SKA1-LOW Array Designs

AADC Meeting, Bologna, 9 May 2016

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Overview

- Examine current V4D station layout.
- What makes a good layout?
- An alternative layout based on V4D (V4O1).
- All results obtained using OSKAR simulations

- Take home message:
- V4D has a sub-optimal PSF that will make it harder to use for general-purpose imaging.

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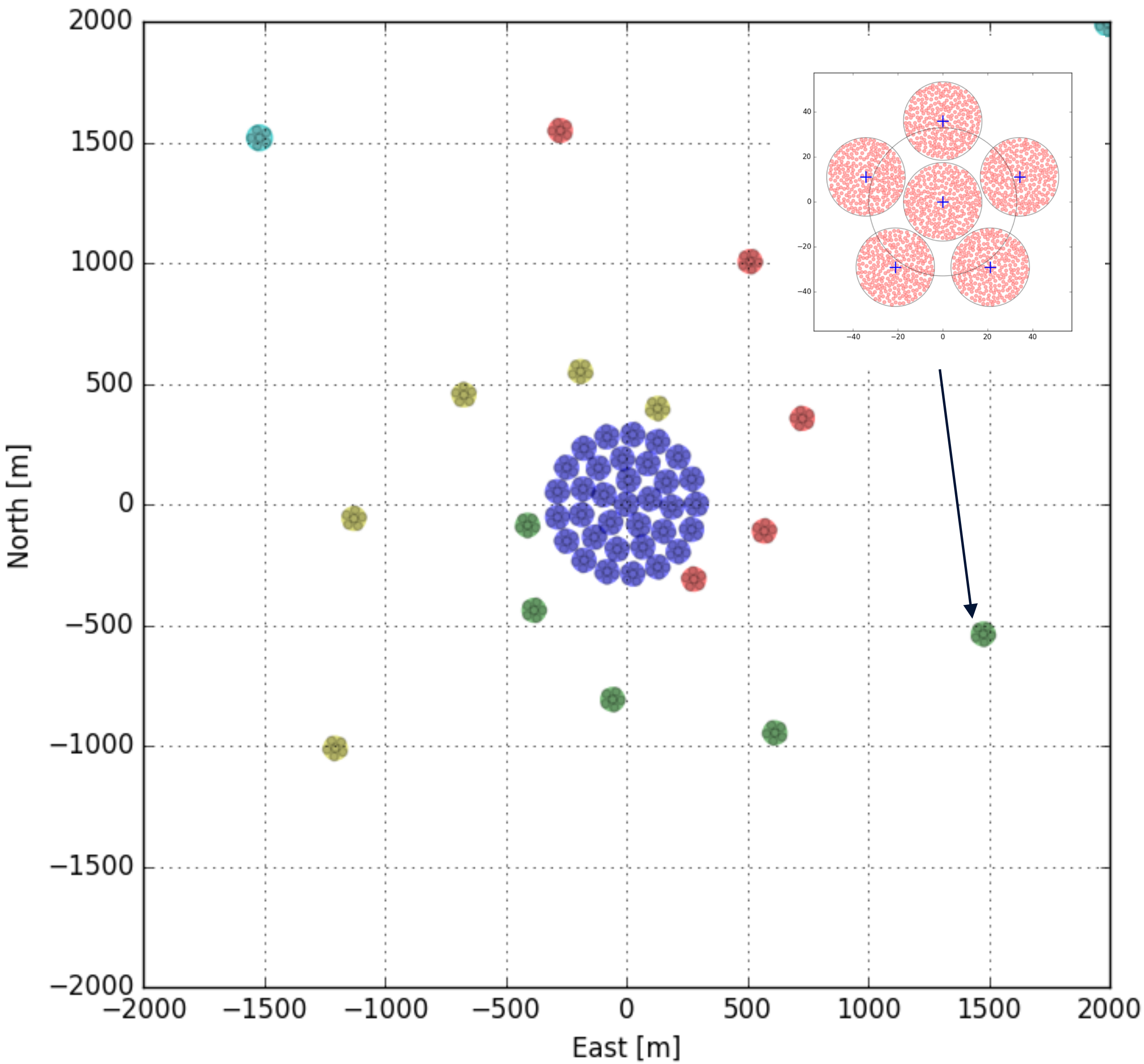
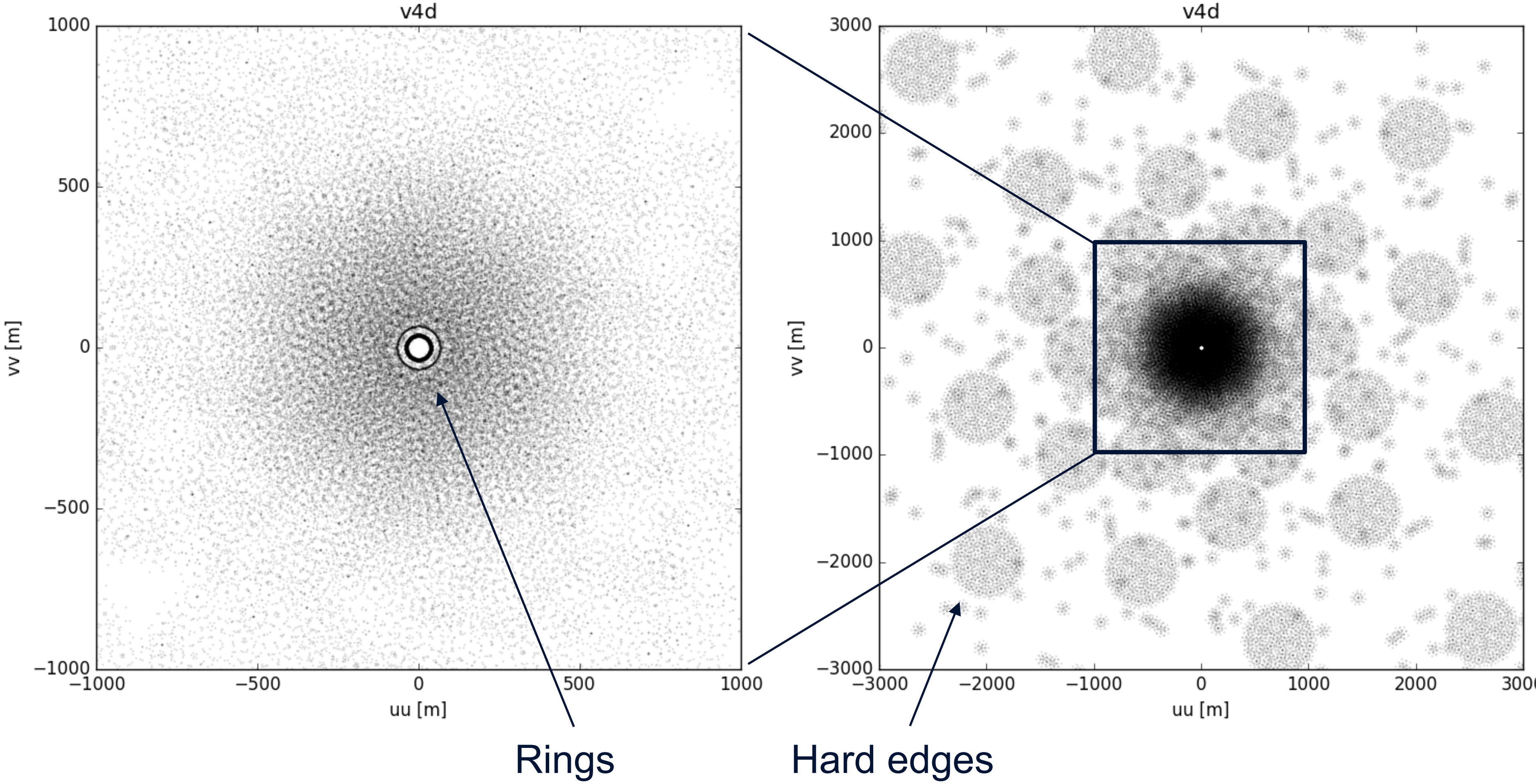
Current Layout: V4D

V4D Layout

- Stations tightly clustered into superstations (groups of 6 stations).
- Lots of redundant baselines on scale of station diameter.

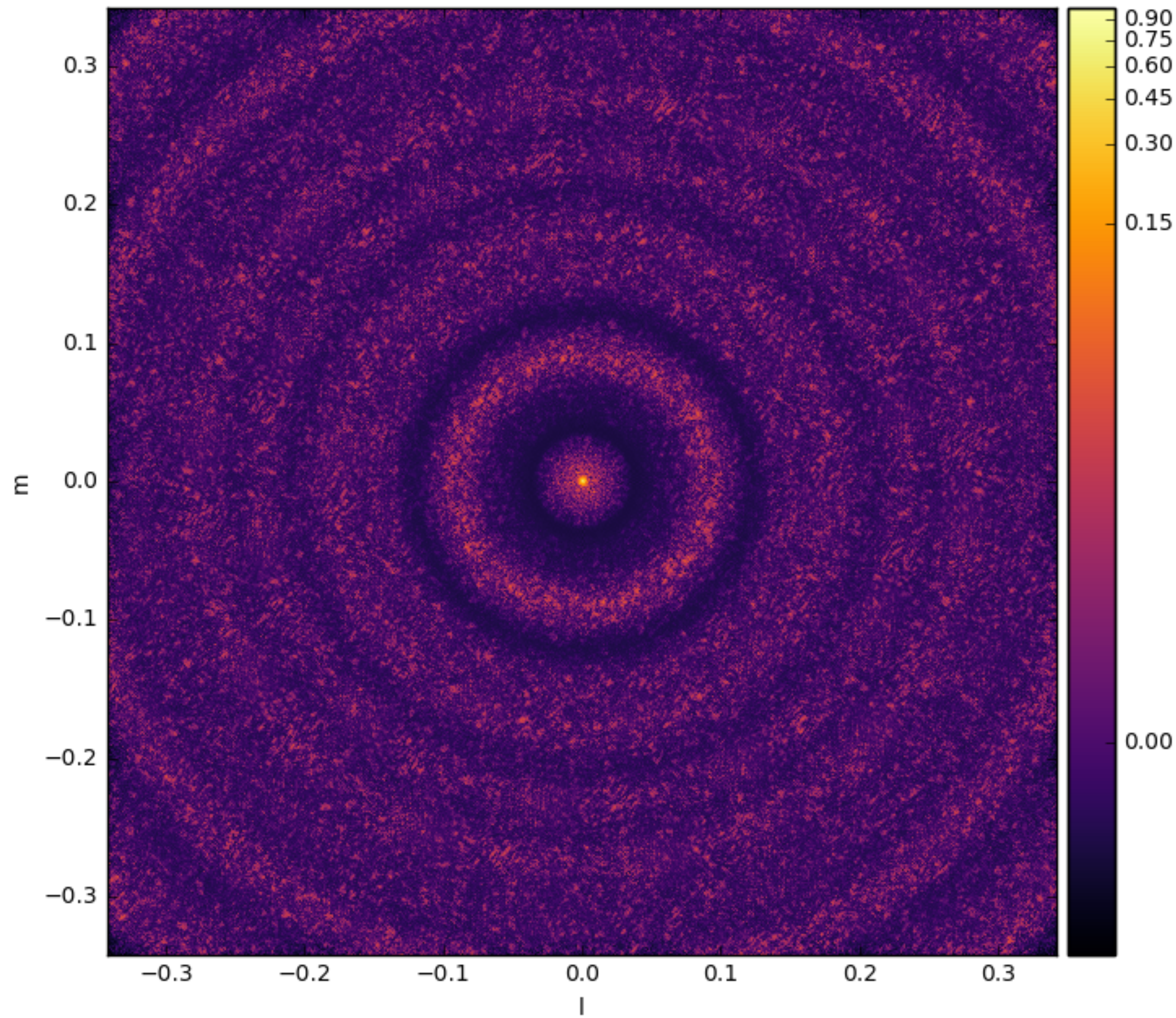


V4D Snapshot UV Coverage



V4D Snapshot PSF

40 degree FoV



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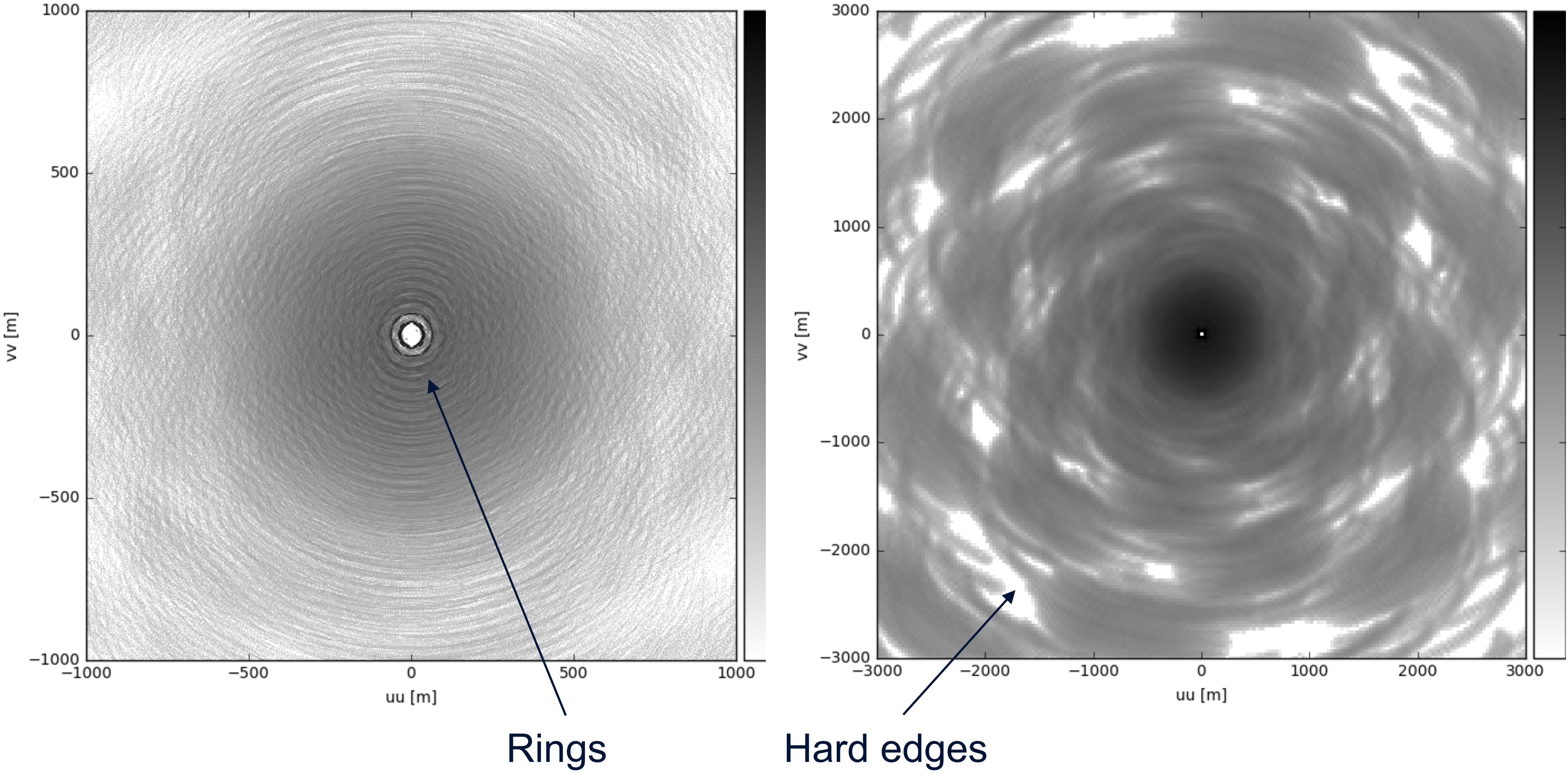
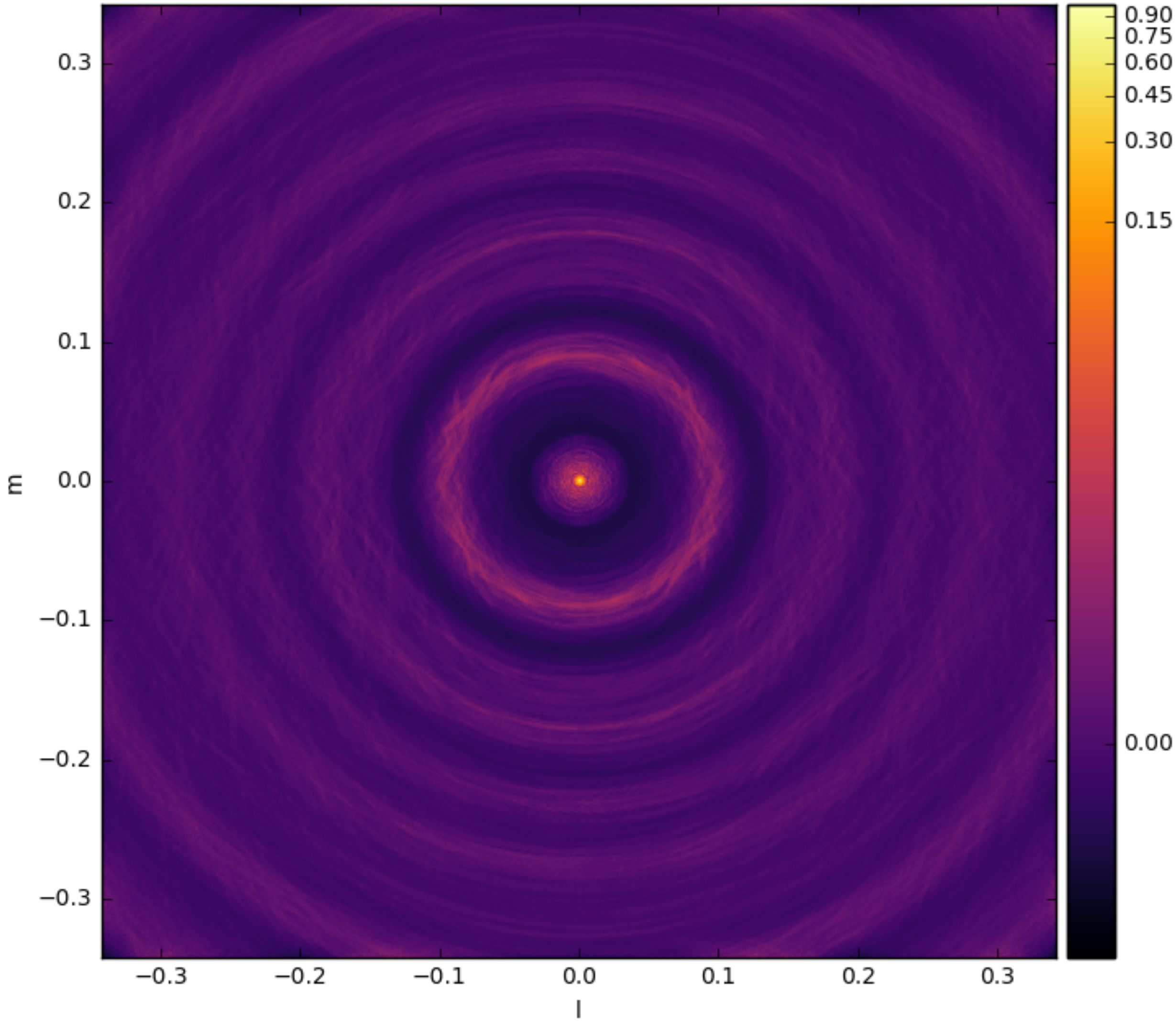
V4D 4-hour UV Coverage



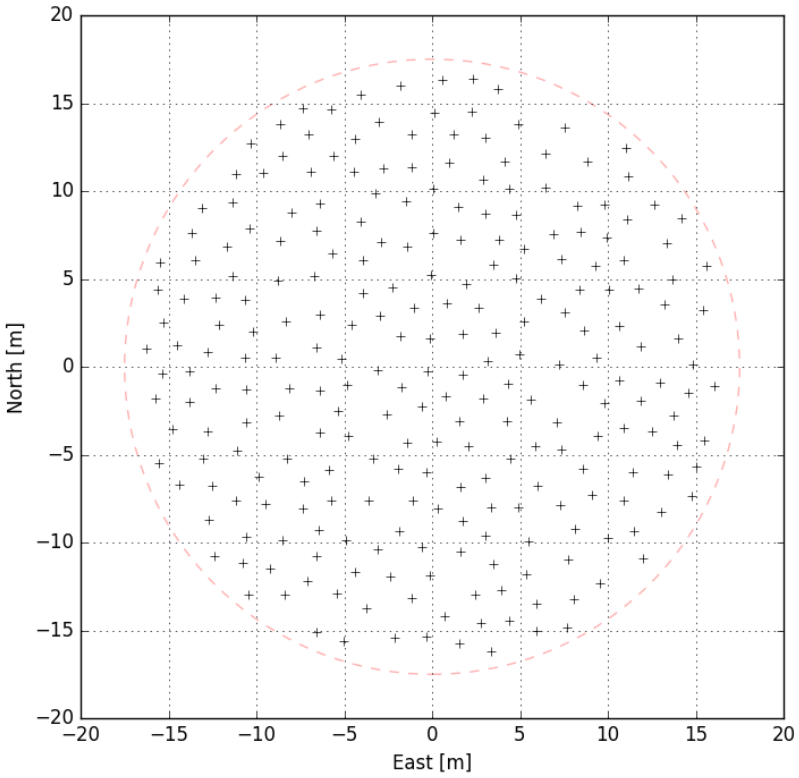
V4D 4-hour PSF

40 degree FoV

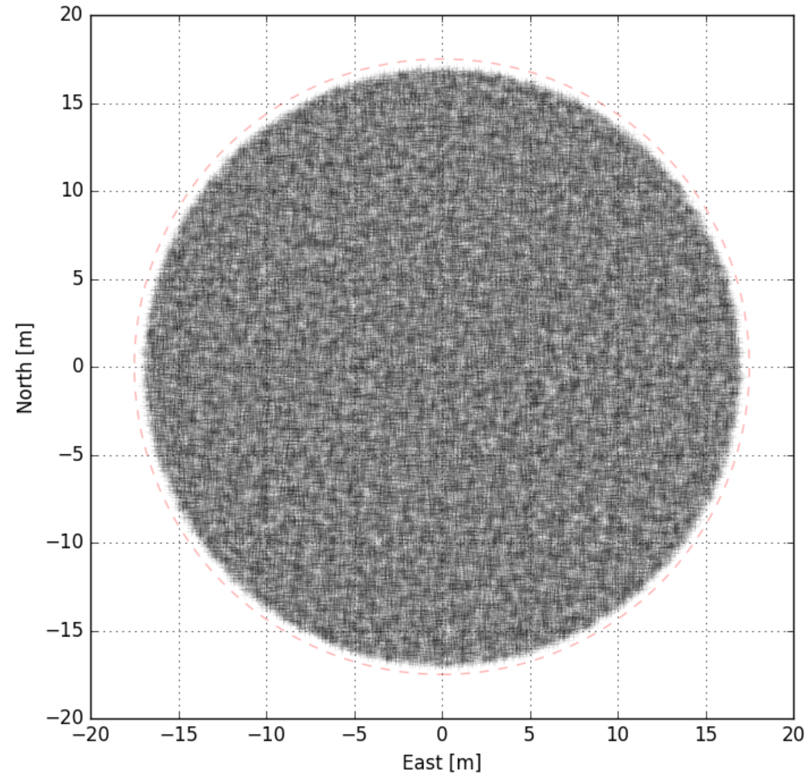


Stations
Randomly generated station antenna positions
256 antennas per station, 510 stations, 35 m diameter

Single station



Superposition of all stations



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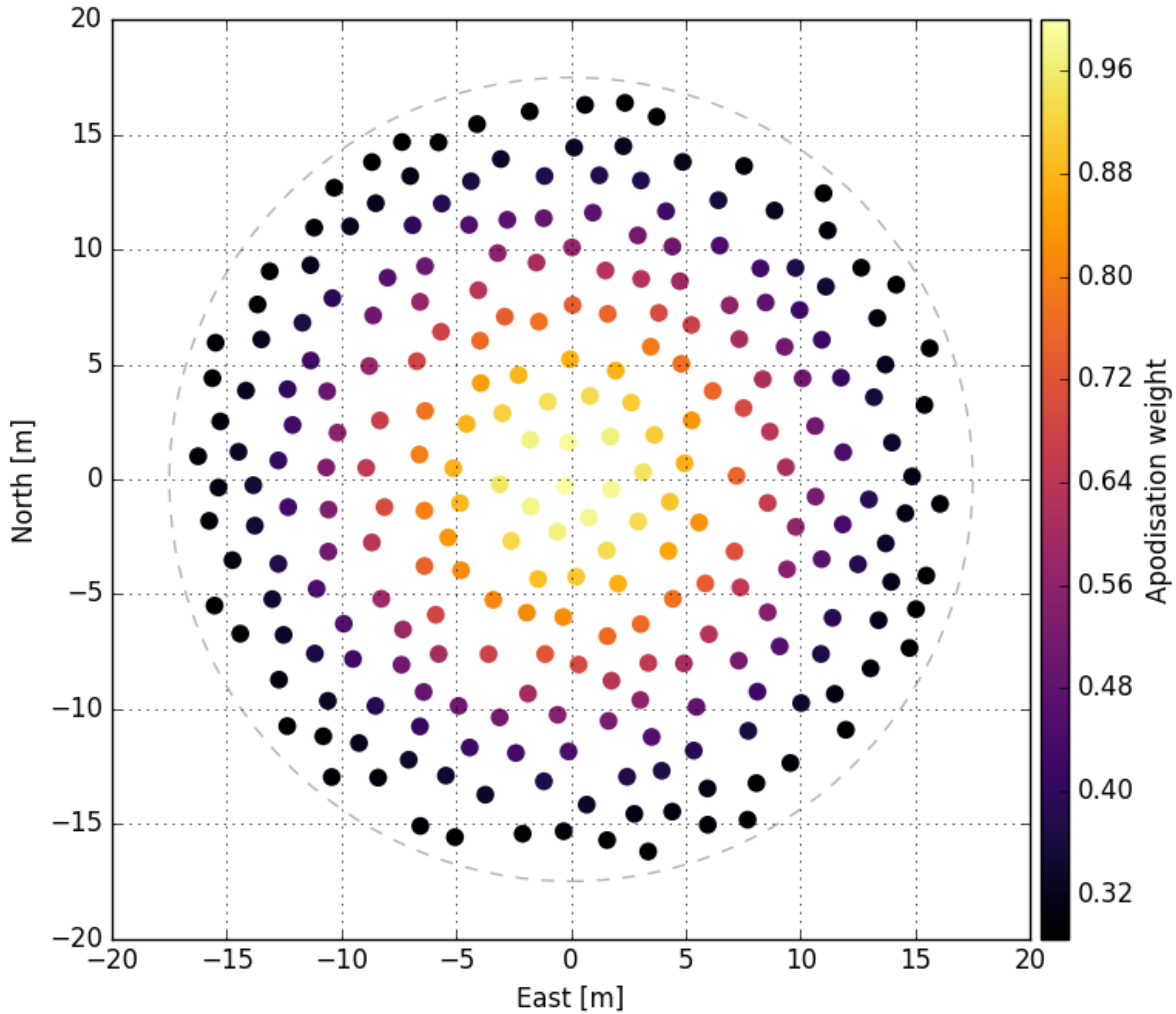
Station apodisation



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Cross-power beams

- First evaluate every station (voltage) beam at every pixel / source position.
- At each pixel, multiply every station beam with every other station beam and average the result.
- Compare with Measurement Equation:

$$\mathbf{V}_{p,q} = \sum_{s} \mathbf{E}_{p,s} \mathbf{B}_{s} \mathbf{E}_{q,s}^{\dagger}$$

$$\mathbf{A}_{s} = \sum_{p,q\ (p \neq q)} \mathbf{E}_{p,s} \mathbf{E}_{q,s}^{\dagger}$$

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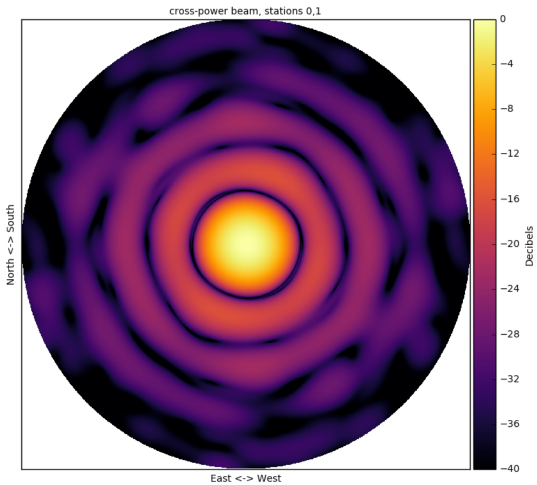
Station beams (cross-power, 50 MHz)

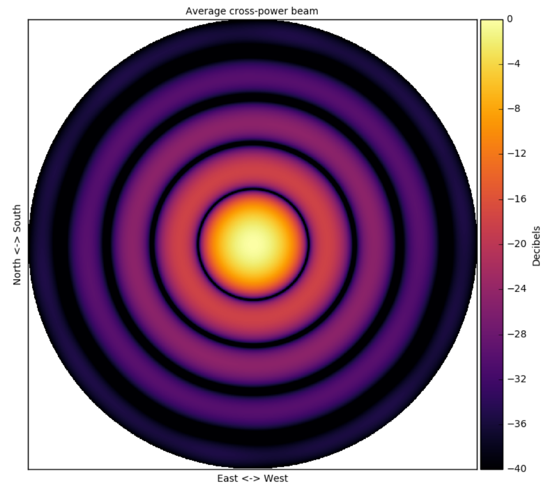
Cross-power beam
Single baseline

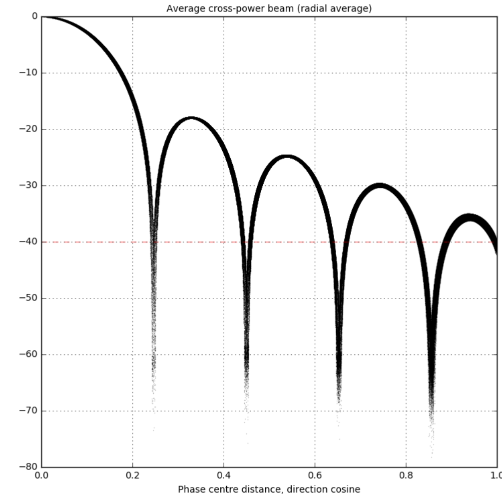
Average cross power beam
All baselines

Average cross power beam
Radial profile

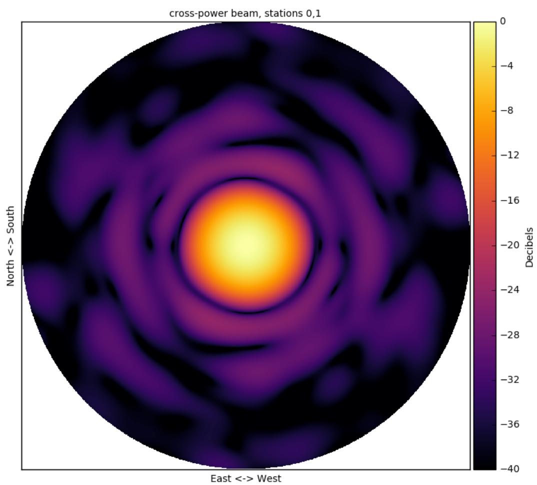
No-apodisation

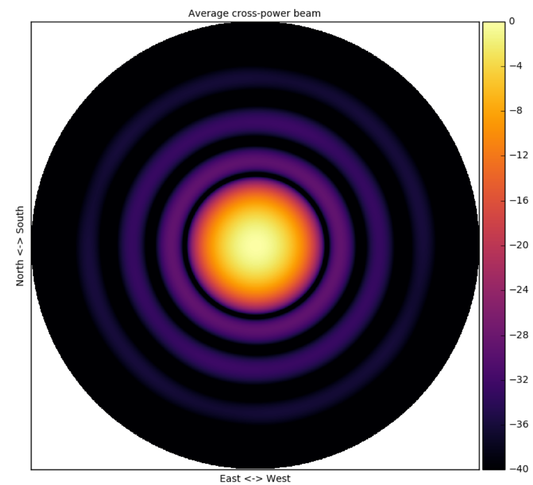


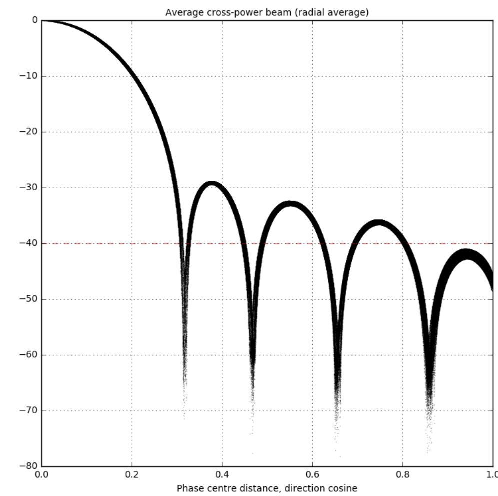




-28 db Taylor weights

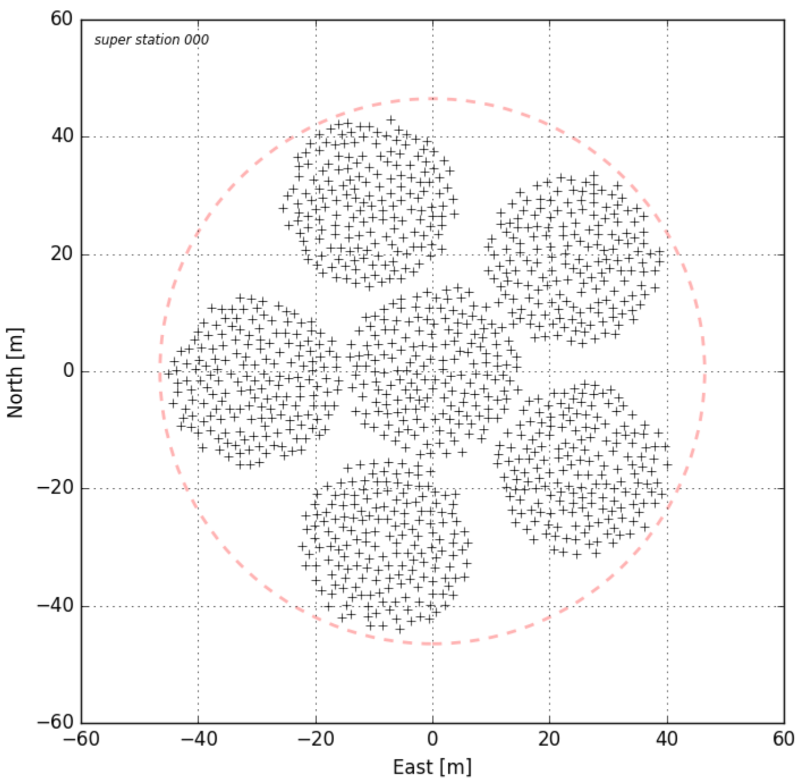




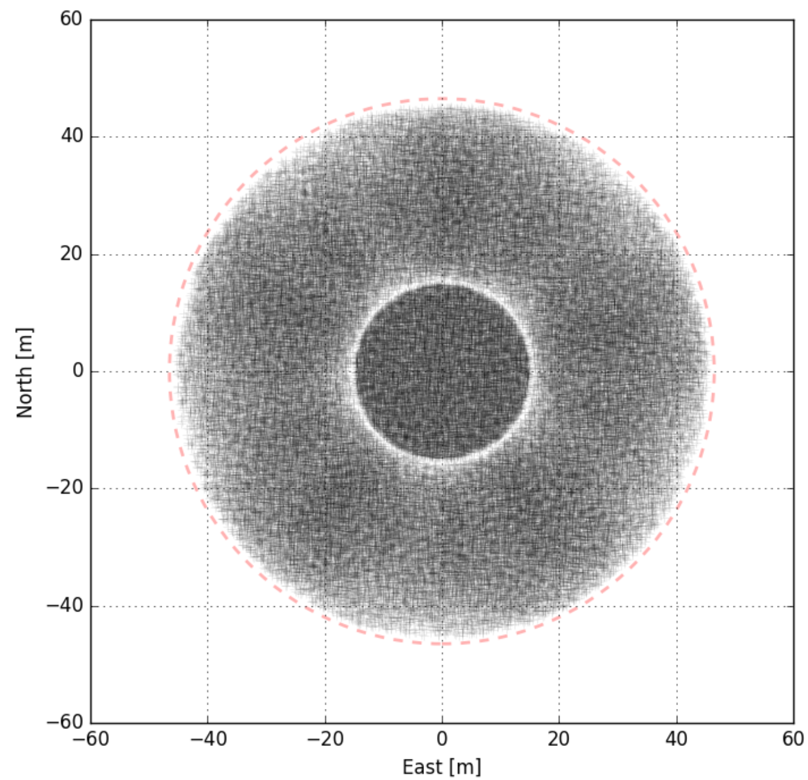


V4D super-stations

Single super-station



Superposition of all super-stations



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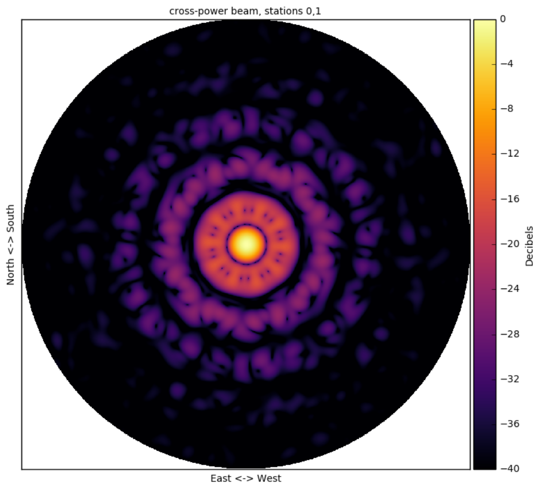
V4D super-station beams (cross-power, 50 MHz)

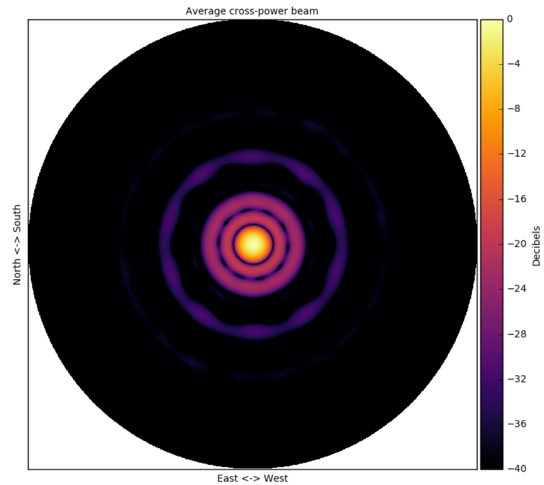
Cross-power beam
Single baseline

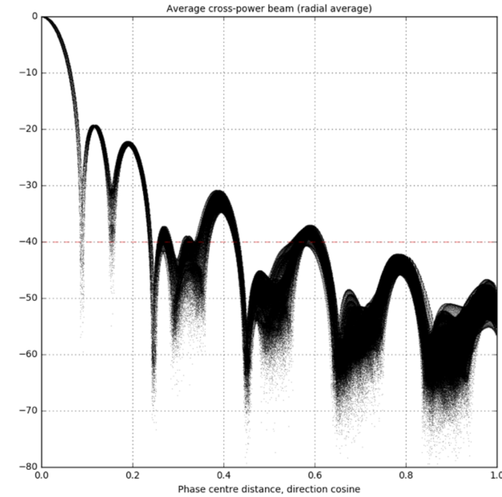
Average cross power beam
All baselines

Average cross power beam
Radial profile

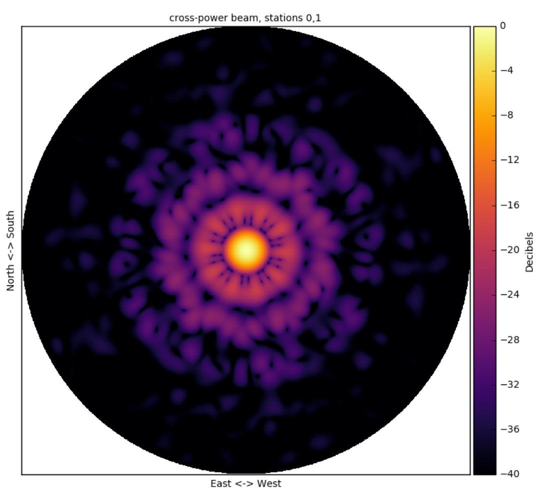
No-apodisation

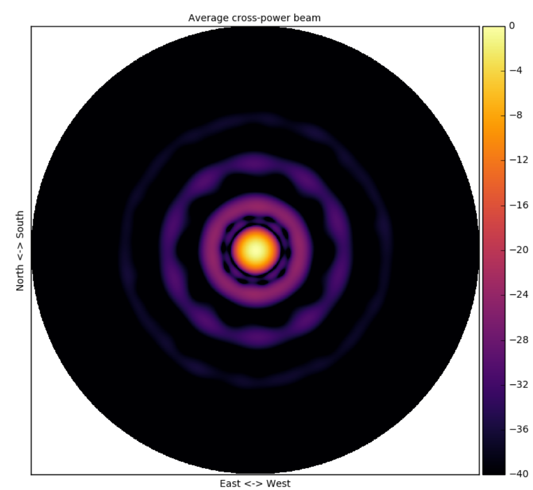


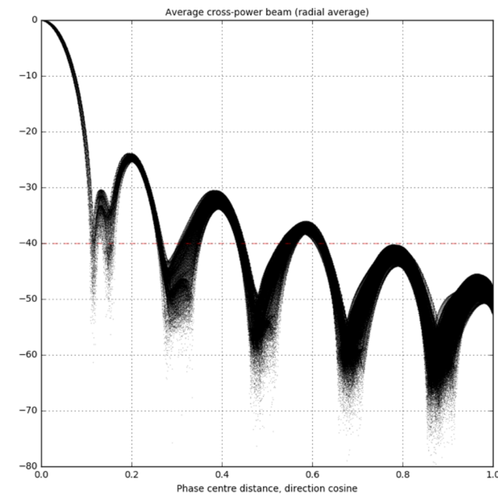




-28 db Taylor weights







V4D: Superstations or not?

- Would anybody wish to use superstation beams from V4D?
- Are there advantages of leaving superstations in the design?
  - Apart from the clustering of stations?
- Could be cheaper to do multiple pointings with superstation beams, because you have to correlate a lot less.
  - Assuming you can use the superstation beam effectively.
  - If not, better to do a single pointing with station beam.
- But we anticipate correlating all stations anyway!
- Can we make the layout better if we don’t need superstations any more?

Design Considerations

- Superstations are not particularly desirable from a scientific point of view.
  - We've already costed for a correlator that will handle all the stations we can afford without super-stationing.
- The station size of D = 35 m (or maybe a bit bigger) is about right.
  - Balance post processing cost (~D^6) vs. minimum baseline with reasonable sensitivity.
  - Slightly bigger stations would save lots of compute; could make up the difference with some intra-station correlations?
- The core should
  - be random and avoid preferred baseline lengths.
  - avoid having a hard edge (all fixed scale structures are bad),
  - have some physical thinning, and maybe a fully dense inner core.
- Outside a radius of ~1700 m
  - break up in to 3 spiral arms with stations that may be clumped in some way,
  - arranged so as to give scale-free and structure-free UV coverage.

Design Considerations: Questions about the Spiral Arms

- Are the (super) station positions fixed?
  - Are we free to slide (super) stations along an arm without deviating too far from the spiral track?
- If the stations along an arm have to be bunched into groups of ~6:
  - how tightly packed do these need to be from a practical point of view?
  - *Is it possible to distribute stations at least in the inner parts of the spiral arms in a way that is less bunched (but still following the arms)?*
    - Options here include using a bigger superstation circular envelope and moving the stations around within that;
    - Or stretching the envelope along the direction of the spiral arms.
  - At larger radii, station bunches may not be so bad from a UV coverage point of view.
- What are geographical constrains in the outer regions?
  - Should we take the station positions at r > ~10km as fixed?

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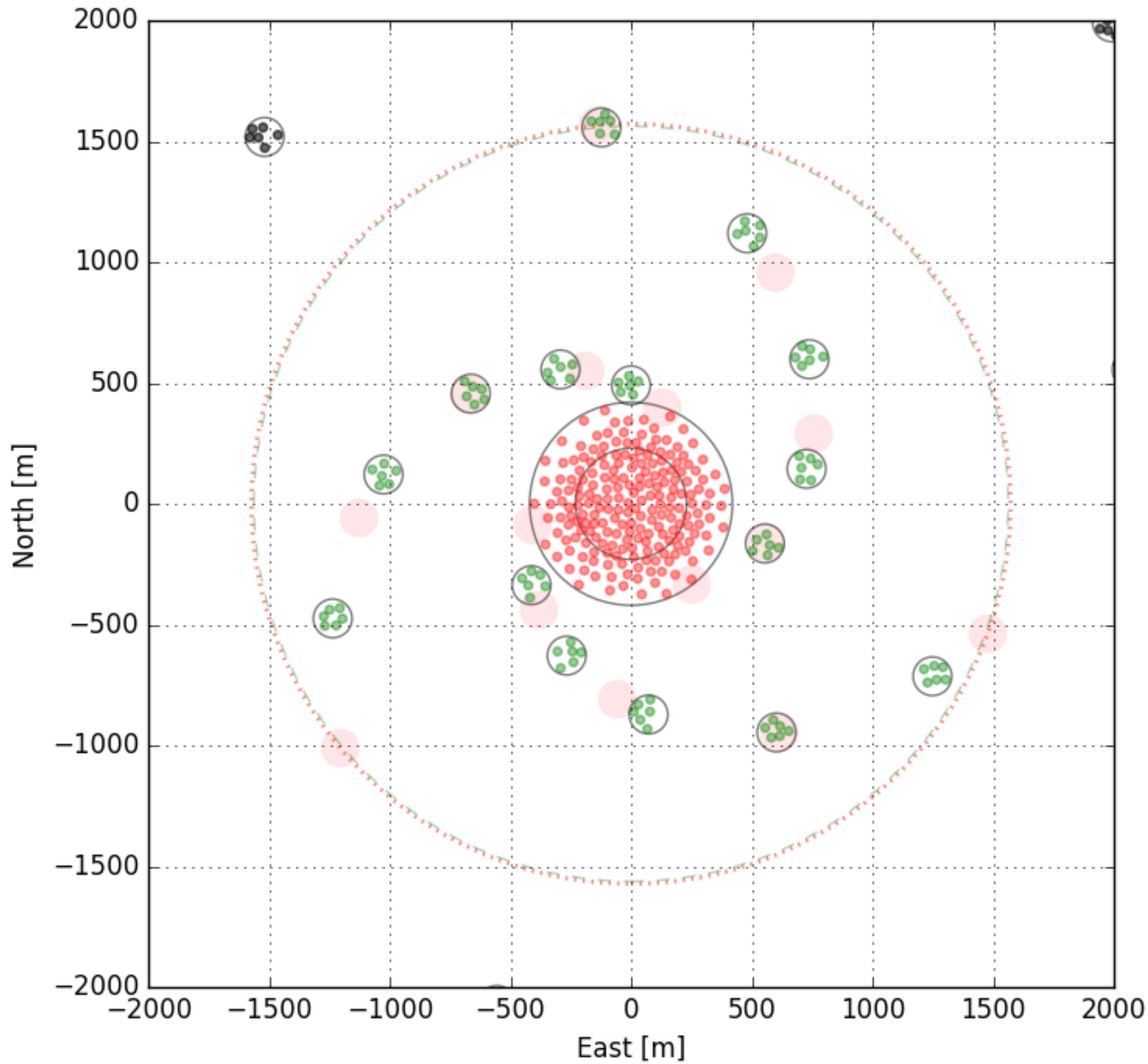
Alternative Layout: V4O1

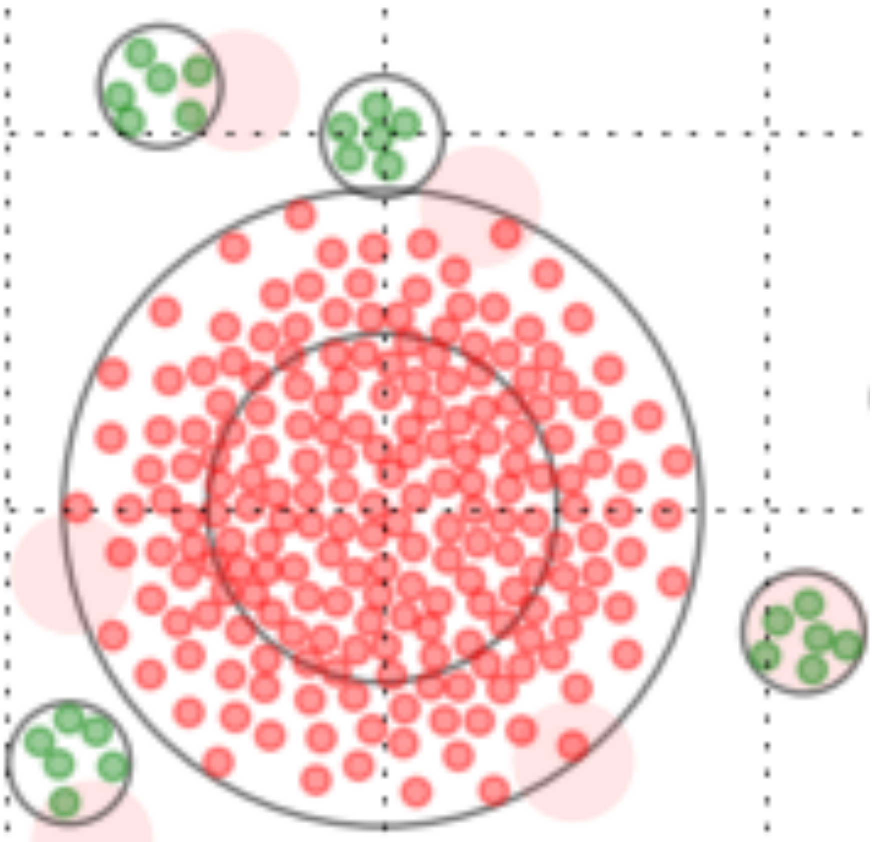
V4O1

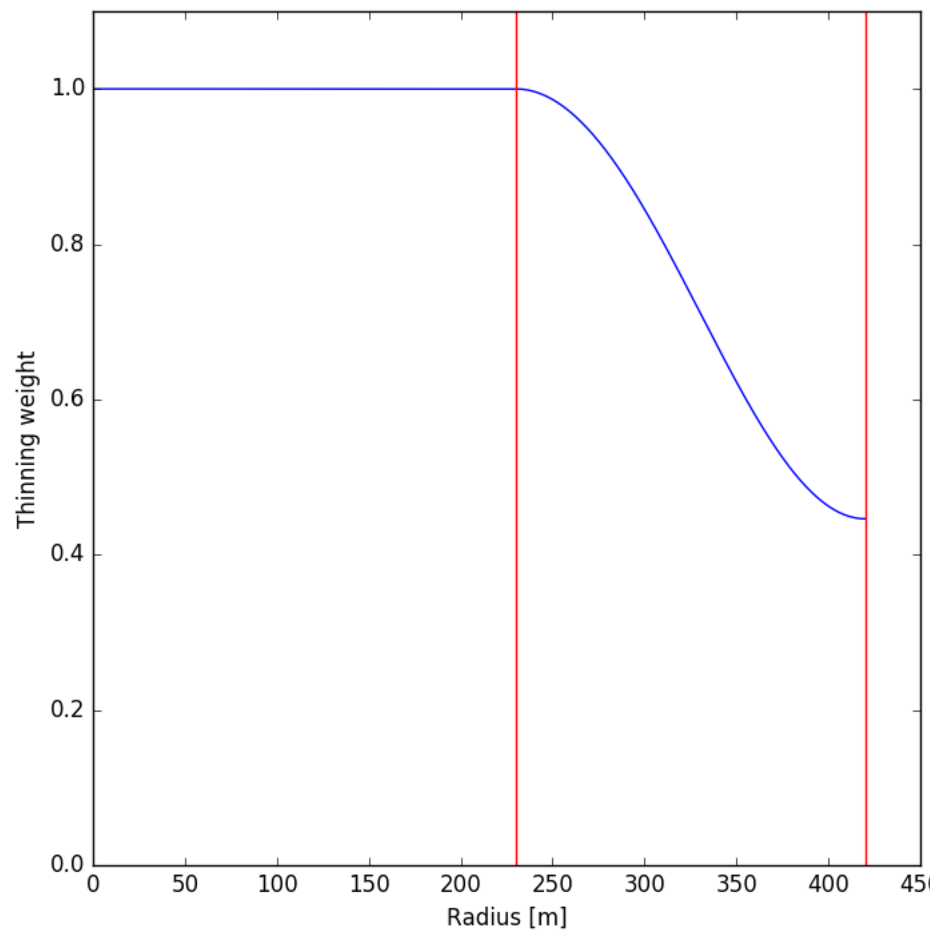
- Spiral arms generated as a single spiral arm, then split into 3.



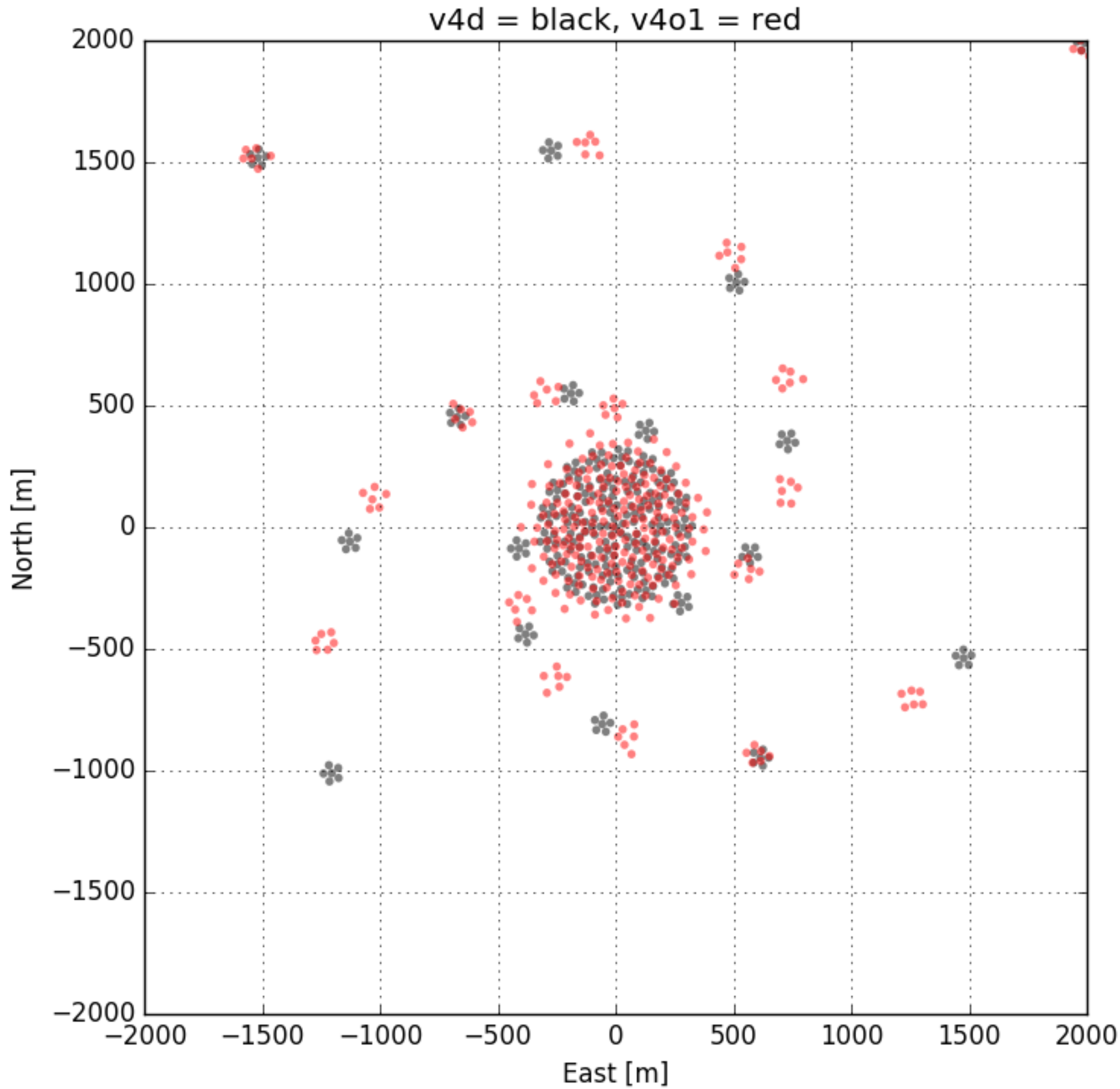
V4O1

- Core is random but thinned at the edge.



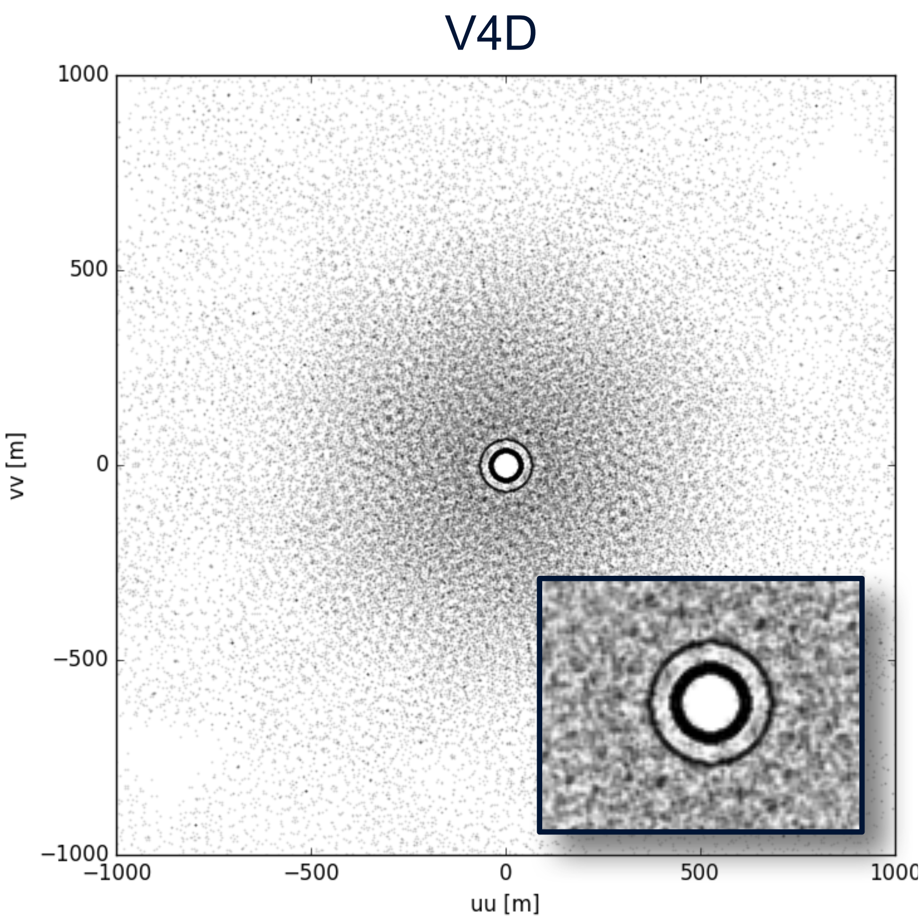


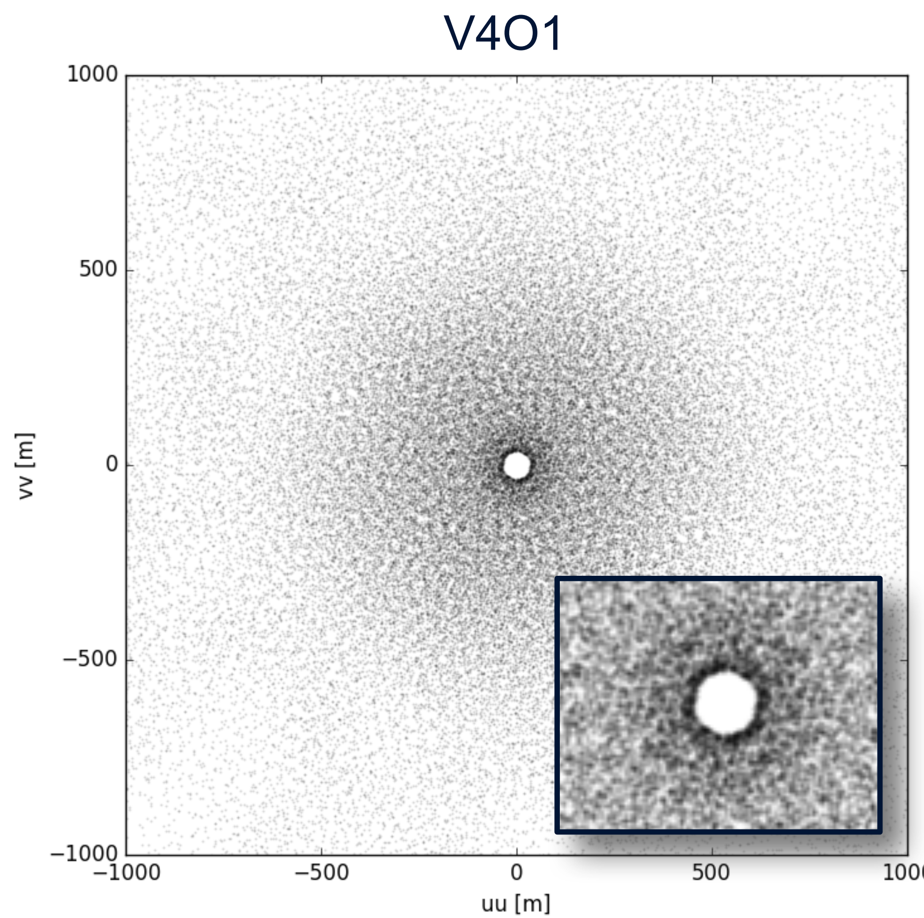
V4O1 vs. V4D



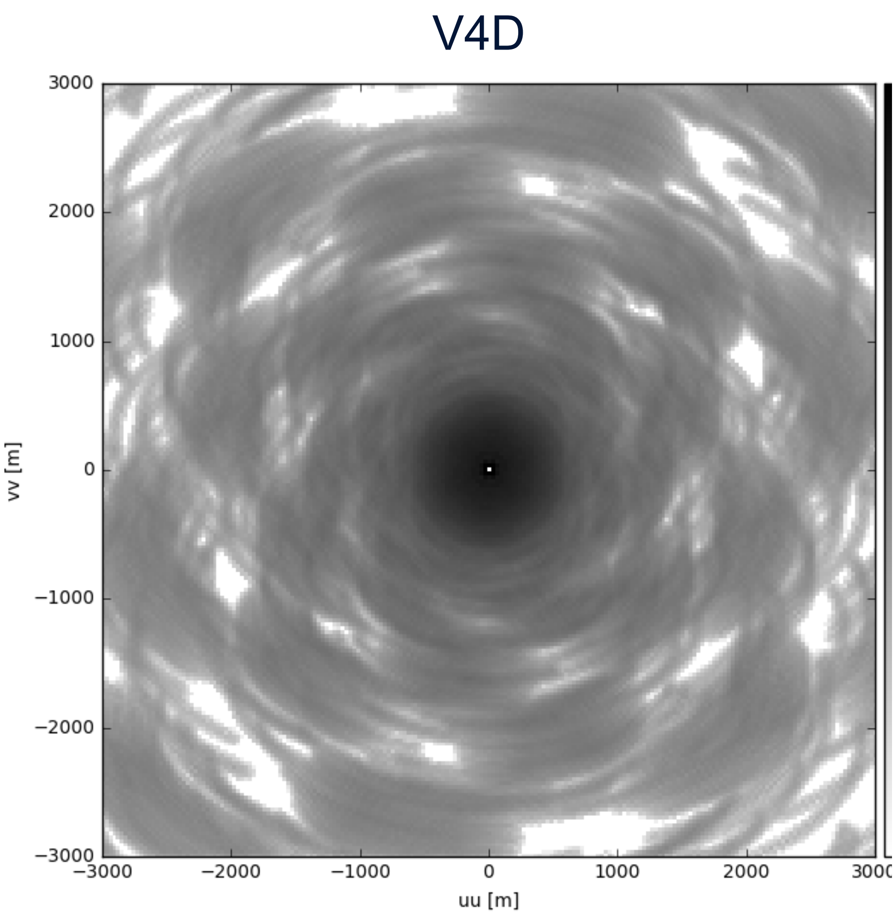
v4d = black, v4o1 = red
North [m]
East [m]
2000
1500
1000
500
0
−500
−1000
−1500
−2000
−2000
−1500
−1000
−500
0
500
1000
1500
2000

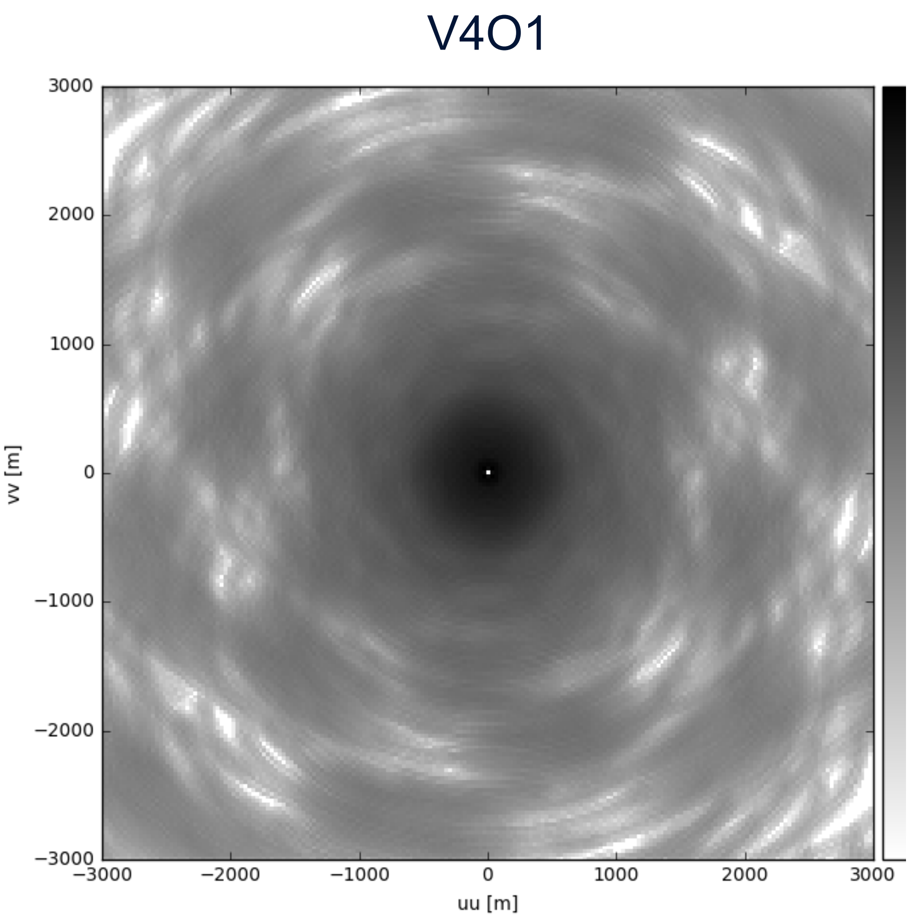
V4D vs. V4O1 Snapshot UV Coverage





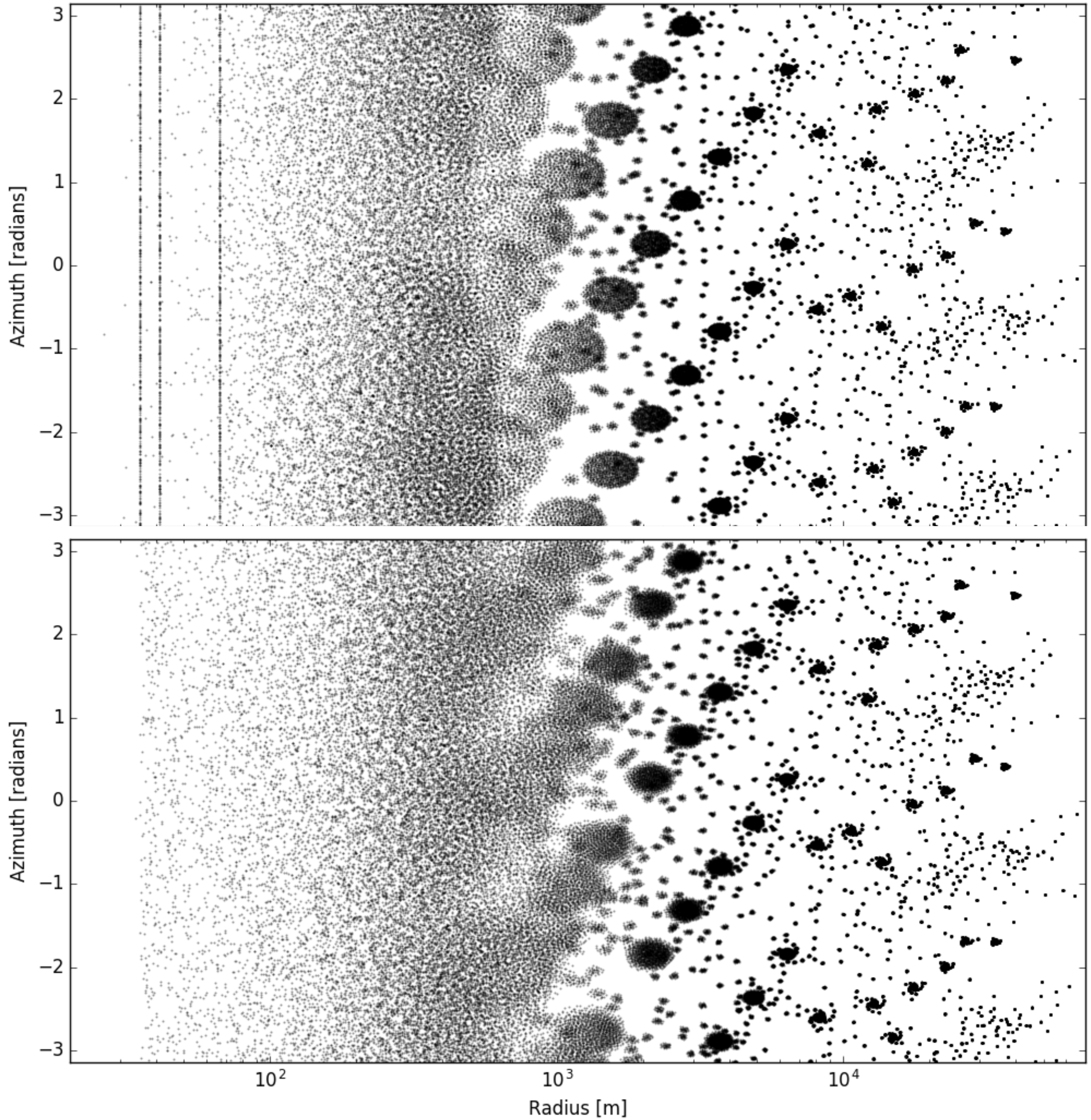
V4D vs. V4O1 4-hour UV Coverage





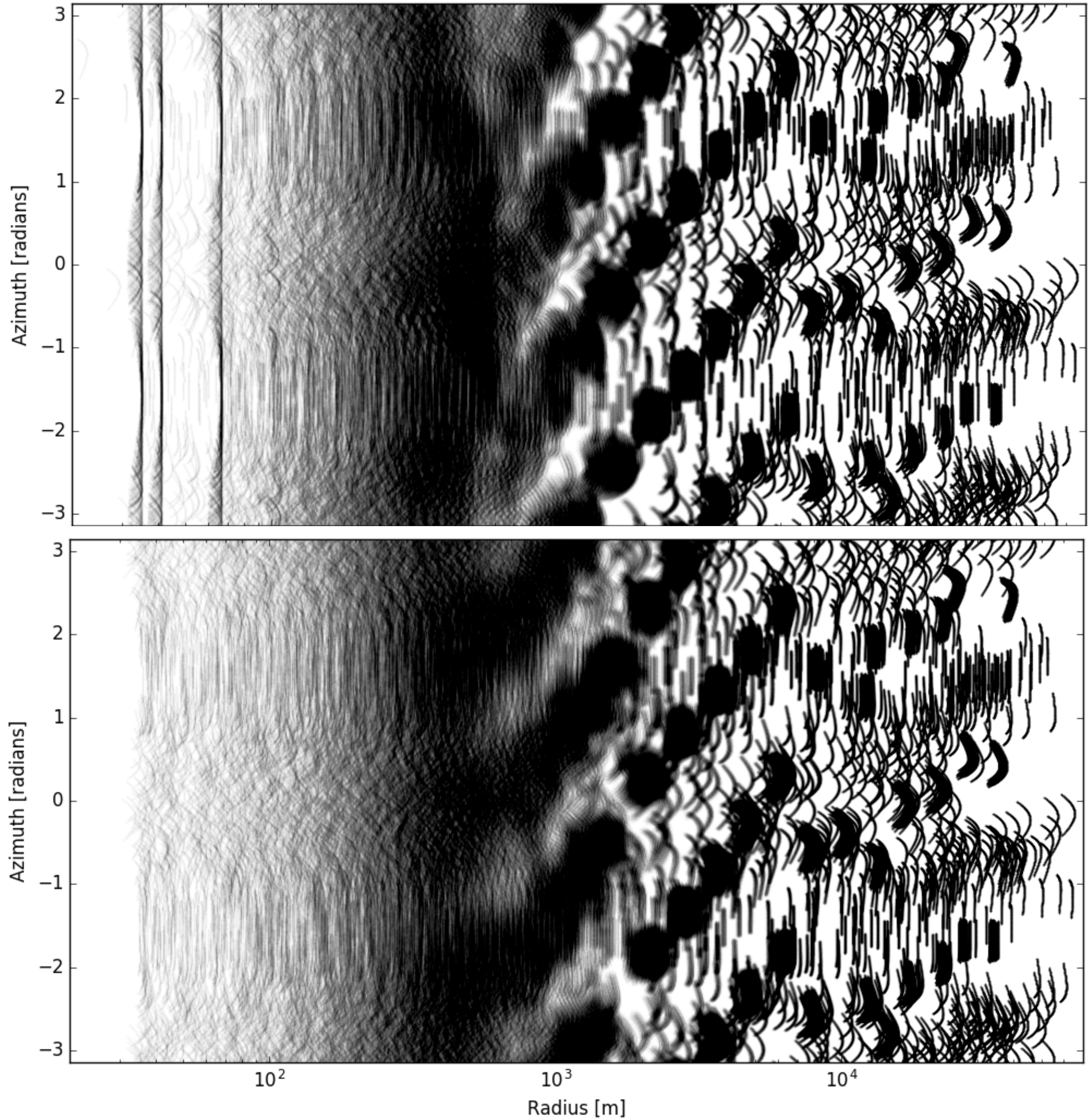
V4D snapshot

V4O1 snapshot



V4D 4-hour

V4O1 4-hour



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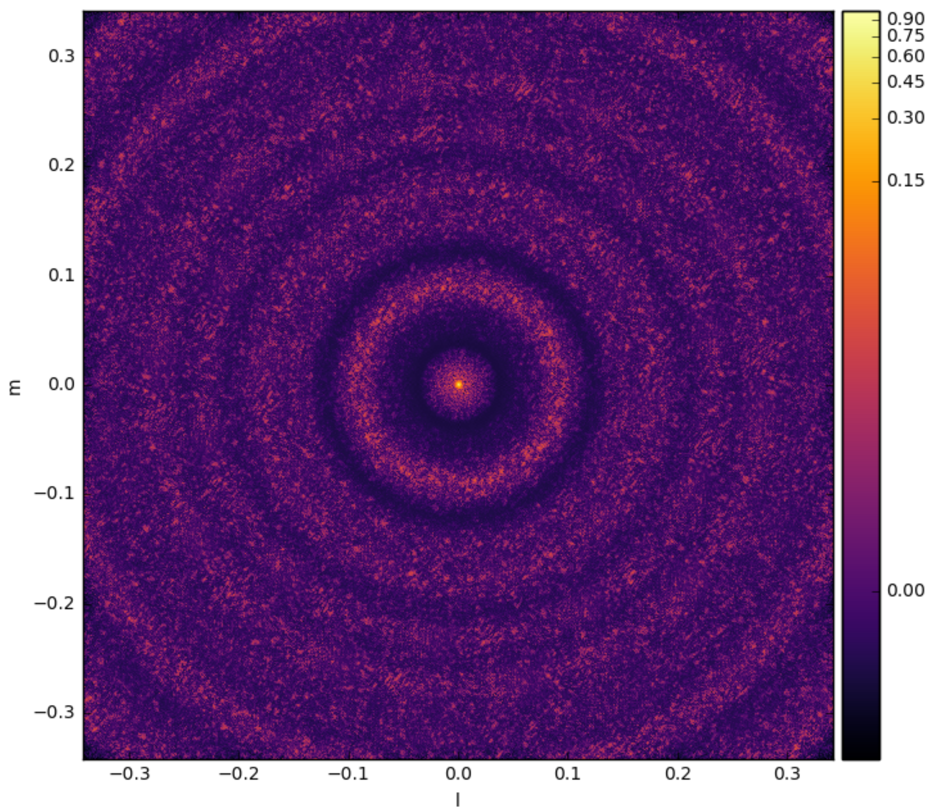
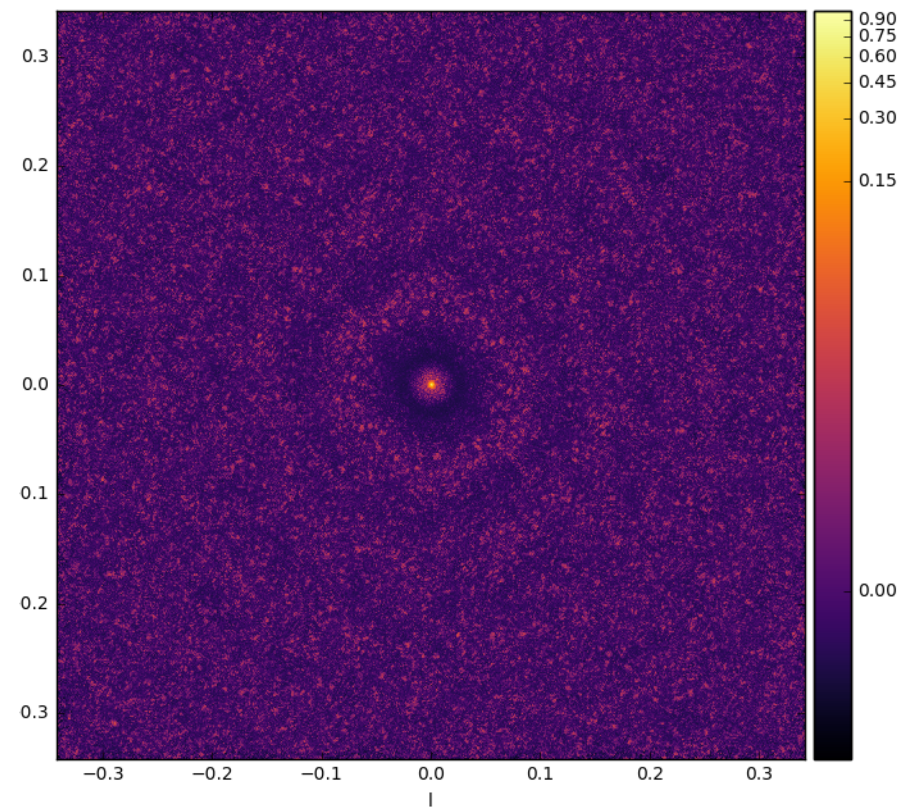
V4D vs. V4O1 Snapshot PSF (40 deg FoV)

V4D



V4O1



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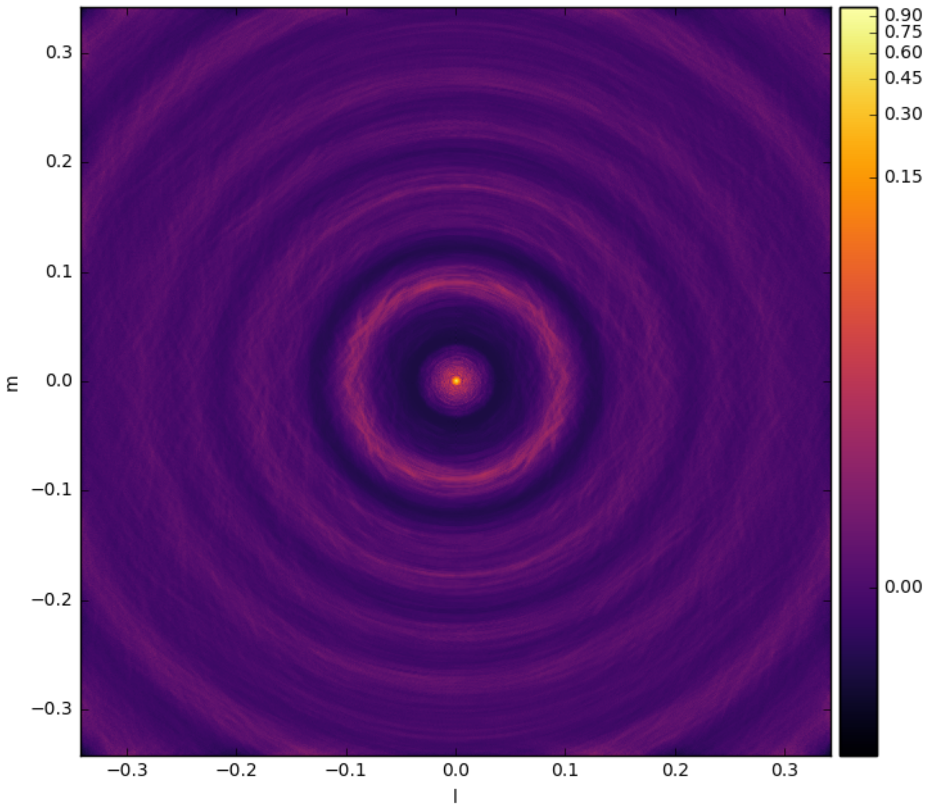
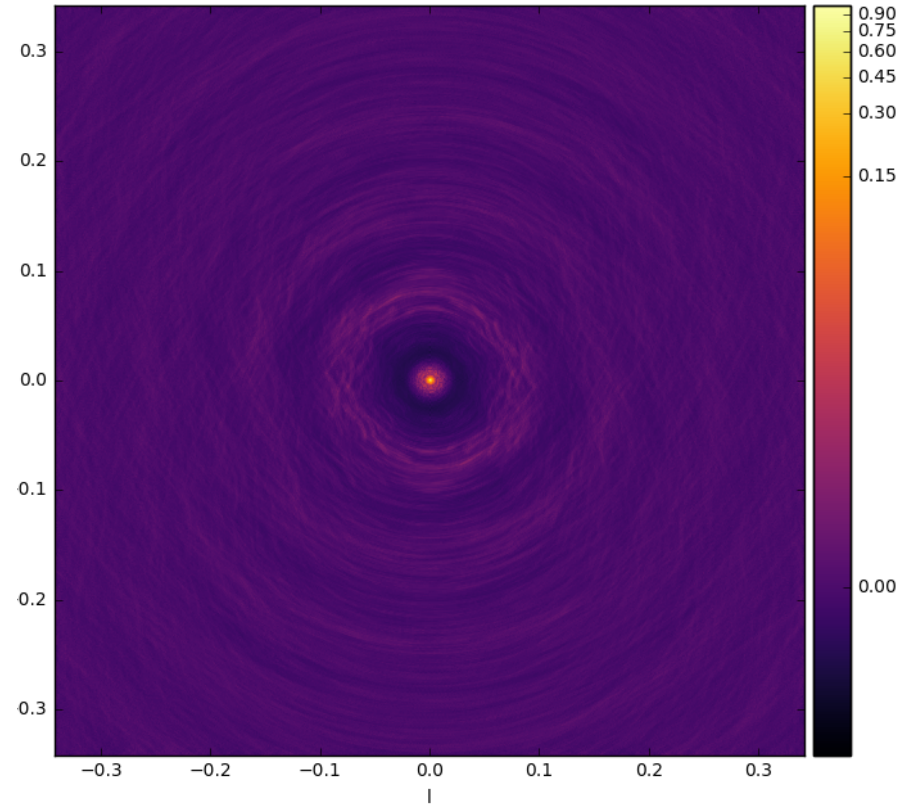
V4D vs. V4O1 4-hour PSF (40 deg FoV)

V4D



V4O1



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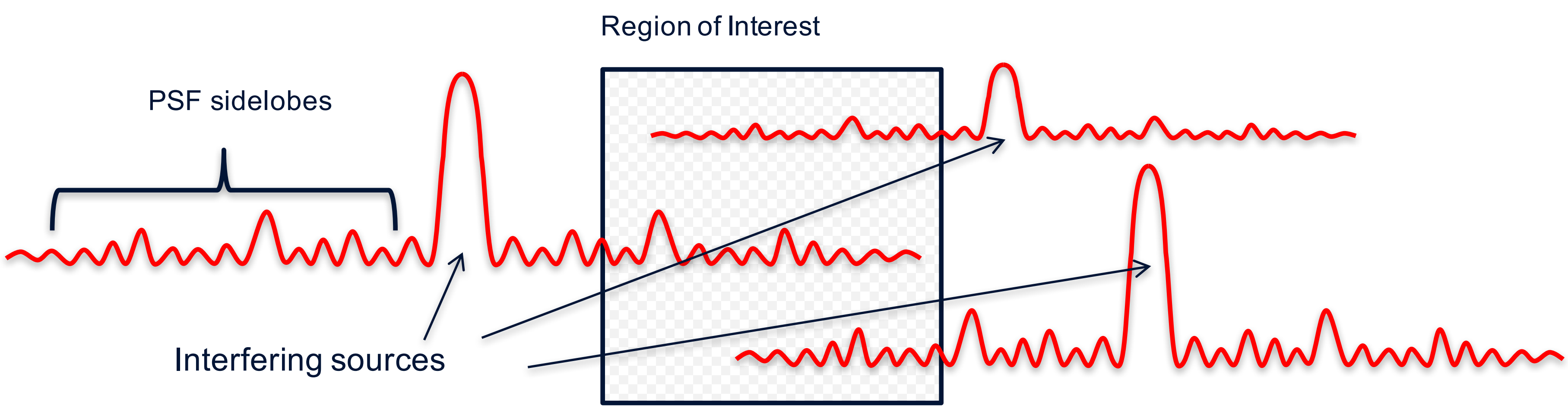
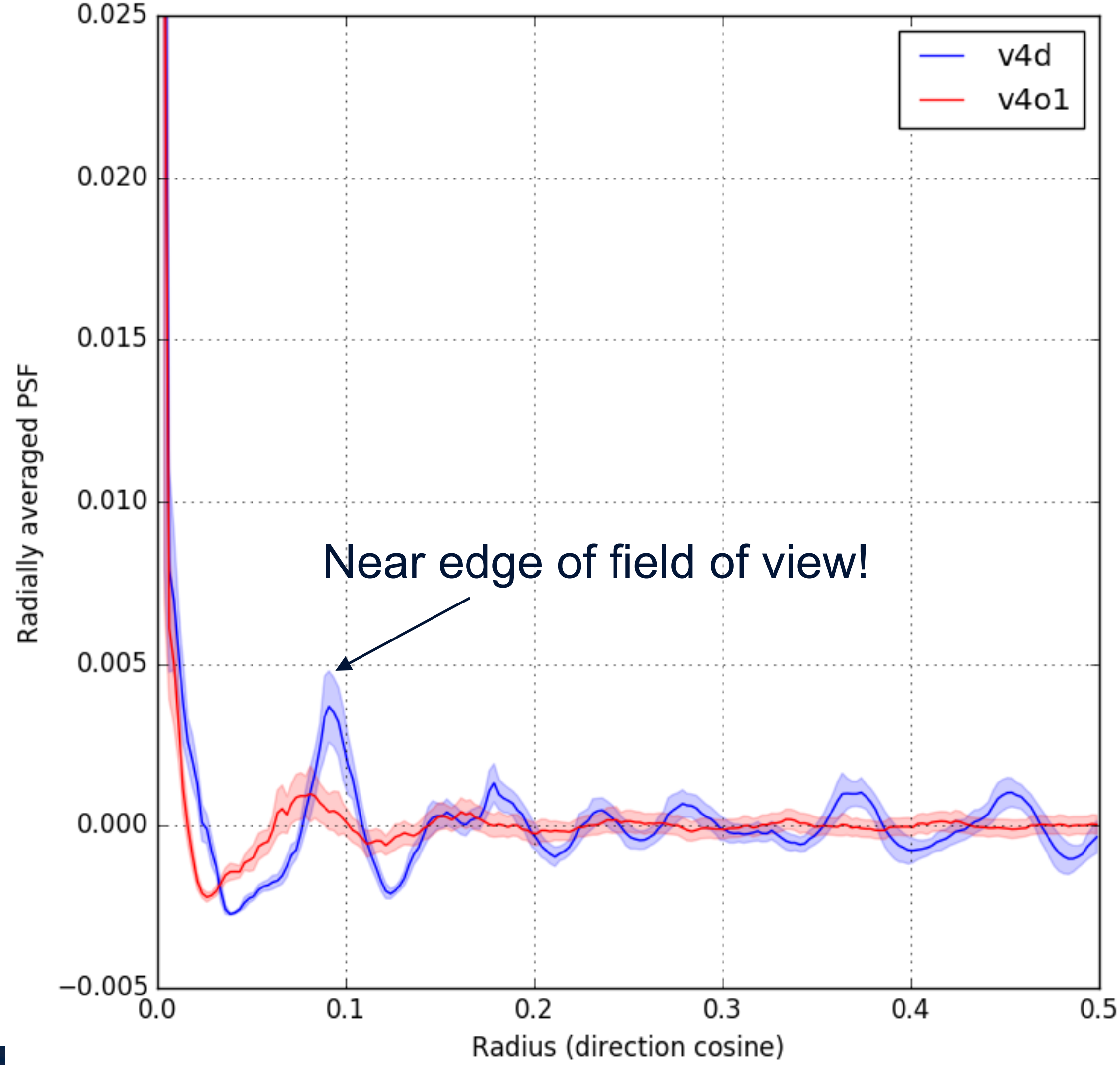
Far Sidelobe Confusion Noise

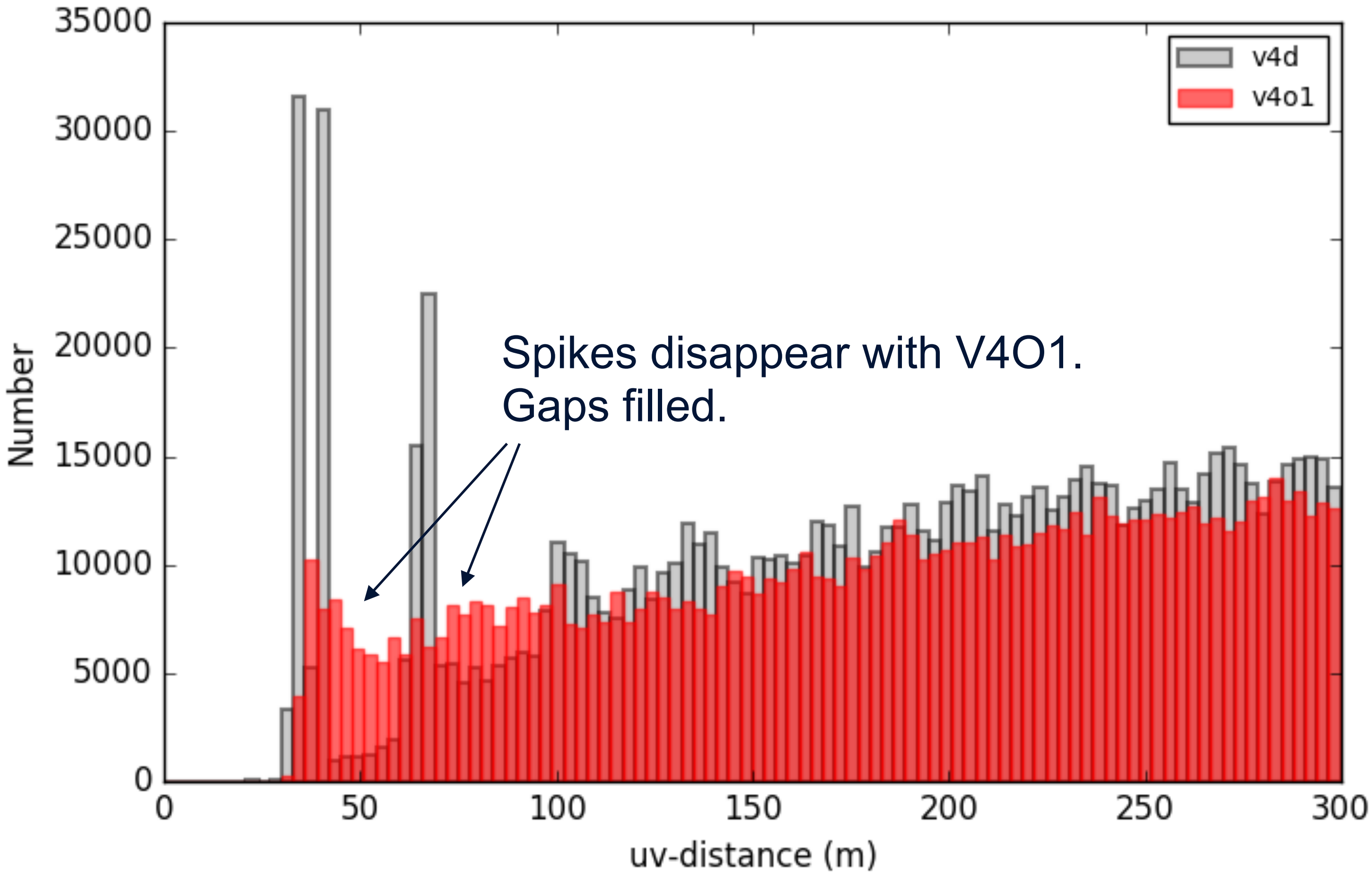


Higher PSF sidelobes will give rise to higher noise in the field from sources far away.

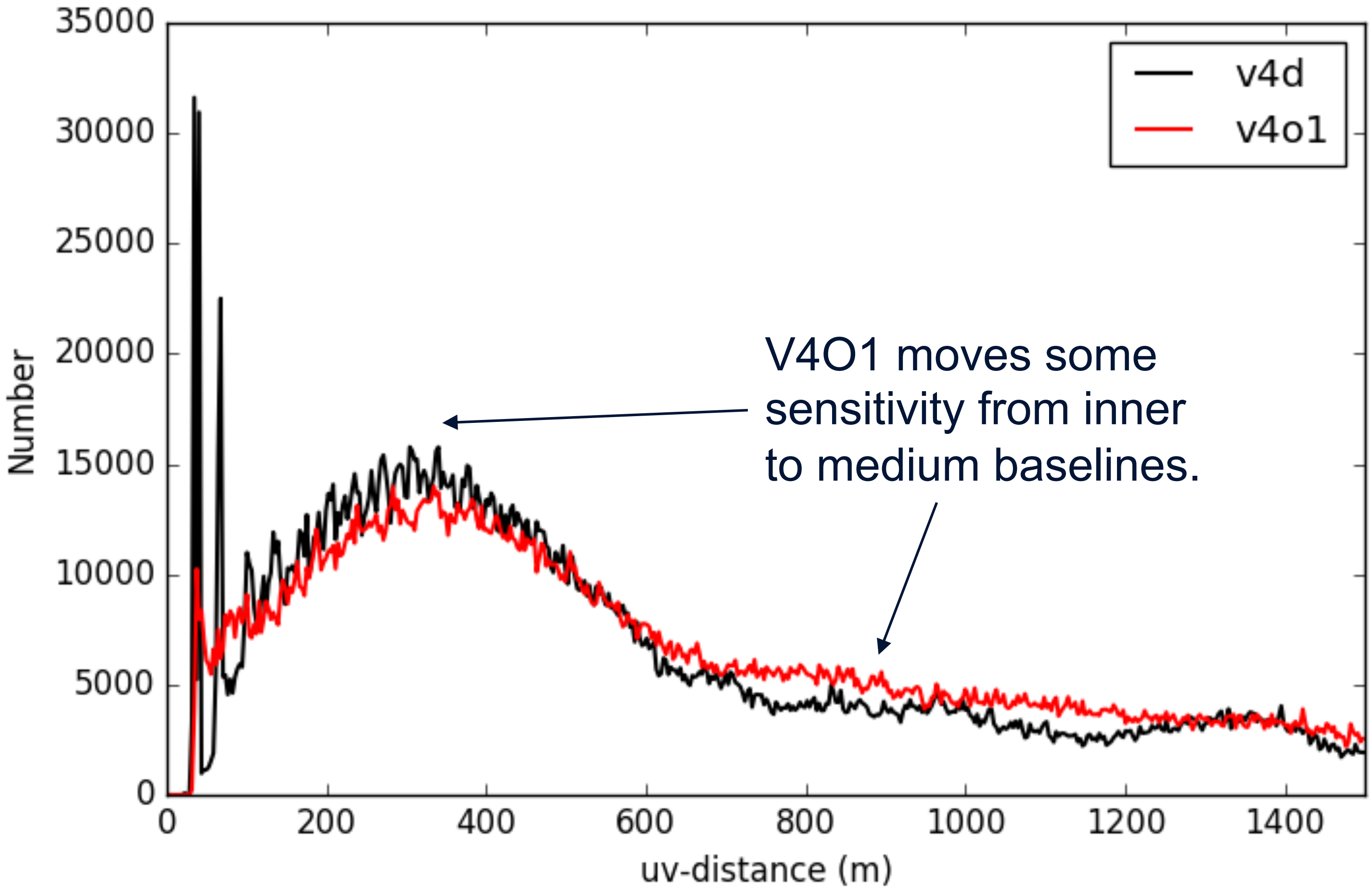
V4D vs. V4O1 4-hour PSF



V4D vs. V4O1 4-hour UV Distribution

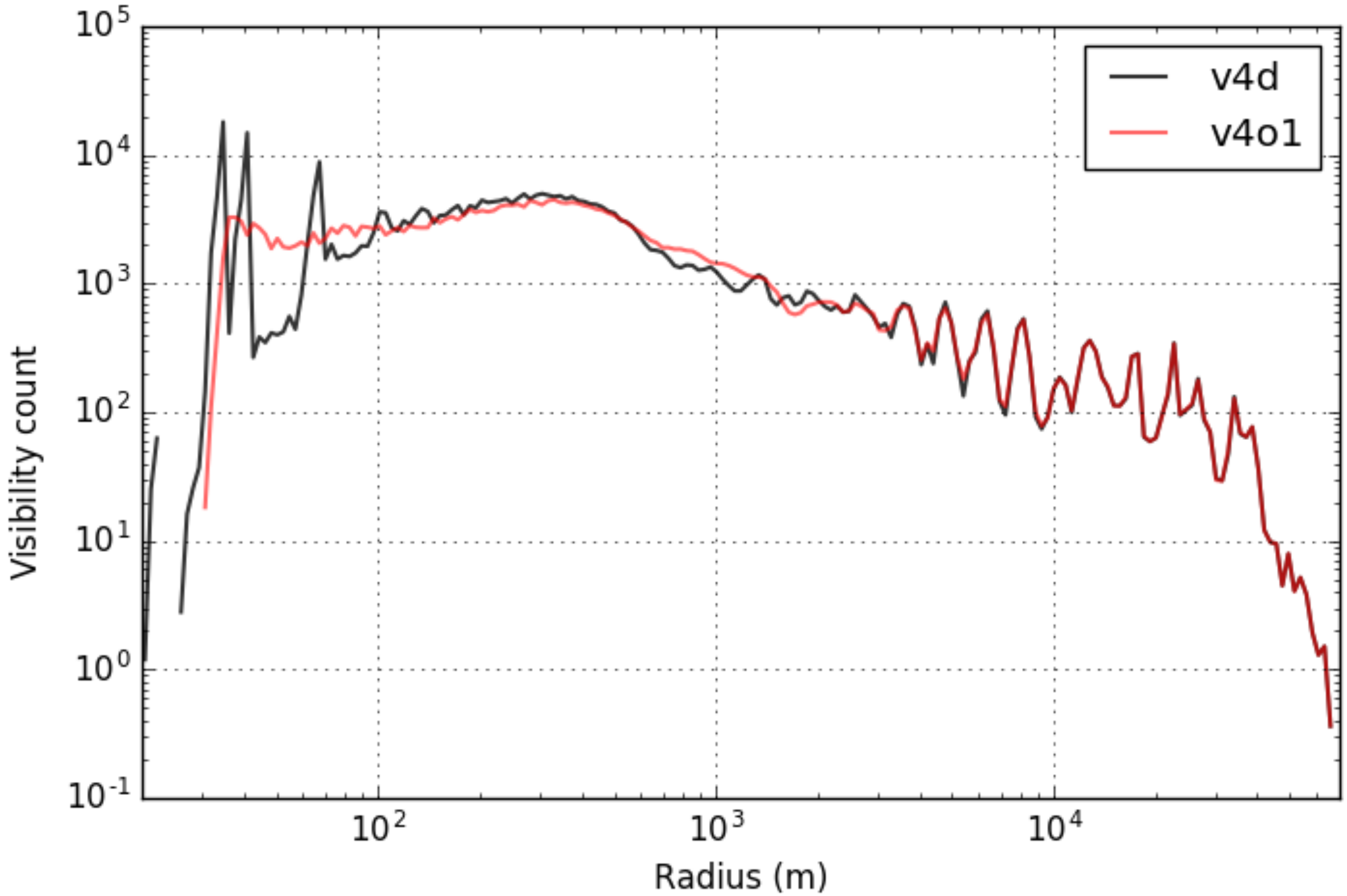


V4D vs. V4O1 4-hour UV Distribution



V4O1 moves some sensitivity from inner to medium baselines.

V4D vs. V4O1 4-hour UV Distribution



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V4D vs. V4O1 UV Coverage

- V4O1 moves a bit of sensitivity from innermost to medium baselines.
  - Is this a problem?
  - Need to match with expected EoR power spectrum.

- V4O1 is a better approximation to a scale-free instrument.
  - SDP will spend some effort providing a Fast Imaging pipeline.
  - Better instantaneous PSF.
  - Better for general-purpose imaging (without mosaicing…)

Mosaicing: Limiting Angular Scales

- Mosaic to recover flux on angular scales comparable to the primary beam.

$$\theta_{PB} \sim \frac{\lambda}{D}$$

Field of view from primary beam

$$\theta_{LAS} = \frac{1}{2}\frac{\lambda}{b_{\min}}$$

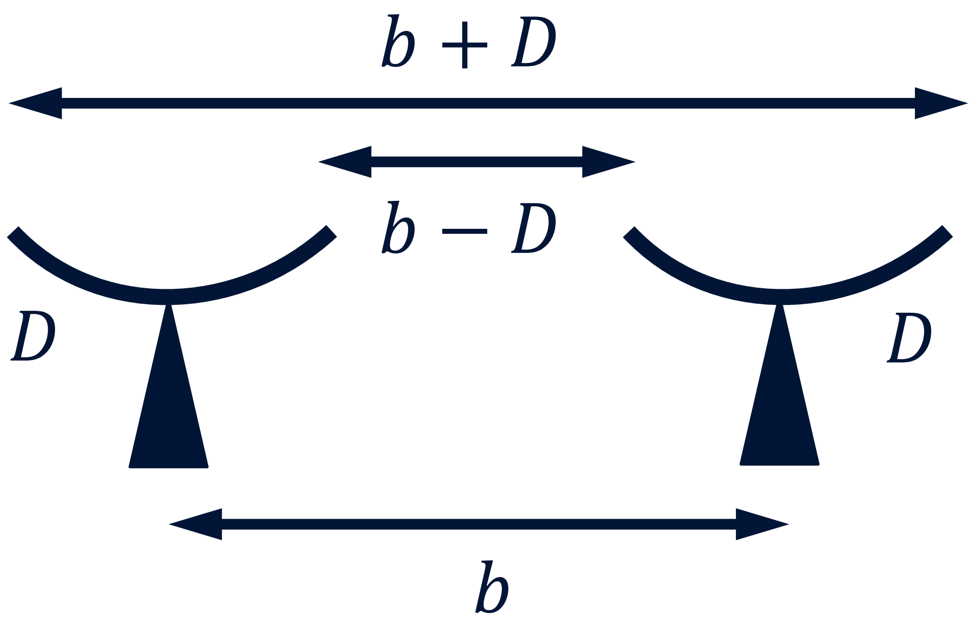
Largest angular scale of the sky brightness measured by the interferometer

$$\theta_{LAS} \leq \frac{1}{2}\frac{\lambda}{D}$$

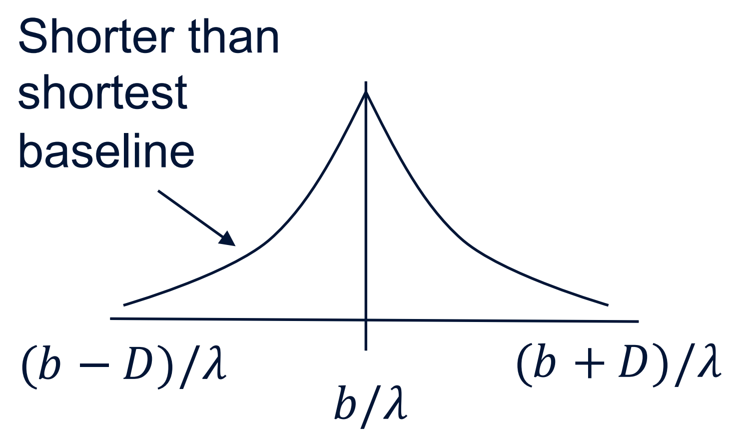
Limiting case

Mosaicing: Ekers & Rots Theorem

- An interferometer baseline of length b doesn't just measure the angular scale $\theta = \lambda/b$.
  - It also measures everything between $\theta = \lambda/(b - D)$ and $\theta = \lambda/(b + D)$



Single baseline UV coverage:

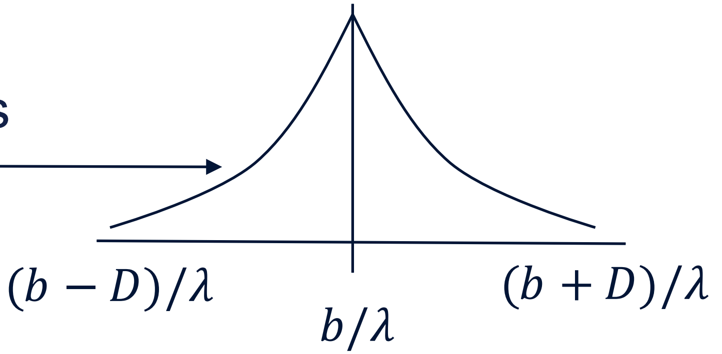


Mosaicing: Ekers & Rots Theorem

- How to recover this information when we have only a single complex visibility?
- Measure it multiple times by scanning the interferometer over the sky.
  - Effectively introduces a phase gradient across samples in the visibility plane.
  - Has effect of re-weighting the visibilities in a way that allows recovery of the extra spatial scales.

- But away from the mid-point, sensitivity drops off, so these scales cannot be measured as well.

Single baseline UV coverage:



Mosaicing: Ekers & Rots Theorem

- Nominal UV coverage (delta functions) must be convolved with aperture illumination function to represent what is actually measured when mosaicing
  - i.e. Fourier transform of primary beam.

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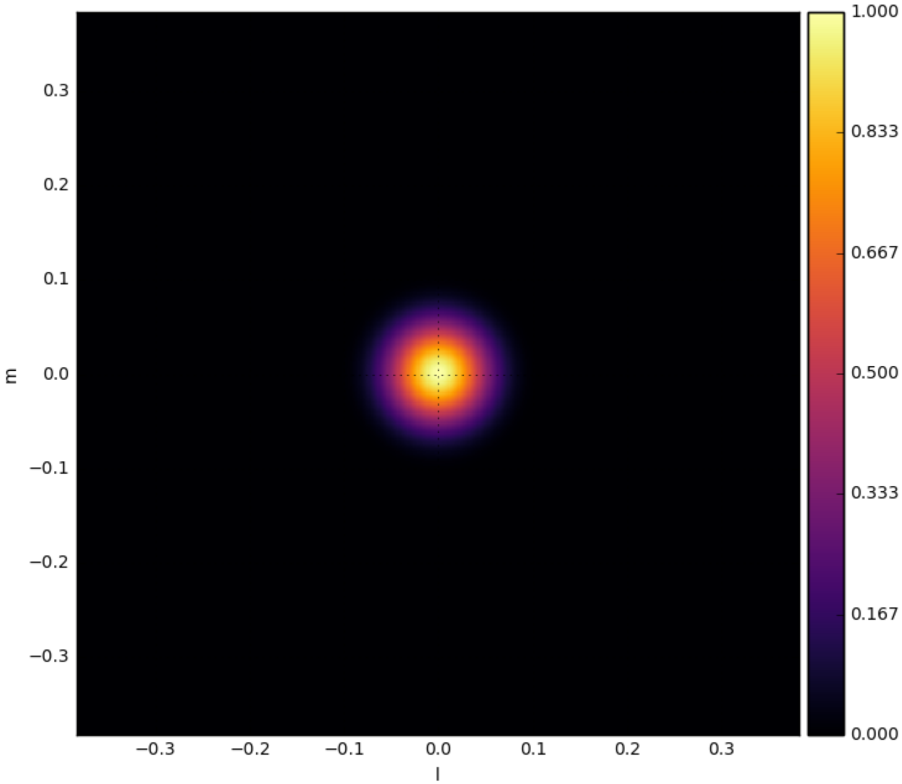
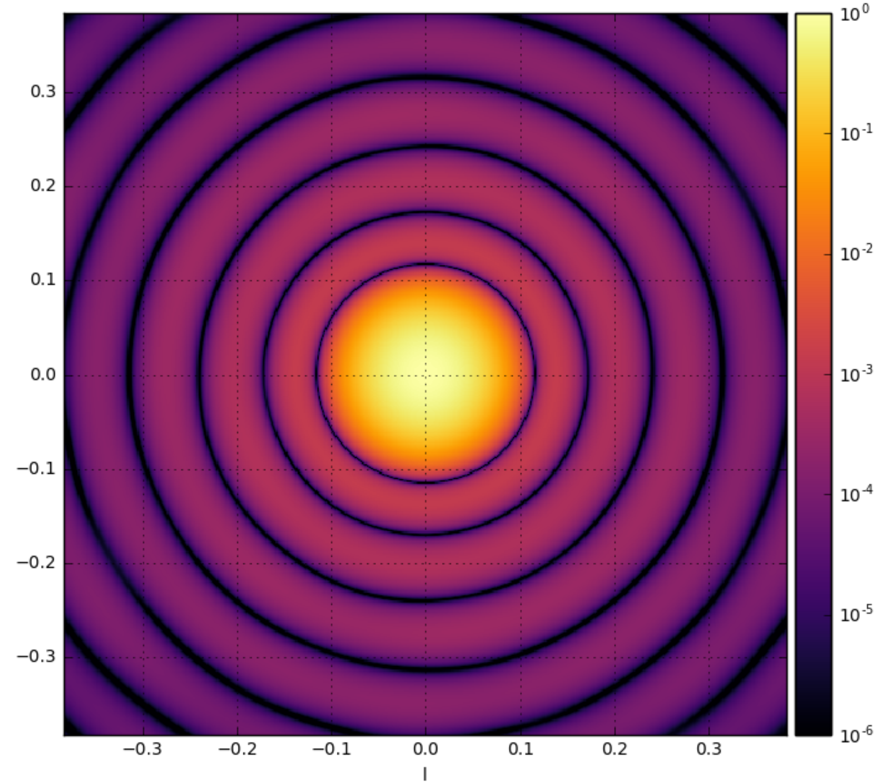
Cross-power station beam (45 deg FoV, 120 MHz)

Linear



Logarithmic



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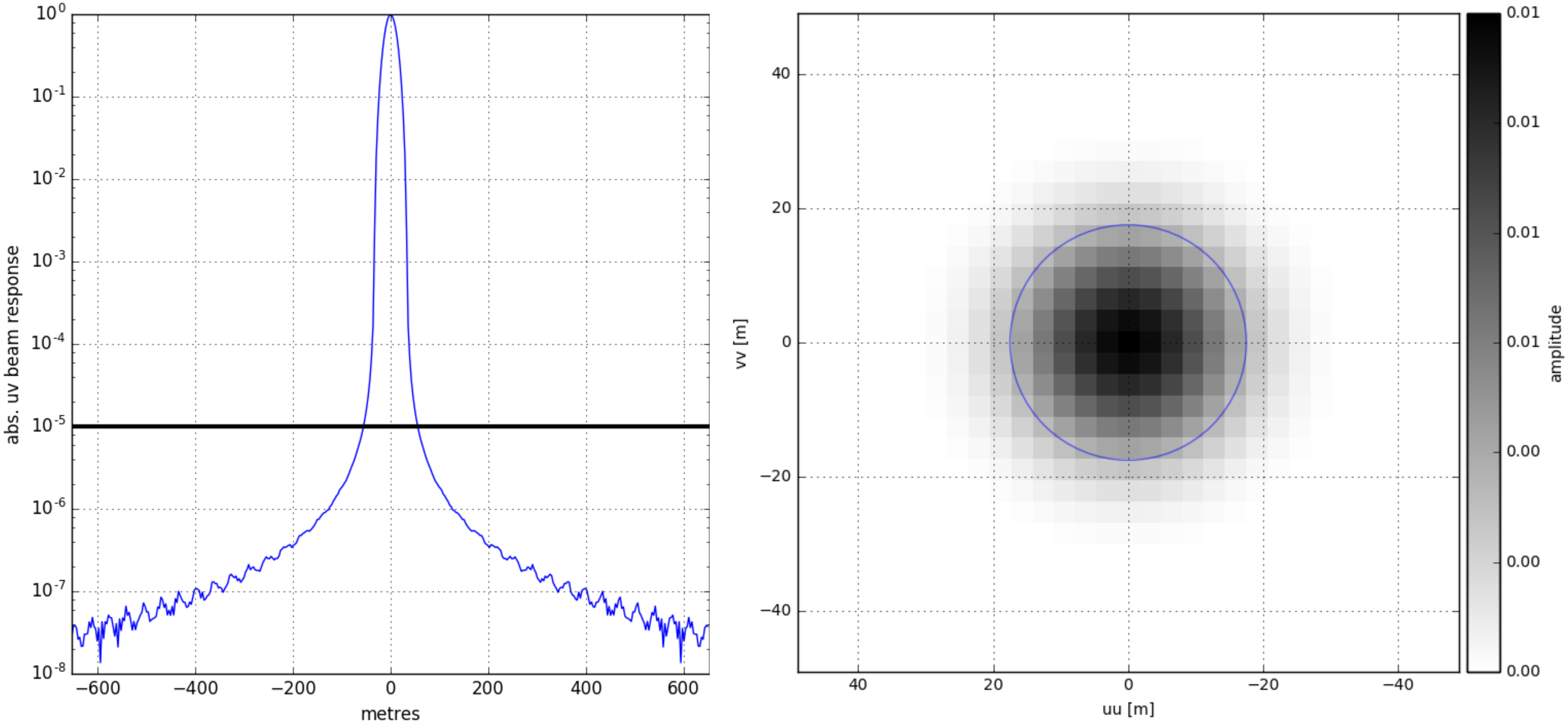
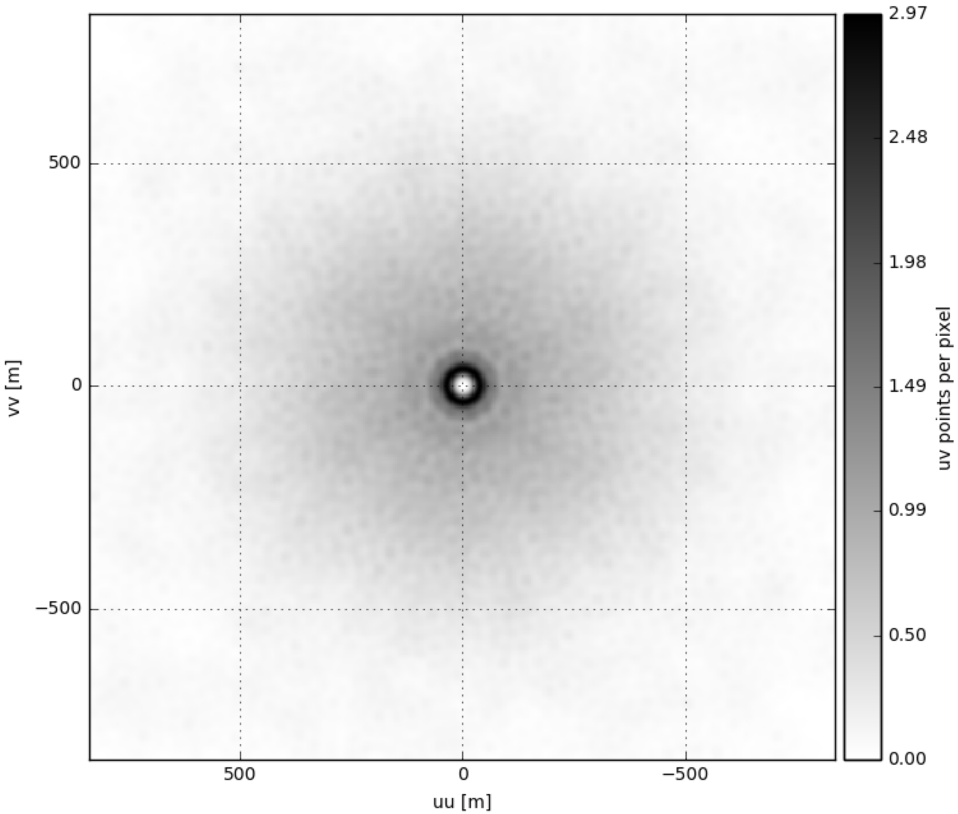
Cross-power station beam FT

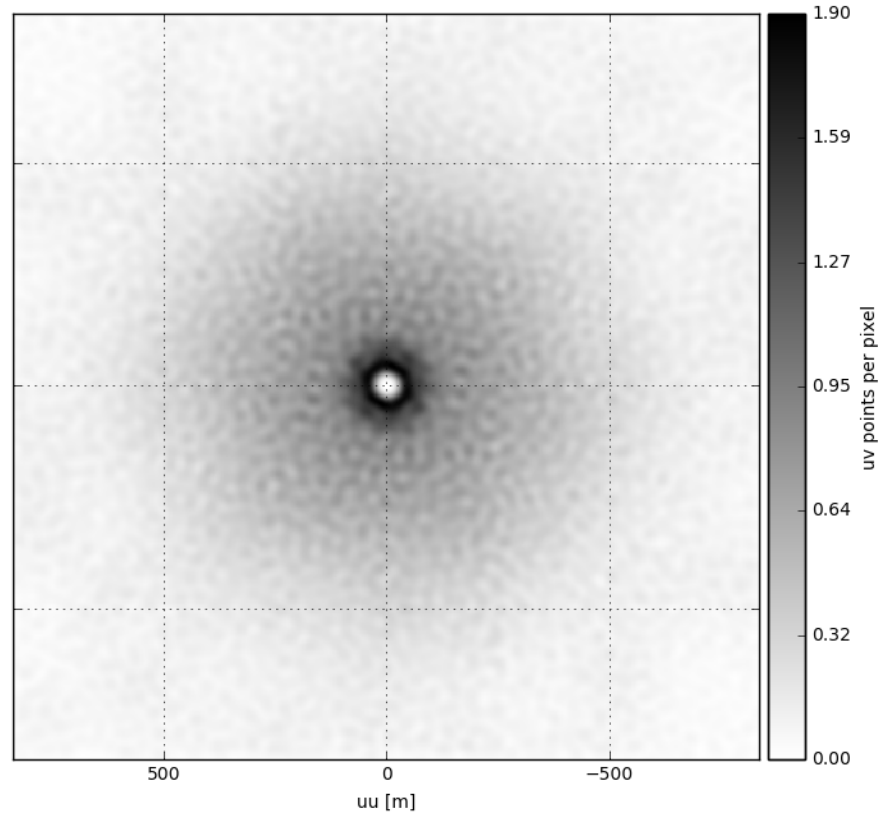


V4D vs. V4O1 Snapshot UV Coverage (convolved with FT(PB))

V4D



V4O1



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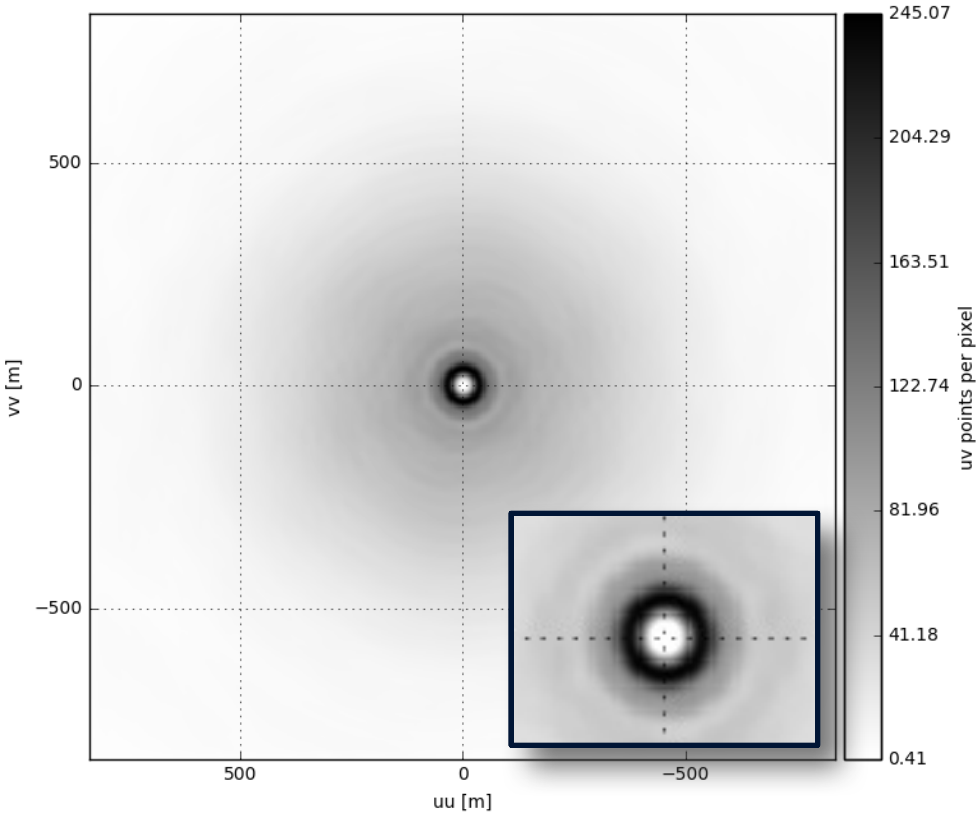
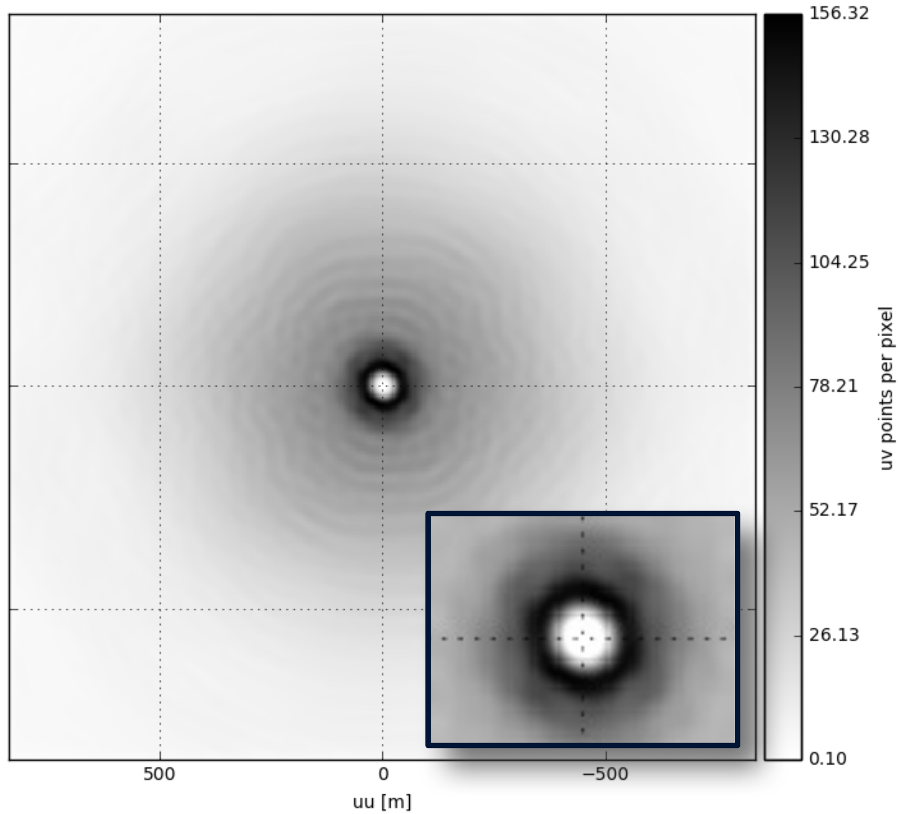
V4D vs. V4O1 4-hour UV Coverage (convolved with FT(PB))

V4D



V4O1



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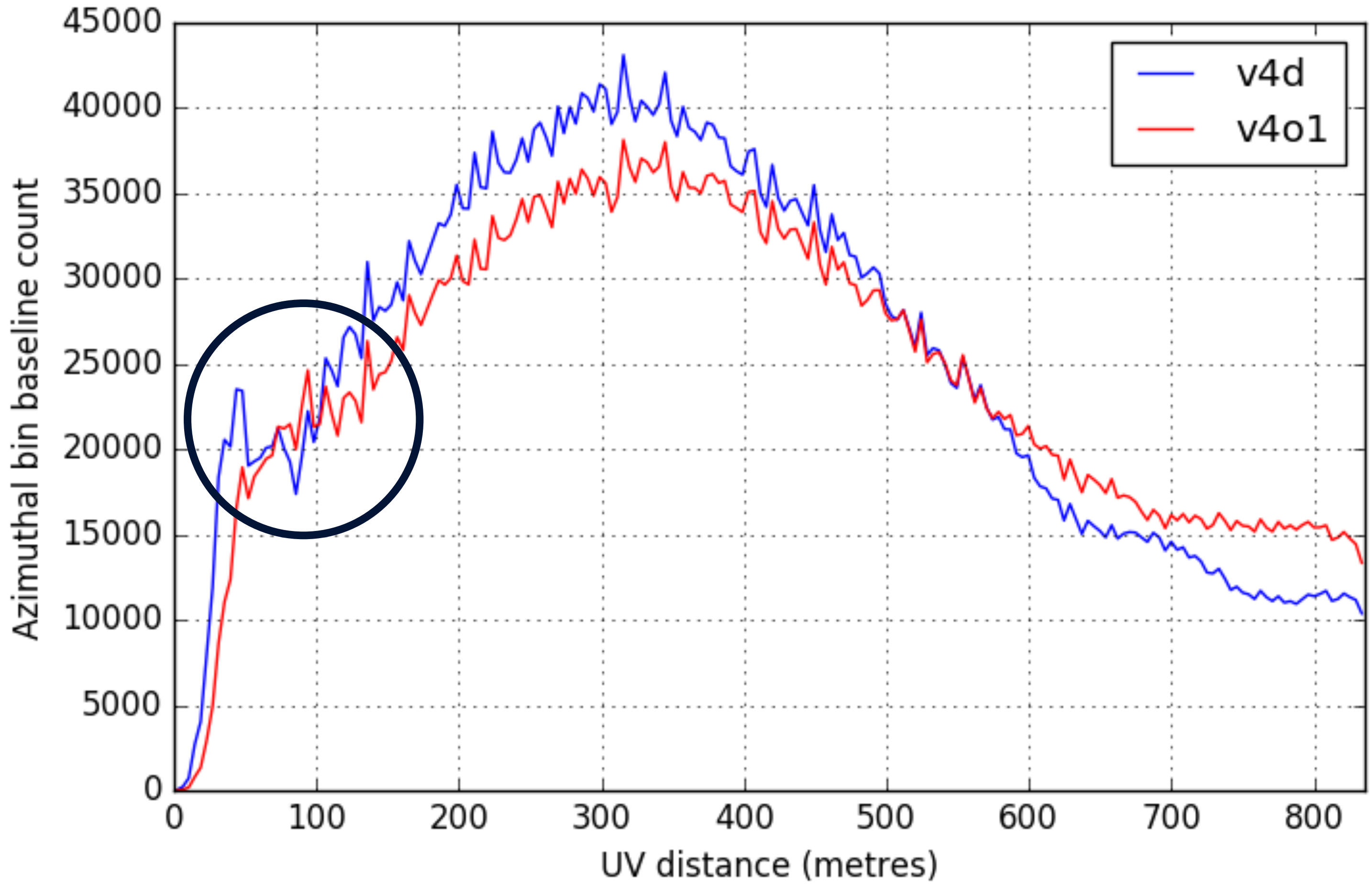
V4D vs. V4O1 4-hour UV Distribution (convolved with FT(PB))



Summary & Next Steps

- V4O1 is a better scale-free instrument than V4D for non-mosaiced observations…
- … and little to choose between them when mosaicing.

- Far-sidelobe confusion noise should be lower with V4O1 when using a fast imaging pipeline.
- Happy to provide any amount of input to support design decisions.
- How to improve on V4O1?
  - Even more dense inner core.
  - Slightly spread out stations on inner spiral arms if possible.