Primary Beams & Radio Interferometric Imaging Performance

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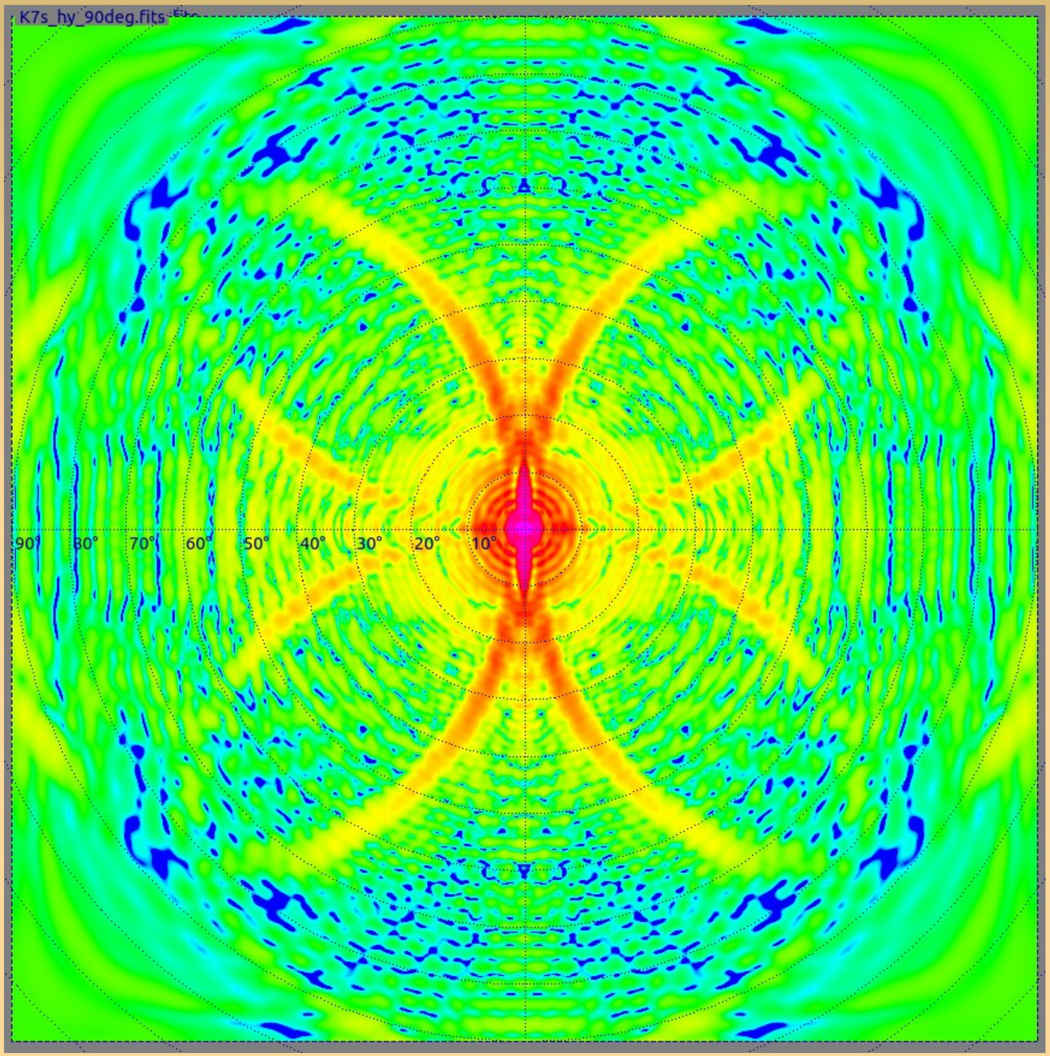
Introduction

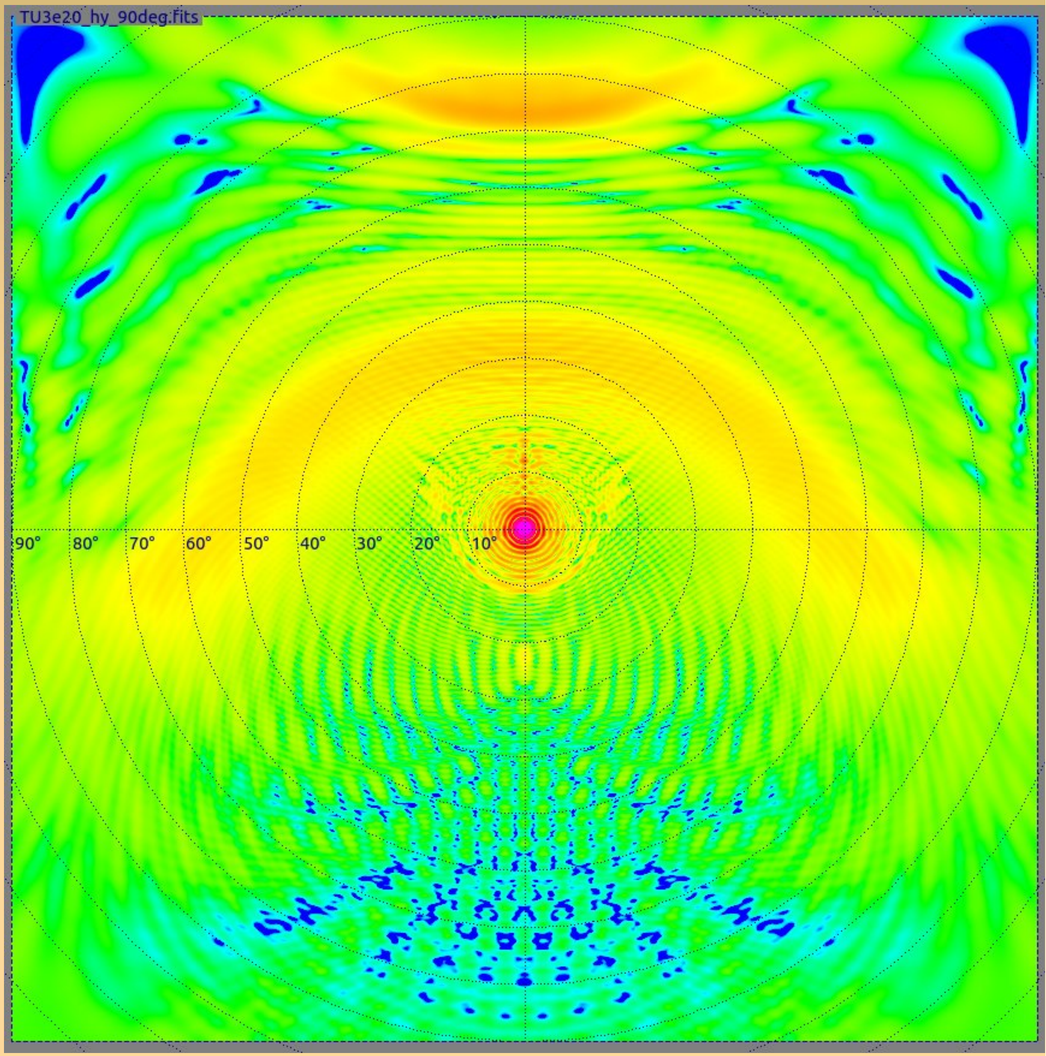
- SKA Dish CoDR (2011), as summarized by Tony Willis:
  "My sidelobes are better than your sidelobes."
- What makes "good" sidelobes, anyway?
  - or more broadly, a "good" primary beam (PB)?
  - important for dishes and AAs
- Big gap between our understanding of scientific performance and engineering specs
- Difficult to make progress analytically
  - Though see talks by Tobia, Stefan

BeamSims: the MeerKAT Context

- KAT-7 pathfinder uses prime focus (PF) design
- Offset Gregorian (OG) design chosen for final MeerKAT dish (end 2010)
  - ...with final refinements (shaped vs. unshaped, illumination strategy) put off until later
- Present work (BeamSims) attempts to measure relative performance via simulations
- Same methodology highly relevant to AAs, so most things I mention today directly apply

MeerKAT BeamSims
Prime focus vs. offset Gregorian





Pick your poison?

What Limits Dynamic Range?

- Thermal noise ~ T_{sys}/A_{eff}, BW, integration
  - lucky if we can reach it
- Classical confusion ~ resolution
- Far sidelobe confusion noise (FSCN)
  - ← PB sidelobes
- Residual calibration artefacts (calibration "noise")
  - ← PB sidelobes
  - ← other PB properties (?)

} this talk

Sidelobe Confusion Noise

- PSF is in principle unbounded, so every pixel contains contributions from all sources in the sky
  - Needs deconvolution (for sources within the image)
- Distant sources are attenuated by
  - PSF sidelobes $\rightarrow 0$
  - PB sidelobes $\rightarrow 0$
  - Time/bandwidth smearing
- LOFAR, WSRT LFFE: brightest (A-team) sources almost always visible, at any distance
- At SKA sensitivities, we start to worry about the far more numerous fainter sources

Far Sidelobe Confusion Noise

- No such thing as an “empty” field:
  - You may image and deconvolve to a radius r_0 from the phase centre
  - ...but even assuming perfect deconvolution (ha ha)...
  - ...each pixel will have a non-zero, noise-like contribution from the “sea” of sources at $r > r_0$
  - This is *far sidelobe confusion noise* (FSCN)
- In principle, can be driven down by imaging and deconvolving the entire sky
  - hard limit with single pointing (sink into the noise!)
  - this is a serious cost driver

Primary Beams & FSCN

- Does choice of PB influence FSCN?
  - of course, PB sidelobes are a modulator
- So how do we
  - estimate this
  - quantify this
  - ...and turn it into a performance metric?

BeamSims

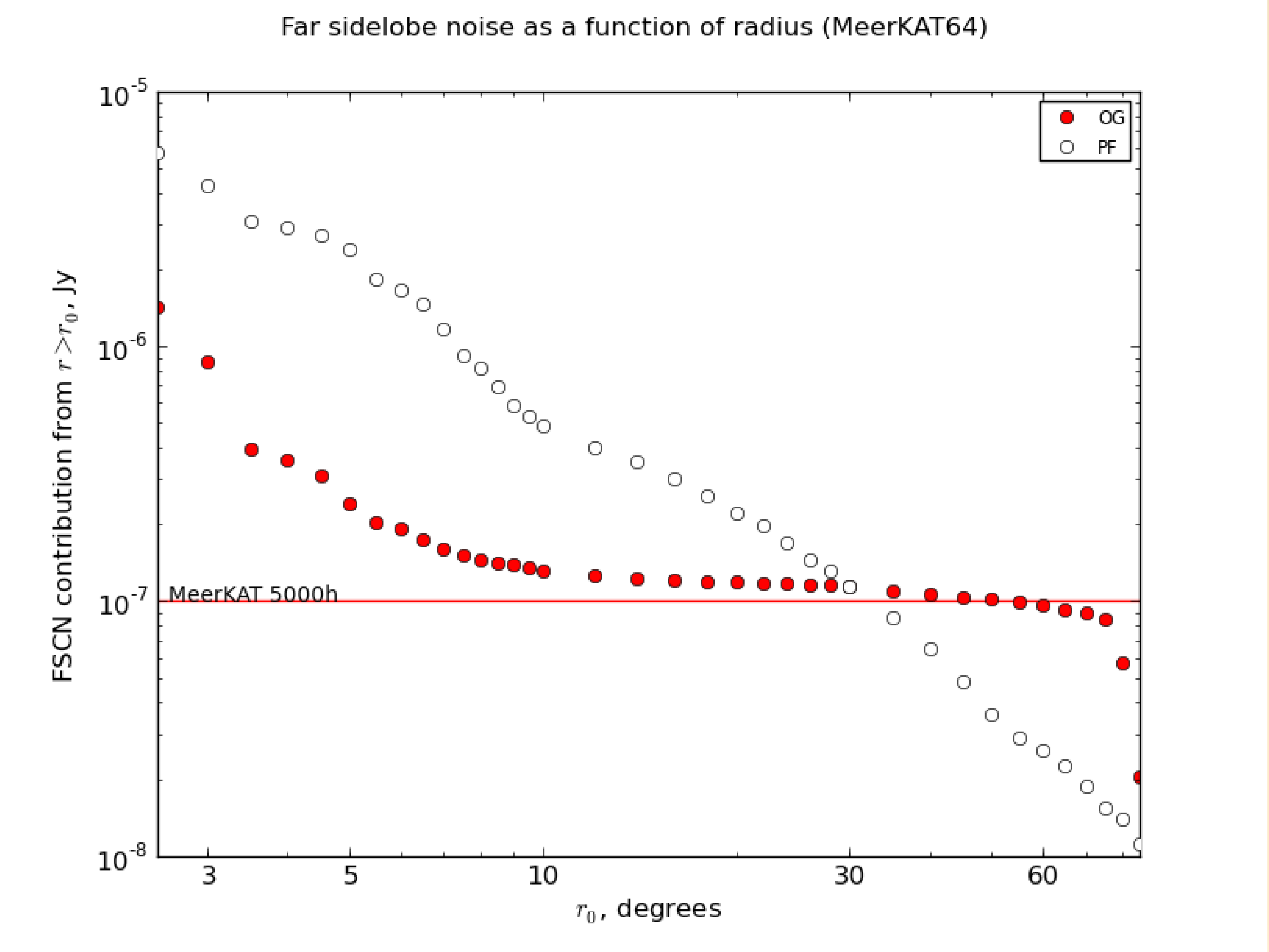
- Strategy: “brute force” interferometric simulation
- NVSS: a realistic all-sky LSM
  - Cutoff *I>.5* Jy (for performance reasons)
  - Use S^3-SEX to derive correction factor (to account for sources <.5 Jy)
- Use full-EM PB simulations provided by EMSS
  - full 2x2 complex voltage patterns, given as gridded “images” (in spherical coordinates)
- MeqTrees module interpolates per-source beam gains, and generates visibilities

Doughnut LSMs

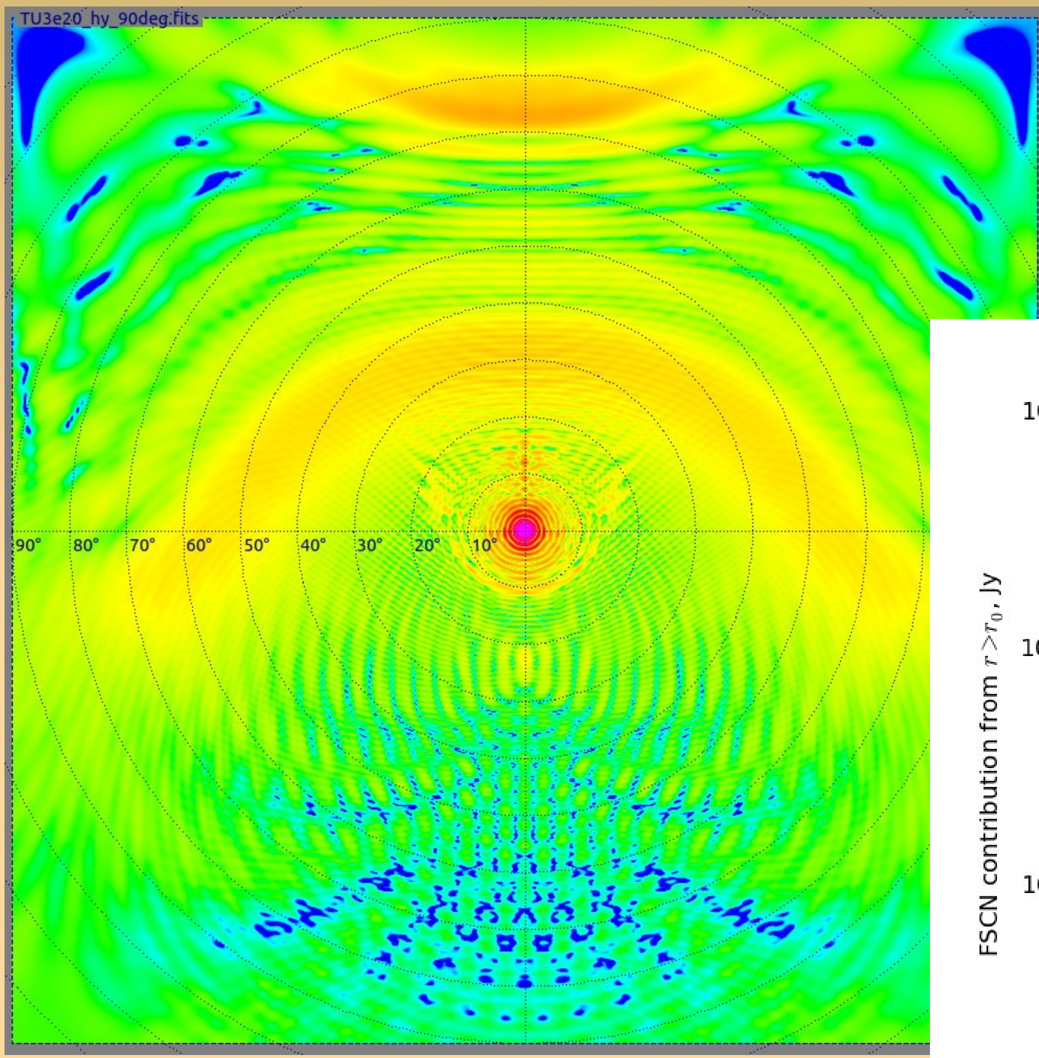
- Split the sky into *n* rings
- For each ring *i*, simulate sources at $r_i \le r < r_{i+1}$
  Image the [nominally] empty sky in the middle
- The rms pixel value is the FSCN contribution from ring *i*

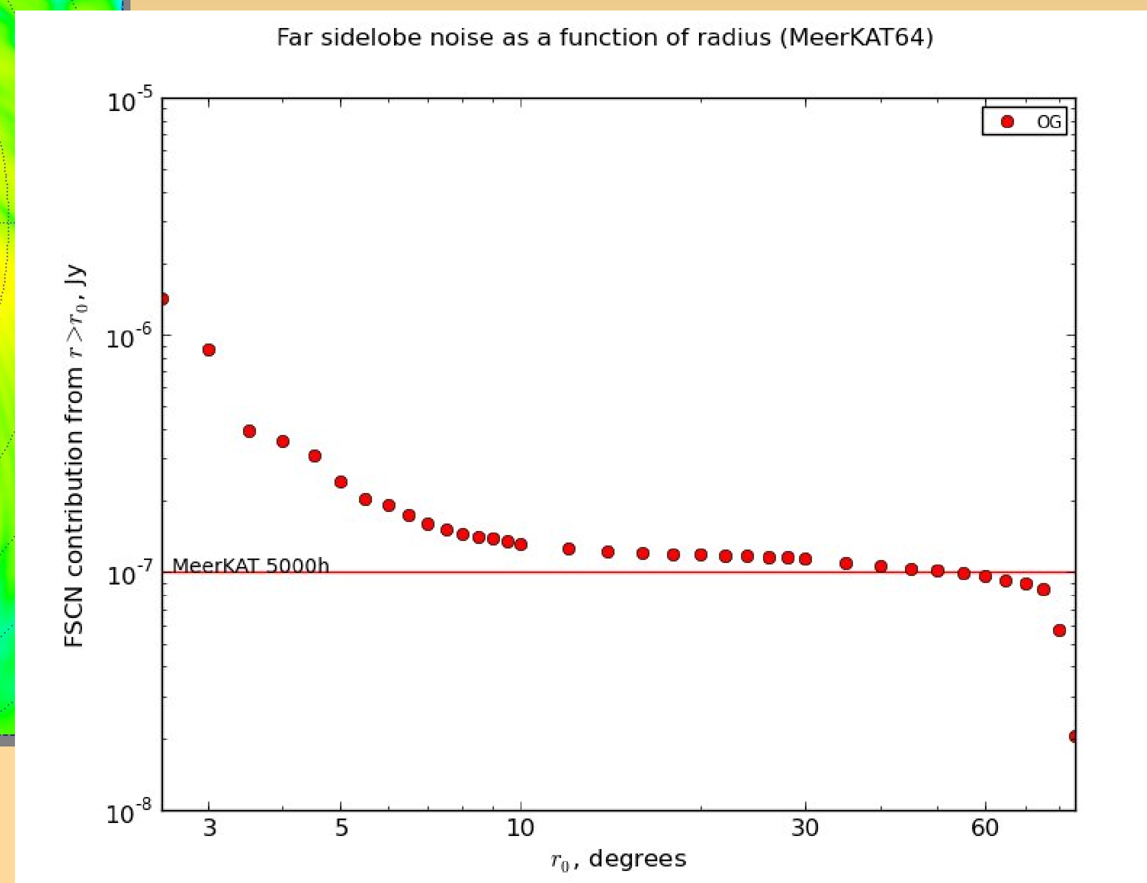
FSCN Cost Curves

- This shows, as a function of r, the FSCN contribution from sources $r \geq r_0$
- i.e. how far out do we have to image & deconvolve to drive FSCN below a given level?

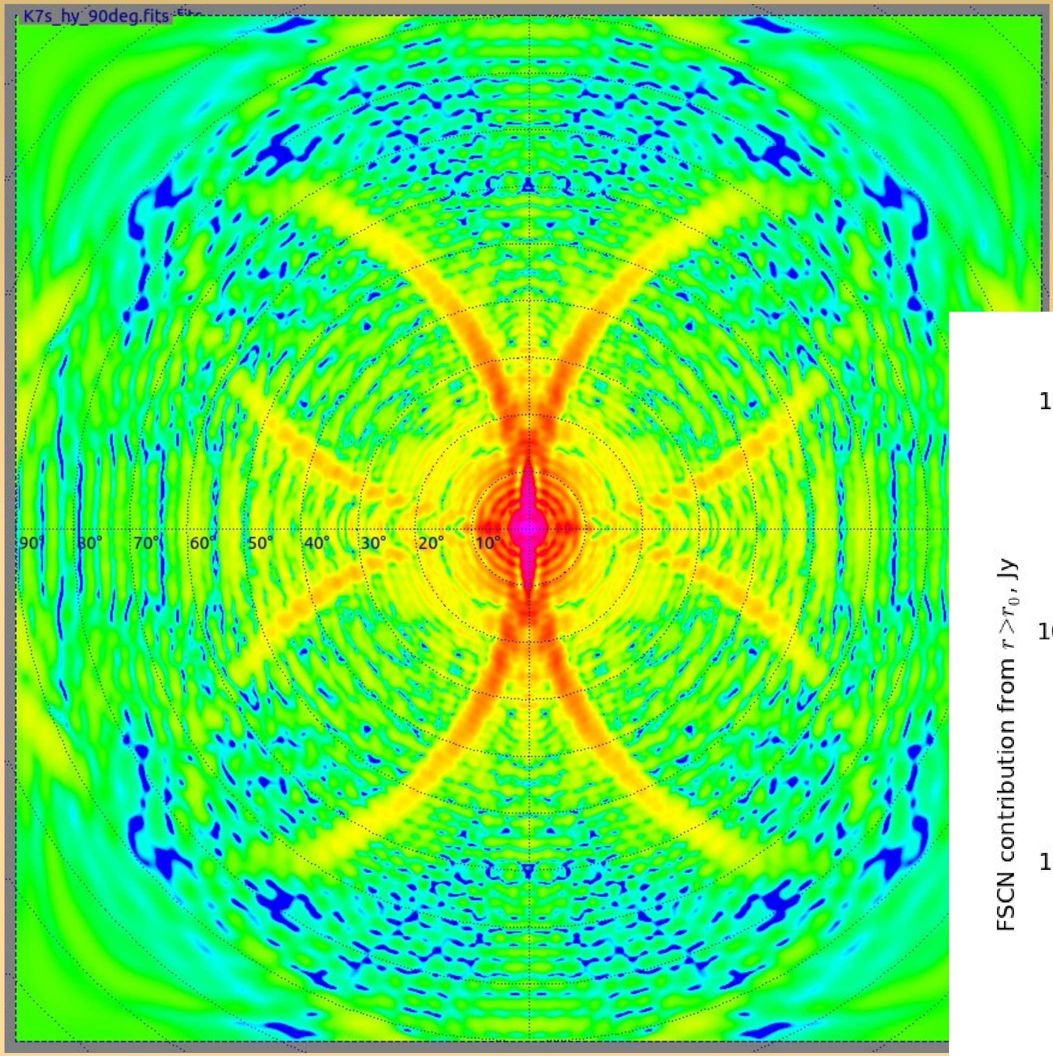


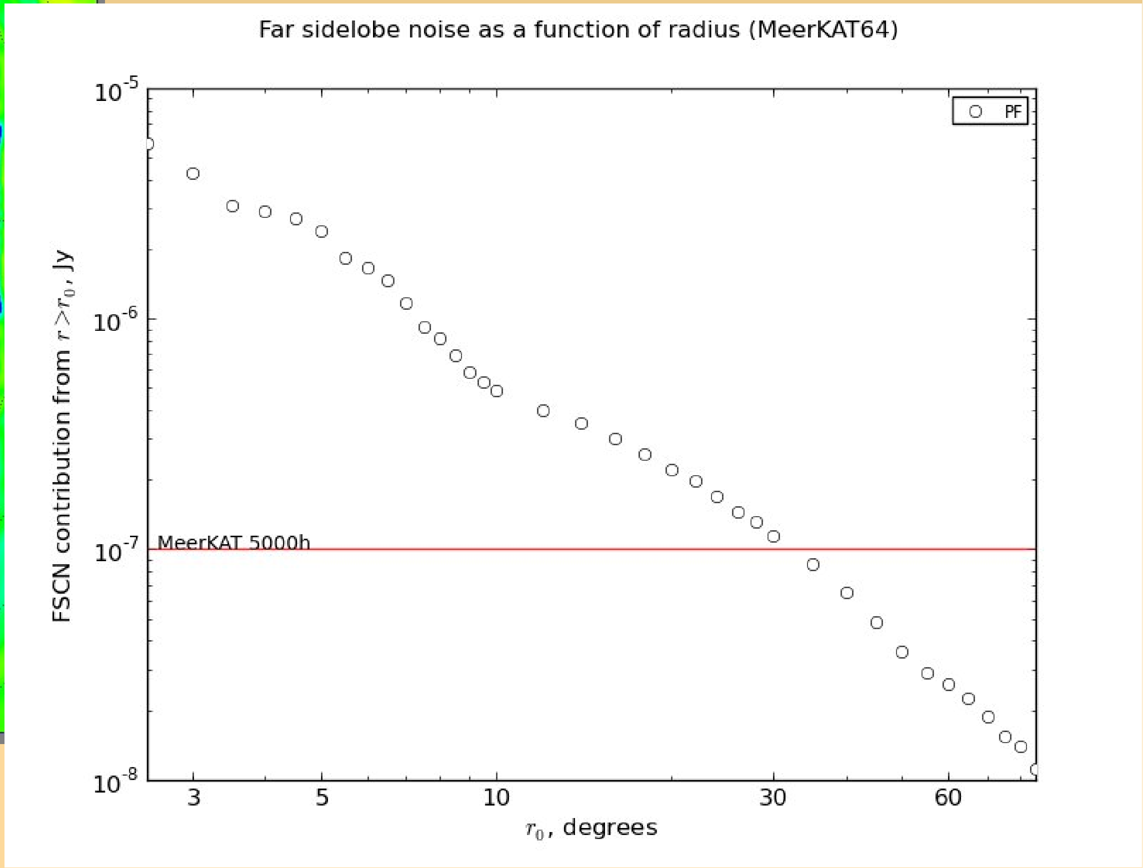
Cost Curve: Offset Gregorians





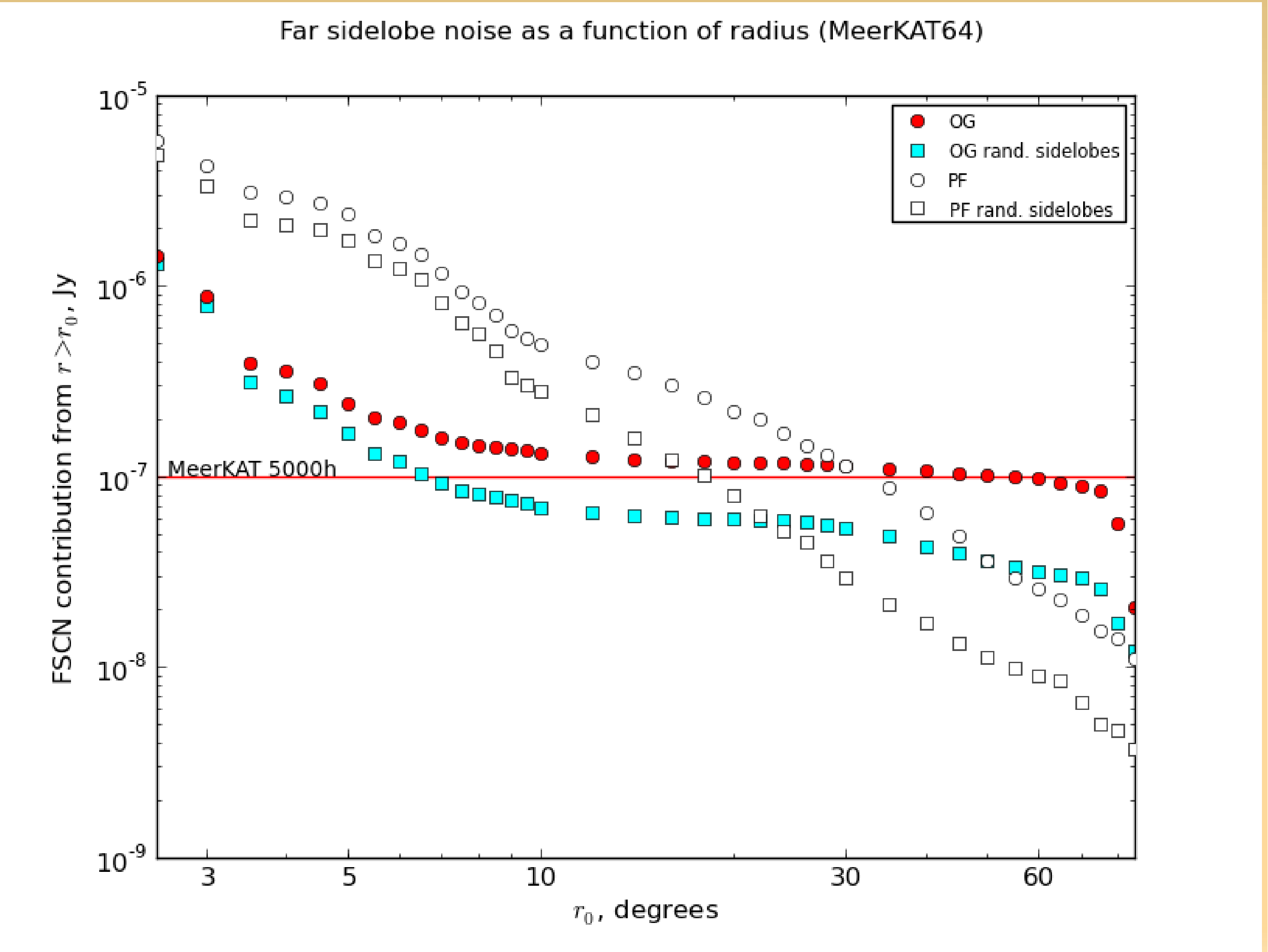
Cost Curve: Prime focus





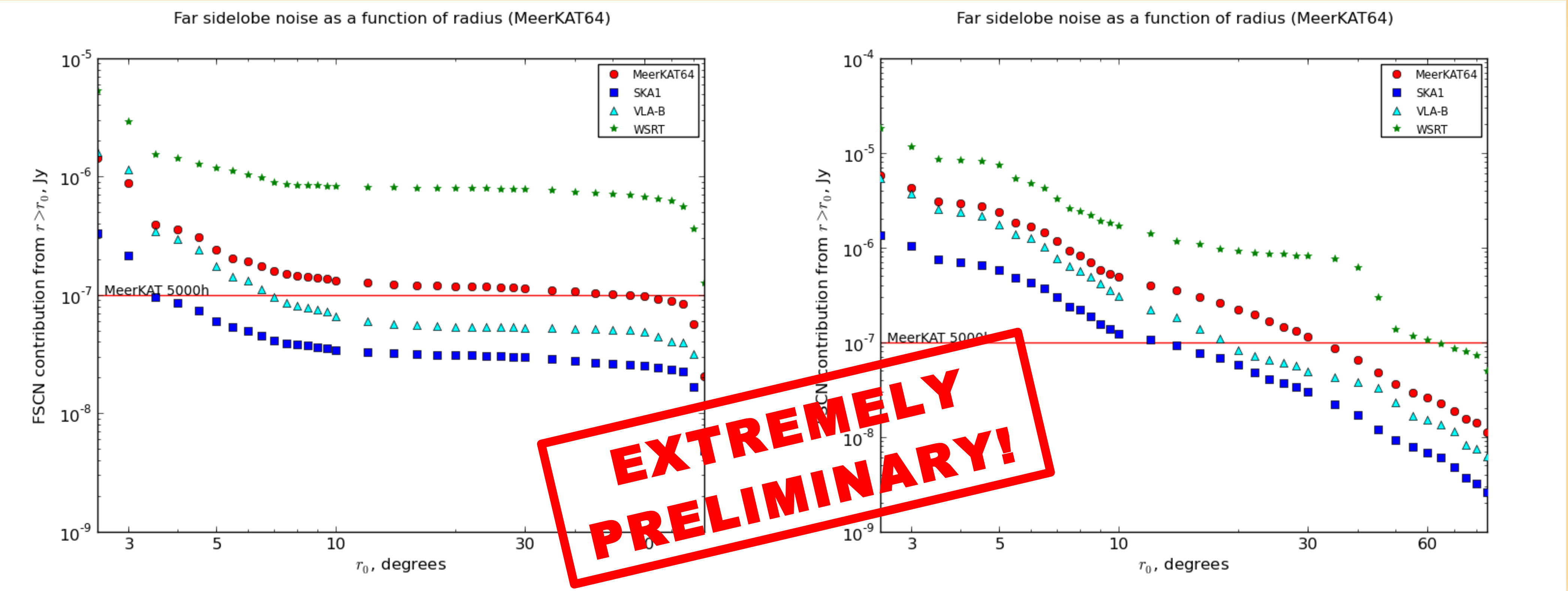
Randomizing Sidelobes

- This shows the effect of randomizing dish orientations



FSCN & Array Size

- Same simulation for OG/PF dish with WSRT, VLA-B and SKA1 layouts.
- Interaction with interferometer PSF evident



Conclusions I
(for the first half of the talk)

- FSCN can be ignored for less-sensitive telescopes, but can become a DR limitation at MeerKAT sensitivities (and @SKA even more so)
- FSCN induces a computing cost vs. noise floor trade-off, as we need image larger areas to suppress FSCN
- FSCN (and the trade-off curves) can be significantly influenced by choice of primary beam
- Equally applies to AAs – need to be studied
  - OSKAR can do this faster!

Part II. Calibration “Noise”

- We have been very successful at eliminating DDE-related artefacts via direction-dependent solutions (peeling, SAGEcal, differential gains)
- And by “eliminating” we mean “driving below the (thermal) noise”
- ...by which we really mean “sweeping under the carpet”
- So, how do we estimate what we have “swept”, and can it come back to haunt us?

Distilling Out The Artefacts

- Use the NVSS + S^3-SEX to make a deep LSM (limited FoV)
- Add a pair of 1 Jy sources at the half-power point (the *contaminators*)
- Make a full interferometric simulation, including [direction independent] gains (***G***-Jones) and pointing errors (***E***-Jones)
  - of the full LSM + thermal noise → simulated DATA
  - of just the contaminators → CONTAM_DATA *<u>with the same simulated G & pointing errors</u>*

Distilling G

1. Run selfcal to obtain ***G*** solutions on DATA using some bright subset of the LSM

2. Image the residuals: this contains artefacts, noise and fainter sources. How to tease these apart?

3. Subtract the contaminators alone from CONTAM_DATA while applying these ***G*** solutions

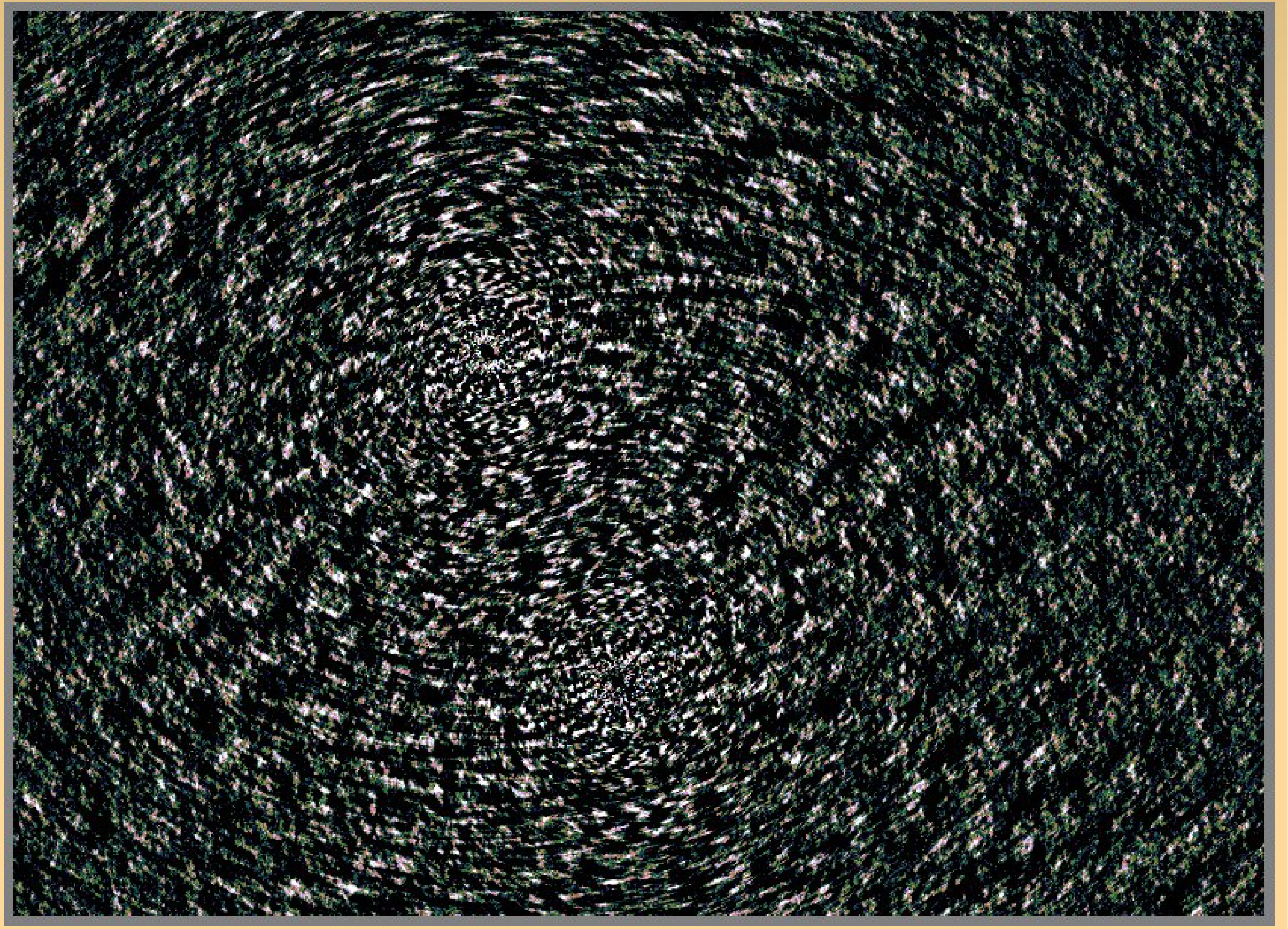
4. Make an image of the residuals from (3)

This is an image of *distilled artefacts,* i.e. exactly the contribution of the contaminator sources to image obtained at step 2.

Calibration Noise, Post-G

- We've isolated "calibration noise" per unit flux!
- Here, rms 4.2 µJy

  (but very non-Gaussian)



Distilling DDEs

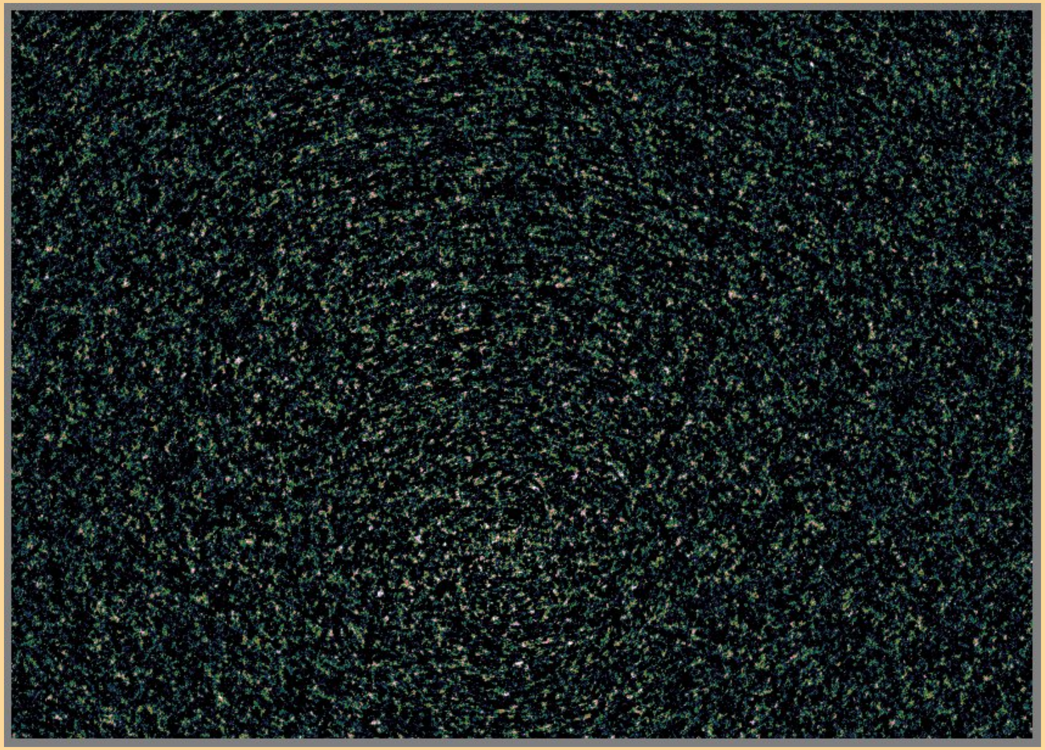
- But nevermind, because direction-dependent solutions can take care of it, right?
- If we run a ***dE*** solution on the two contaminator sources, the resulting image (of the full residuals) becomes thermal noise limited; remaining artefacts are below the noise.
- But we can repeat the same trick with CONTAM_DATA to distill them out anyway

Calibration Noise, Post-dE

- Here, rms 2.6 µJy, and far less spatially correlated

Why Do We Care?

- Just an extra noise-like contribution that's below the thermal noise, so what's the big deal?
- But it can be a big deal if its statistics are non-Gaussian



Scenario: Deep Survey

- Consider a deep survey where we obtain many pointings of the same field
  - MIGHTEE/LADUMA: 5000 hours
- Each pointing must have independent DDE solutions
  - Beam stability, ionosphere, etc. always different
  - So for each pointing we leave an independent set of calibration artefacts buried in the thermal noise
- We now combine the pointings – thermal noise adds up as √n (0.1 μJy after 5000 hours)
- How do the artefacts add up?

Distill, Rinse, Repeat

- We can repeat the distillation experiment multiple times, with different random realizations of **G/dE** errors
  - Stefcal is a huge boost here
- ...and add up the “distilled” maps

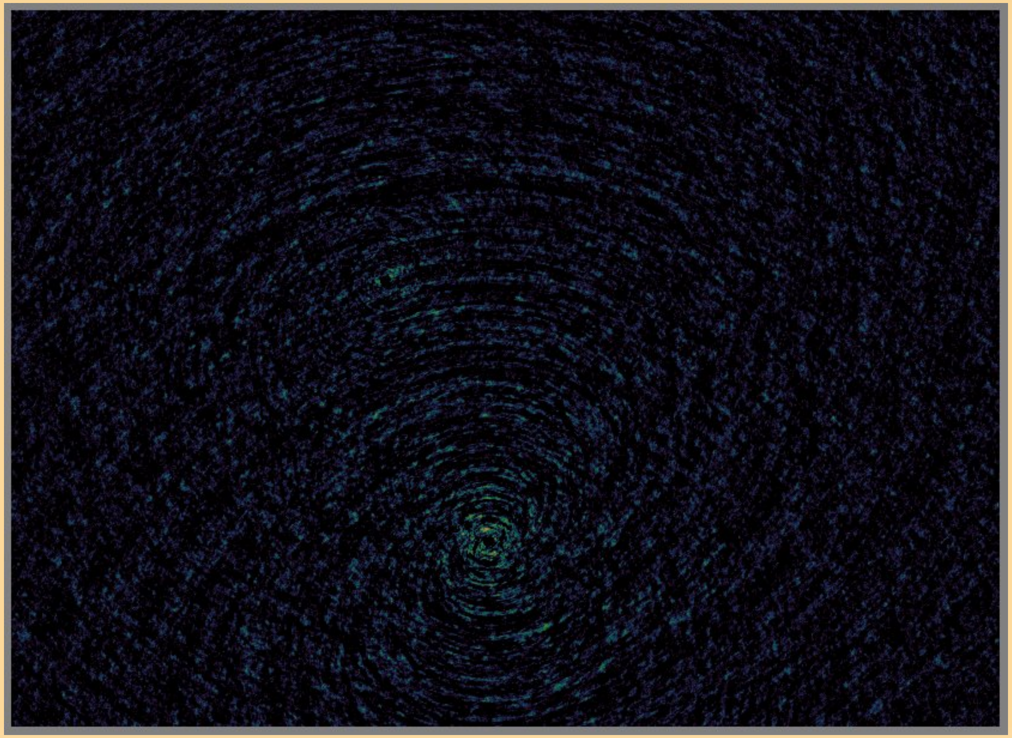
Mean Of 10 dE-Distills

EXTREMELY PRELIMINARY!

- Structure shows up
- Does not scale as a Gaussian

1 distill, rms 2.6 μJy

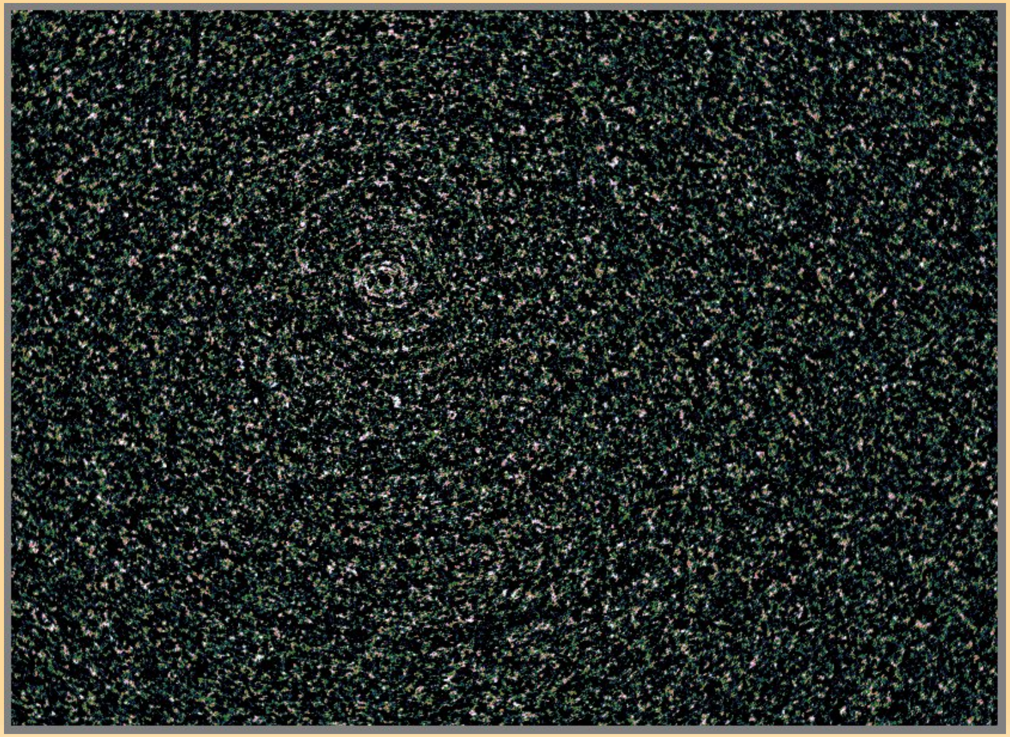
10 distills, rms 1.2 μJy



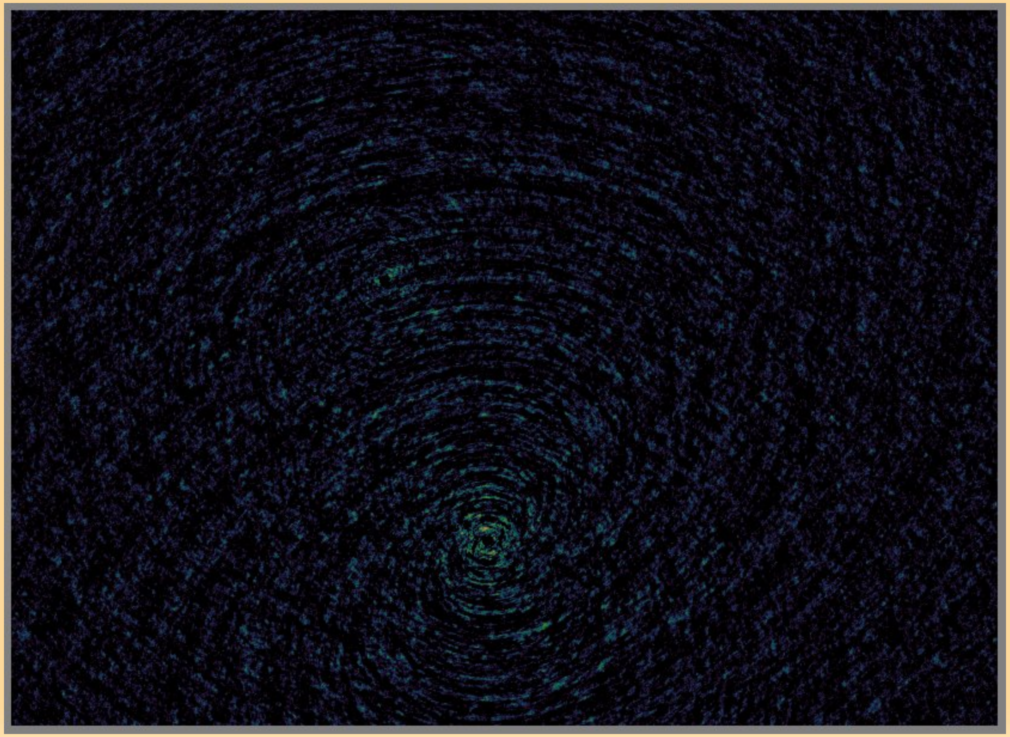
PF vs OG

- Repeat this experiment for PF and OG beam patterns
- Calibration “noise” for OG lower by a factor ~3

PF: rms 3.6 μJy

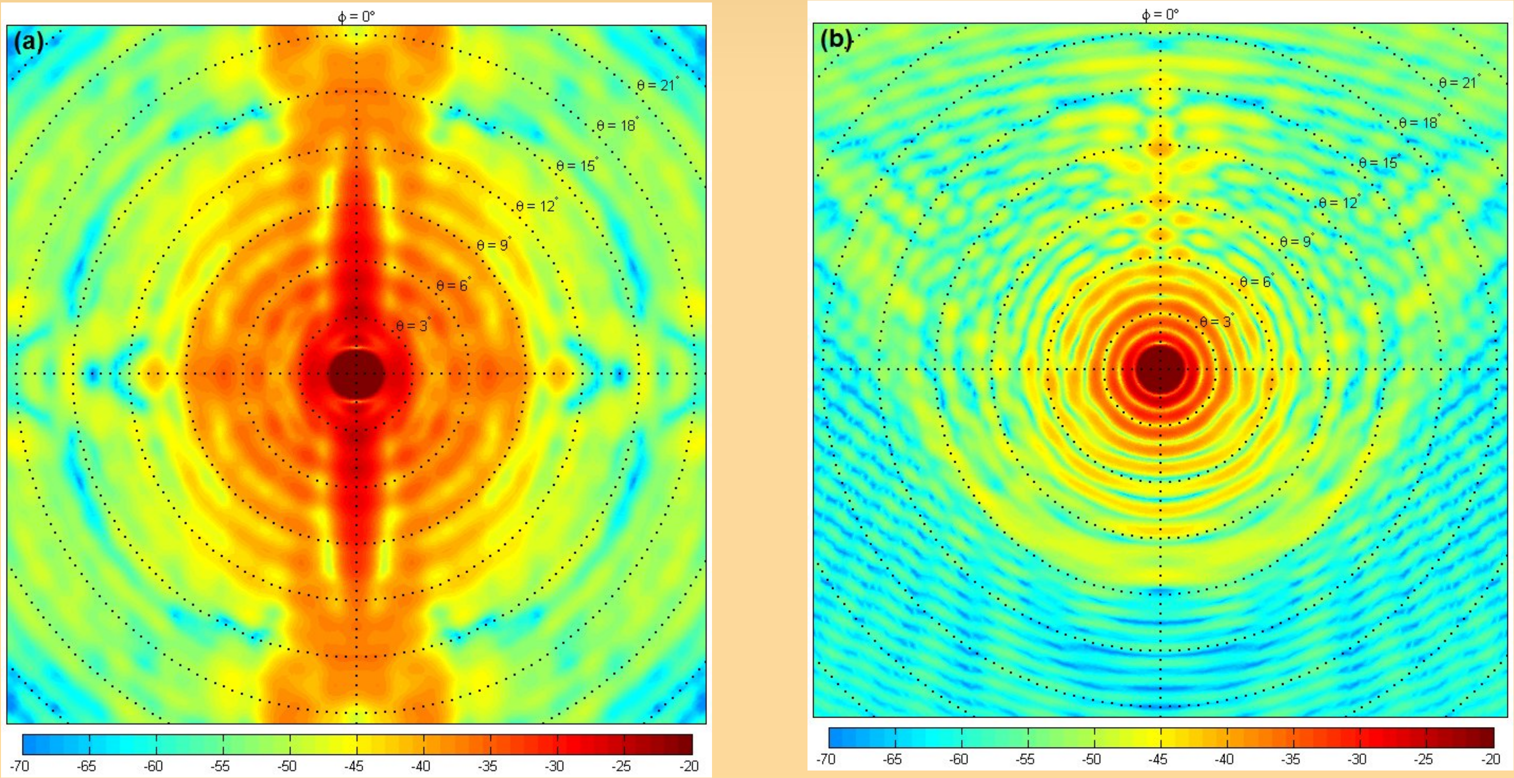


OG: rms 1.2 μJy



Why The Difference?

- Difference probably due to OG's smoother beam pattern
- same amount of pointing error causes more gain variation in the PF case



Conclusions II

- All calibration, including direction-dependent solutions leave non-Gaussian artefacts buried in the noise
- May become a DR limitation for deep surveys
  - can be mitigated by dynamically scheduling deep observations during favourable conditions (wind etc.)
- Calibration “noise” due to pointing error significantly higher (x3) for the KAT-7 PF design than for the MeerKAT OG design
- More study needed!
  - AA factors: beam stability, ionosphere