SKA1 Low station configuration workshop 25-26th February 2016

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Take home messages

1. Regular arrays should be avoided!
2. We need to develop a new station configuration with consideration for the electromagnetic effects and geometric limitations → V5 needed!

Overview

- Why regular arrays cannot be used (slides from Eloy)
- An analysis of current configurations
- Answers to workshop questions

The problem with regular arrays

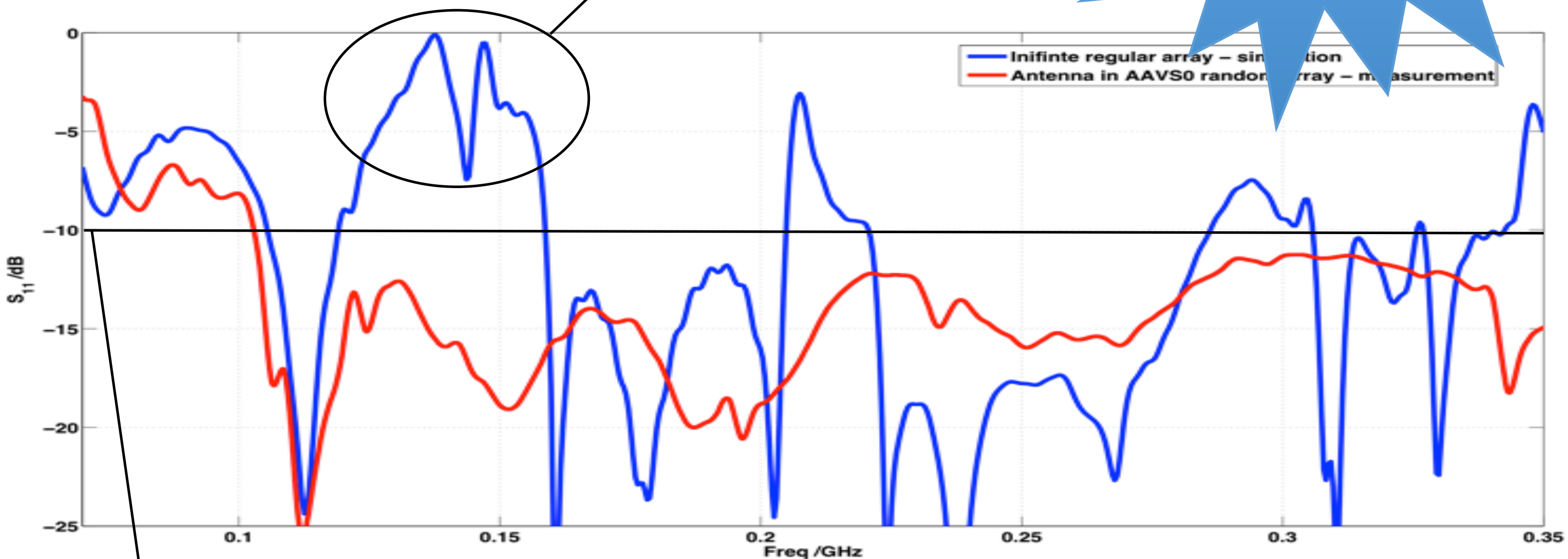
Regular versus irregular antenna positions inside the stations

- Mutual coupling in wideband regular arrays can cause in band anomalies in both the impedance and embedded element patterns of the antennas leading to scan blindness for which all power is effectively reflected.
- This is the case for the 7:1 SKA-LOW band.

Regular versus irregular antenna positions inside the stations

Regular arrays won't work!!!

All power reflected



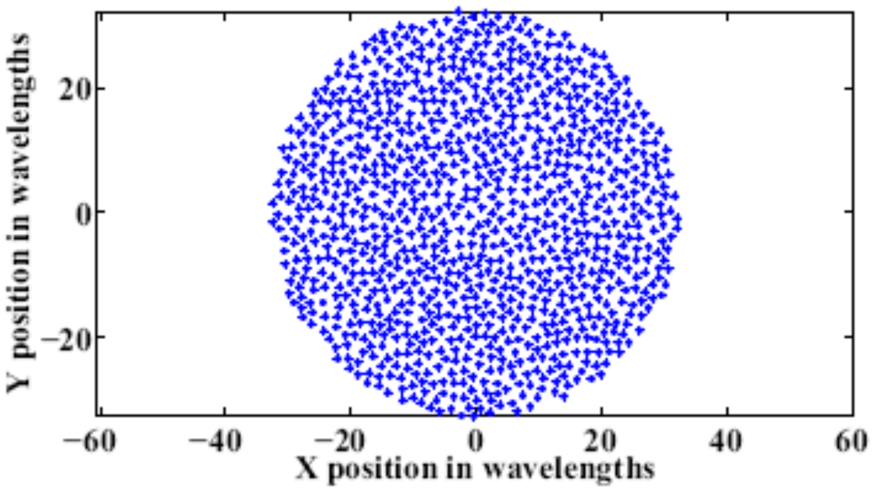
Anywhere below this line for Trec < 35 K

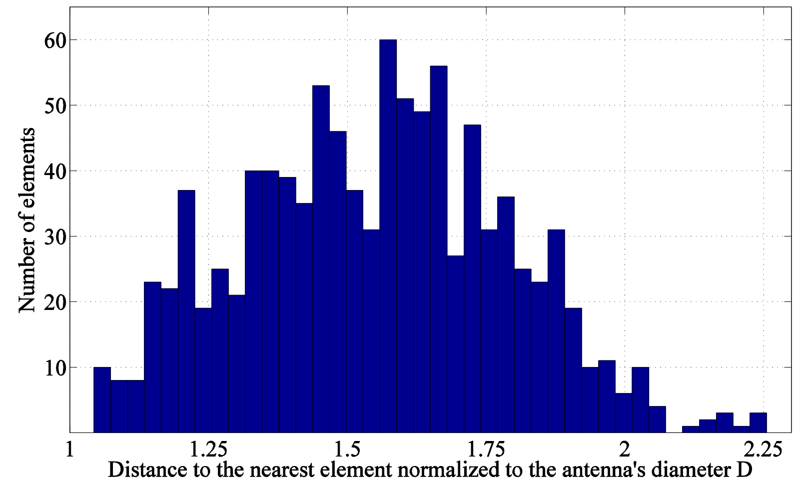
* de Lera et al. Experimental Astronomy 2015

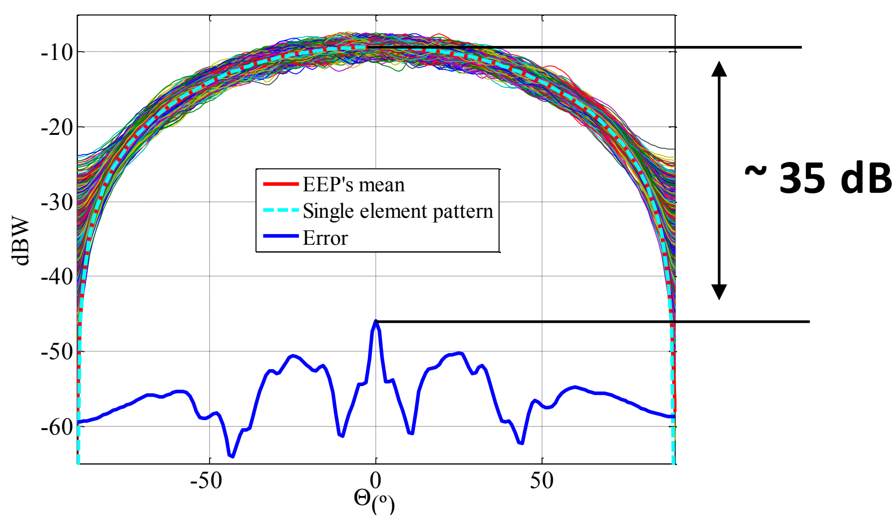
Regular versus irregular antenna positions inside the stations II

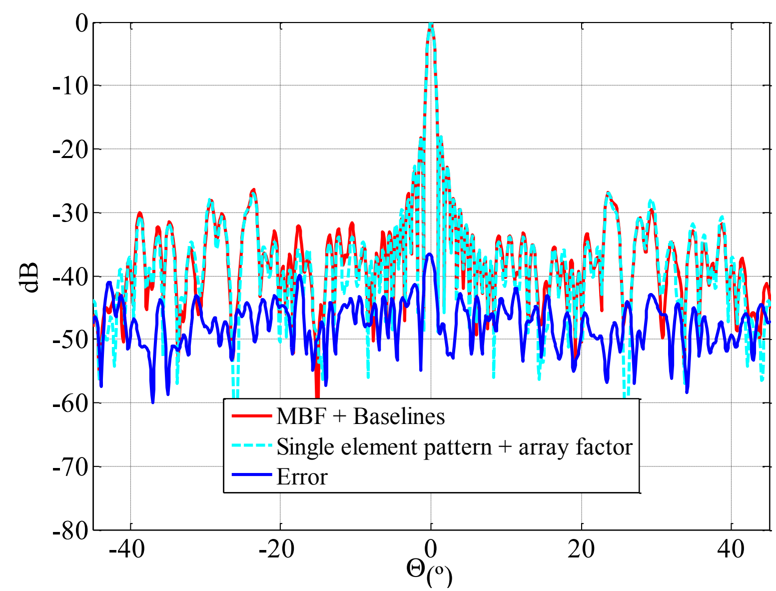
- An irregular (randomized is the best case) configuration of the antennas in the stations randomizes the effects of mutual coupling. This is beneficial to the performance of the instrument as well as to its calibratability.

Mutual Coupling in Irregular Arrays









An analysis of some current configurations

(Ignoring the problems of regular arrays!)

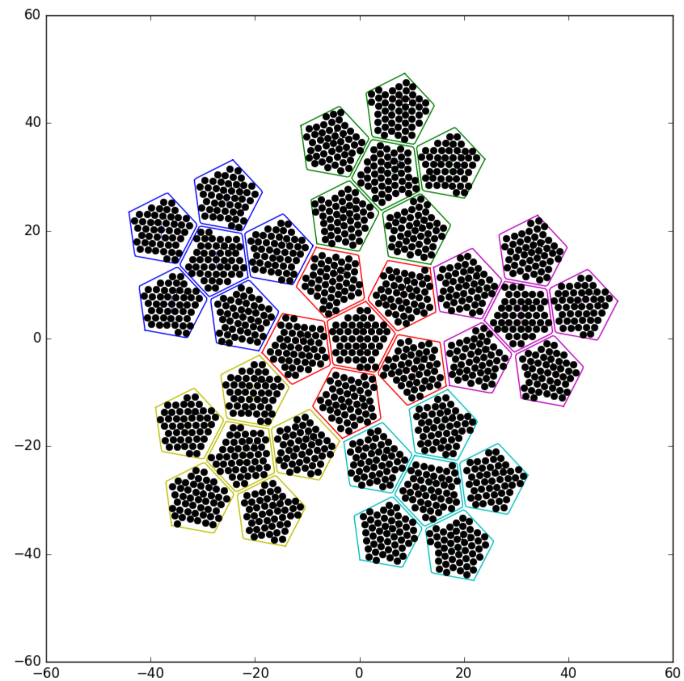
Introduction

- Currently 3 configurations:
  - V4A – Pentagonal geometry (sub-stations, stations, super-stations)
  - V4D – Circular stations arranged into super-stations
  - V4X – Sea of elements super-station

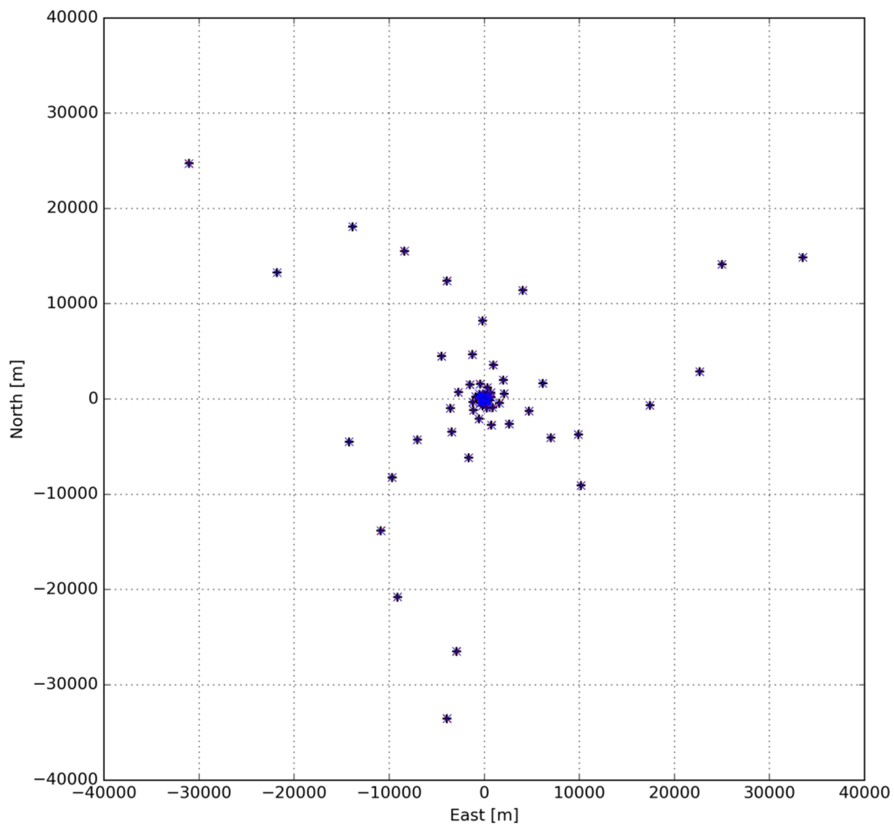
- Python scripts:
  - https://github.com/OxfordSKA/SKA1-low-layouts

V4A

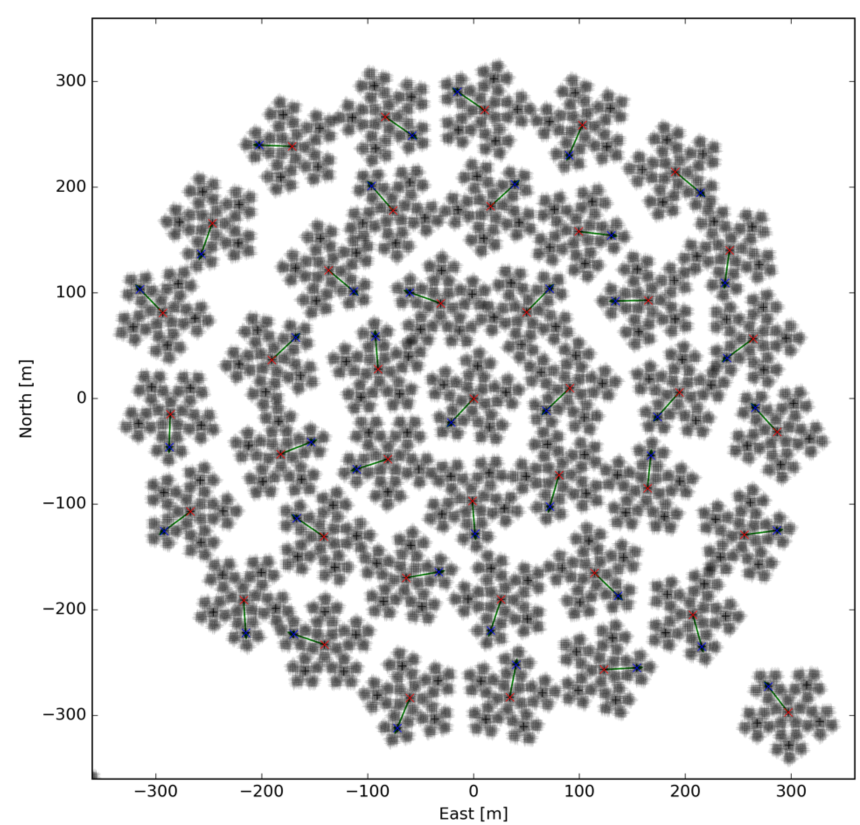
- Stations and super-stations built from a set of pentagonal sub-stations.
- Pentagons filled with:
  - Randomly rotated hexagonal lattice or
  - Random antenna positions
- Reference configuration
  - 48 antennas per sub-station
  - Super-station diameter of ~90 m
  - 94 super-stations
  - 564 stations
- Rotation of super-stations based on 'v7ska1lowN1v2arev3R.enu.564x4.txt'
- **Random positions result in fewer antennas per station**



V4A showing full array

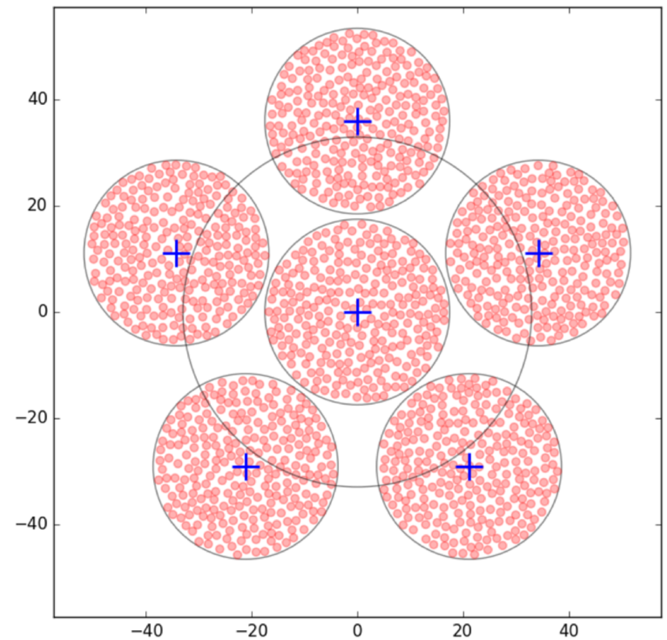


Zoom into the central core

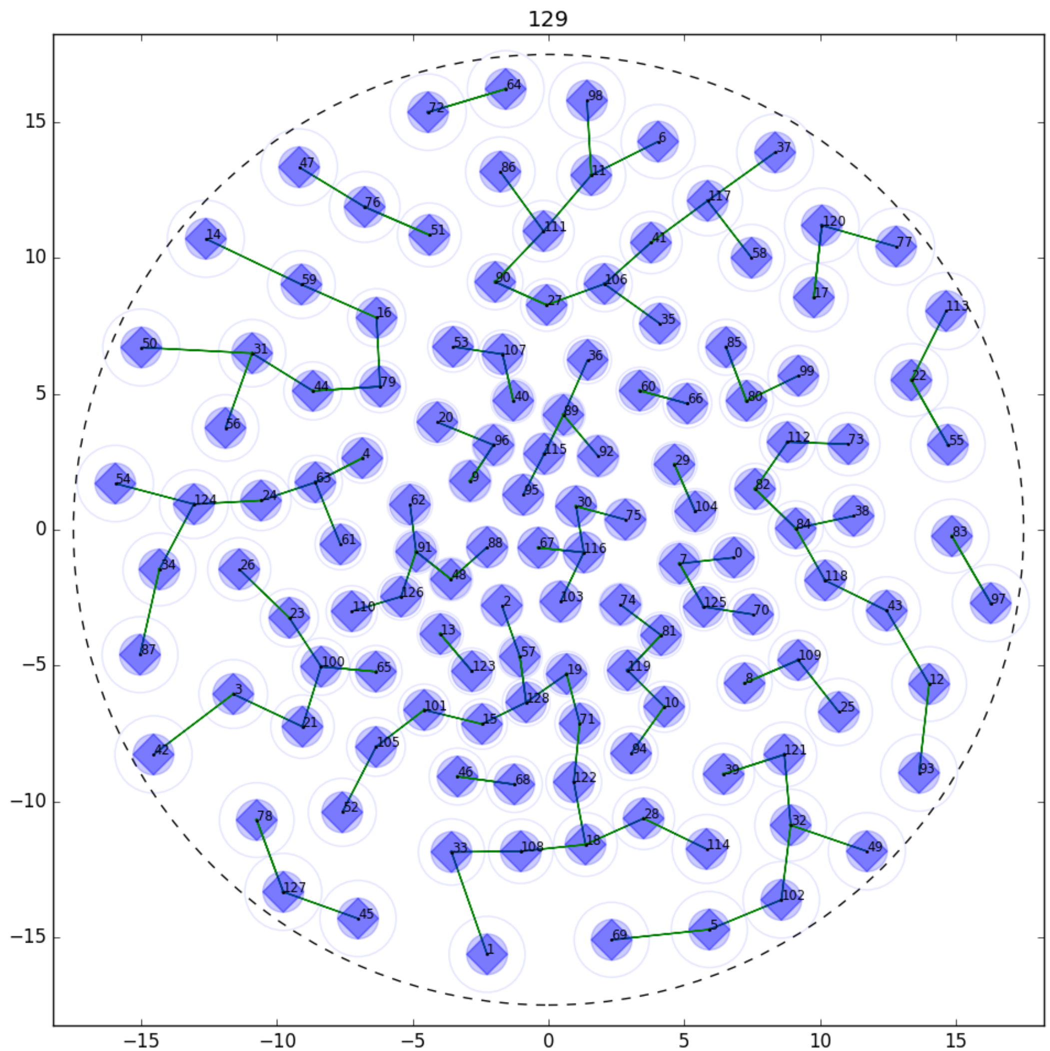


V4D

- Pentagonal arrangement of circular stations grouped into super-stations
- Random antenna positions within each station.
  - Generated using a placement algorithm based on a uniform distribution of trial locations, allowing for the antenna footprint
- Reference configuration
  - 256 antennas per station
  - ~90 m (?) diameter super-stations
  - 85 super-stations
  - 510 stations
- Actual configuration
  - 180 antennas per station
  - Limited by random generation with 2.25 m^2 antenna footprint
- Random rotation of station centres
- Possible physical thinning of stations by growing the antenna separation as a function of radius.

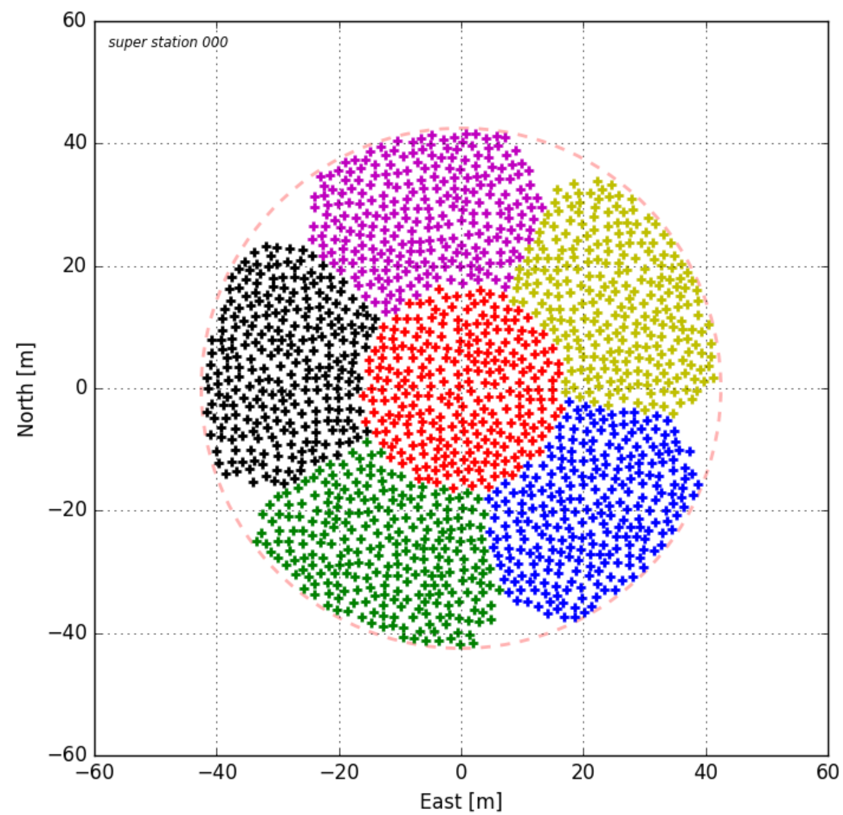


An example thinned random array



V4X

- Super-stations constructed from a 'sea' of elements
- Configuration (based on V4D)
  - 256 antennas per station (selectable)
  - 1536 antennas per super-station
  - Super-station diameter of 85 m
- Random rotation of station centres



A note on the generation of random arrays

- Random arrays will have larger average spacing than regular arrays
- For this analysis we have chosen to respect the specification of station/ super-station diameters at the expense of fewer antennas per array.

Station beams

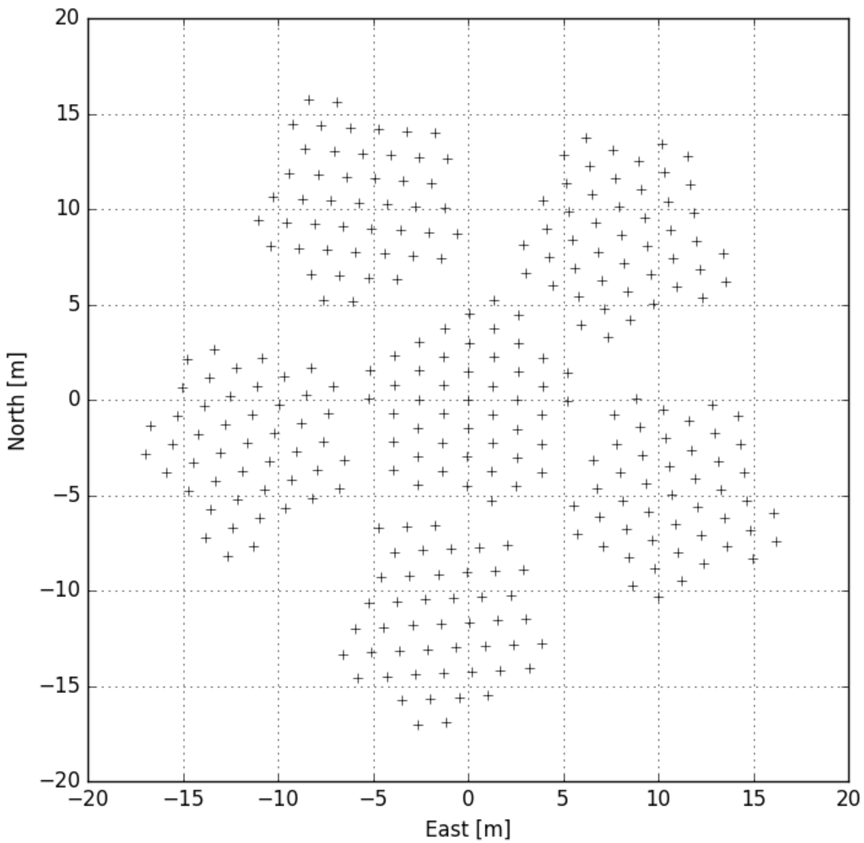
- Average cross power stokes I station beams where generated by cross correlation of all station pairs
- Beams generated for both stations and super-stations
- Telescope models
  - V4A
    - Hexagonal lattice within pentagonal sub-station
    - Random antenna positions within pentagonal sub-station
  - V4D
    - With and without physical thinning
  - V4X
- Beams generated with and without apodisation using Taylor weighting
- Frequencies of 50 MHz and 350 MHz (each end of the SKA1-low band)
- Zenith beam pointing (lower scan angles simulated, but not presented here)

Station beams

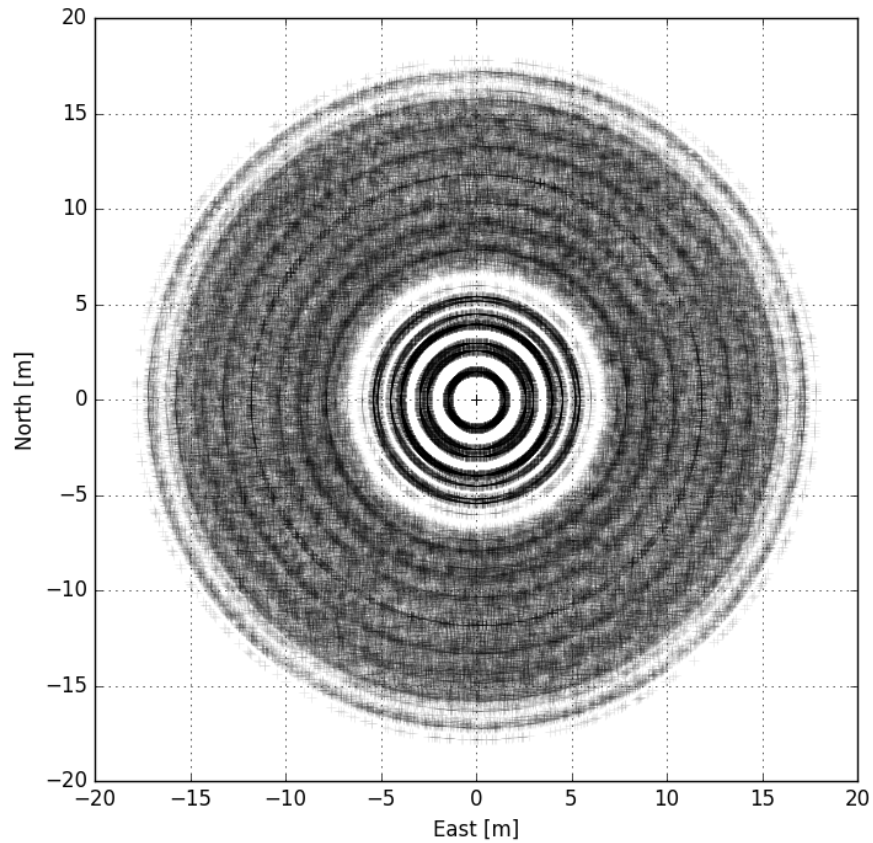
(this section is mainly for reference)

V4A stations: Randomly rotated pentagonal shaped sub-station centred hexagonal lattices
Station orientations defined by coordinates in 'v7ska1lowN1v2arev3R.enu.564x4.txt'
48 antennas per sub-station, 288 antennas per station, 564 stations, ~35 m diameter

Single station



Superposition of all stations



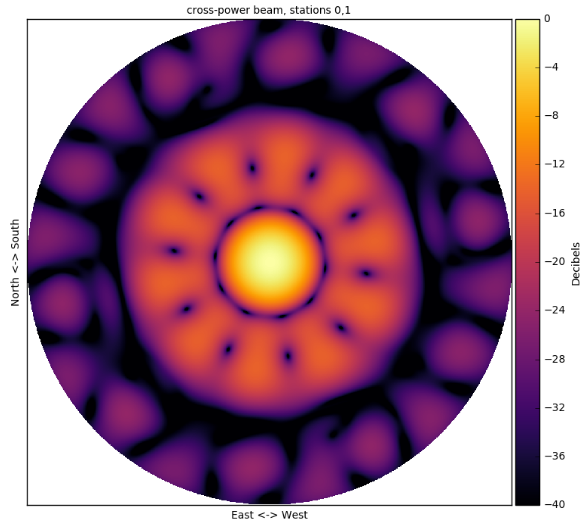
V4A station beams: Randomly rotated sub-station centred hexagonal lattices
Stokes-I cross-power station beams, 50 MHz, zenith pointing

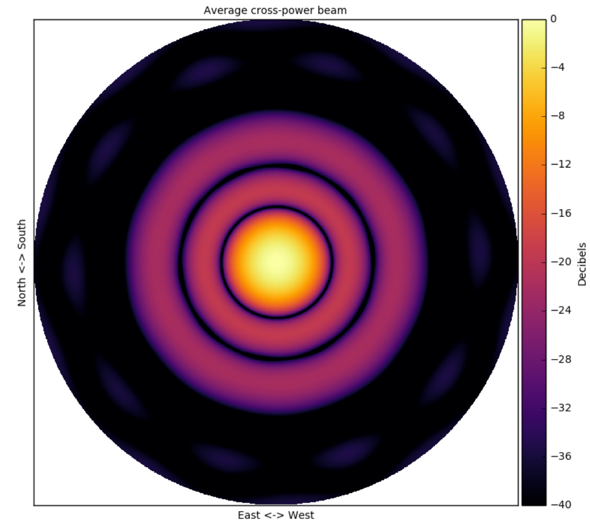
Cross-power beam
Single baseline

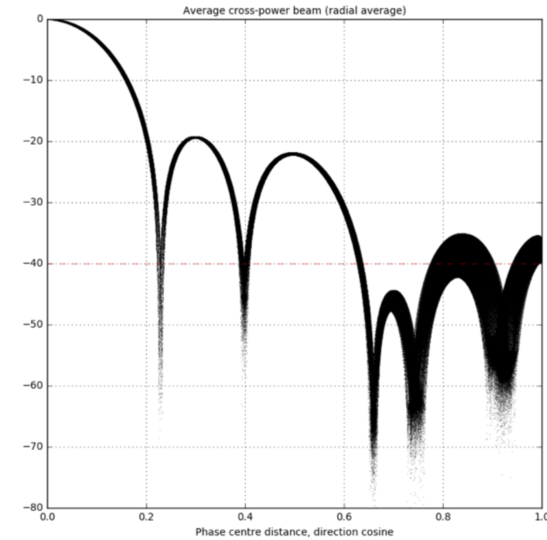
Average cross power beam
all baselines

Average cross power beam
Radial profile

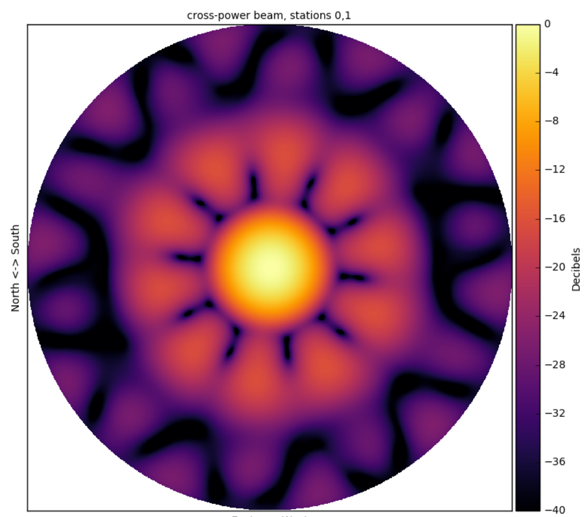
No-apodisation

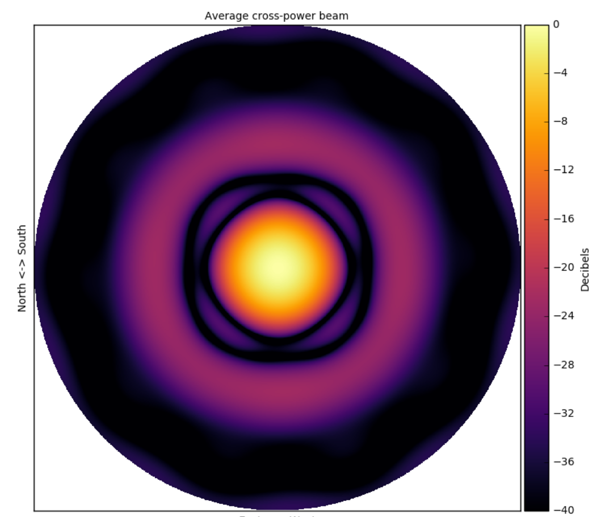


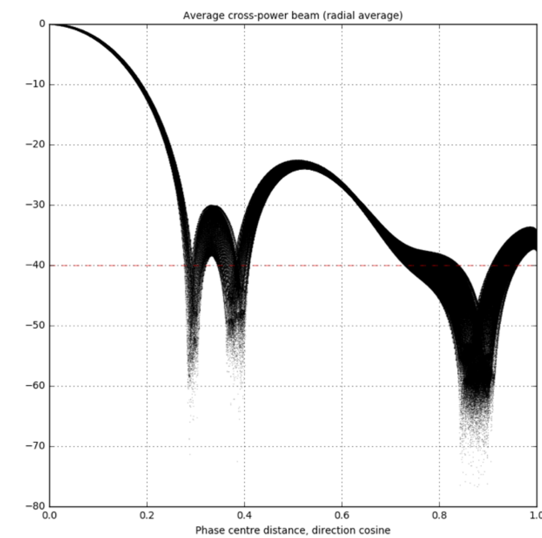




-28 db Taylor weights







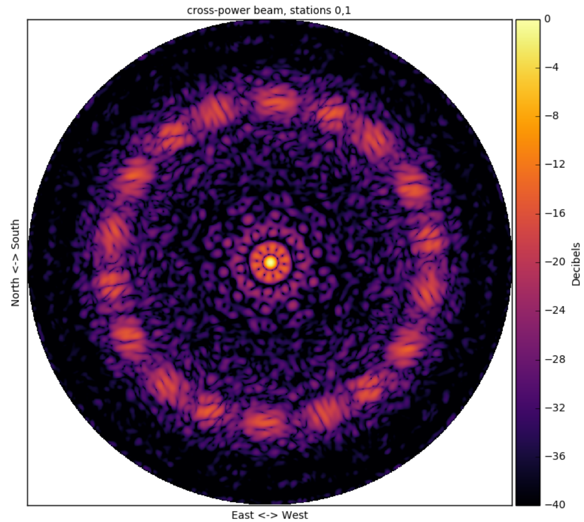
V4A station beams: Randomly rotated sub-station centred hexagonal lattices
Stokes-I cross-power station beams, 350 MHz, zenith pointing

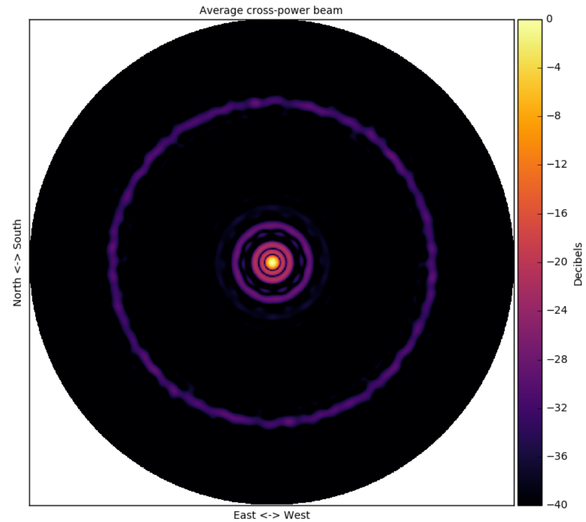
Cross-power beam
Single baseline

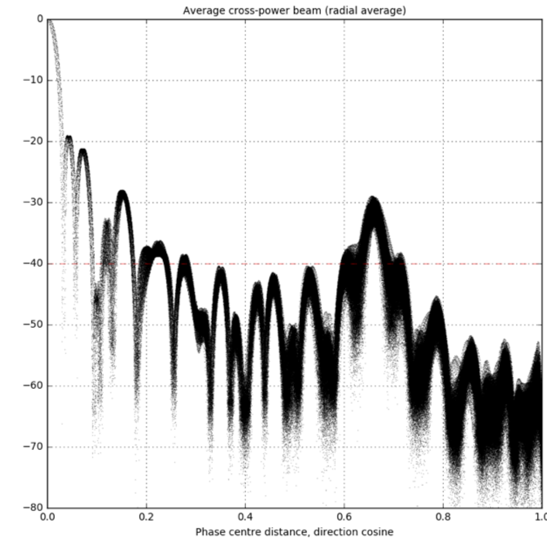
Average cross power beam
all baselines

Average cross power beam
Radial profile

No-apodisation







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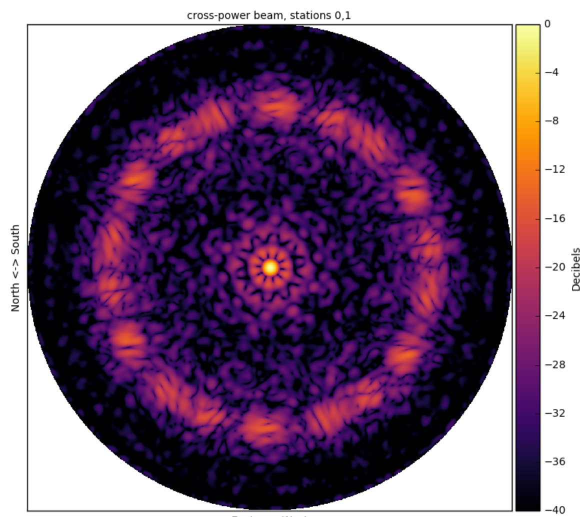
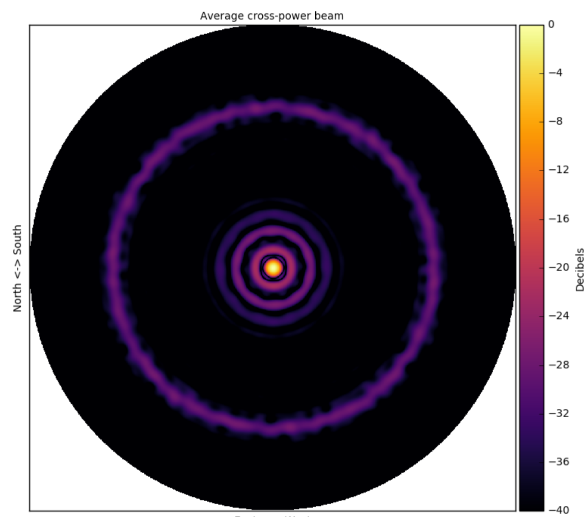
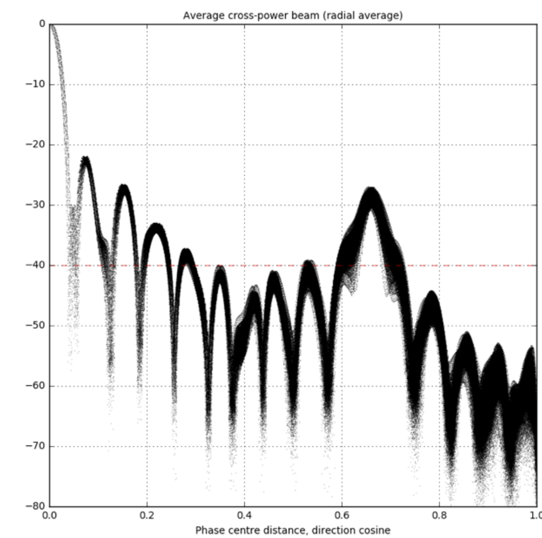
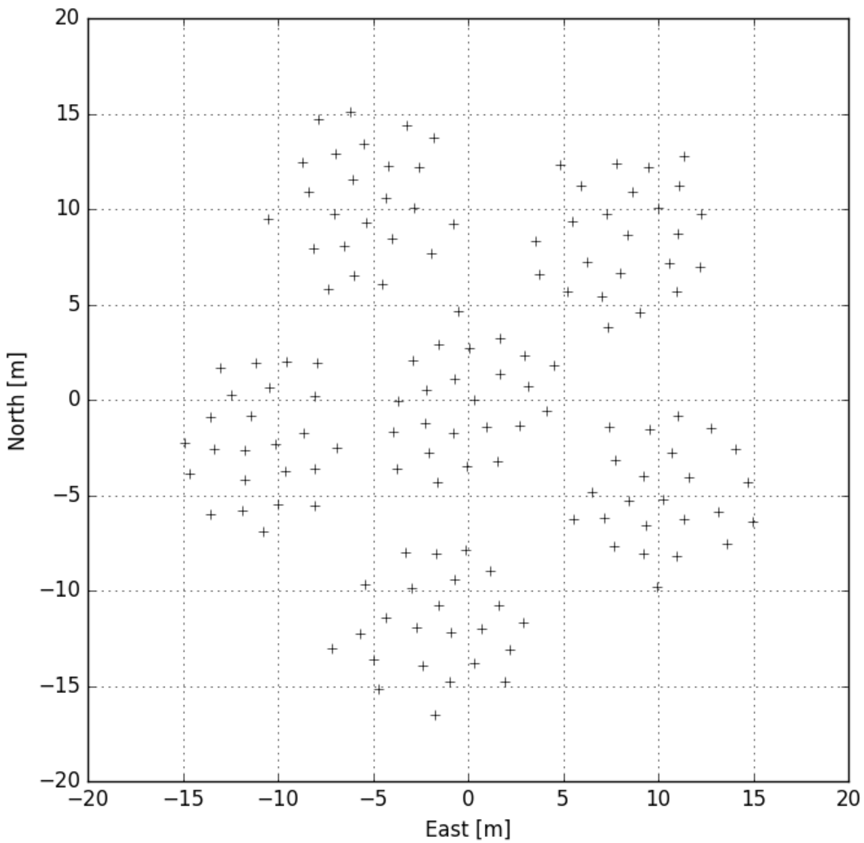




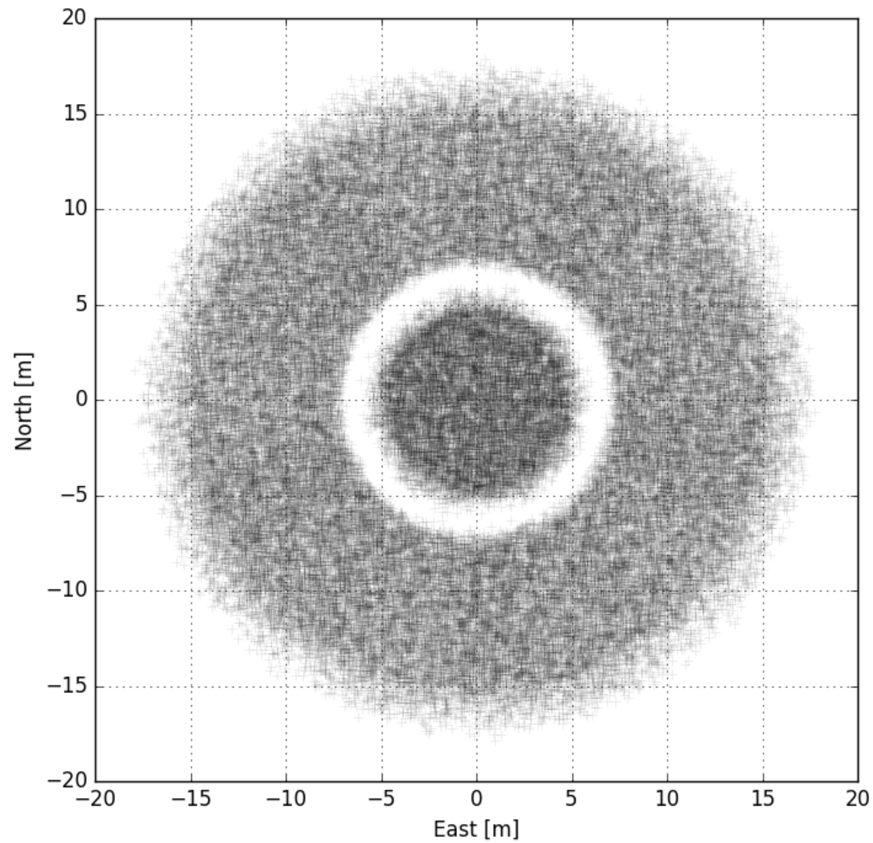


V4A like stations: Randomly generated sub-station antenna positions
Pentagon shaped sub-stations from original V4A layout
Station orientations defined by coordinates in 'v7ska1lowN1v2arev3R.enu.564x4.txt'
24 antennas per sub-station, 144 antennas per station, 564 stations, ~35 m diameter

Single station



Superposition of all stations



V4A station beams: Randomly generated sub-stations
Stokes-I cross-power station beams, 50 MHz, zenith pointing

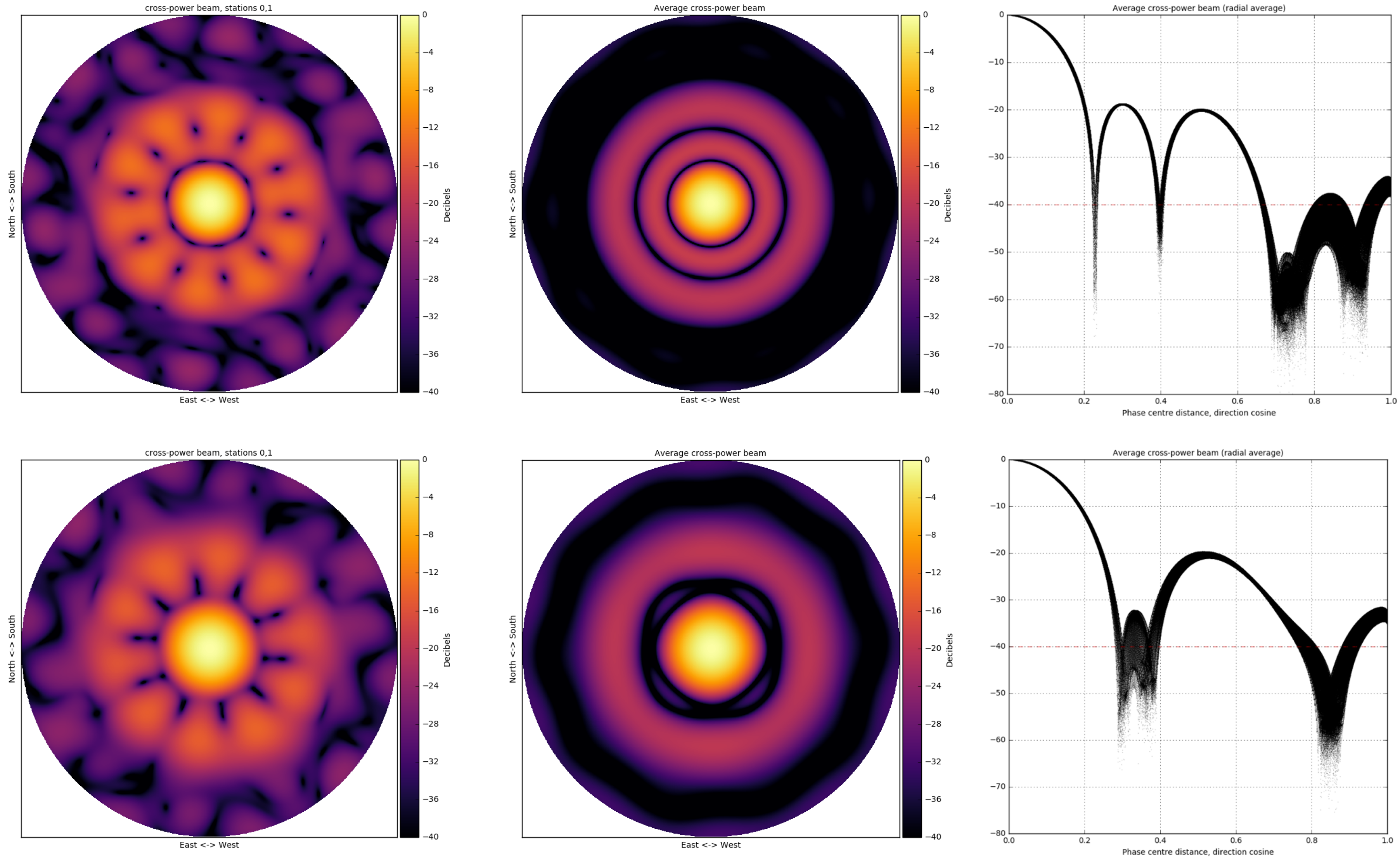
Cross-power beam
Single baseline

Average cross power beam
all baselines

Average cross power beam
Radial profile

No-apodisation

-28 db Taylor weights

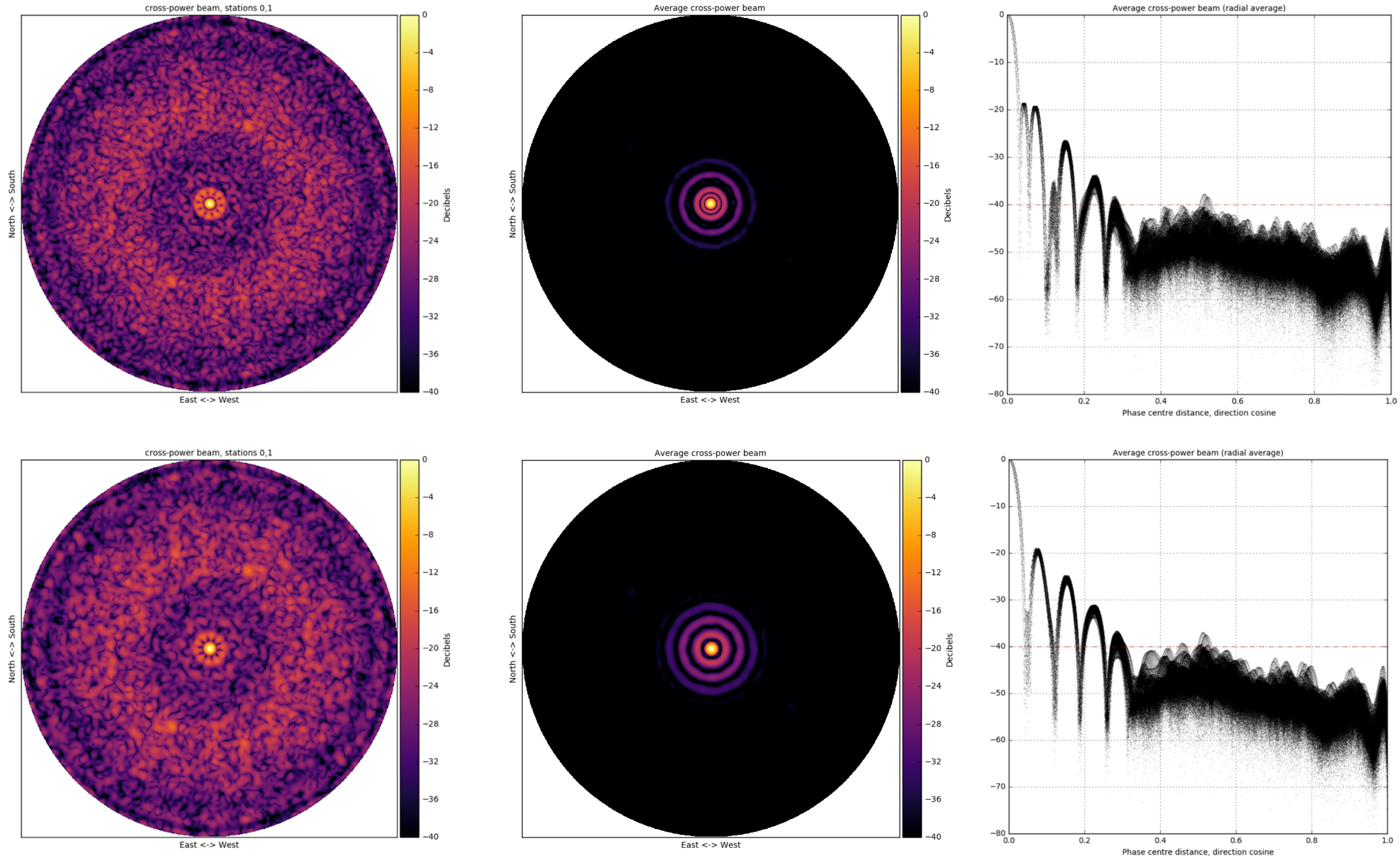


V4A station beams: Randomly generated sub-stations
Stokes-I cross-power station beams, 350 MHz, zenith pointing

Cross-power beam Single baseline | Average cross power beam all baselines | Average cross power beam Radial profile

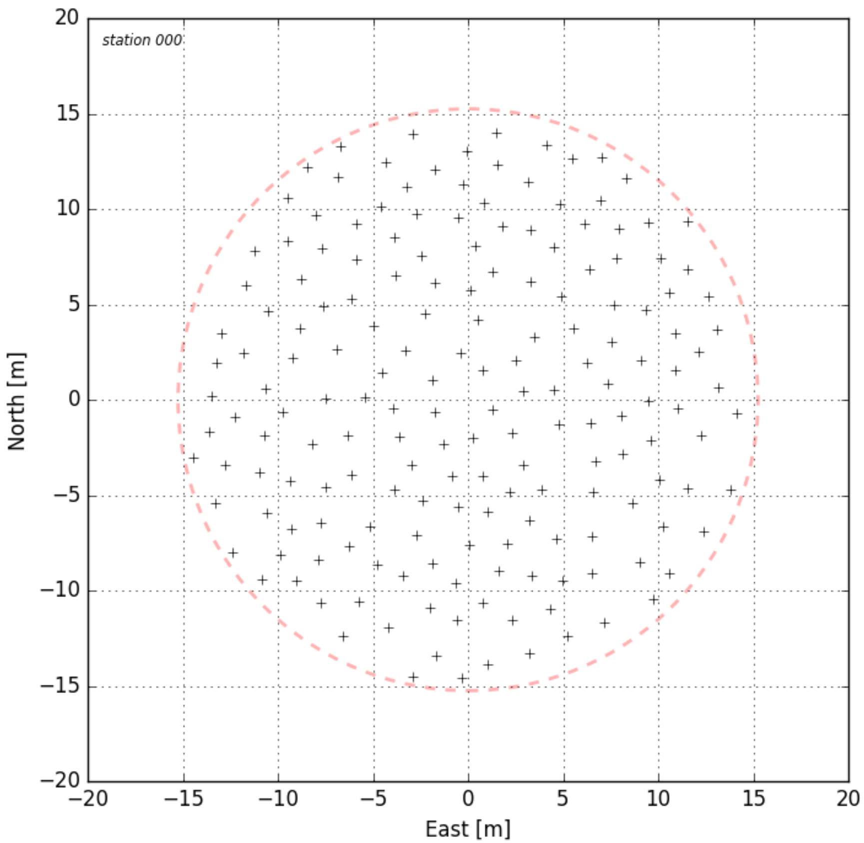
No-apodisation

-28 db Taylor weights

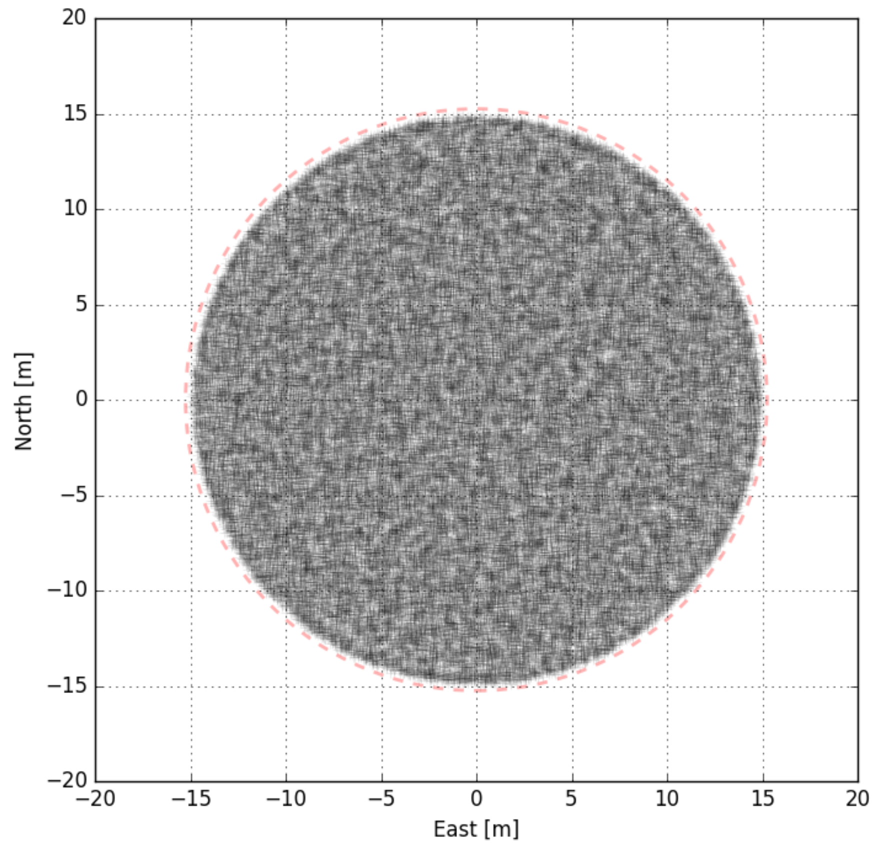


V4D stations: Randomly generated station antenna positions
Randomly generated station orientations
180 antennas per station, 510 stations, 30 m diameter

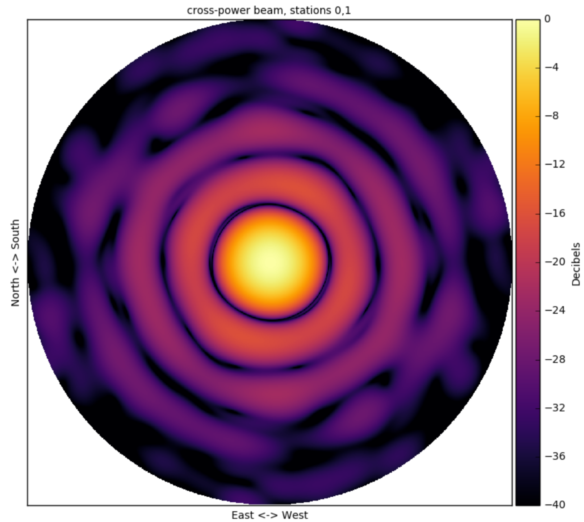
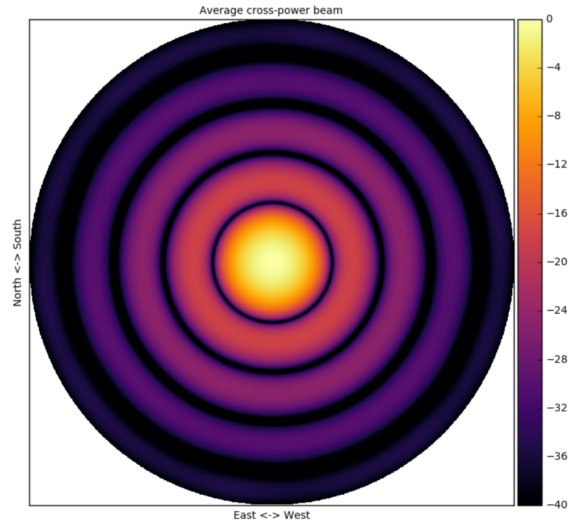
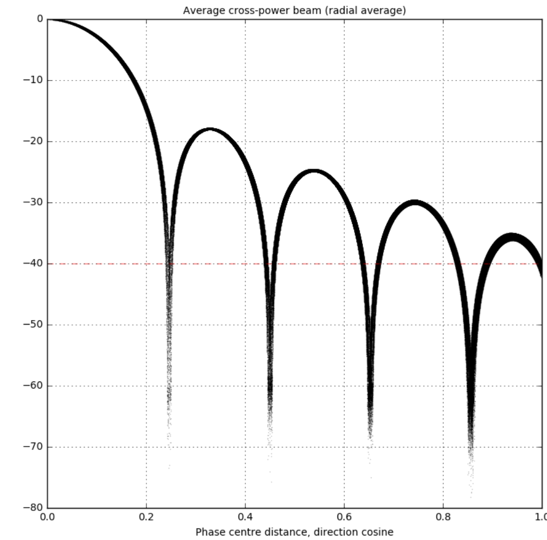
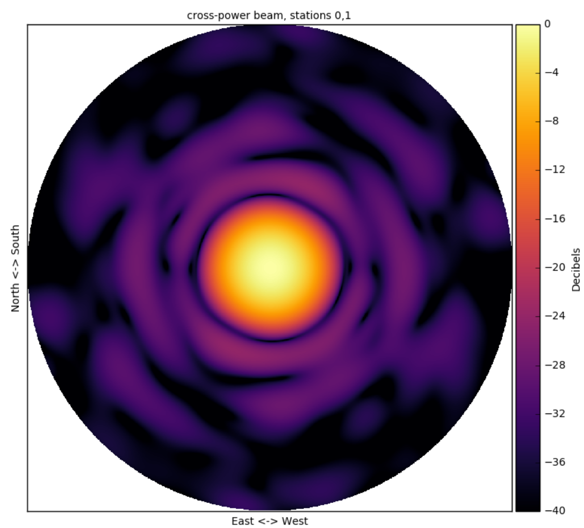
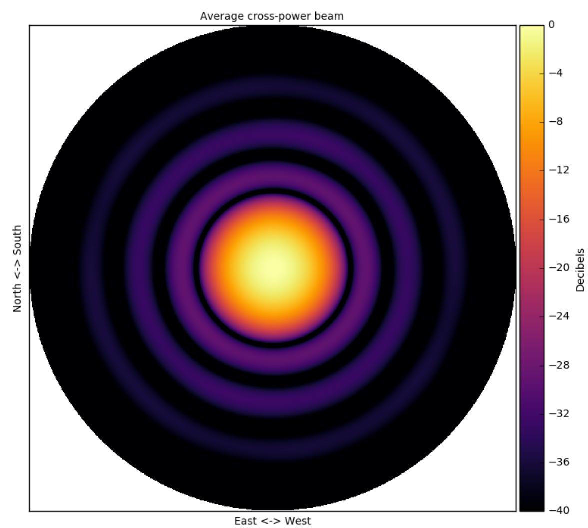
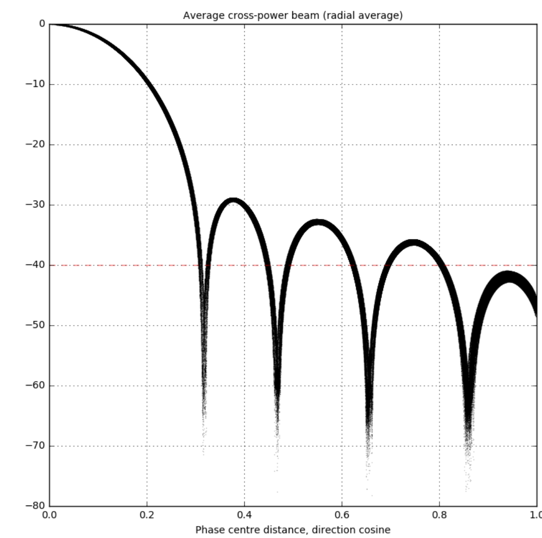
Single station



Superposition of all stations



V4D station beams: Randomly generated station antenna positions
Stokes-I cross-power station beams, 50 MHz, zenith pointing

	Cross-power beam Single baseline	Average cross power beam all baselines	Average cross power beam Radial profile
No-apodisation			
-28 db Taylor weights			

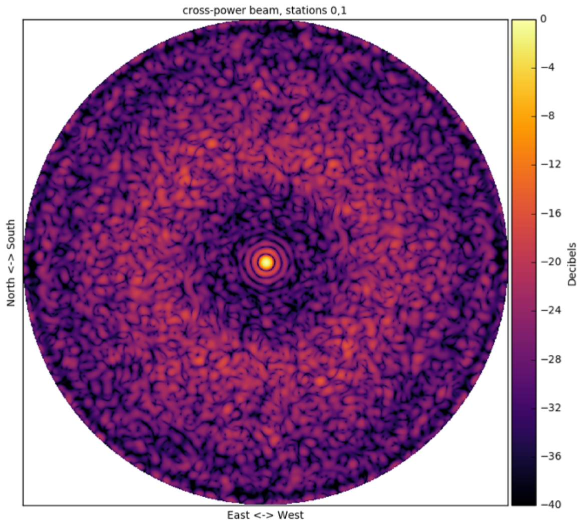
V4D station beams: Randomly generated station antenna positions
Stokes-I cross-power station beams, 350 MHz, zenith pointing

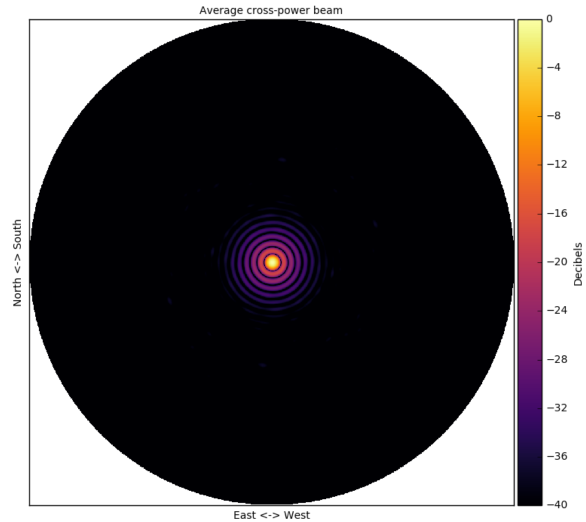
Cross-power beam
Single baseline

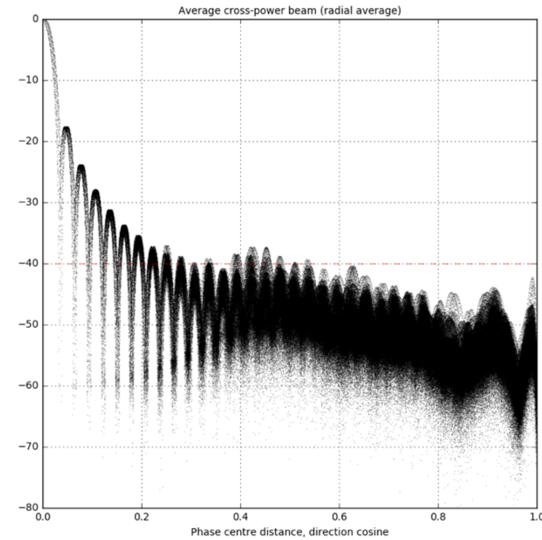
Average cross power beam
all baselines

Average cross power beam
Radial profile

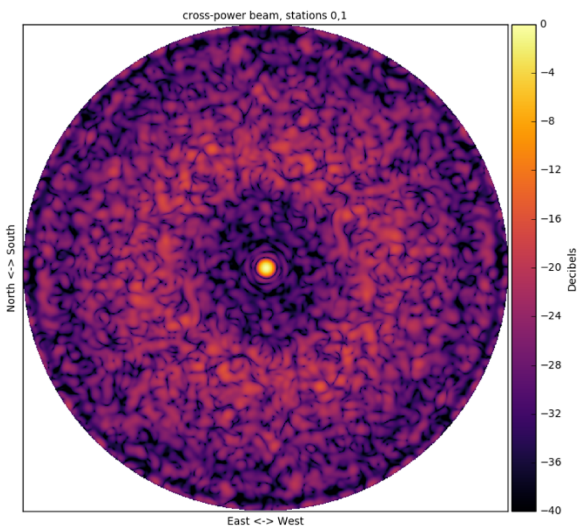
No-apodisation

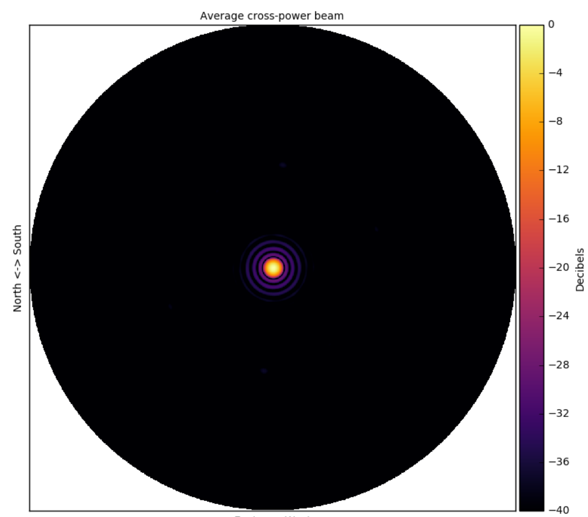


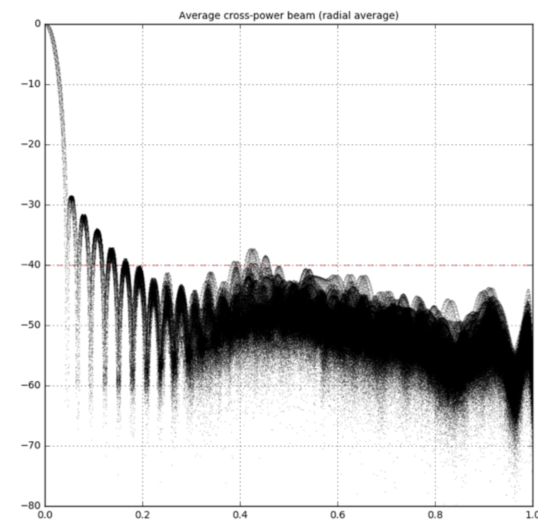




-28 db Taylor weights

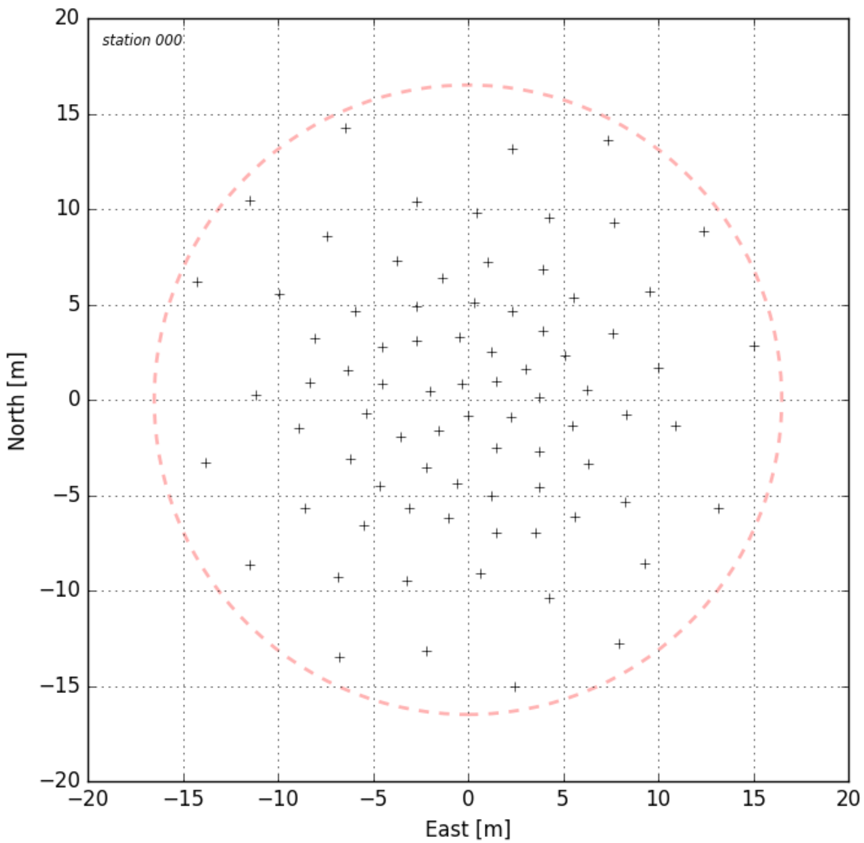




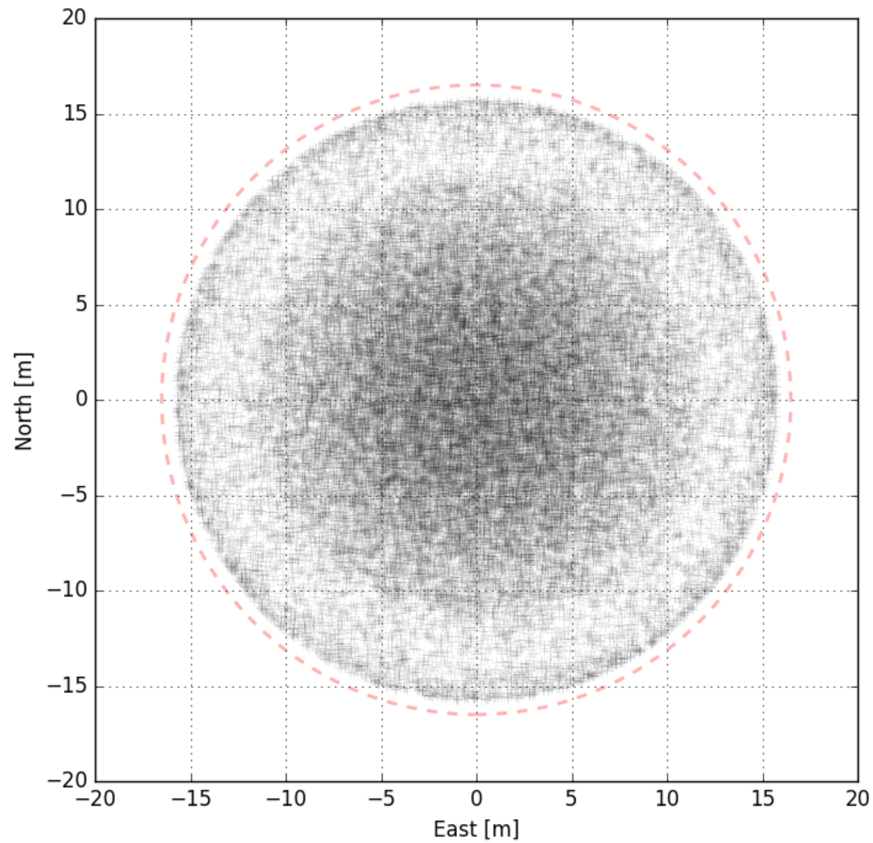


V4D stations: Randomly generated station antenna positions, -28 db Taylor thinning
Randomly generated station orientations
80 antennas per station, 510 stations, 33 m diameter

Single station



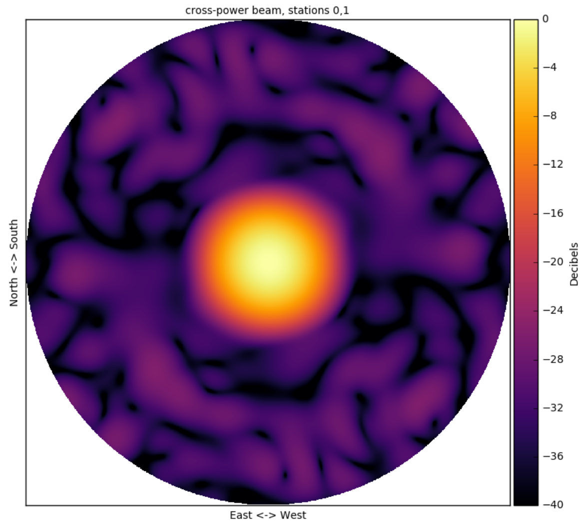
Superposition of all stations



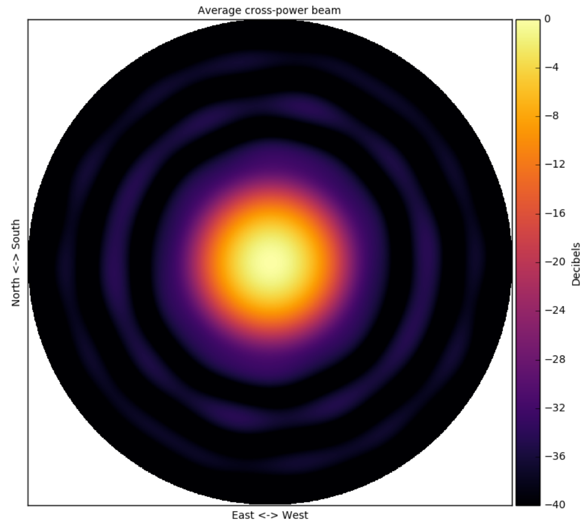
V4D station beams: Randomly generated station antenna positions, -28 db Taylor thinning
Stokes-I cross-power station beams, 50 MHz, zenith pointing

No-apodisation

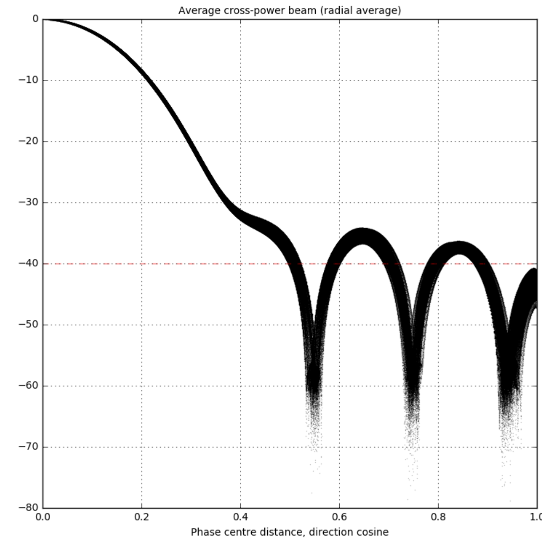
Cross-power beam
Single baseline



Average cross power beam
all baselines



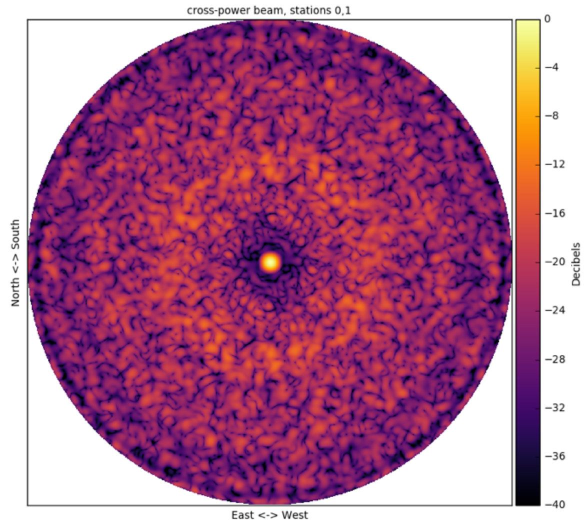
Average cross power beam
Radial profile



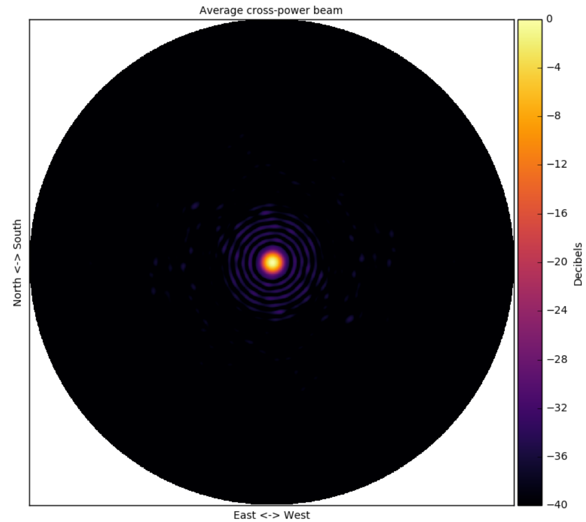
V4D station beams: Randomly generated station antenna positions, -28 db Taylor thinning
Stokes-I cross-power station beams, 350 MHz, zenith pointing

No-apodisation

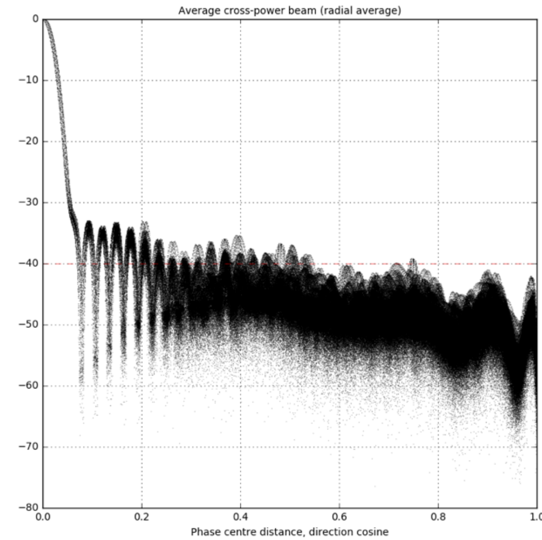
Cross-power beam
Single baseline



Average cross power beam
all baselines

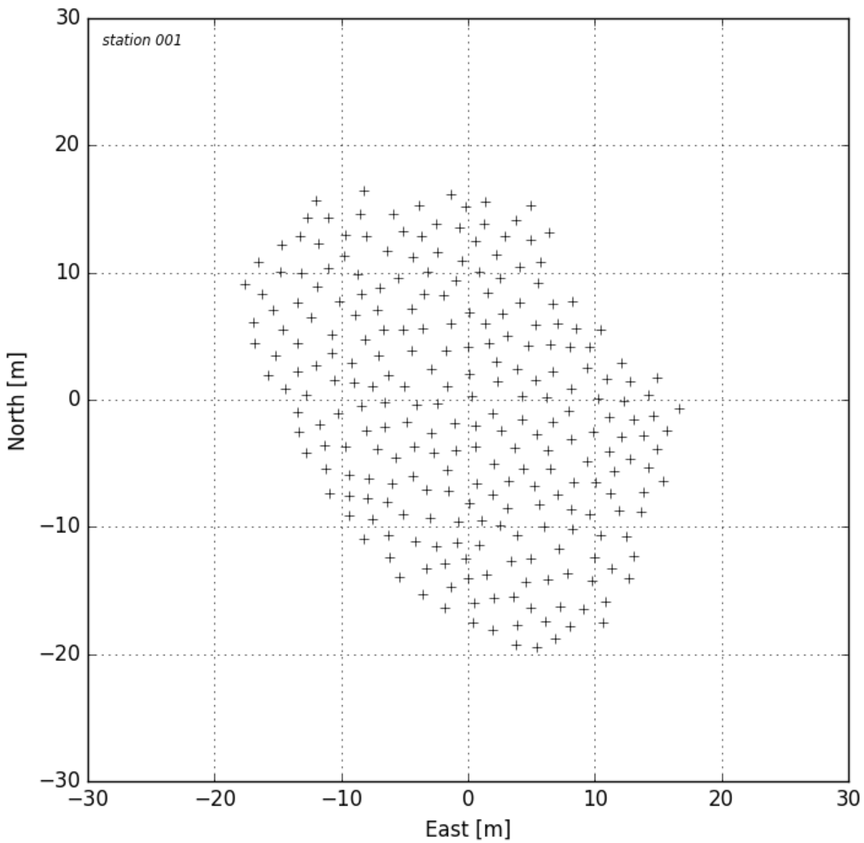


Average cross power beam
Radial profile

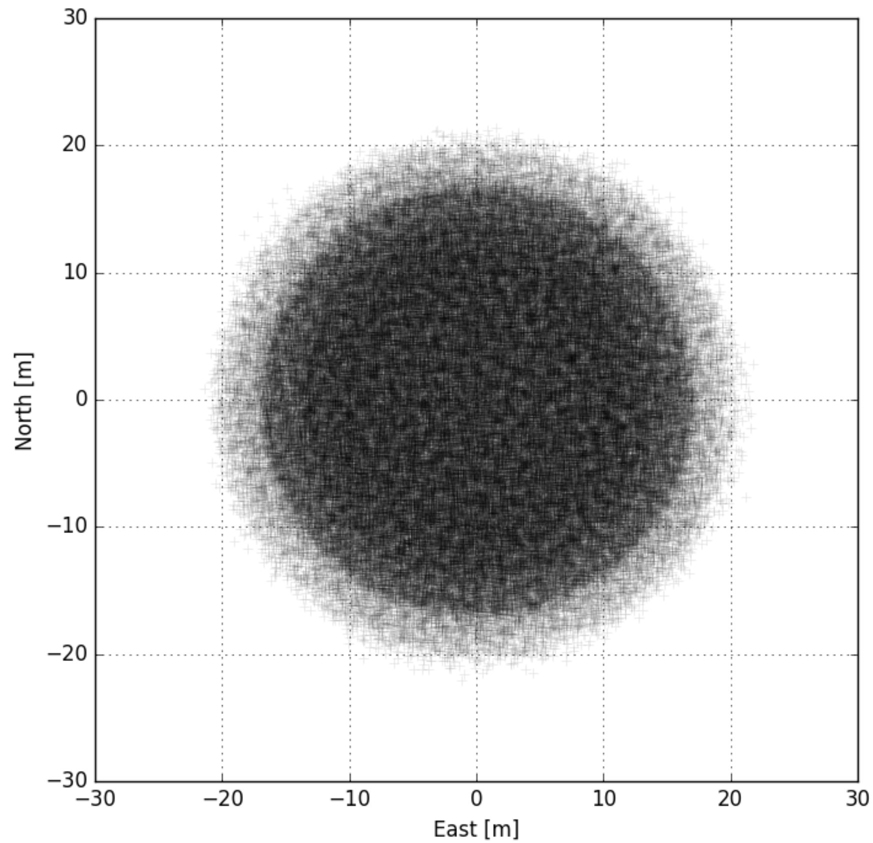


V4X stations: Stations selected from randomly generated super-station 'sea'
Stations selected from super station based on distance from nominal station centres.
Randomly generated station orientations
256 antennas per station, 510 stations, 30-40 m diameter

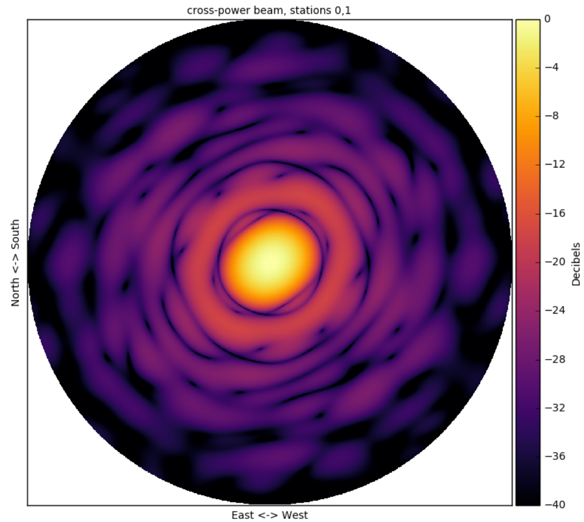
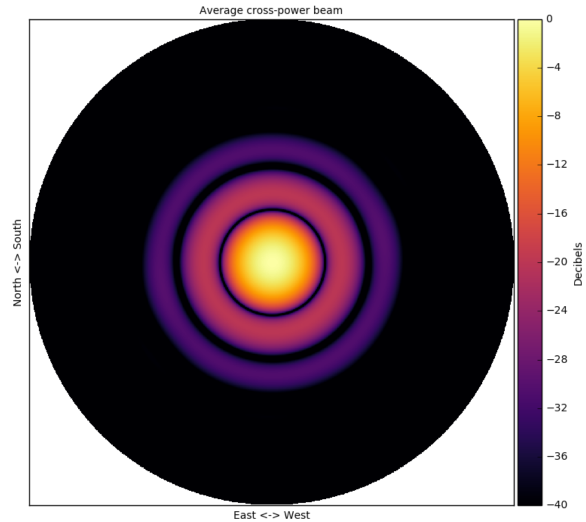
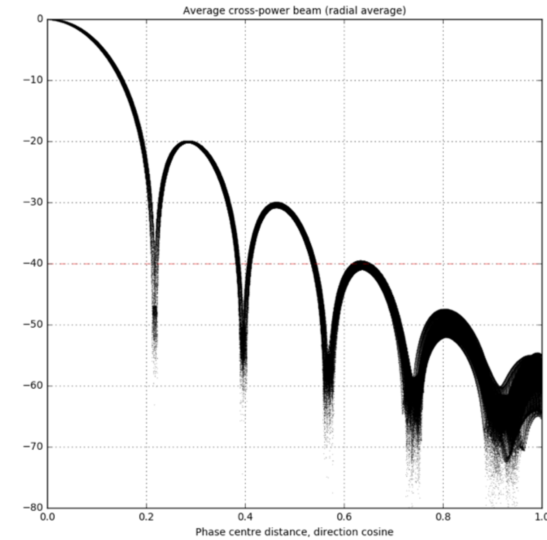
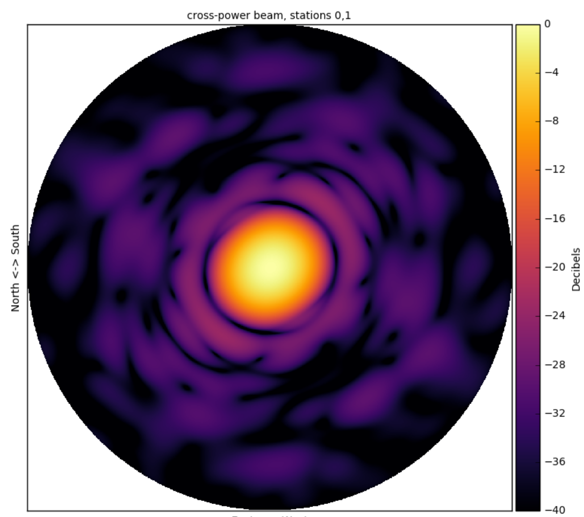
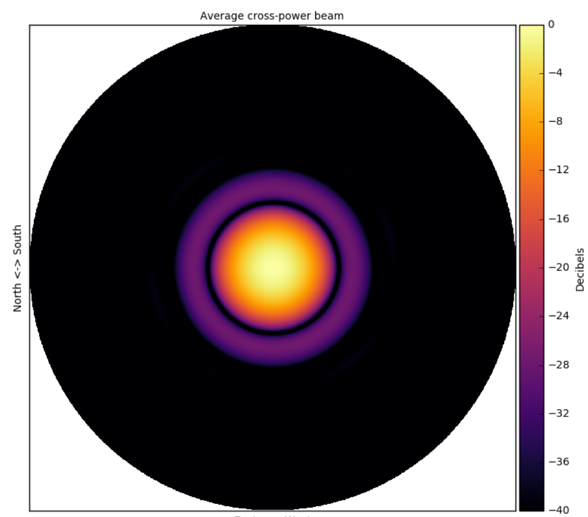
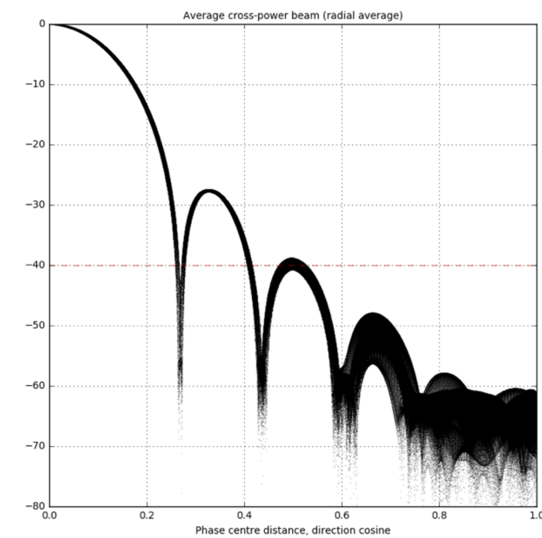
Single station



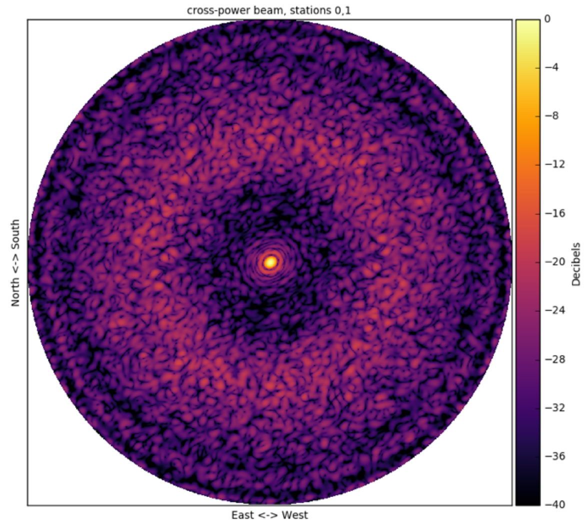
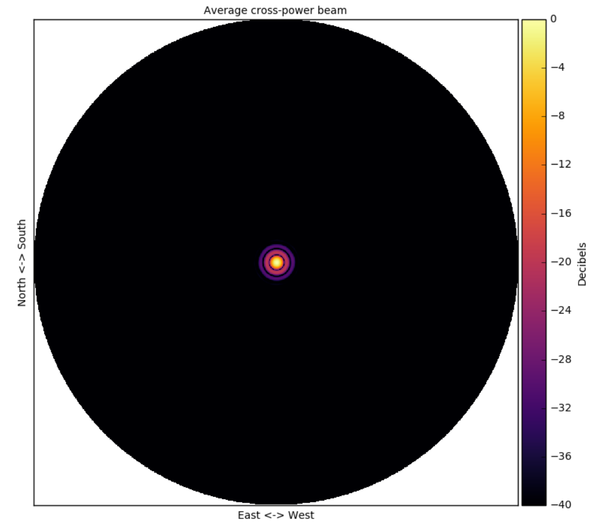
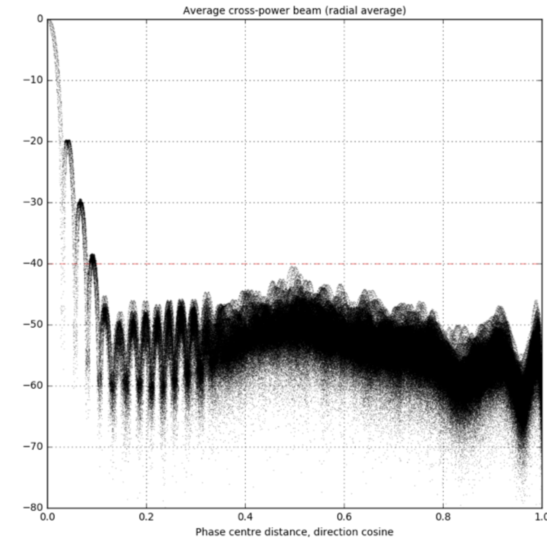
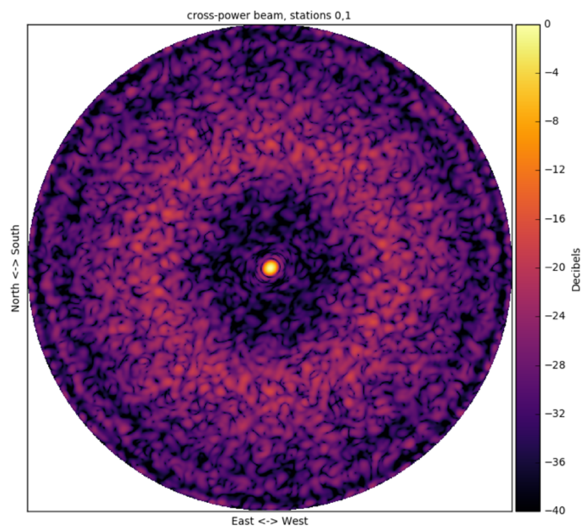
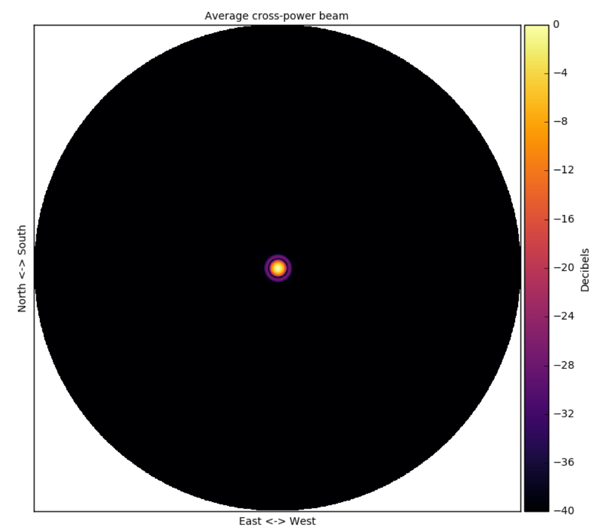
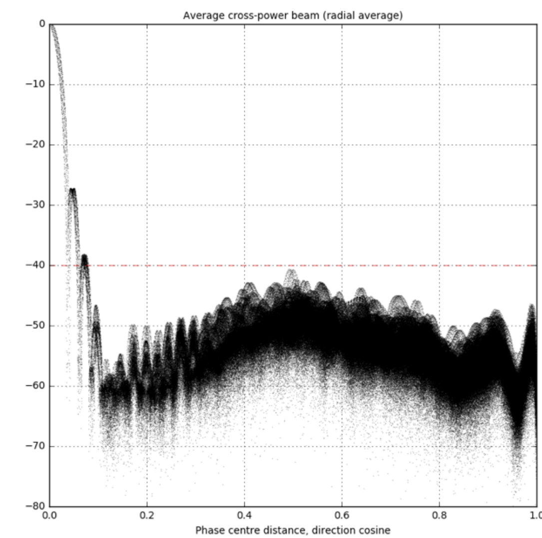
Superposition of all stations



V4X station beams: Stations selected from randomly generated super-station 'sea'
Stokes-I cross-power station beams, 50 MHz, zenith pointing

	Cross-power beam Single baseline	Average cross power beam all baselines	Average cross power beam Radial profile
No-apodisation			
-28 db Taylor weights			

V4X station beams: Stations selected from randomly generated super-station 'sea'
Stokes-I cross-power station beams, 350 MHz, zenith pointing

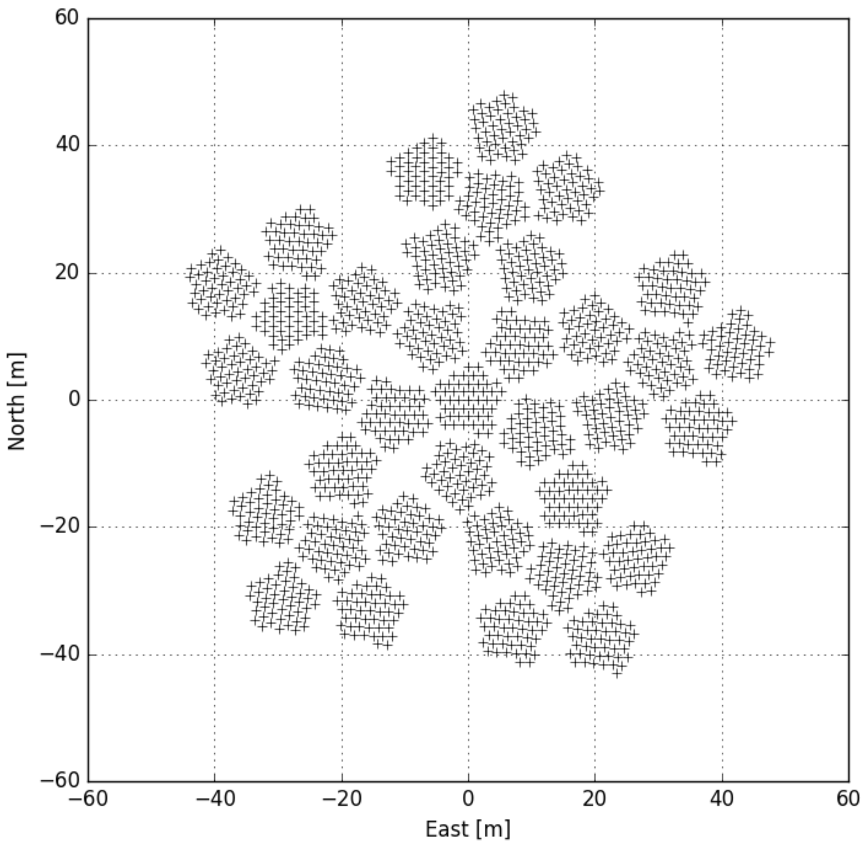
	Cross-power beam Single baseline	Average cross power beam all baselines	Average cross power beam Radial profile
No-apodisation			
-28 db Taylor weights			

Super-station beams

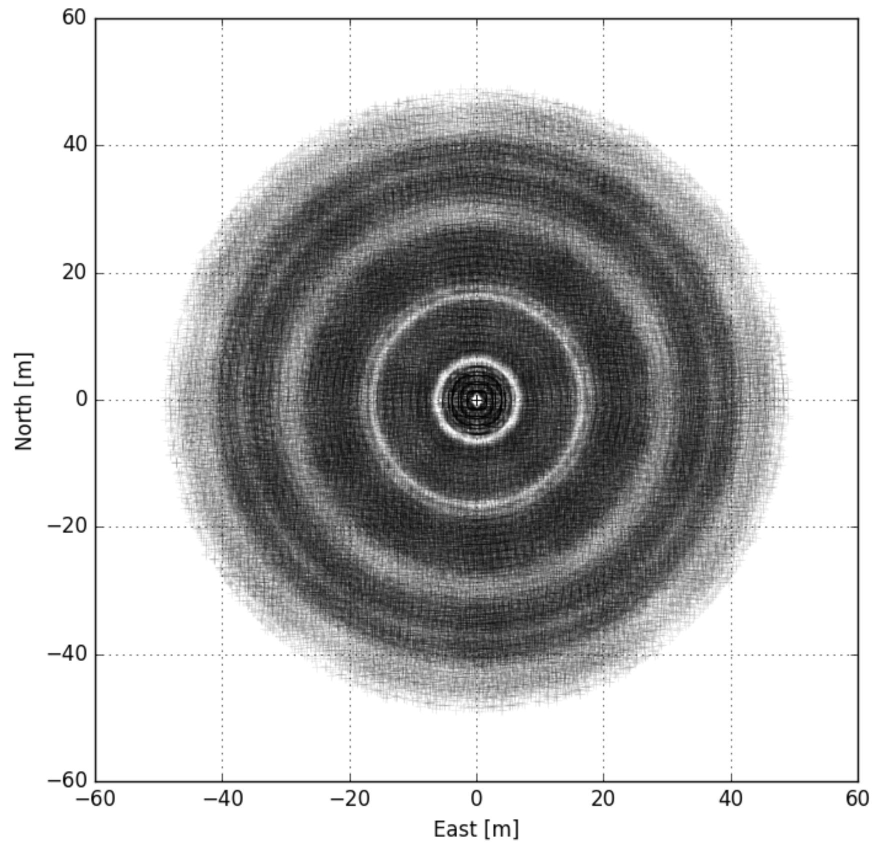
(this section is mainly for reference)

V4A super-stations: Randomly rotated (per sub-station) sub-station centred hexagonal lattice
Pentagon sub-station stencil
Station orientations defined by coordinates in ‘v7ska1lowN1v2arev3R.enu.564x4.txt’
48 antennas per sub-station, 1728 antennas per super-station, 94 super-stations, ~90 m diameter

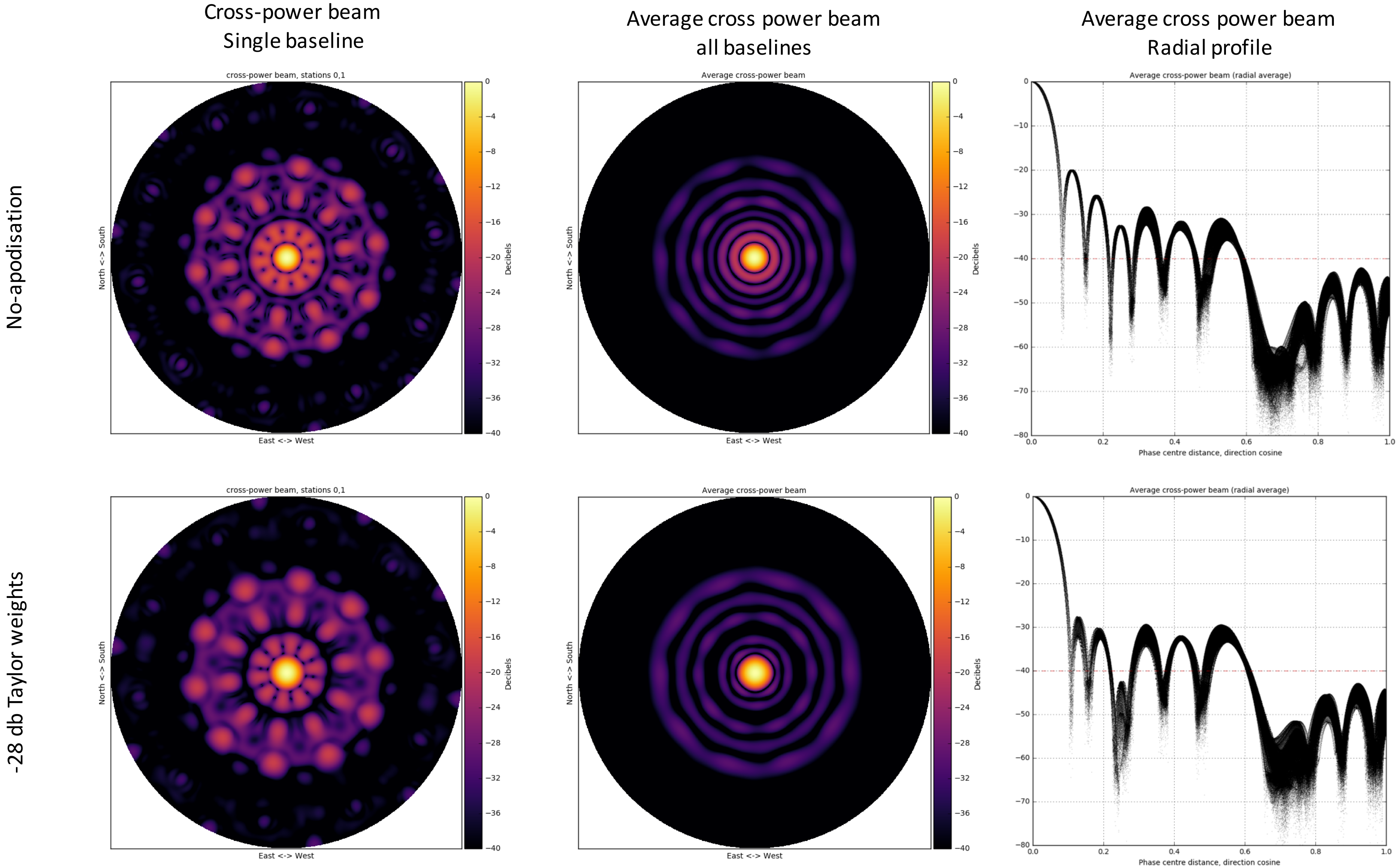
Single super-station



Superposition of all super-stations



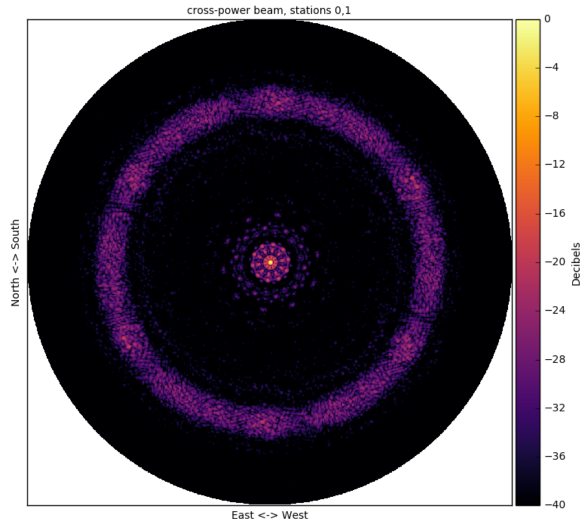
V4A super-station beams: Randomly rotated sub-station centred hexagonal lattices
Stokes-I cross-power station beams, 50 MHz, zenith pointing

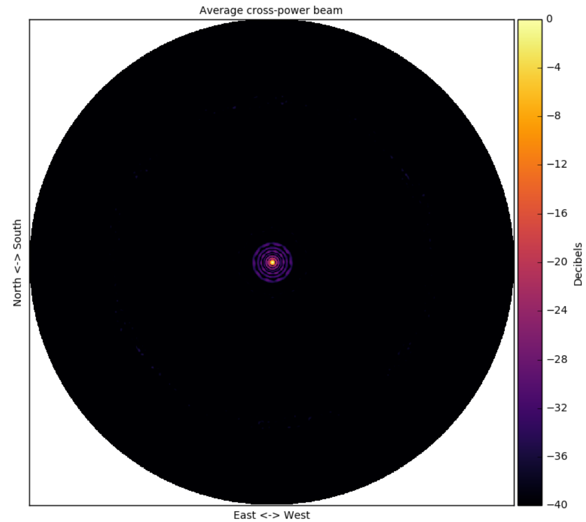


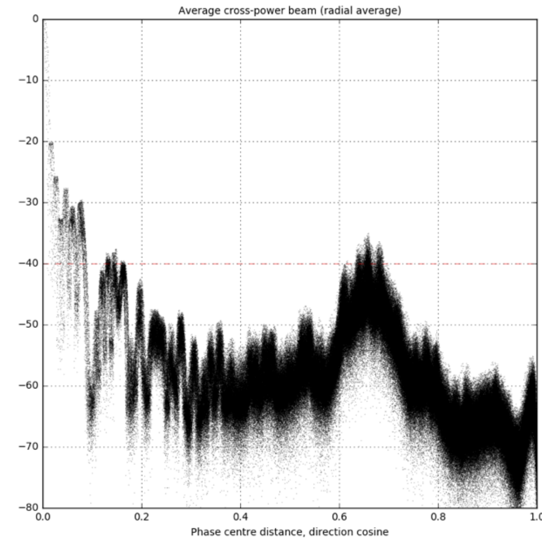
V4A super-station beams: Randomly rotated sub-station centred hexagonal lattices
Stokes-I cross-power station beams, 350 MHz, zenith pointing

	Cross-power beam Single baseline	Average cross power beam all baselines	Average cross power beam Radial profile

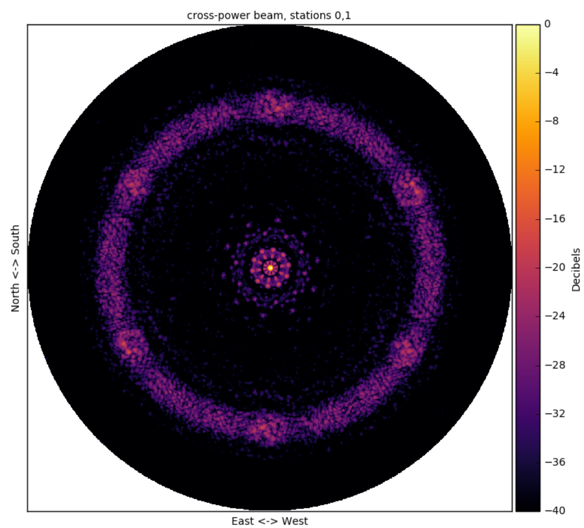
No-apodisation

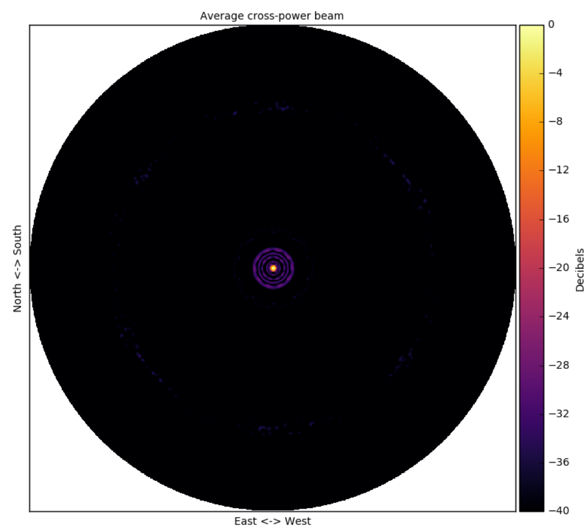


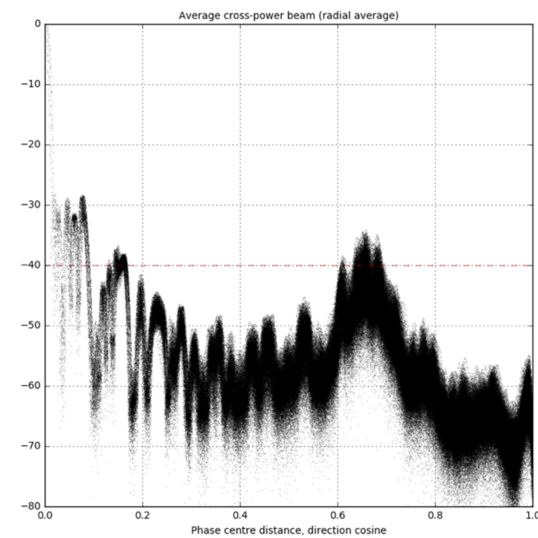




-28 db Taylor weights

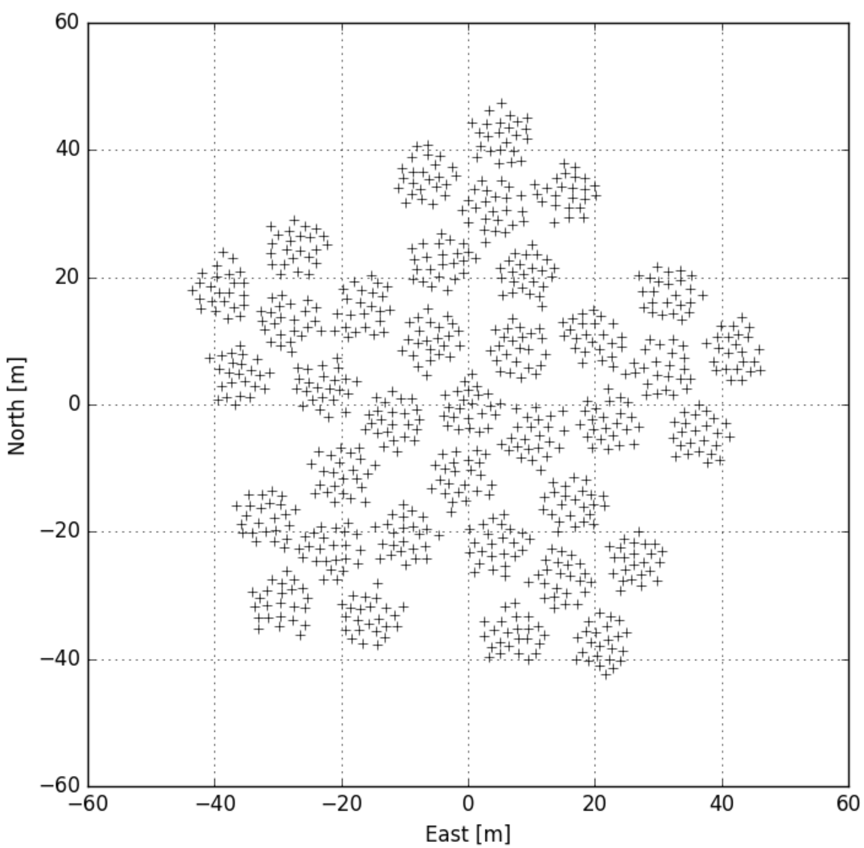




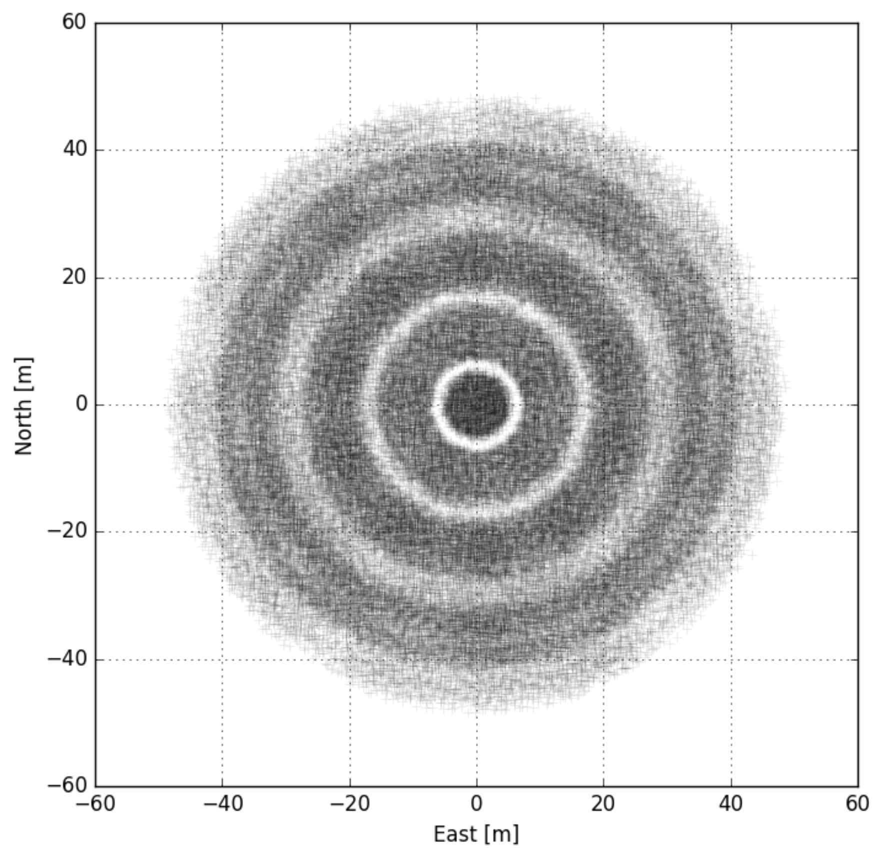


V4A super-stations: Randomly generated sub-station antenna positions
Pentagon sub-station stencil
Station orientations defined by coordinates in ‘v7ska1lowN1v2arev3R.enu.564x4.txt’
24 antennas per sub-station, 868 antennas per super-station, 94 super-stations, ~90 m diameter

Single super-station



Superposition of all super-stations



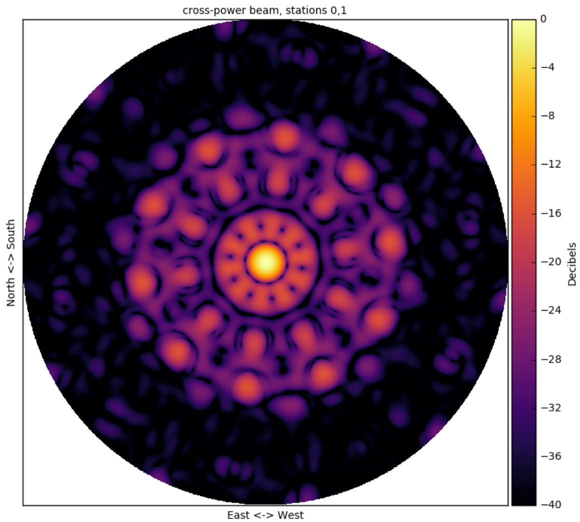
V4A super-station beams: Randomly generated sub-station antenna positions
Stokes-I cross-power station beams, 50 MHz, zenith pointing

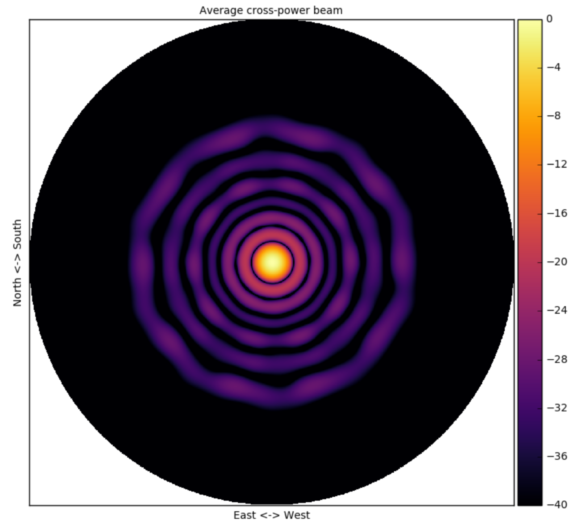
Cross-power beam
Single baseline

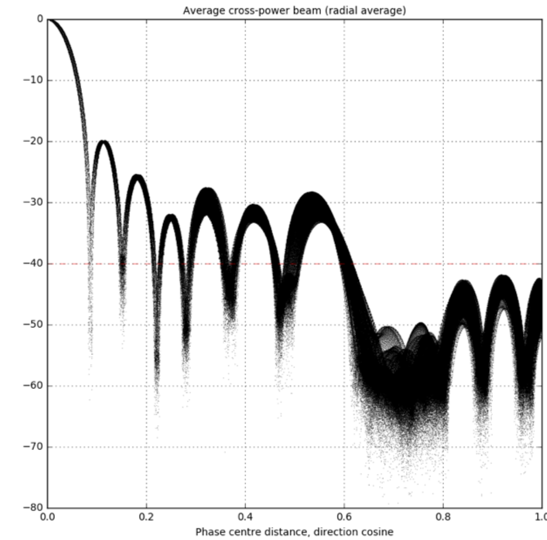
Average cross power beam
all baselines

Average cross power beam
Radial profile

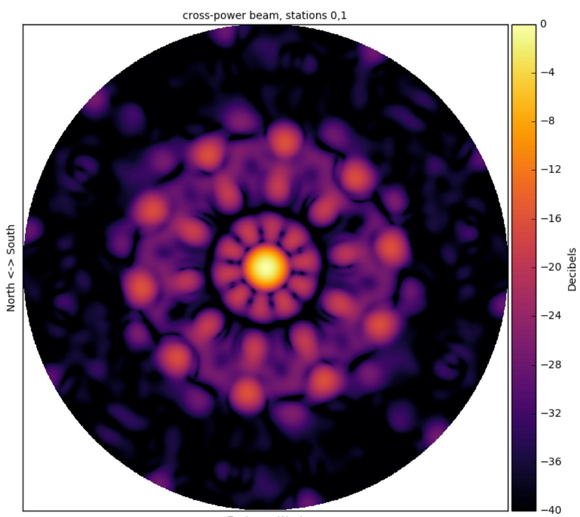
No-apodisation

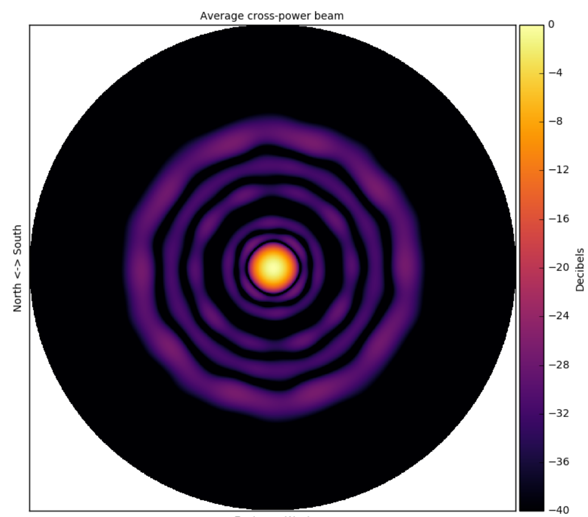


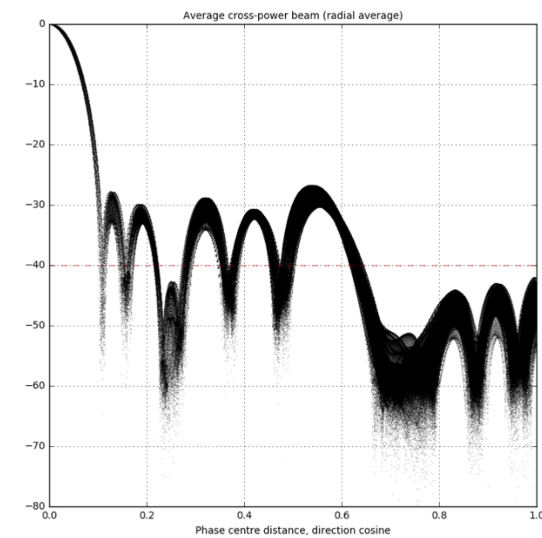




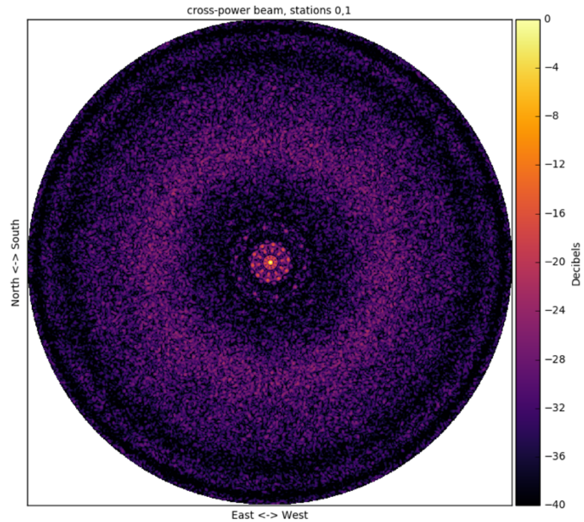
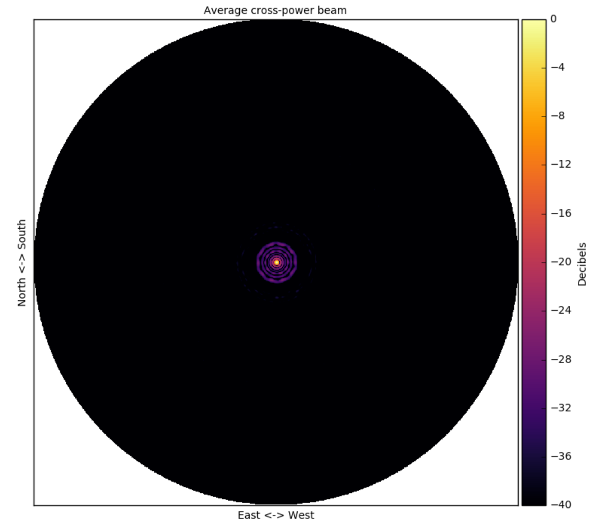
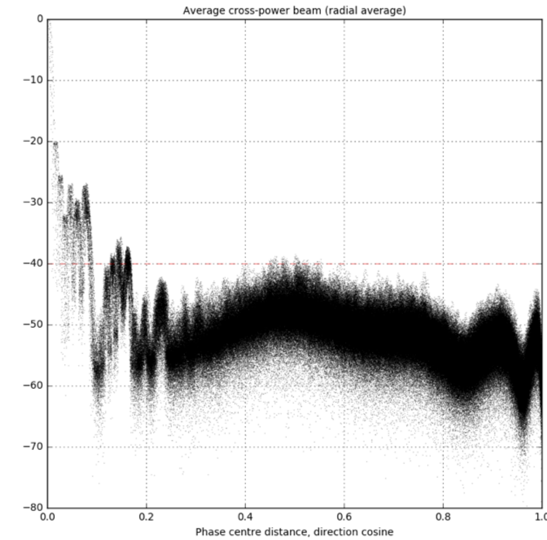
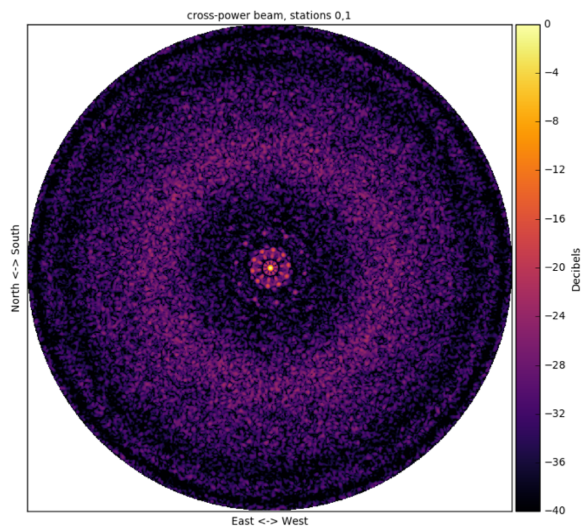
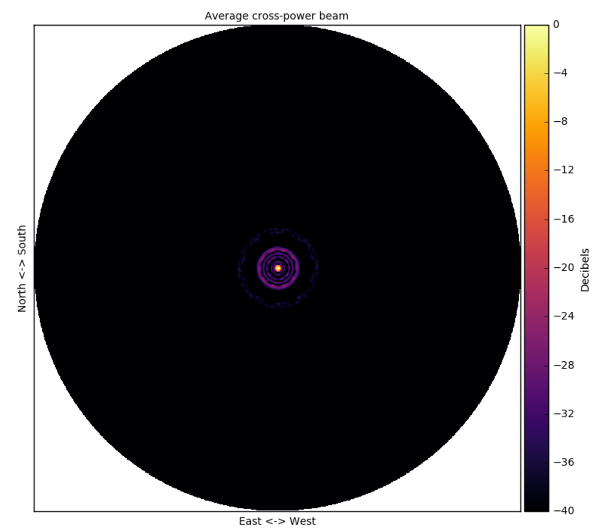
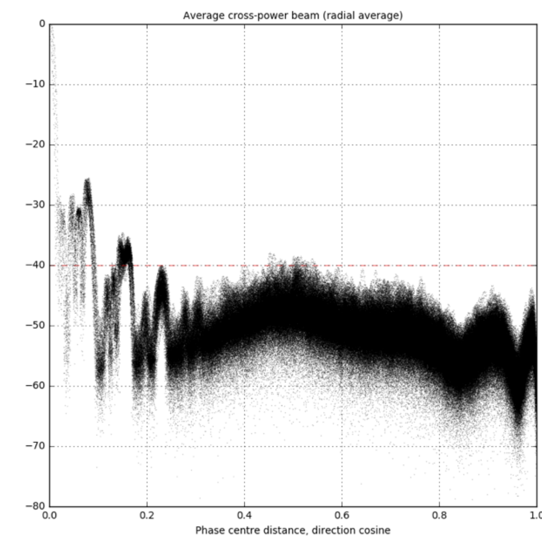
-28 db Taylor weights





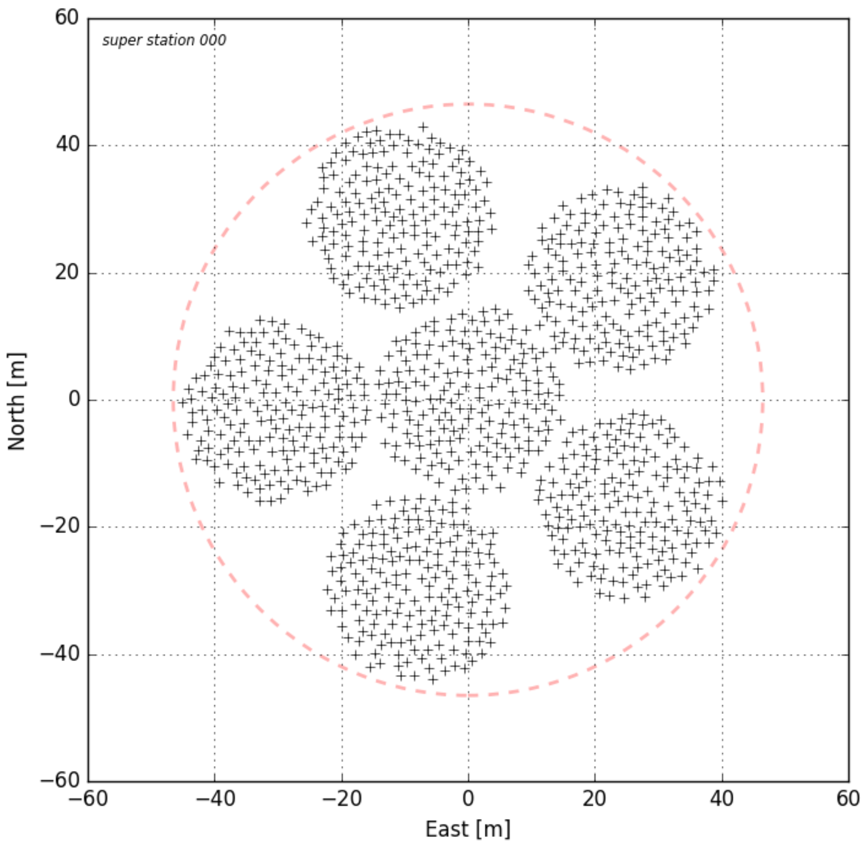


V4A super-station beams: Randomly generated sub-station antenna positions
Stokes-I cross-power station beams, 350 MHz, zenith pointing

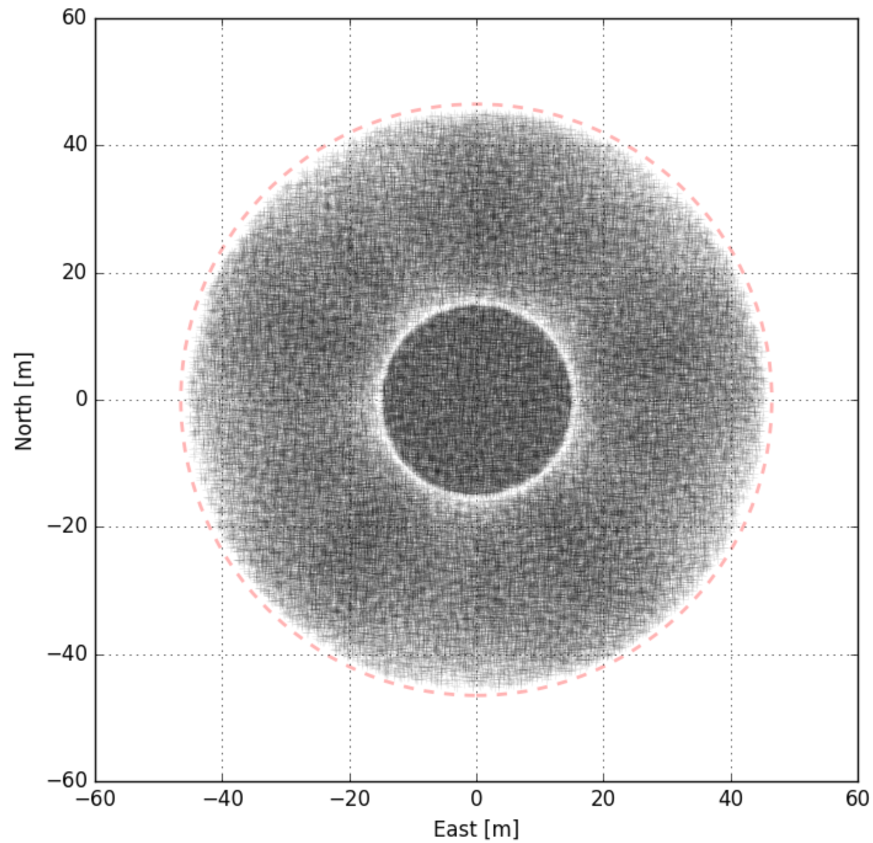
	Cross-power beam Single baseline	Average cross power beam all baselines	Average cross power beam Radial profile
No-apodisation			
-28 db Taylor weights			

V4D super-stations: Randomly generated station antenna positions
Randomly generated station orientations
180 antennas per station, 1080 antennas per super-station, 85 super-stations, ~90 m diameter

Single super-station



Superposition of all super-stations



V4D super-station beams: Randomly generated station antenna positions
Stokes-I cross-power station beams, 50 MHz, zenith pointing

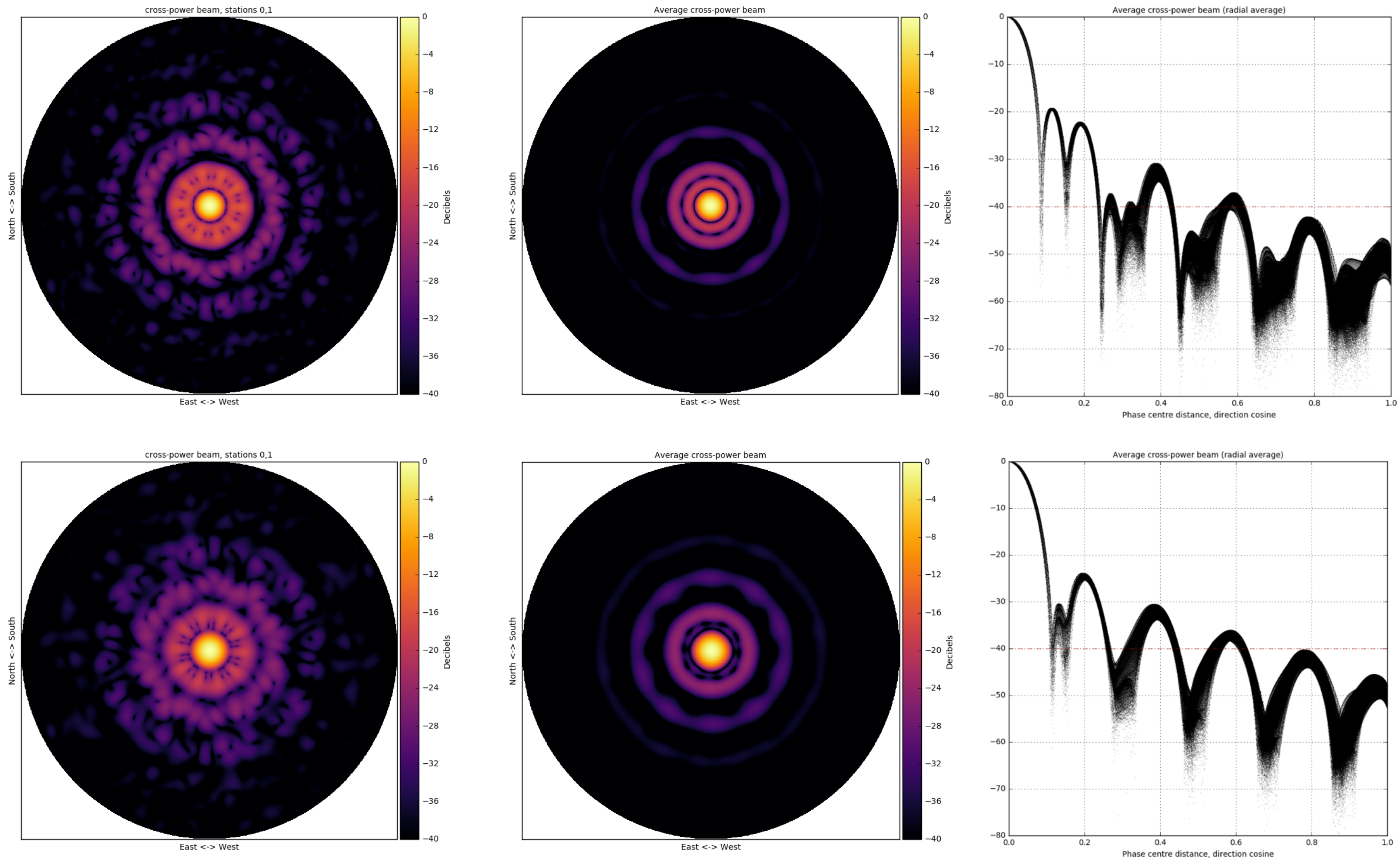
Cross-power beam
Single baseline

Average cross power beam
all baselines

Average cross power beam
Radial profile

No-apodisation

-28 db Taylor weights



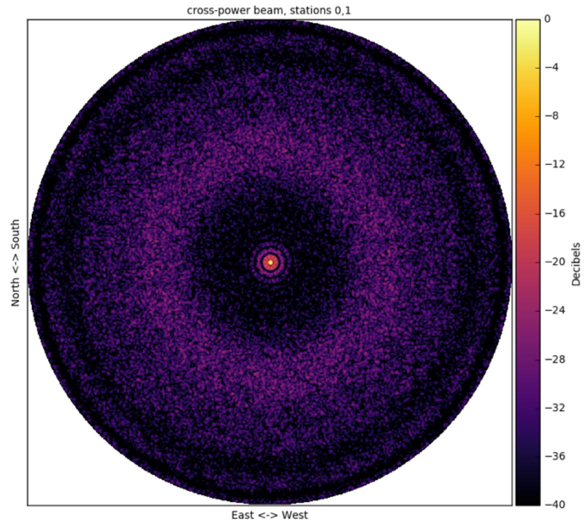
V4D super-station beams: Randomly generated station antenna positions
Stokes-I cross-power station beams, 350 MHz, zenith pointing

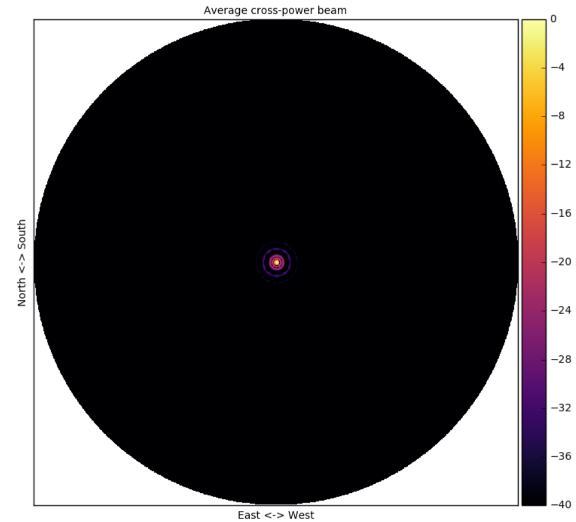
Cross-power beam
Single baseline

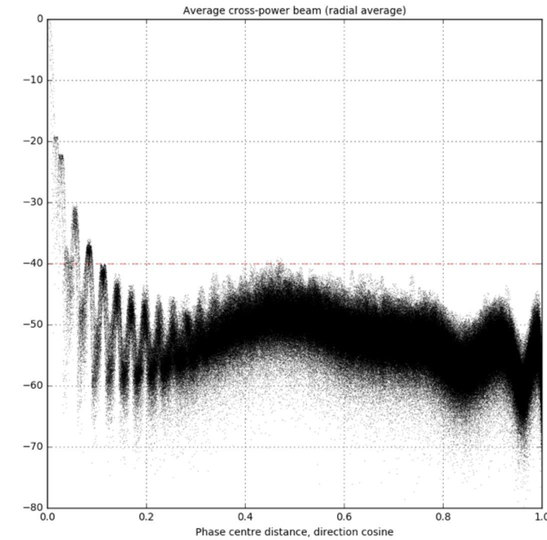
Average cross power beam
all baselines

Average cross power beam
Radial profile

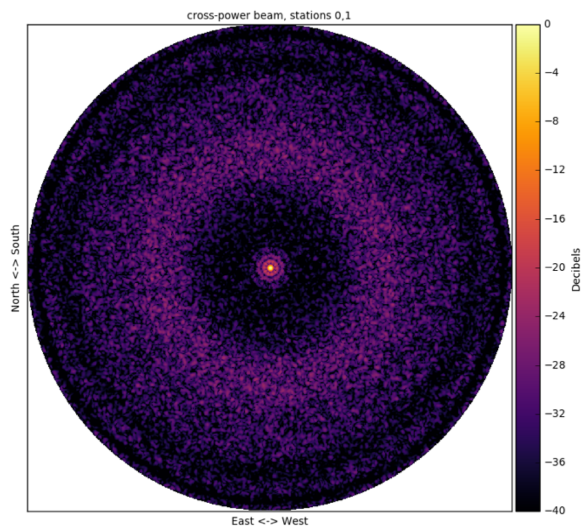
No-apodisation

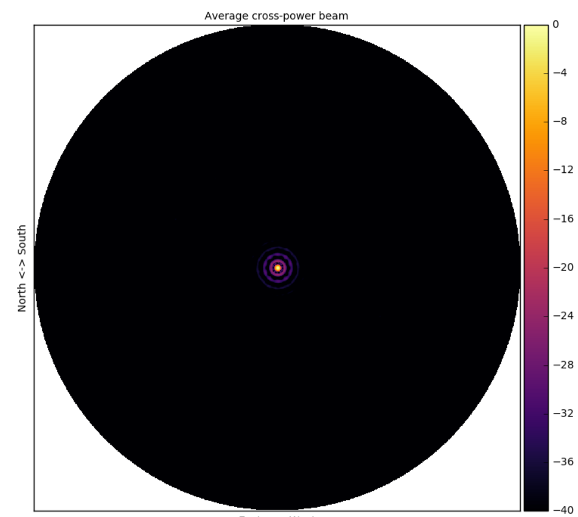


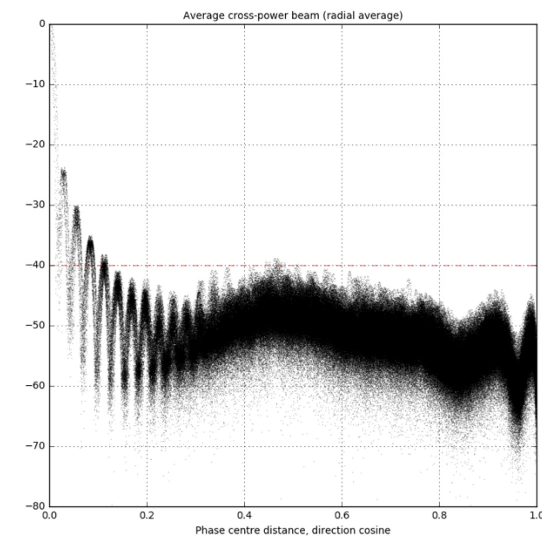




-28 db Taylor weights

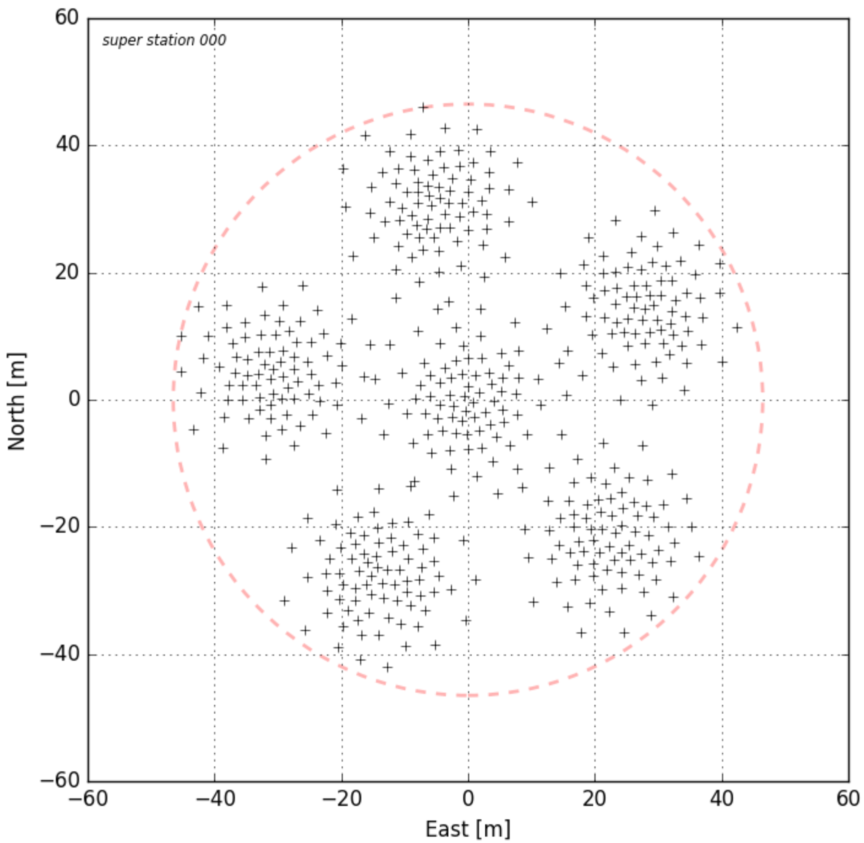




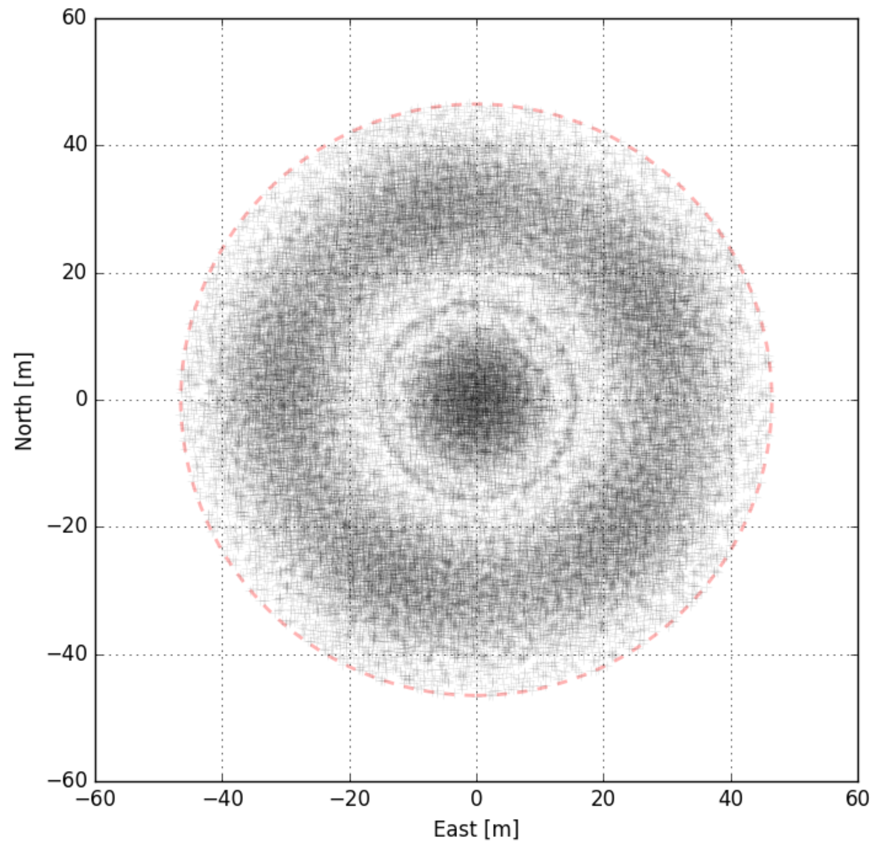


V4D super-stations: Randomly generated station antenna positions, -28 db Taylor thinning
Randomly generated station orientations
80 antennas per station, 480 antennas per super-station, 85 super-stations, ~90 m diameter

Single super-station



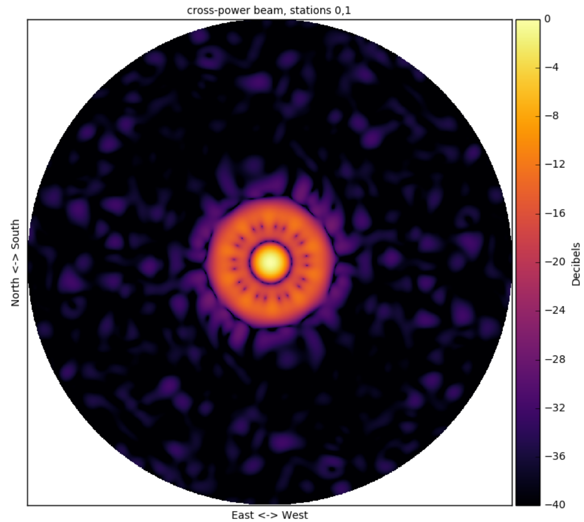
Superposition of all super-stations



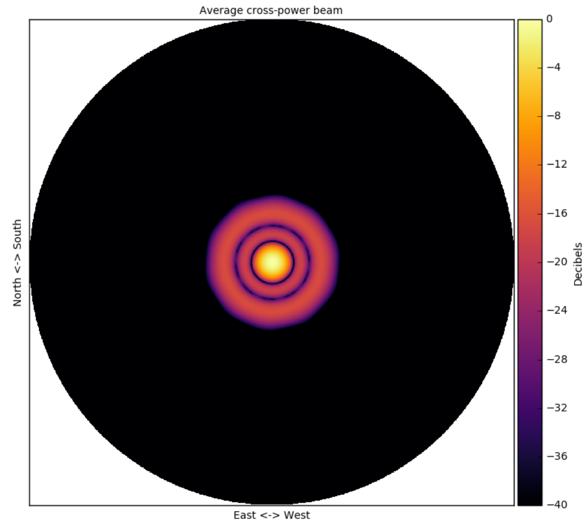
V4D super-station beams: Randomly generated station antenna positions, -28 db Taylor thinning
Stokes-I cross-power station beams, 50 MHz, zenith pointing

No-apodisation

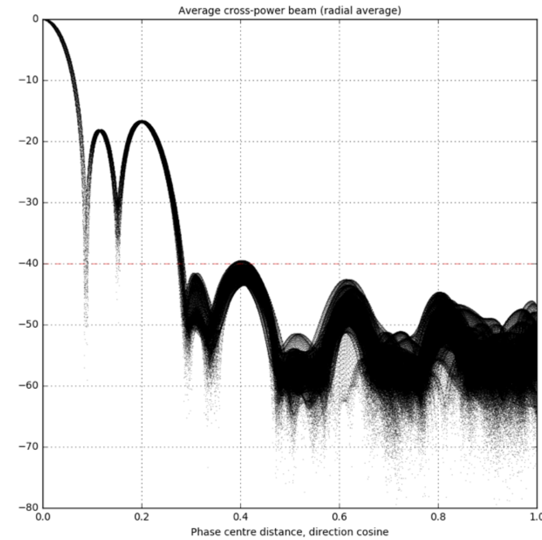
Cross-power beam
Single baseline



Average cross power beam
all baselines



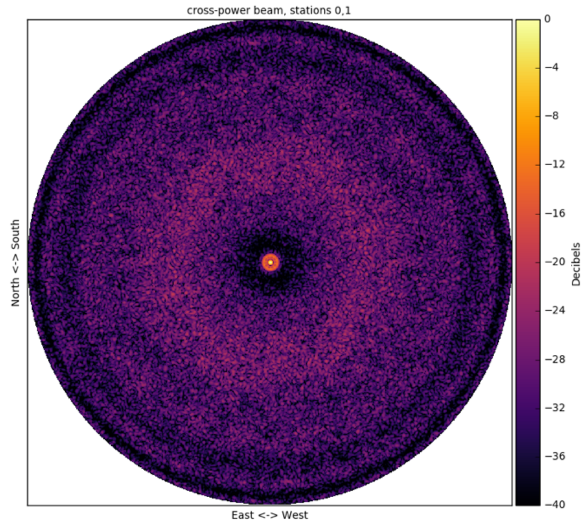
Average cross power beam
Radial profile



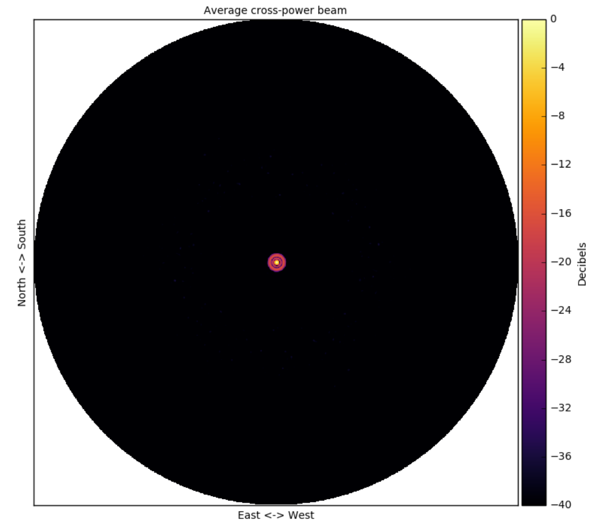
V4D super-station beams: Randomly generated station antenna positions, -28 db Taylor thinning Stokes-I cross-power station beams, 350 MHz, zenith pointing

No-apodisation

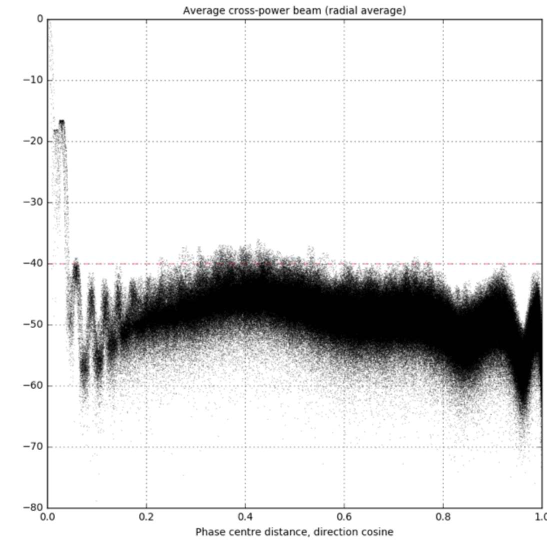
Cross-power beam
Single baseline



Average cross power beam
all baselines

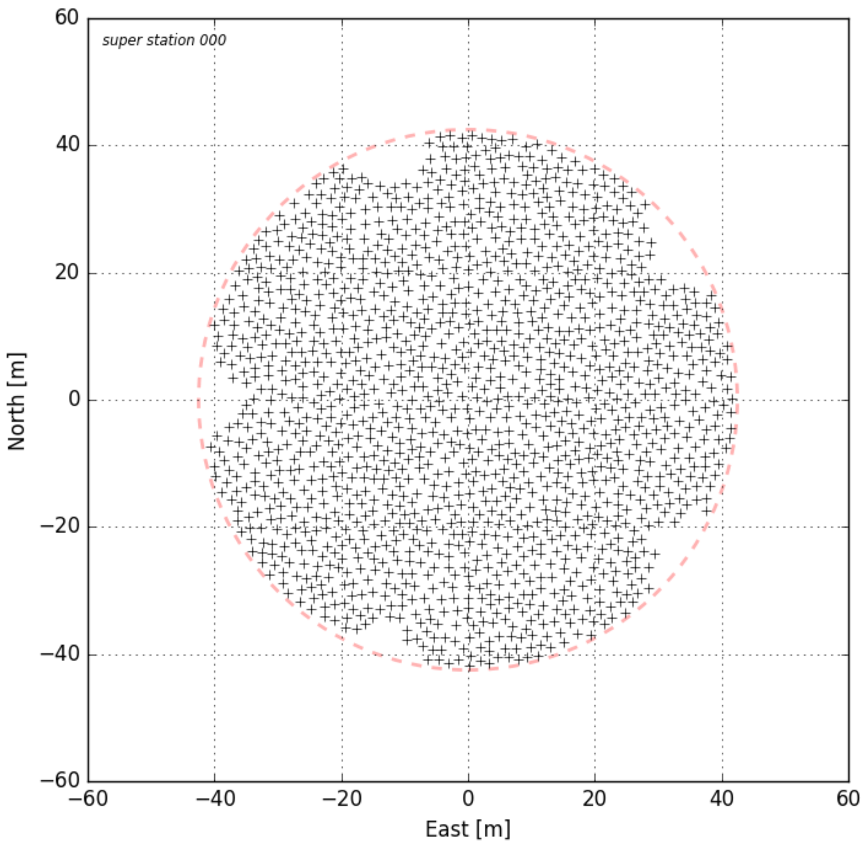


Average cross power beam
Radial profile

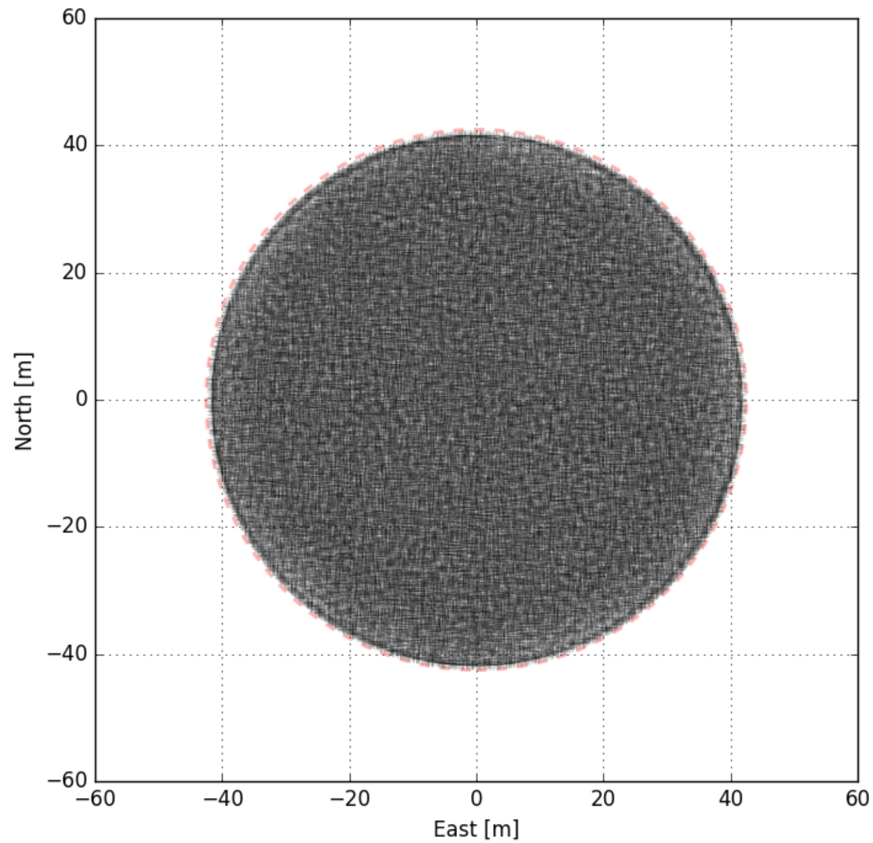


V4X super-stations: Super-station 'sea'
1536 antennas per super-station, 85 super-stations, ~85m diameter

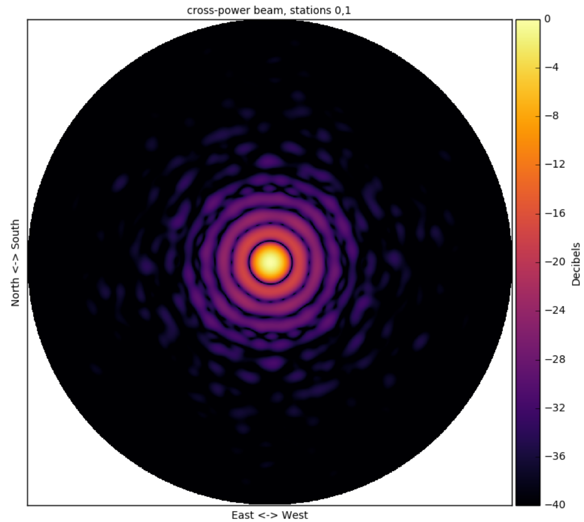
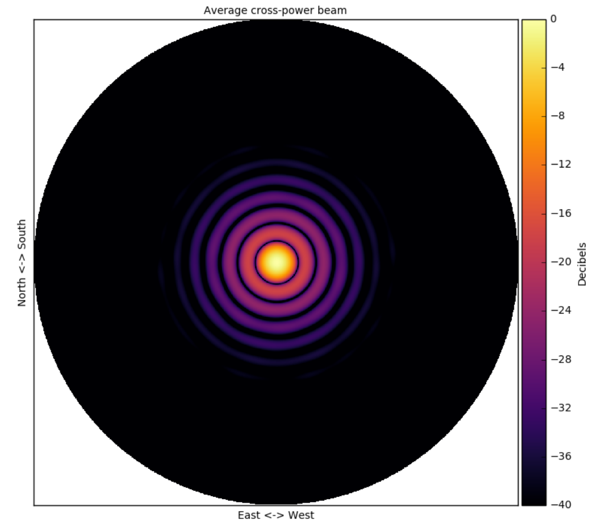
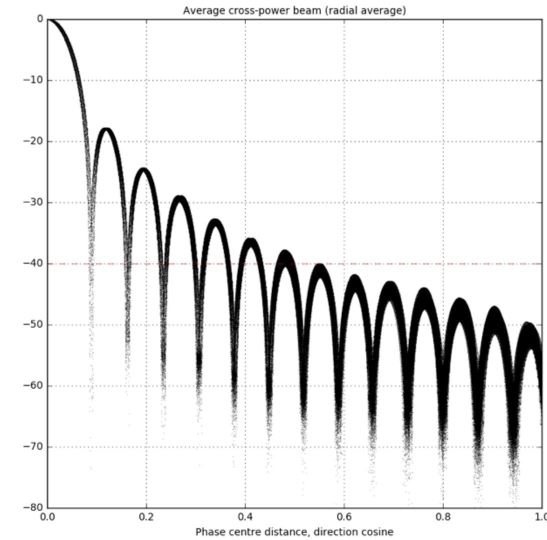
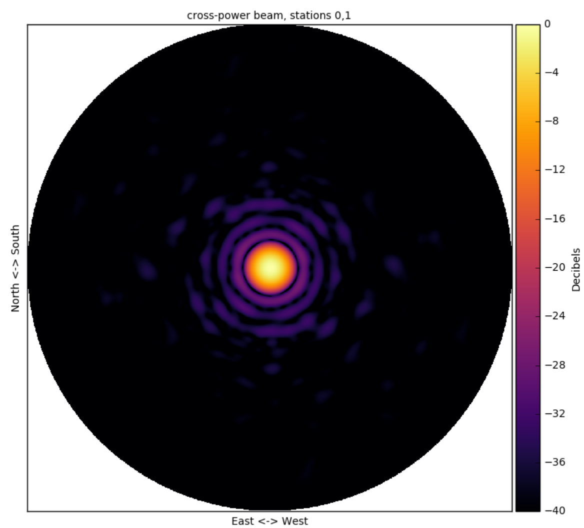
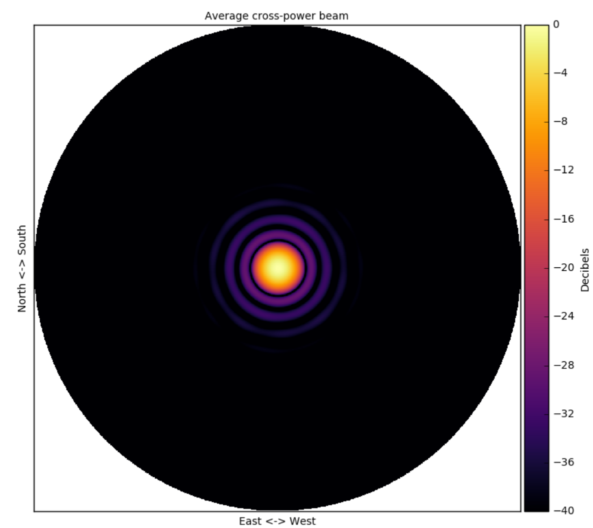
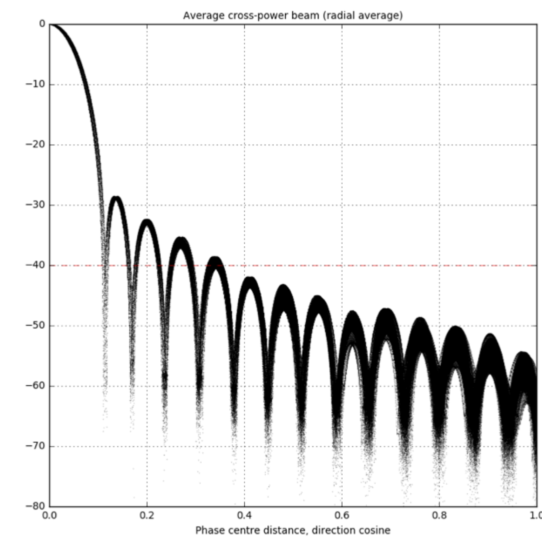
Single super-station



Superposition of all super-stations



V4X super-station beams: Super-station 'sea'
Stokes-I cross-power station beams, 50 MHz, zenith pointing

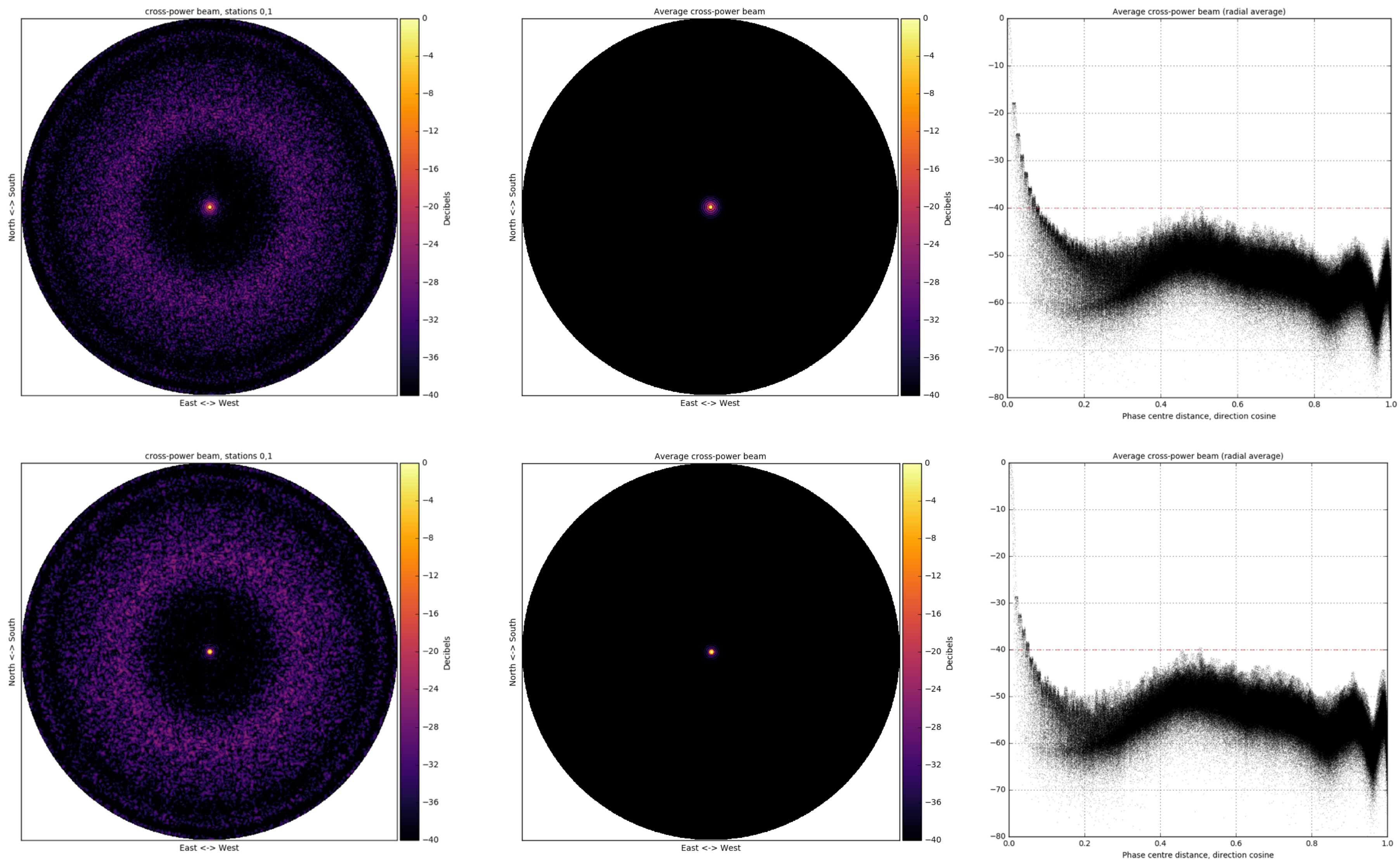
	Cross-power beam Single baseline	Average cross power beam all baselines	Average cross power beam Radial profile
No-apodisation			
-28 db Taylor weights			

V4X super-station beams: Super-station 'sea'
Stokes-I cross-power station beams, 350 MHz, zenith pointing

	Cross-power beam Single baseline	Average cross power beam all baselines	Average cross power beam Radial profile

No-apodisation

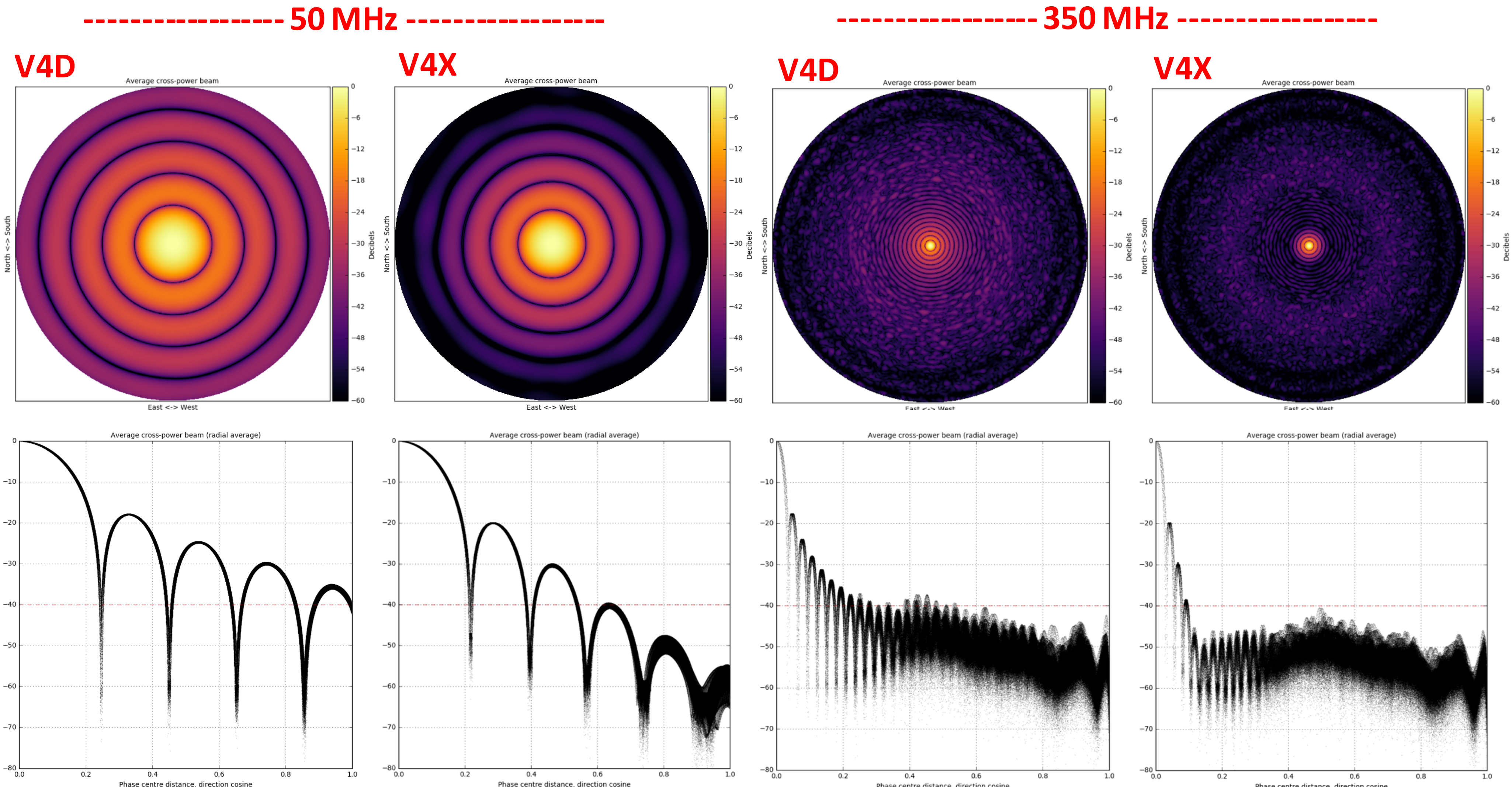
-28 db Taylor weights



Summary of results

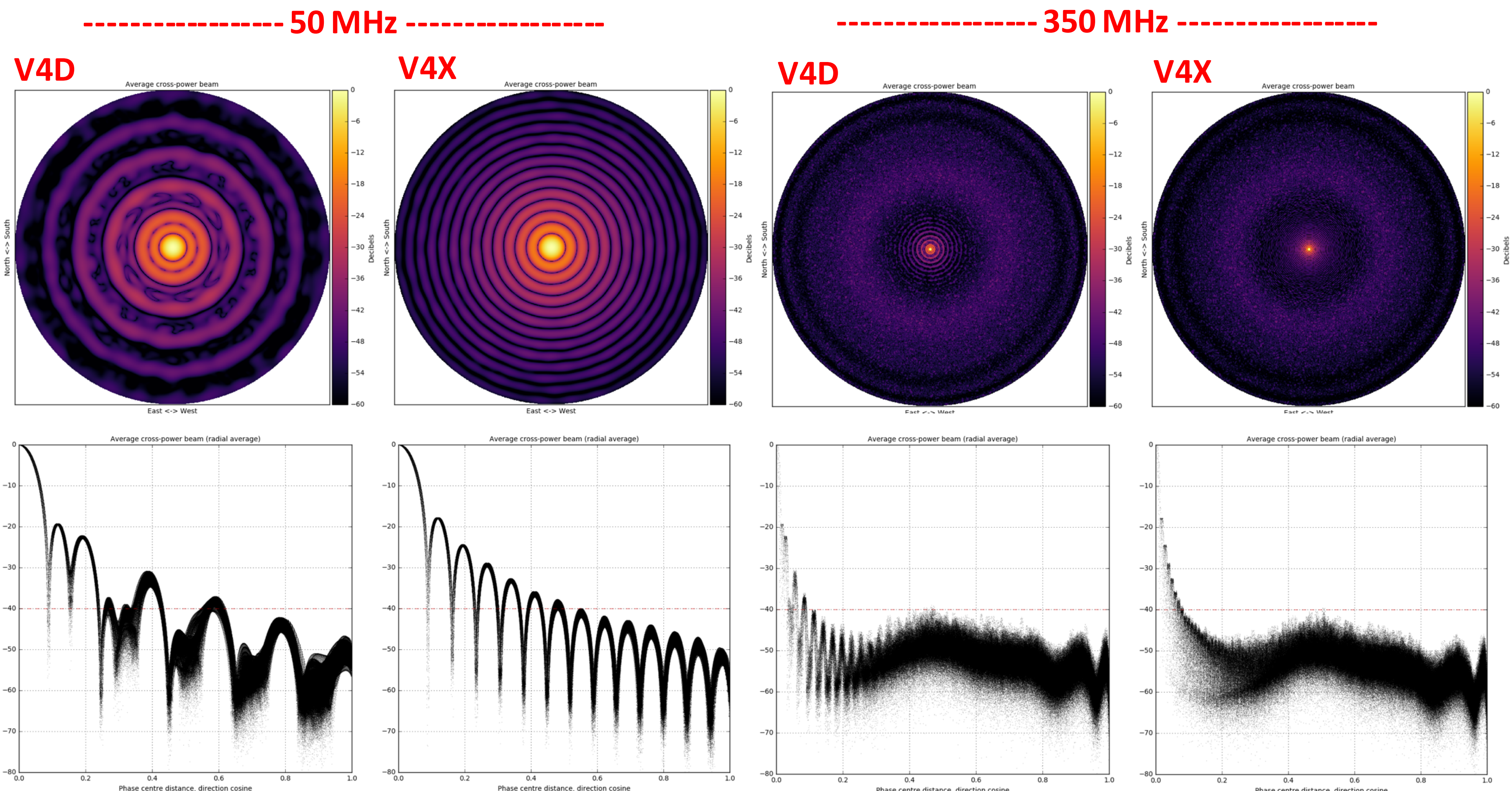
V4D vs V4X: Station beams

Discrete stations vs sea of elements?



V4D vs V4X: Super-station beams

Discrete stations vs sea of elements?



V4D vs V4X: Super-station beams

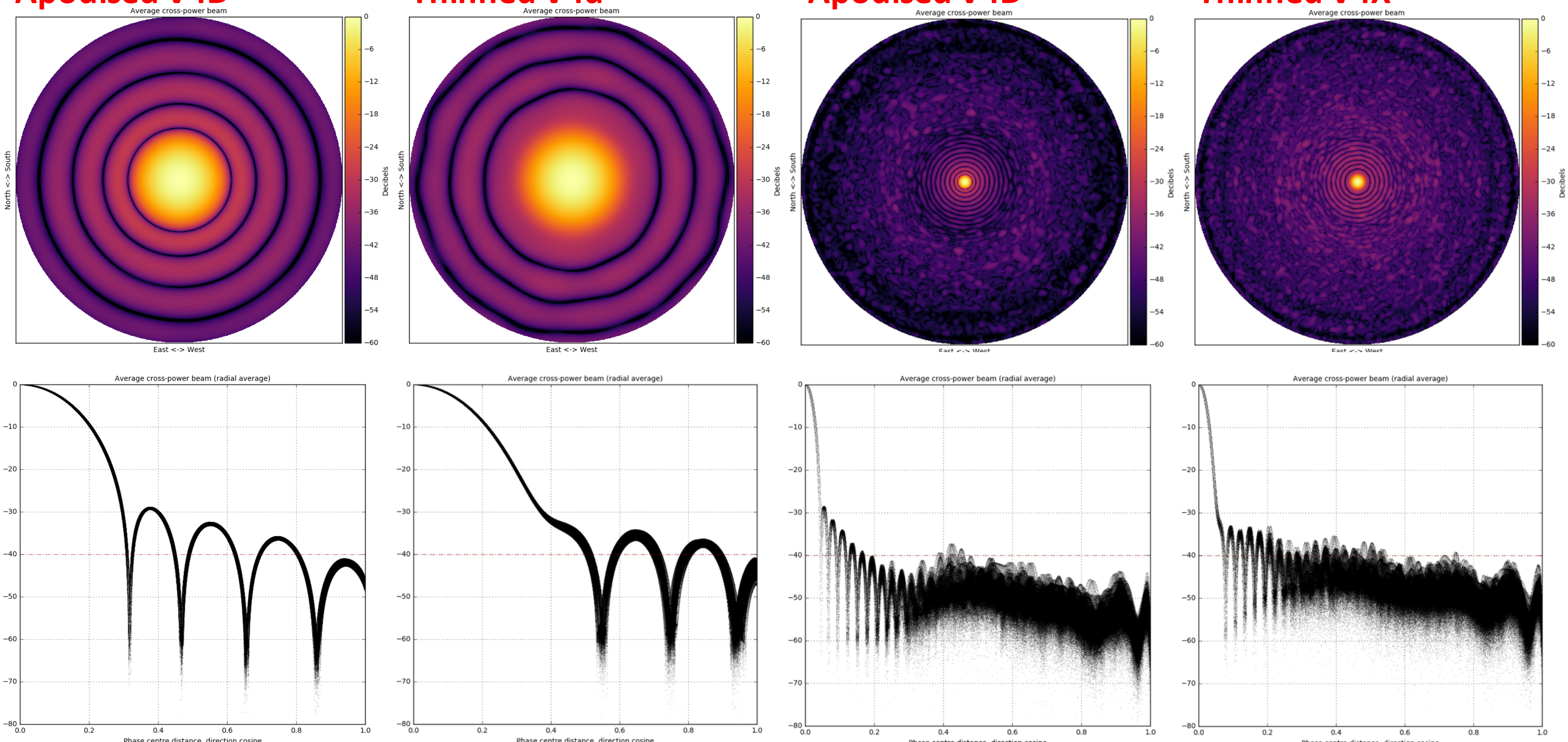
Discrete stations vs sea of elements?

- The increased flexibility in forming stations from the sea of elements (V4X) results in station and super-station beams with lower and more well behaved sidelobe levels.
- The ‘gap’ in the superimposed rotated super-station for V4D leads to higher inner sidelobes.

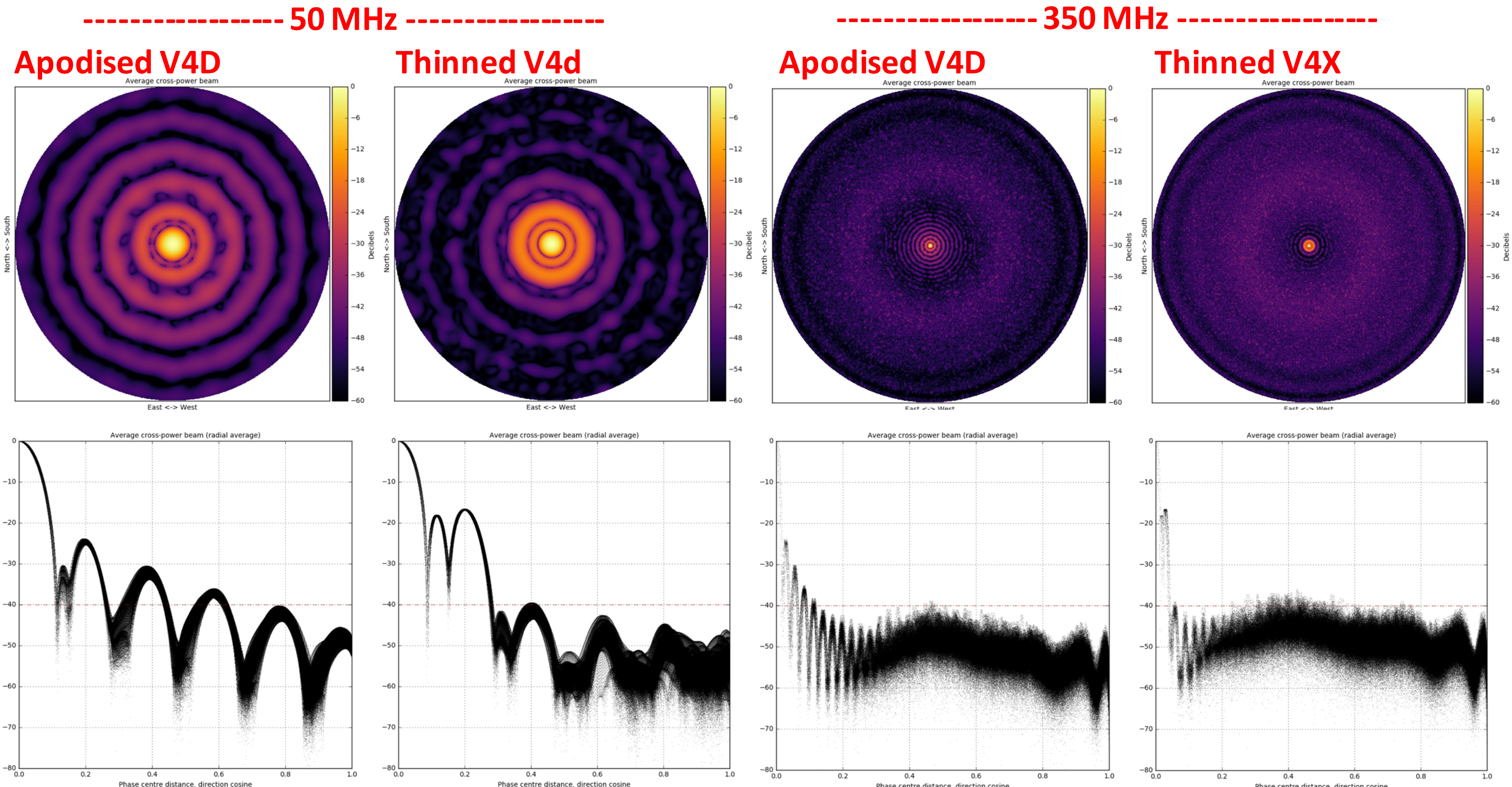
Apodisation vs Thinning: Station beams

----------------- 50 MHz ----------------- **----------------- 350 MHz -----------------**

Apodised V4D | **Thinned V4d** | **Apodised V4D** | **Thinned V4X**



Apodisation vs Thinning: Super-station beams



Apodisation vs Thinning: Super-station beams

- Thinning and apodisation give qualitatively similar results for zenith pointings
- Thinning removes all flexibility for beam optimisations
- Thinning results less control over the side-lobes
- Super-station beams of the thinned array suffer from the introduction of the ’gap’ in the antenna density near the edge of the inner station, which leads to high inner sidelobes.

Answers to questions

Answers to questions

- Q1: Ideal station diameter?
  - Answer has to come from science analysis
- Q2: Argument for multiple station sizes?
  - Answer has to come from science analysis, but building in flexibility unless it greatly impacts cost sounds like a good idea.
- Q3: Ratio of area in core to outer stations
  - Again, answer has to come from science analysis. Point source removal will require sufficient sensitivity on the longer baselines to not be confusion limited.

Answers to questions

- Q4: Must all station configurations be identical?
  - For imaging we believe it will be helpful if the station beams, and resulting average cross-power beam are as stable as possible as this will lessen the requirement for direction dependent corrections during imaging. Indeed it may be even desirable to dynamically reshape stations to make this possible which can be achieved using a sea of elements.
  - Use of mixed station sizes for calibration would need further analysis.
  - While we believe that common station sizes are a good thing, our studies of Far Sidelobe Source Noise (FSSN) (arXiv:1602.01805 [astro-ph.IM]), have shown that the noise picked up by the far-out sidelobes can be dramatically reduced in the interferometric sense if each station's antenna configuration is different. This is easily achievable since each station can have a different pseudo-random configuration whilst maintaining a given minimum distance criteria.

Answers to questions

- Q5: Benefit of different station sizes? What are the ideal sub-station, station and super-station sizes?
  - Superstations will reduce the instantaneous field-of-view but provide greater control of station side-lobes.
  - If substations are allowed, it is unlikely to be possible to correlate them all (because of the large number).
  - For many standard imaging observations which don't require a large FoV having the option to use large super-stations (leading to lower sidelobe levels) will result in lower contamination from sources in sidelobes (FSSN).
  - (Nima to explain) The level of station sidelobes scale as the inverse of the number of antennas, therefore a larger station will result in lower far-out sidelobes. Furthermore, the number of controllable sidelobes (or coherent sidelobes) increases as ~0.3sqrt(N), where N is the number of antennas in a given station. However these will have a width roughly defined as wavelength/2D, where D is the station diameter. Despite this, having "greater control" of sidelobes in a superstation is not really true. It should be noted that some undesirable grating responses will be present in a superstation beam if there is a non-uniform (approx.) distribution of antennas. As such petal-like structures will suffer from such effects.

Answers to questions

- Q6: Technical impediments to multiple station diameters
  - None / possibly cost
- Q7: Technical impediments to building and using substations and super-stations
  - None / possibly cost

Answers to questions

- Q8: For / against physical tapering
  - Weight tapering provides many of the same benefits as spatial or "physical" tapering of antennas. Depending on the approach taken, there can be a loss in sensitivity even in spatial tapering. If the minimum distance requirement which is mostly based on the antenna footprint is maintained, some beamshaping (only over the controllable sidelobes) can be achieved with minimal loss of sensitivity. Note, however, that the region of controllable sidelobes in *l-m* space decreases the more the array is thinned out, because while the number of antennas may remain the same, the array diameter would surely have to increase. The biggest argument against such an approach is the variable station sizes, which will no longer be feasible if spatial tapering is employed. Weight tapering can also be designed with minimal loss of sensitivity, with the added benefit that variable station sizes can be allowed under such an approach. Reducing the controllable sidelobes by 10+ dB using weight tapering will result in approx. a 15% loss in sensitivity.

Answers to questions

- Q9: Ideal antenna density? Dense/ sparse transition frequency?
  - Whilst we cannot comment on what is the “optimal” distribution, it is clear that the highest density is limited to the antenna footprint (typically 1.5m). Based on current density requirements in the baseline design, an average antenna spacing of ~1.9m is obtained, as such resulting in a dense/sparse transition region around 80 MHz.
  - An important factor which is often ignored in the calculation of antenna density or packing, is that with a pseudo-random configuration which has a minimum distance spacing equal to a desired regular lattice spacing, an approx. packing density of only 2/3 will be achieved in comparison to the regular lattice.
  - Images of the average cross power station beam (shown here) as well as our studies of the effects of FSSN suggest that the precise value of the dense sparse transition frequency does not impact the standard imaging performance when using randomised stations.

Answers to questions

- Q10: Cost / benefit of a 'sea of antennas' approach for a super-station?
  - Adopting a sea of elements would allow some optimisation of the station beams over what can be achieved with a more fixed layout (see V4D vs V4X slide).
  - Dynamic reshaping of stations is far more practical when using a sea of elements.
  - The sea of elements would also permit the formation of different stations effectively randomizing the side lobes and allowing larger integration times (Mort, Dulwich, Razavi, de Lera, Grainge, MNRAS 2016 - submitted).

Take home messages (reprise)

1. Regular arrays should be avoided!
2. We need to develop a new station configuration with consideration for the electromagnetic effects and geometric limitations → V5 needed!