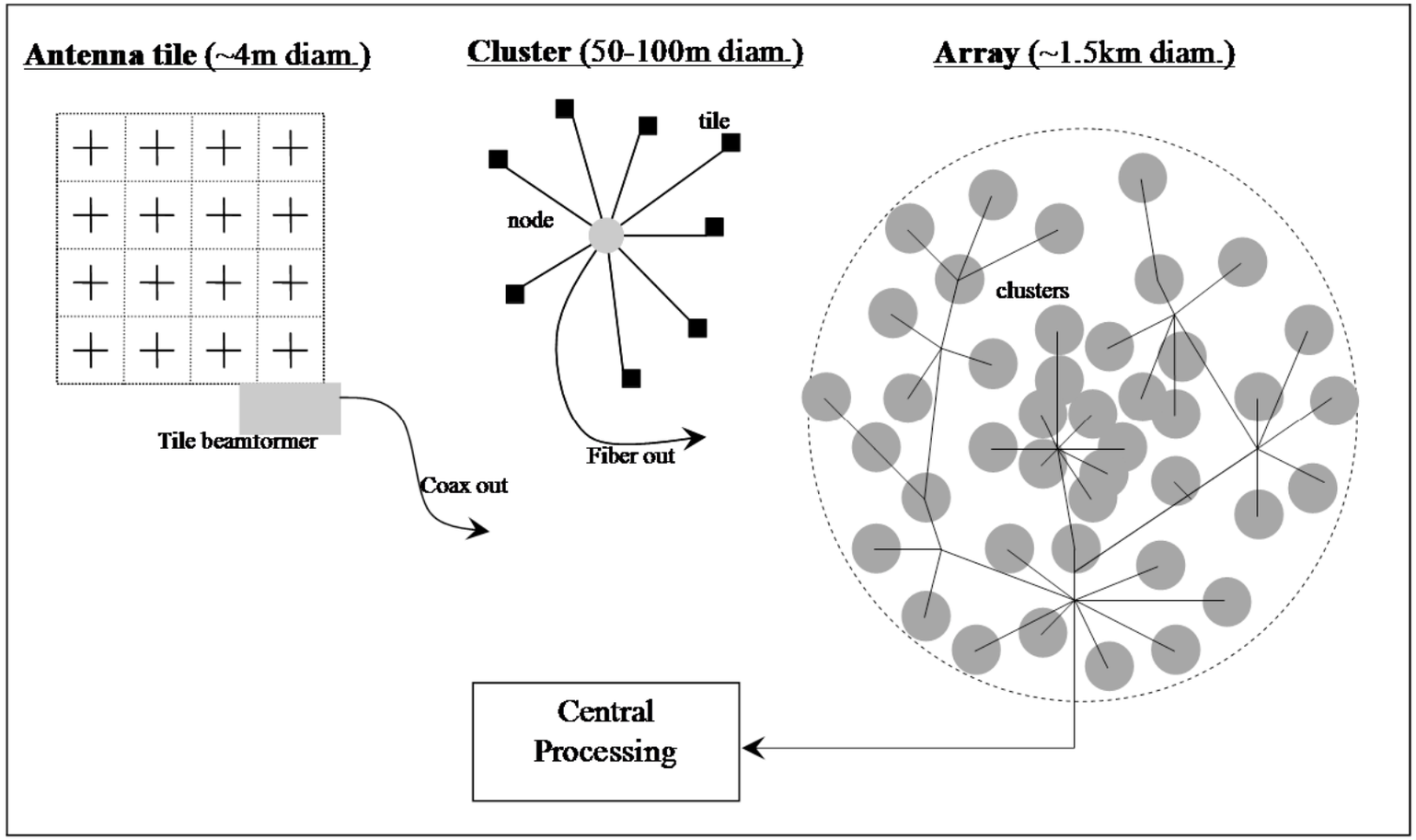
LFD and xNTD Science

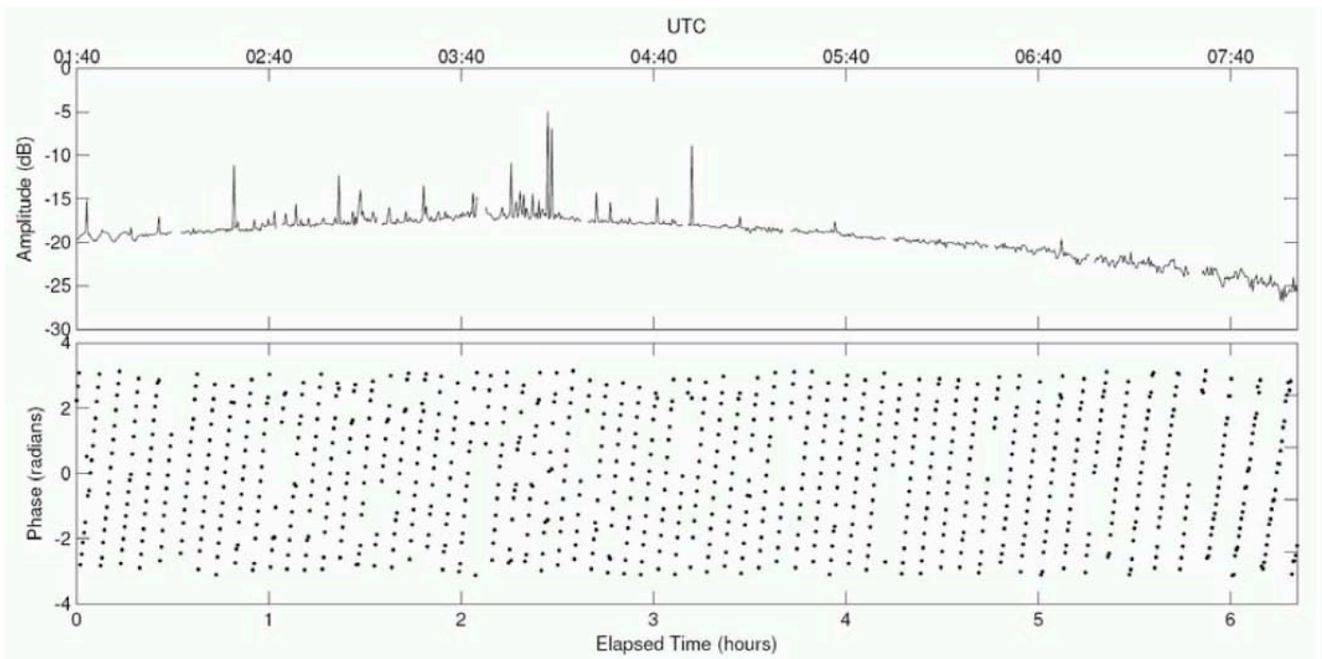
- LFD will try to observe HI reionizing around quasars just turning on
- xNTD will survey HI out to redshift 0.2 (all sky) and 0.6 (one patch)
- And lots of other science….
- SKA will observe “all” HI in the universe



Low Frequency Demonstrator (LFD)

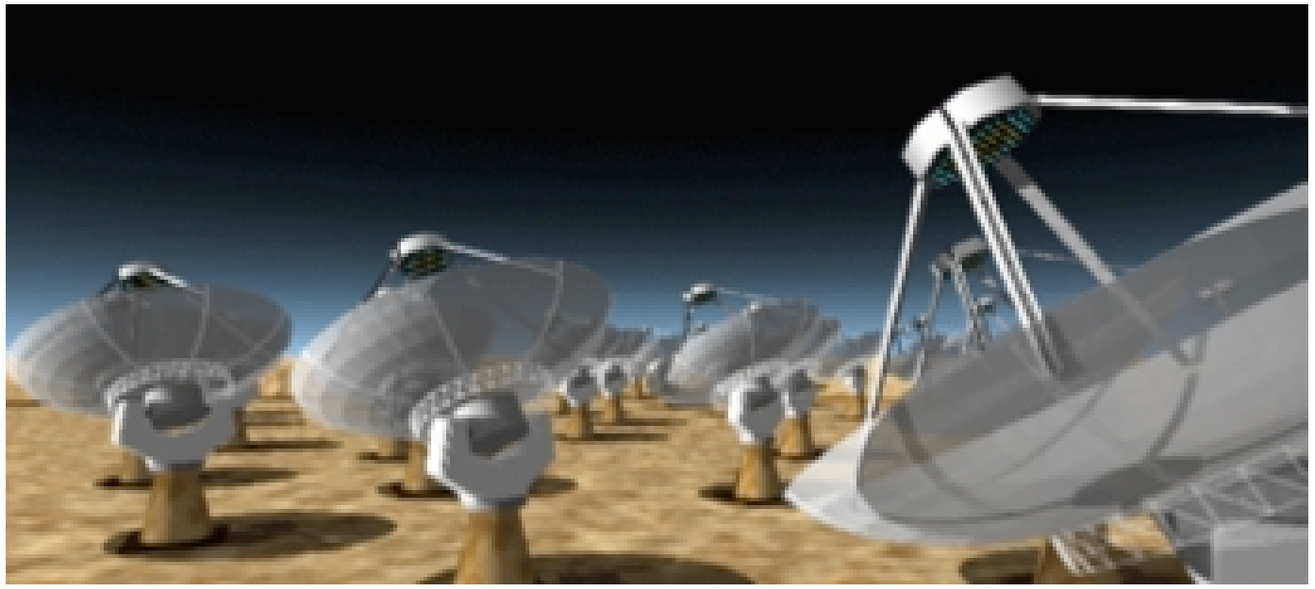
- "Antenna" = collection of tiles
  - Can form a beam or multiple beams electronically
- Correlate antenna beams
- Form images by normal synthesis techniques
- Maximum baseline ~ km
- Detect EOR statistically



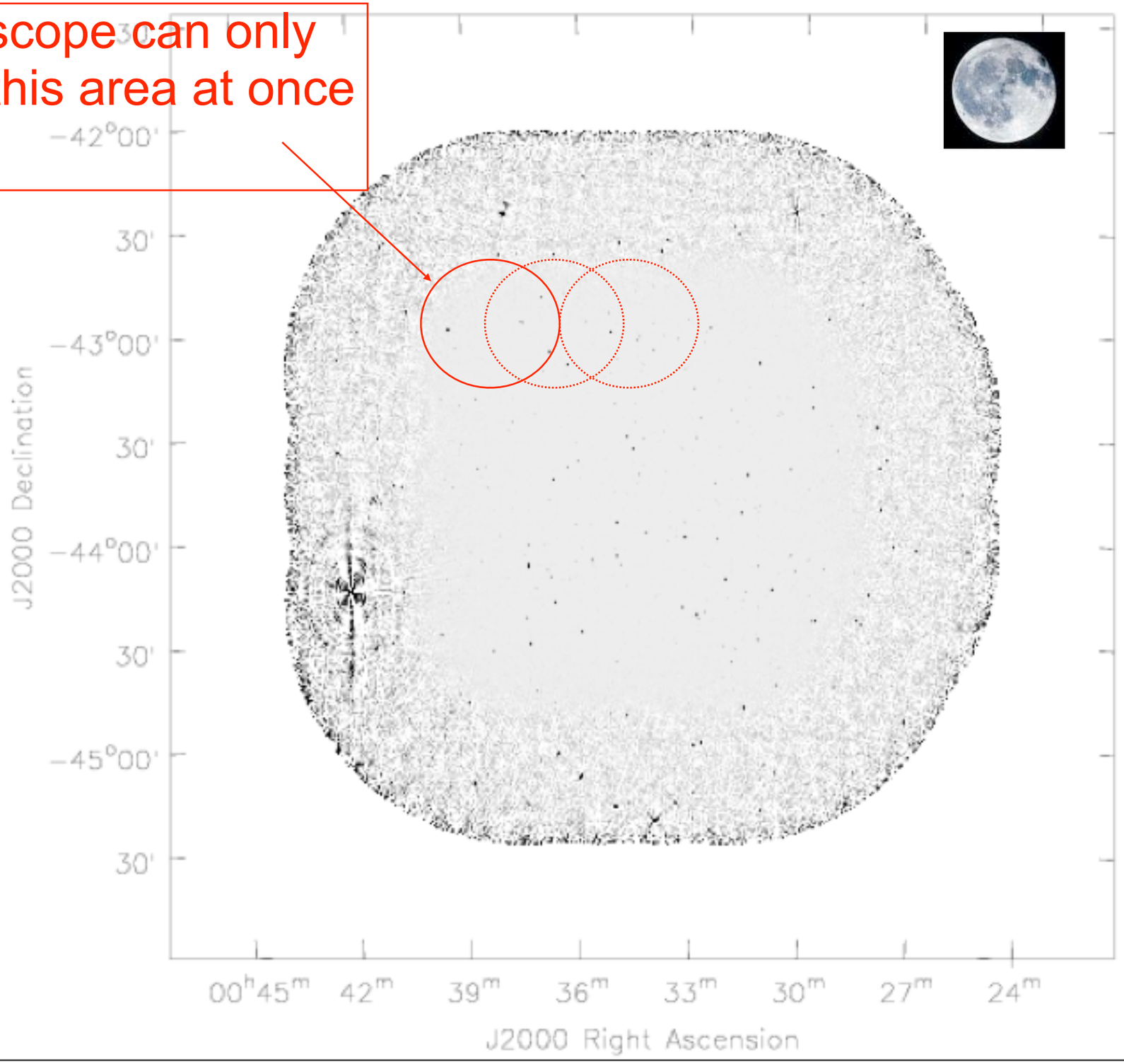


Extended New Technology Demonstrator (xNTD)

- 30 antennas of 12m diameter
- Baselines of about 2km
- Phased array feeds of about 30 elements
- 0.7-1.4 GHz
- To be sited at Mileura, Western Australia
- $50M+ budget
- Operational 2011



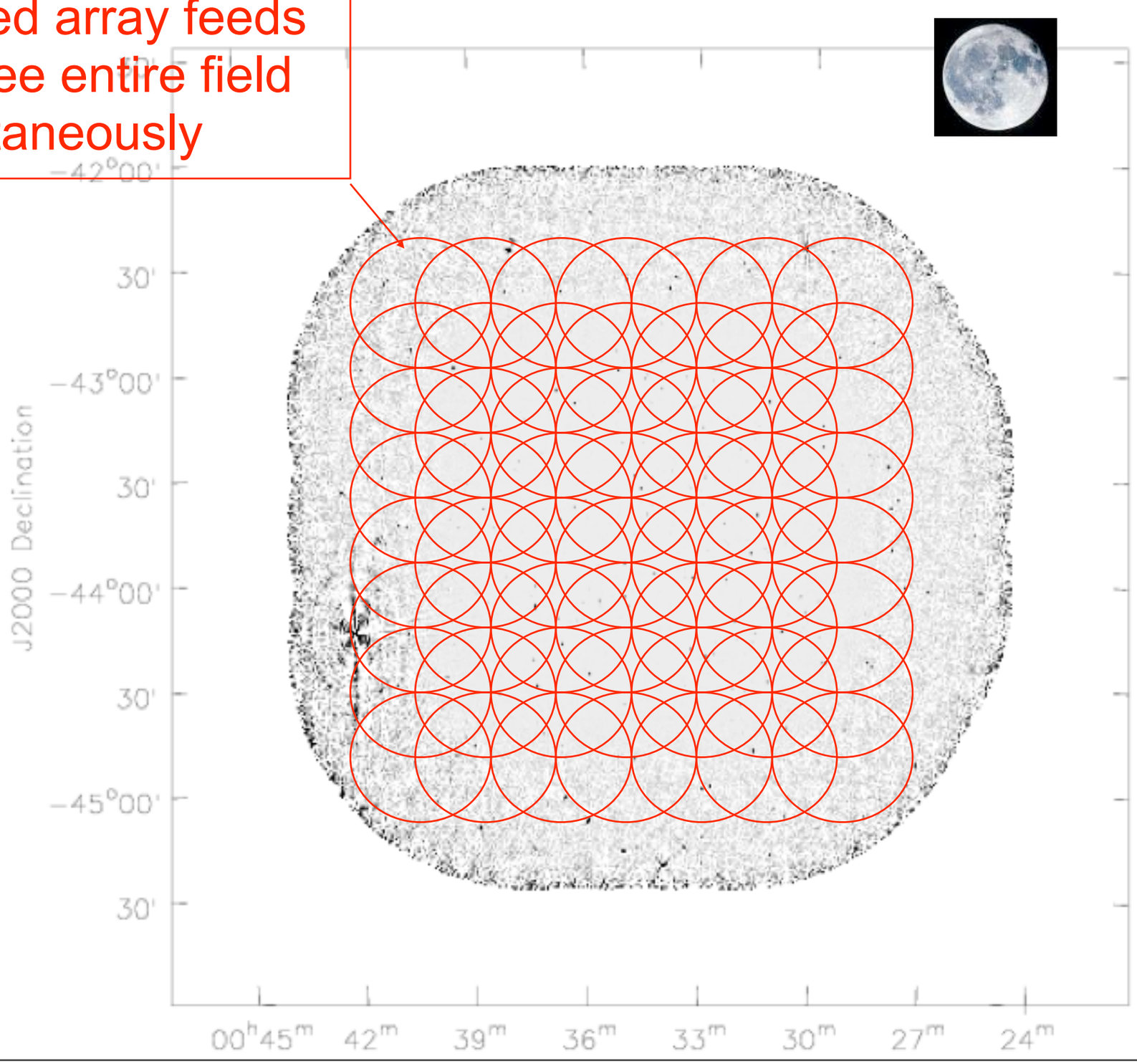
ATCA mosaic of Chandra Deep South South



- Painstakingly made from about 20 separate pointings
- About 60 days observing with Compact Array

xNTD will image entire field in about 30min

Phased array feeds can see entire field simultaneously



xNTD = survey telescope

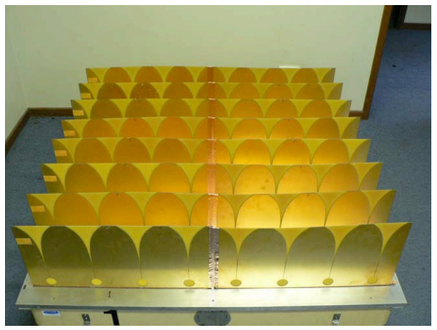
Survey entire continuum sky in a week

Survey all HI out to z ~ 0.2 in 1 years

Survey HI in one pointing out to z ~ 0.6 in half a year

Transient sky - minutes to days

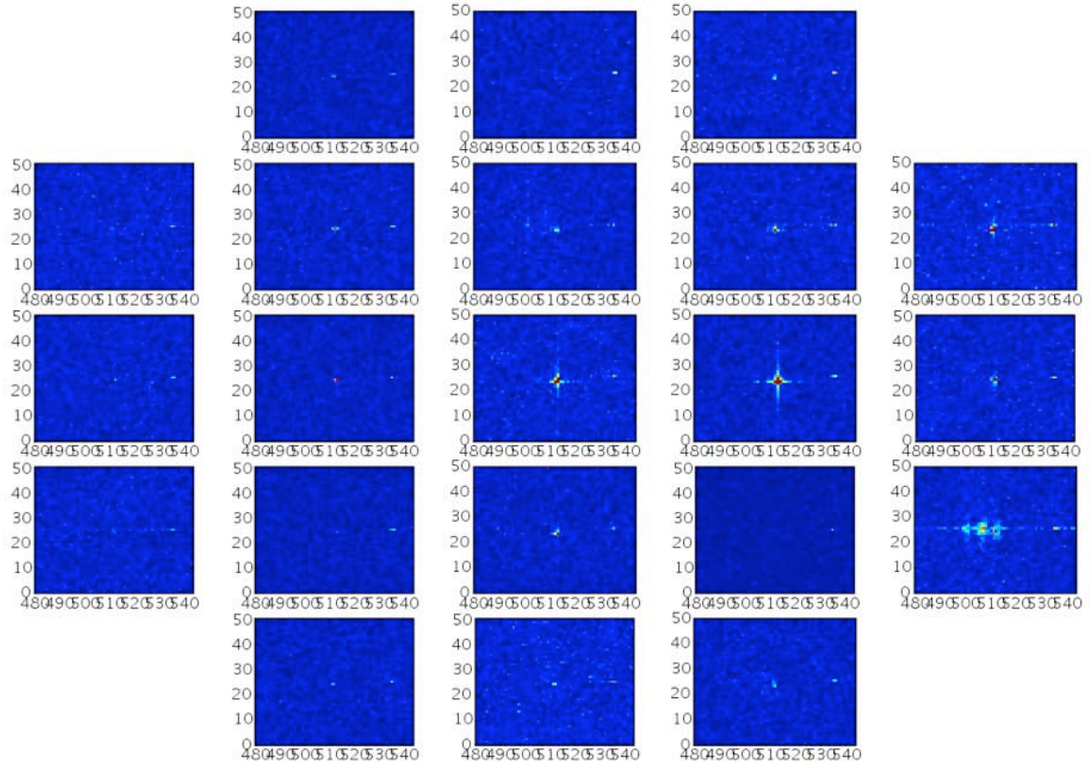
Performance of PAF

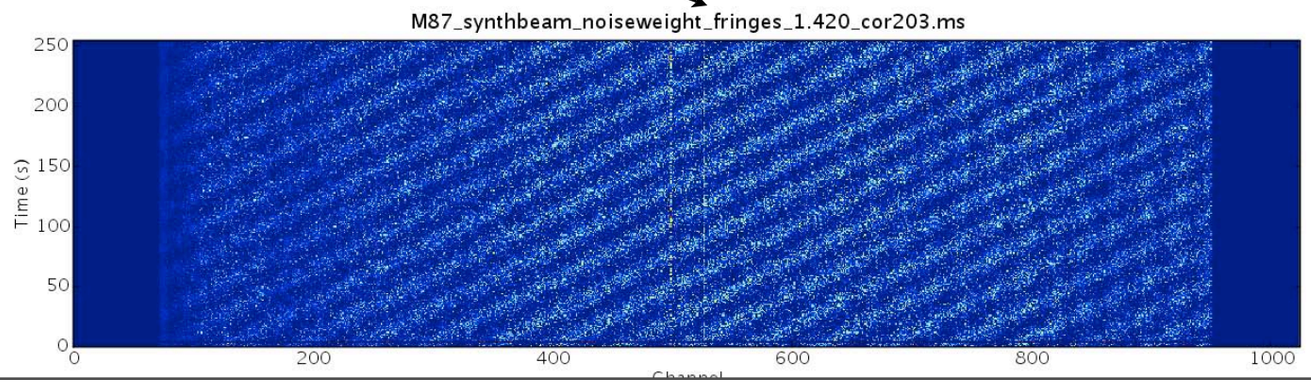


- Number of elements summed determines quality of synthesized antenna beams
- Cost of beamformer is directly proportional to the number of summed elements
- Gain stability of PAF will possibly limit the dynamic range in continuum and spectral line
- Bandpasses of Vivaldi PAF poor
  - CSIRO developing novel design with better behaviour
- Investigating schemes to calibrate eigen-modes of PAF by switching
  - Prototype these on the New Technology Demonstrator

New Technology Demonstrator

- Test bed for PAF development required for xNTD
- Two element interferometer in Sydney
- One element has PAF
- Recently observed fringes on M87 at 1.4GHz
  - element by element
  - summed



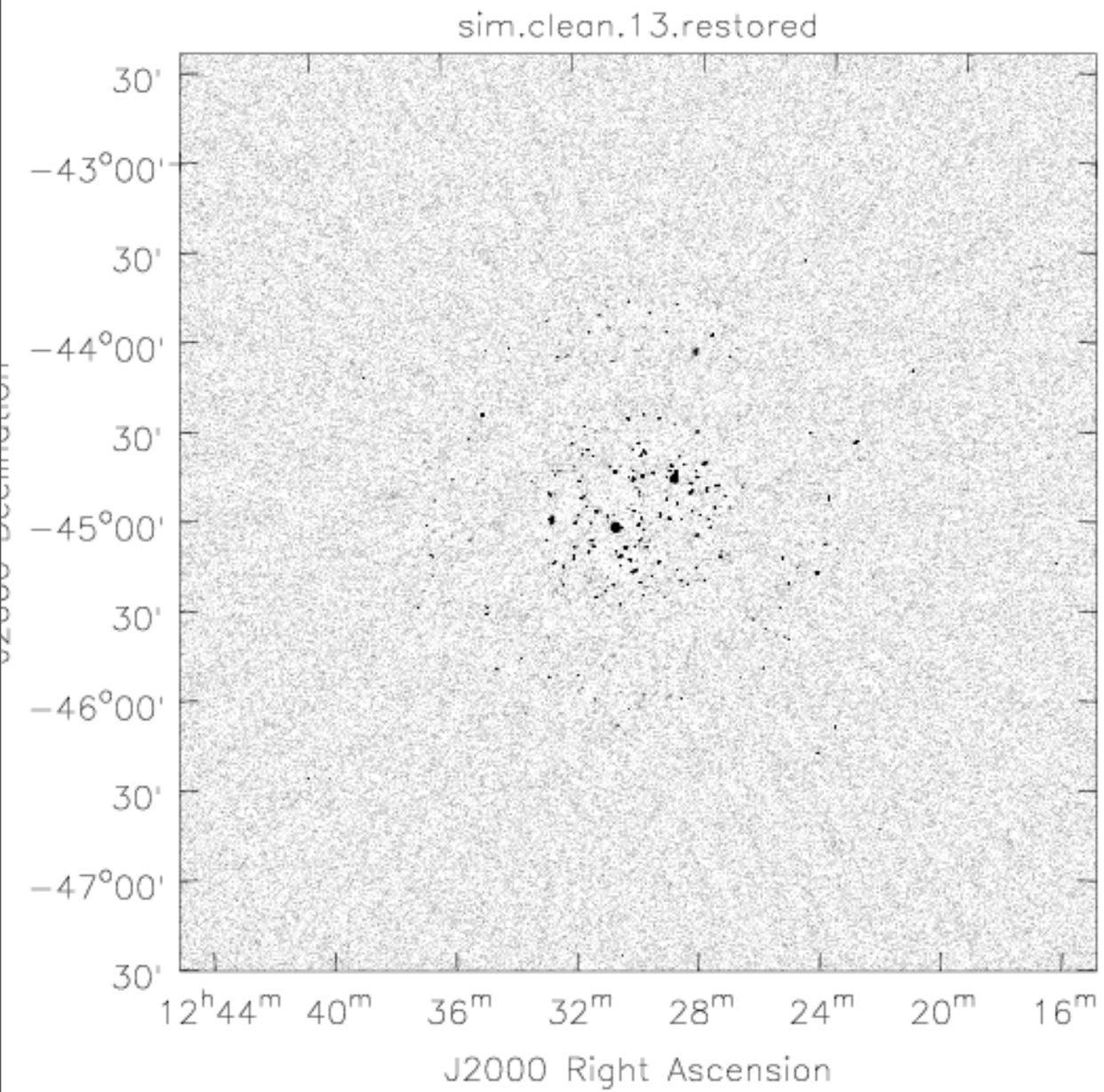


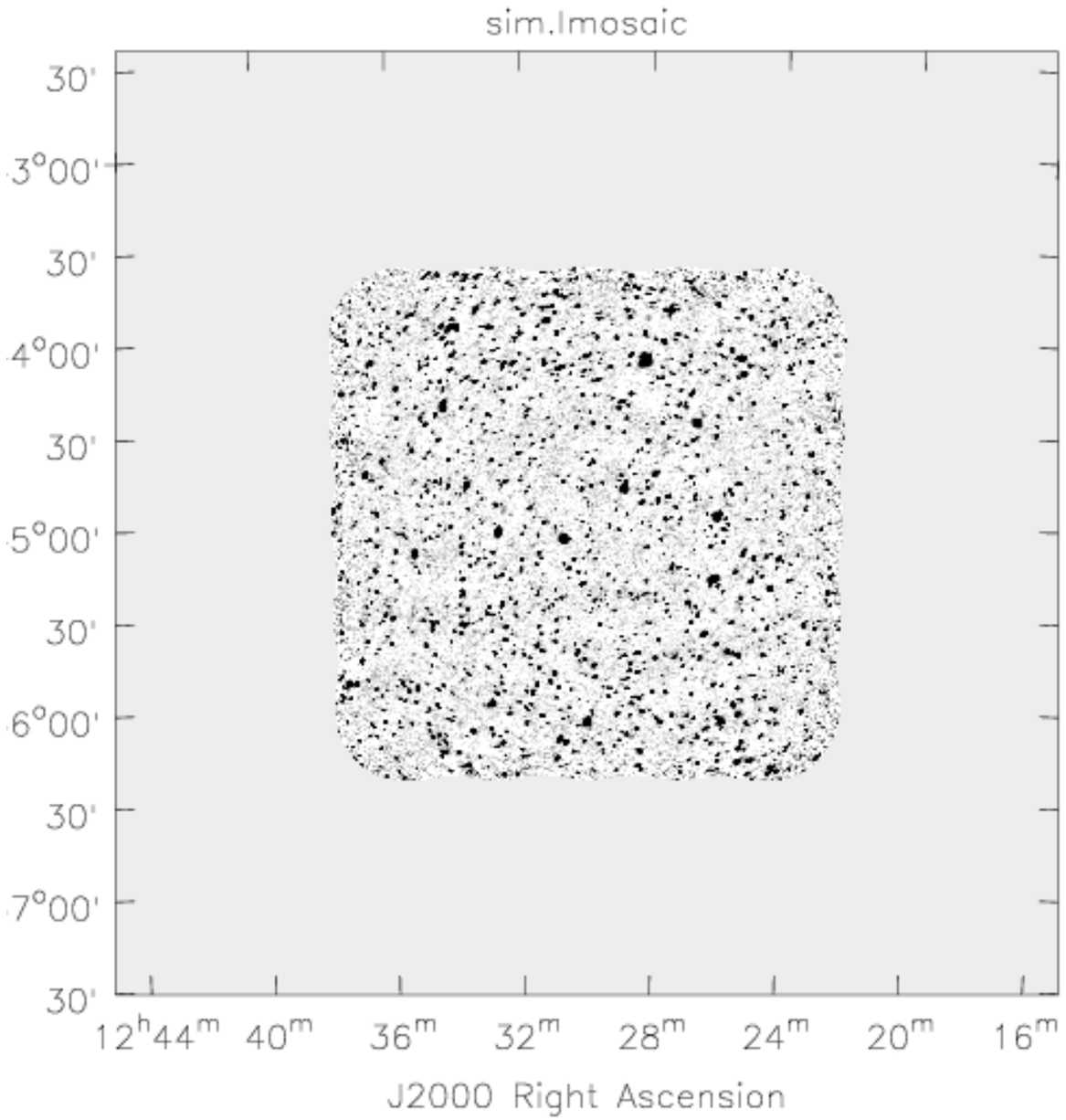
Imaging for PAF enabled synthesis arrays

- Imaging straightforward - can use standard mosaicing theory
  - Image fields separately and then combine (deconvolved) images
  - Use Fourier plane convolution techniques for fast mosaicing
- Need to model and remove bright sources in the primary beam sidelobes
- For xNTD, can take advantage of excellent point spread function from long integration with 30 antennas and multi-frequency synthesis
- Need high accuracy, broad band multi-frequency synthesis deconvolution algorithms
- Polarization likely to be difficult - element coupling must be calibrated

Example xNTD mosaic from 30 min observing

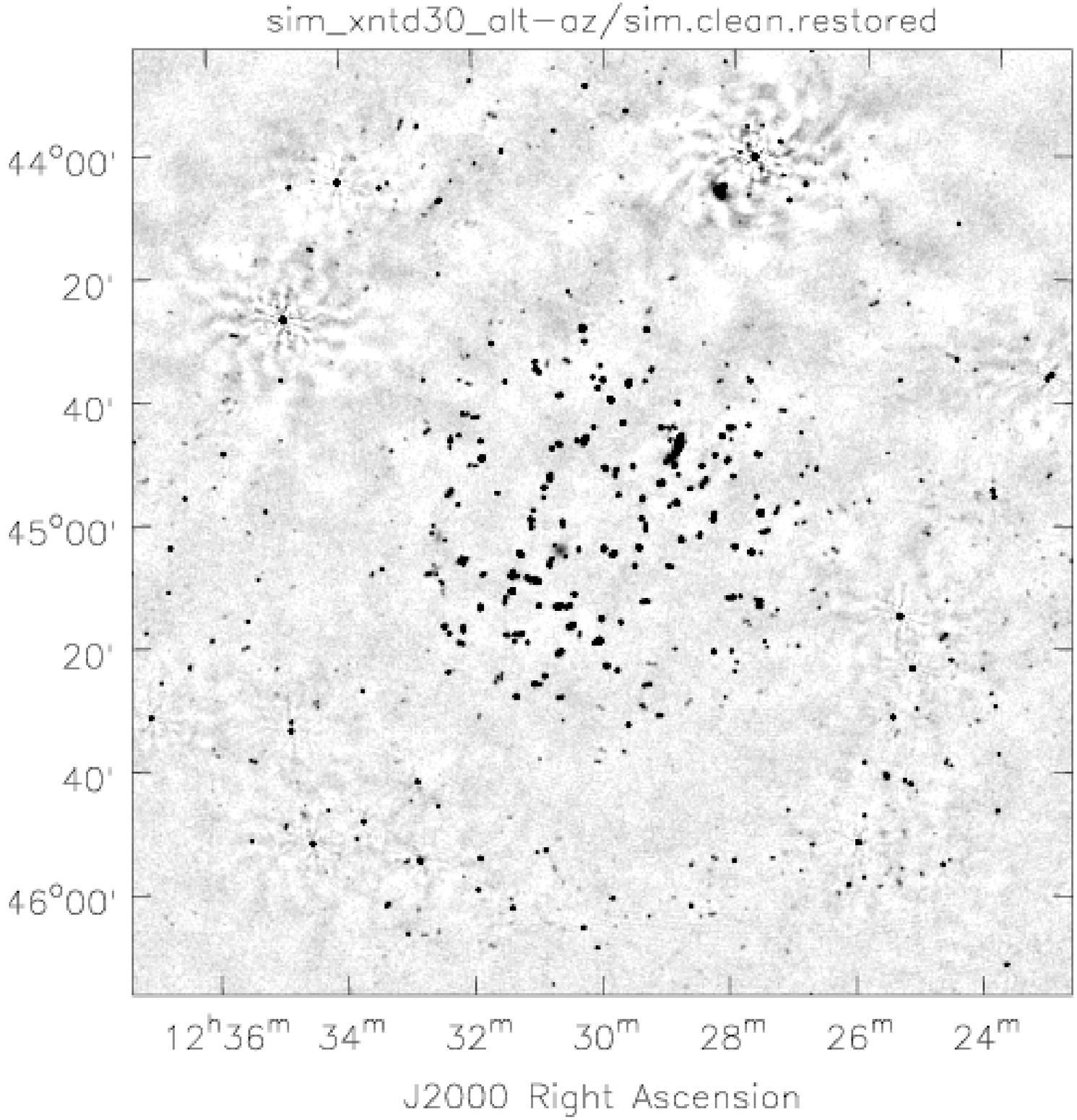
- 25 element PAF, beams separated by $\frac{\lambda}{2D}$
- Linear mosaic of Cleaned images





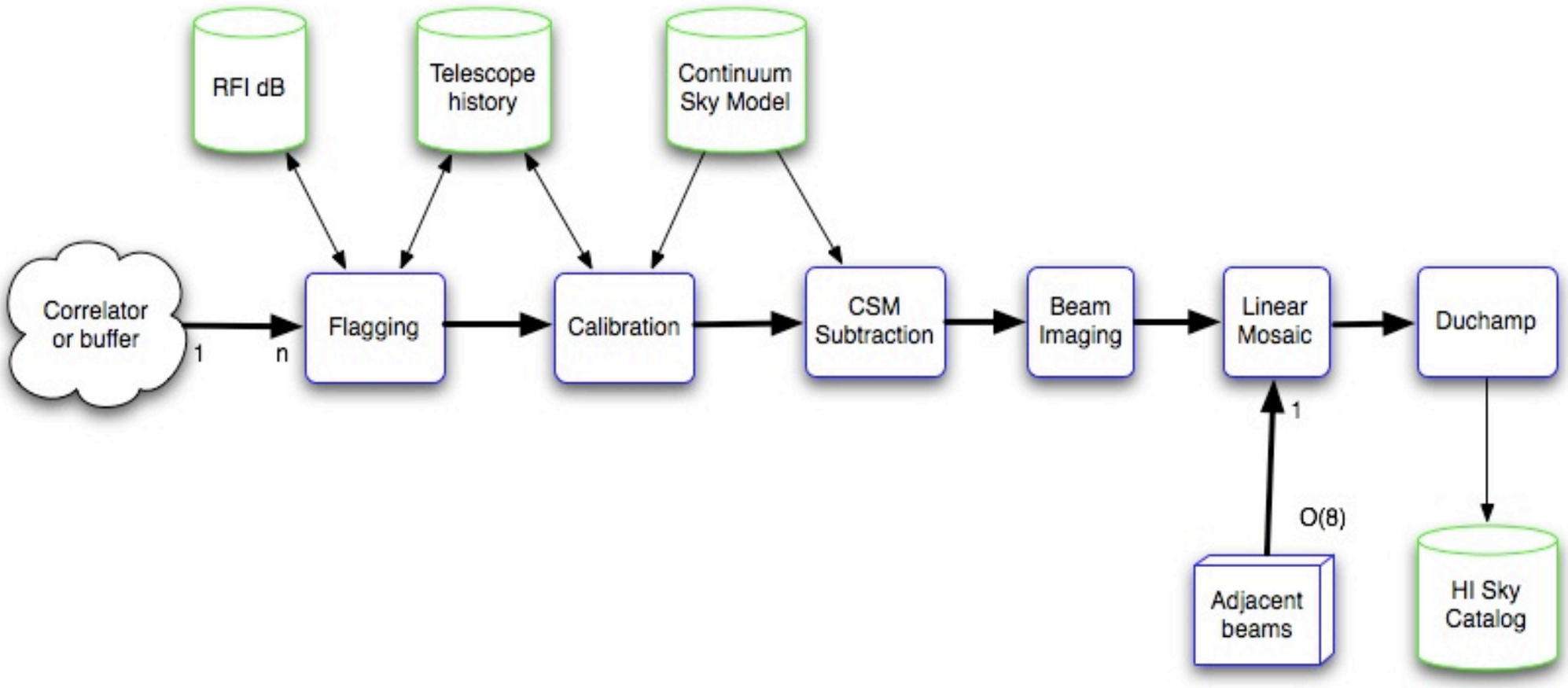
Rotating Phased Array Feed

- For alt-az telescope, PAF rotates on sky
- Could take out in:
  - Antenna (equatorial mount)
  - Mechanical feed rotator
  - Beam former
  - Imaging software
- Still evaluating
- What happens to the feed legs?
  - Probably ok to ignore
  - Especially with special PAF weighting



xNTD pipeline processing

- Data volume ~ many TB per hour
- Spectral line processing -16384 channels - dominates
- Partition by beam and spectral channels (a chunk)



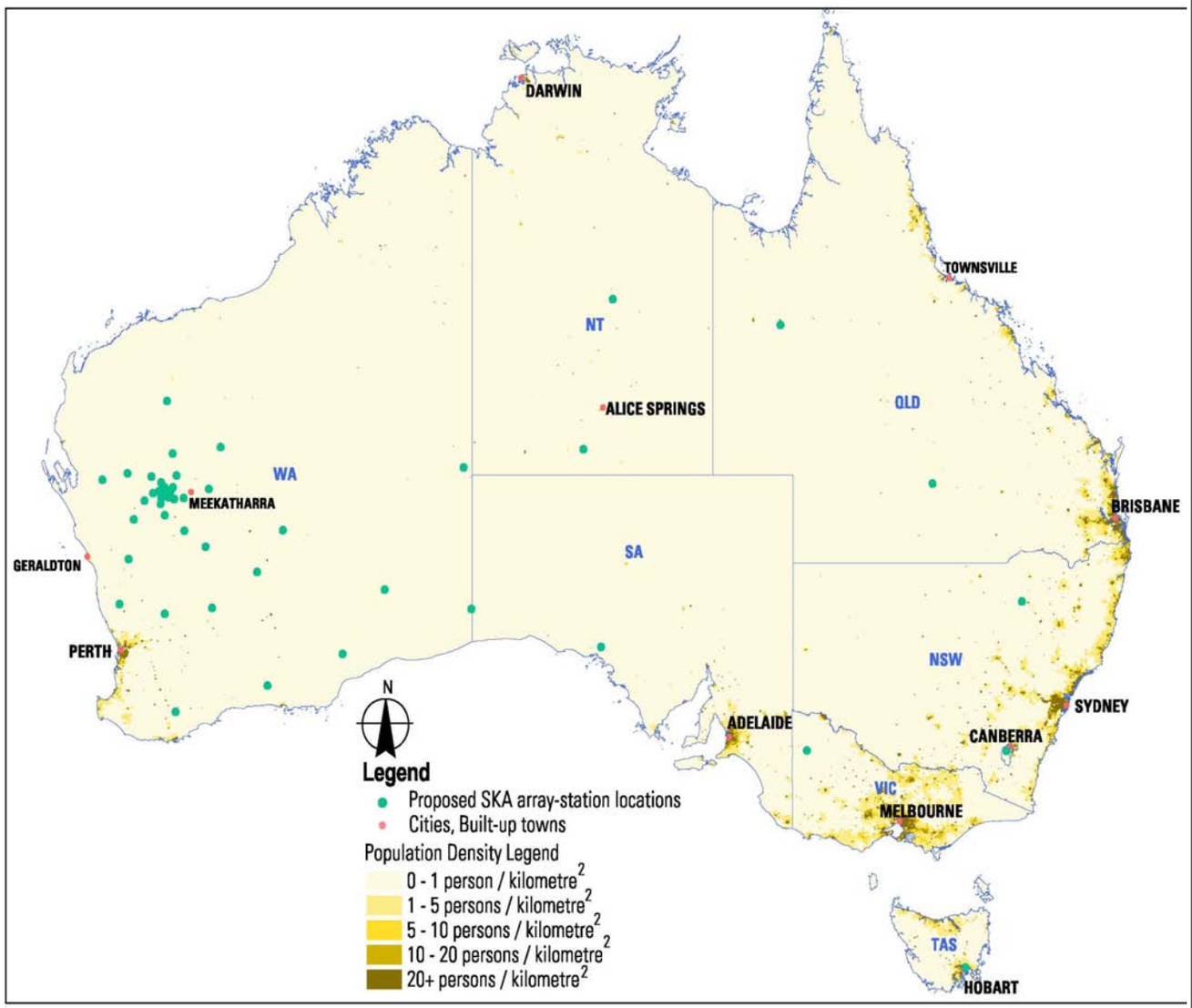
xNTD HI emission pipeline
- One per search volume
- Single pass
- Coupled to continuum only via sky catalog

Aperture Array calibration and imaging

- Calibration
  - Mostly low frequency issues
  - Calibration of non-isoplanatic ionosphere very hard
  - Many objects to calibrate on but questions about computability and stability
  - Talk by Nijboer later in this session
- Imaging is hard because array shape as seen from the source is constantly changing
  - Analogous to but worse than PAF field rotation
  - Algorithms exist but are intrinsically expensive
  - Still being worked on....

From xNTD to SKA

- If xNTD works one part of SKA could be composed of ~ 100 xNTDs spread over 3000km
- Challenges increase!
- SKA computing >1000 xNTD computing
  - >100Pflop instead of 20Tflop



More info

- Talk at http://www.atnf.csiro.au/people/tim.cornwell
- xNTD at http://www.atnf.csiro.au/ska
- SKA at http://www.skatelescope.org