Warped Snapshot Imaging for Low-frequency Dipole Arrays

Daniel Mitchell
Harvard-Smithsonian Center for Astrophysics

Outline

- Quick review of the MWA RTS
- Running the RTS off-line on stored visibilities
- Some thoughts on wide-field gridding

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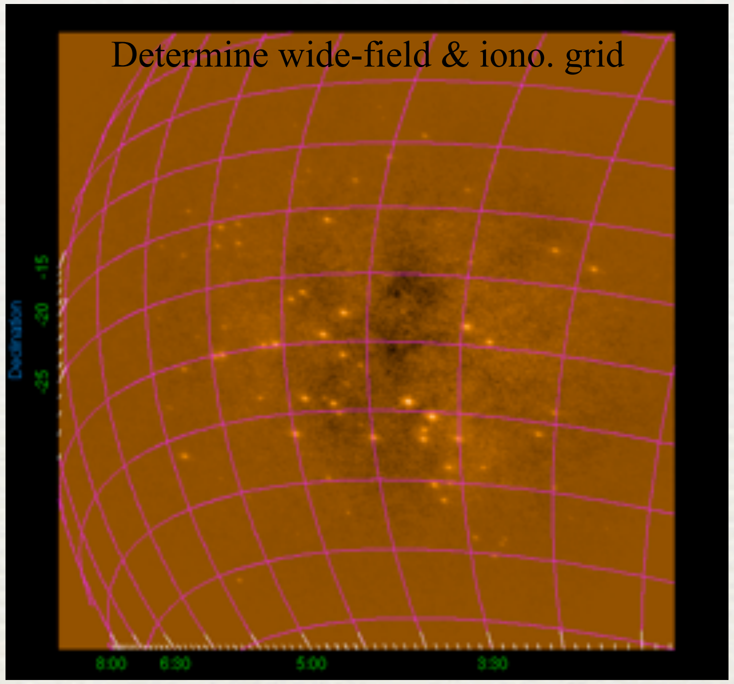
Wide-field Approaches

- c.f., Cornwell et al., arXiv:0807.4161
- 3D transforms
  - FFT (sparse volume)
  - DFTs (expensive)
- 2D transforms
  - image-plane facets
  - uvw-space facets
  - **warped snapshots** →
  - w-projection
- Combinations (e.g., peeling and segmenting)

Good fit for MWA

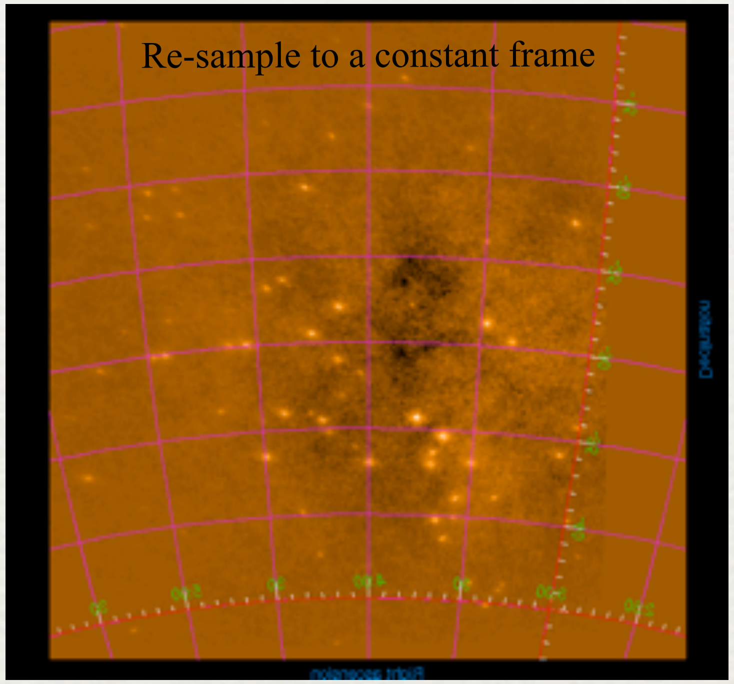
- snapshot imaging with image resampling for time-dependent ionospheric corrections (in image plane).
- snapshot imaging for transient detection.
- good snapshot beam.

Warped Snapshots



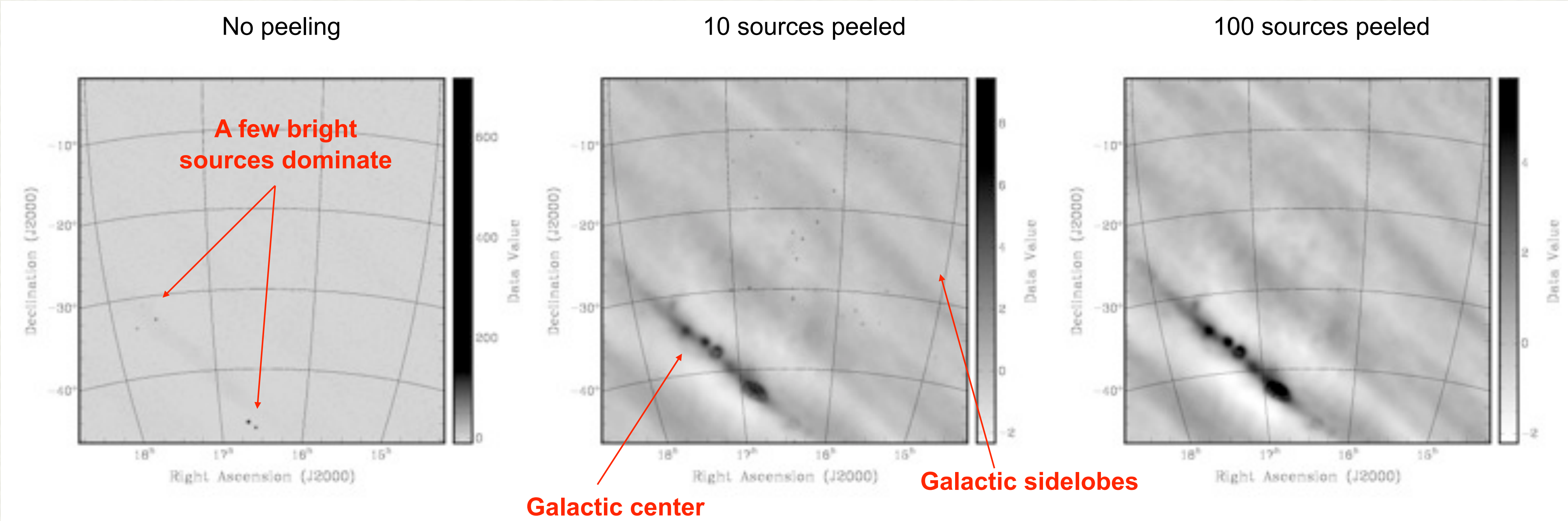
Simulated data

- HA: -3.5 to +3.5 hrs
- Weighted by gain squared (c.f. A-projection, mosaicing)
- Fast pipeline (mostly) running routinely on GPUs

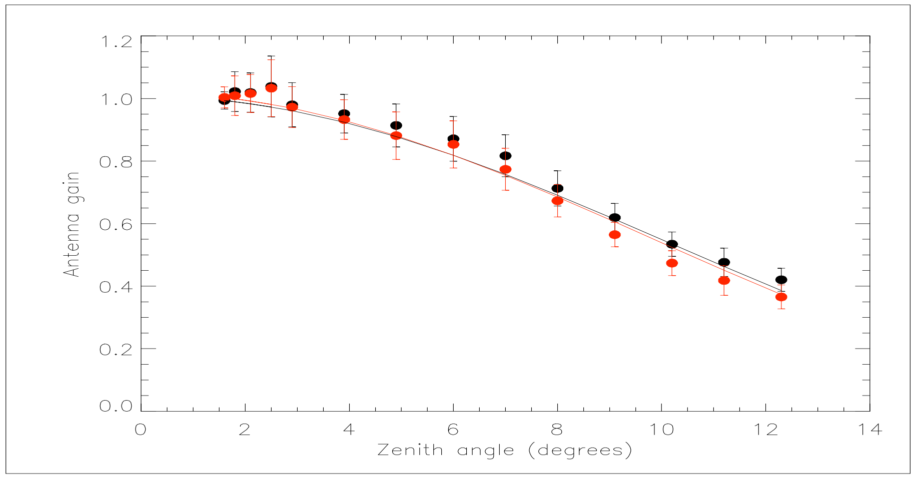


Simulated data containing the galactic centre, antenna- & direction-dependent beams and peeling.

Mitchell et al., *IEEE JSTSP*, **2** (5), 707--717, 2008. [arxiv:0807.1912]

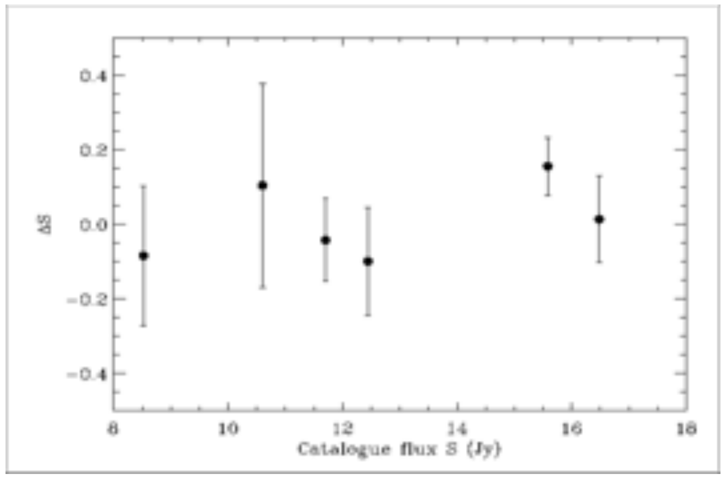


3 × 5 min RTS + image-based averaging & deconvolution

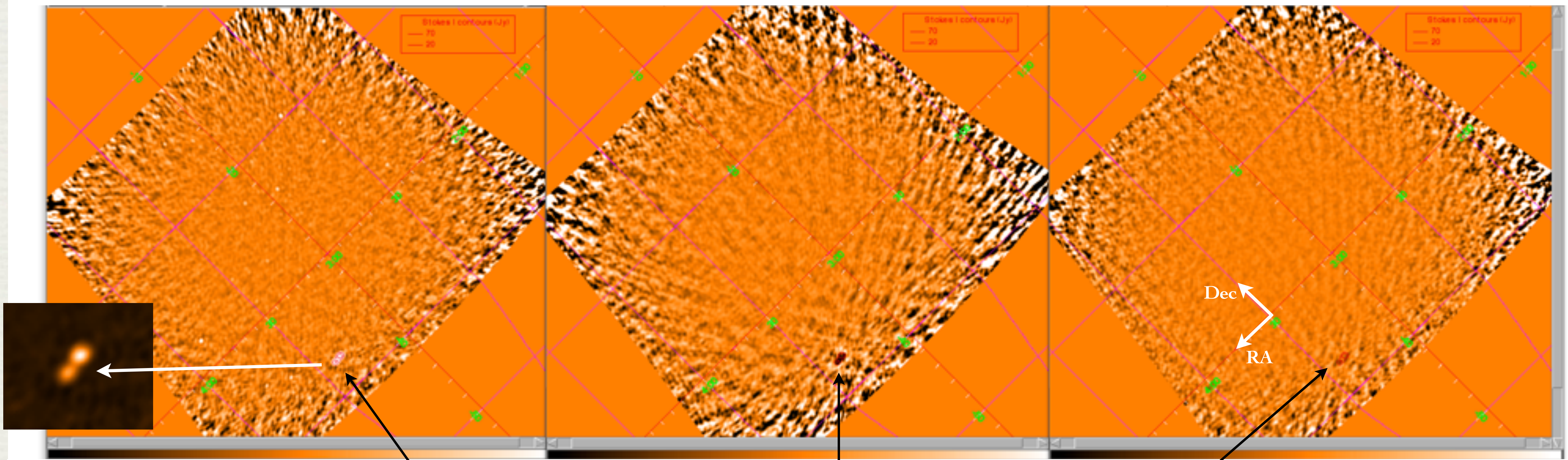


Forward modelling using a simple beam model (fitted using drift-scan data).

beam error ~ 2%
flux rms ~ 5%



Stokes I Stokes Q Stokes U



-10 Jy/beam 10 Jy/beam -1 Jy/beam 1 Jy/beam -1 Jy/beam 1 Jy/beam

Not using antenna-dependent DD gains in forward modelling, but could be

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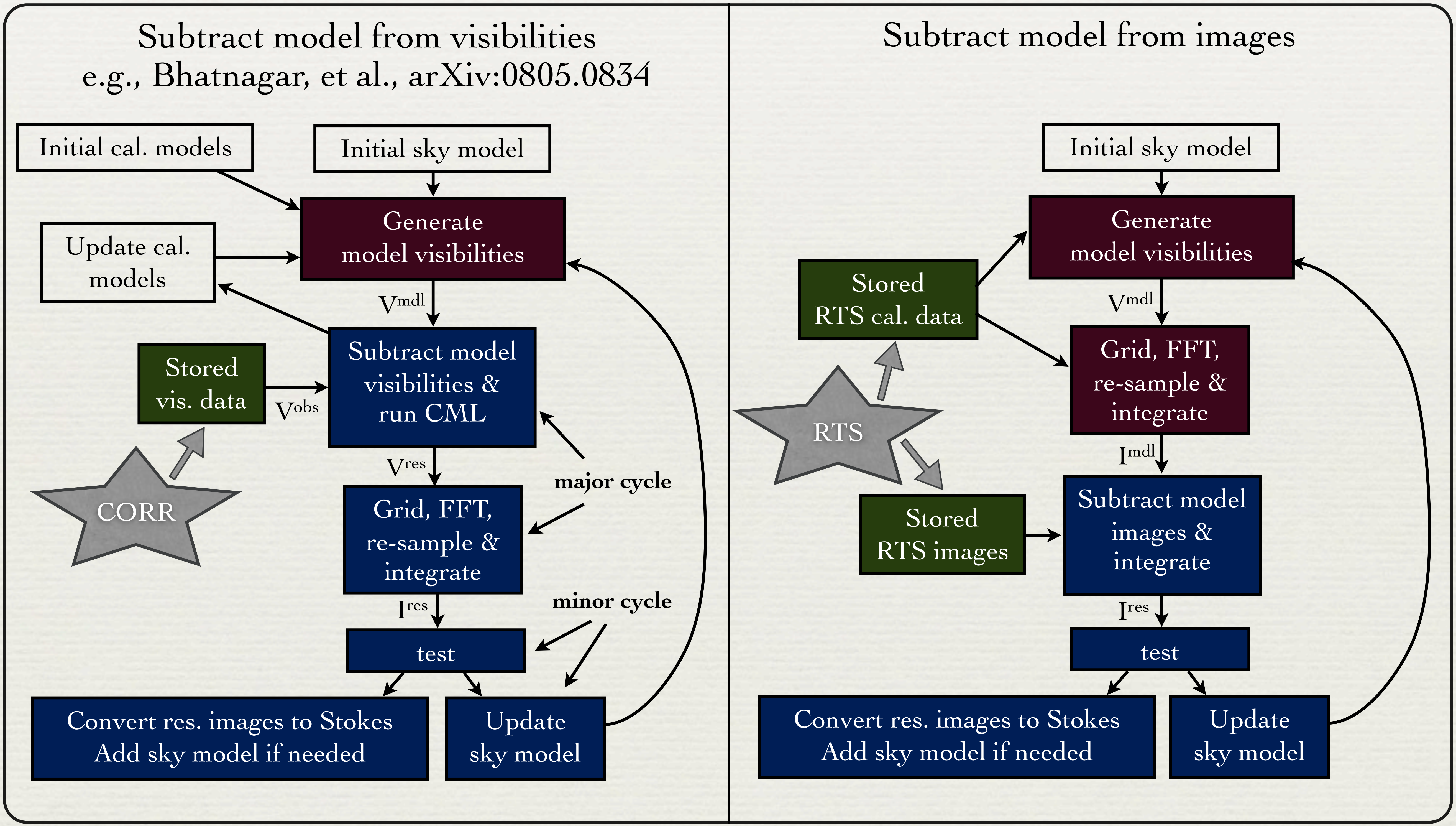
Iterative Deconvolution

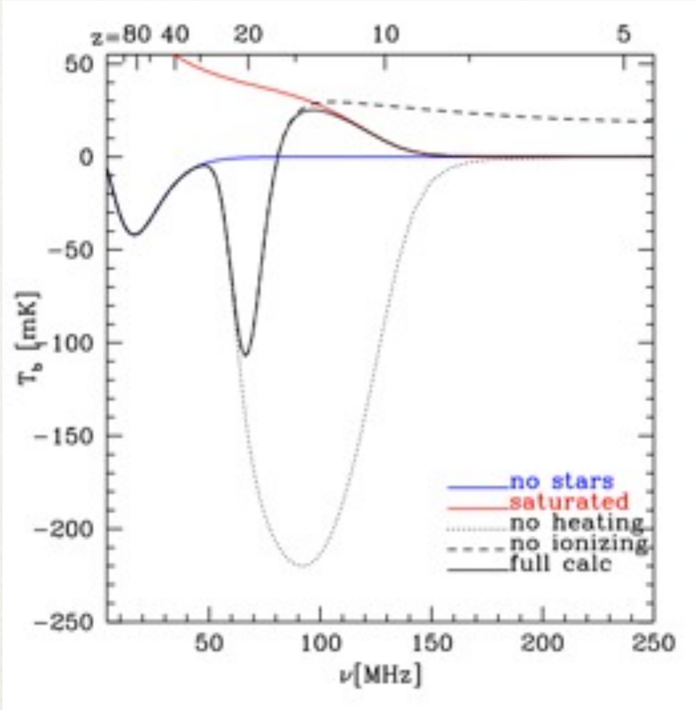


Off-line RTS

- CUWARP: CUDA-based wide-field array processor, based on warped-snapshot imaging.
  - LEDA (recommended for award by NSF). Full broadband FPGA+GPU correlator for the 256-element LWA1, with off-line wide-field calibration.
  - MWA 128T: Initial EoR dataset for MWA will be stored visibilities.
  - Test off-line version against real-time version.
  - Most of the code is running routinely on GPUs.

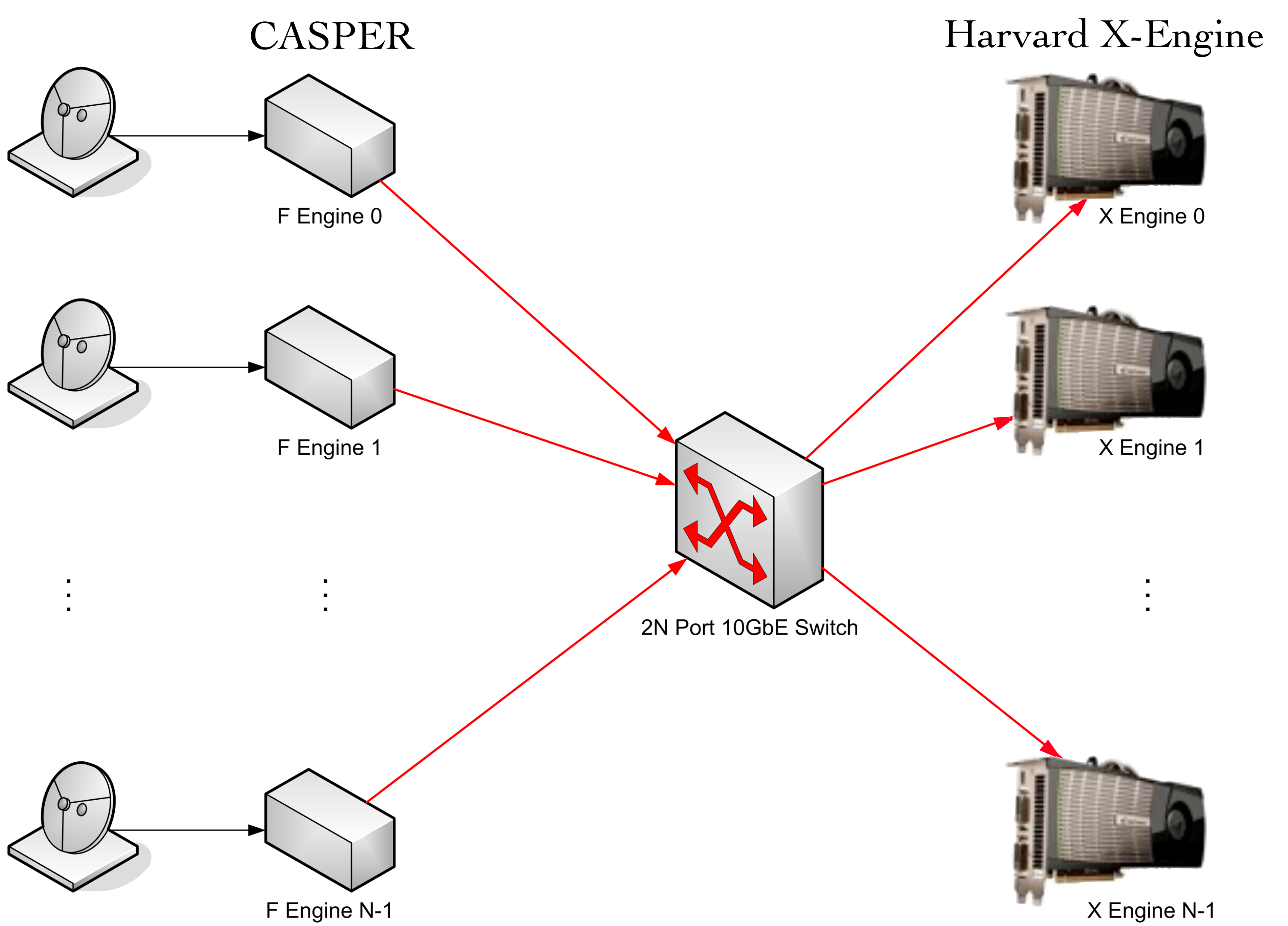
Large Aperture Experiment to Detect the Dark Age (LEDA).

Pritchard & Loeb, arxiv:1005.4057



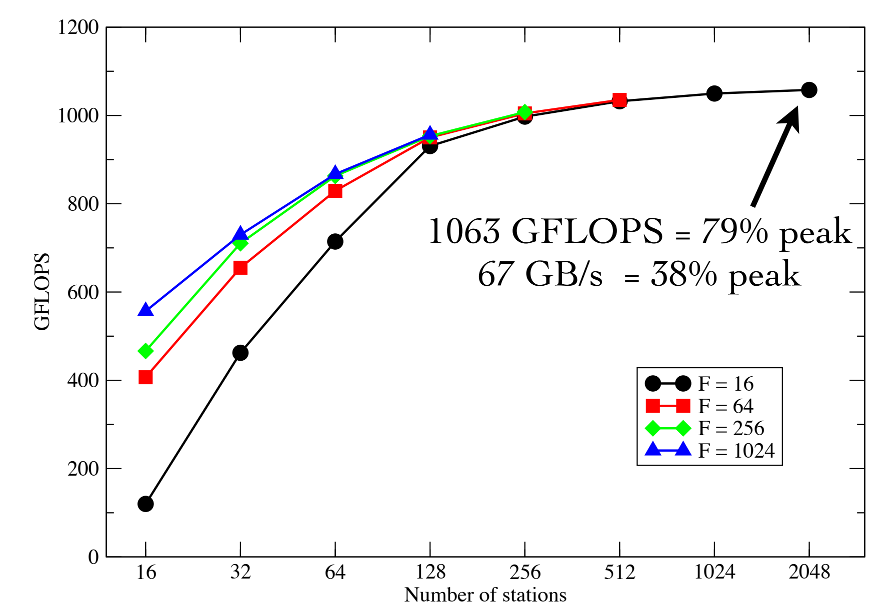
- L. Greenhill, Harvard (PI)
- Multiple total-power dipoles near LWA1 (redshifted 21cm)
- Correlate each against the LWA1 dipoles
  - CASPER F-engines + Harvard GPU X-engines.
  - A parallel multi-object gate furthers calibration (c.f. Pen et al).
- CUWARP software to be used off-line to fit beam and sky models: strengthen calibration and reduce systematics.

LEDA Hybrid Correlator



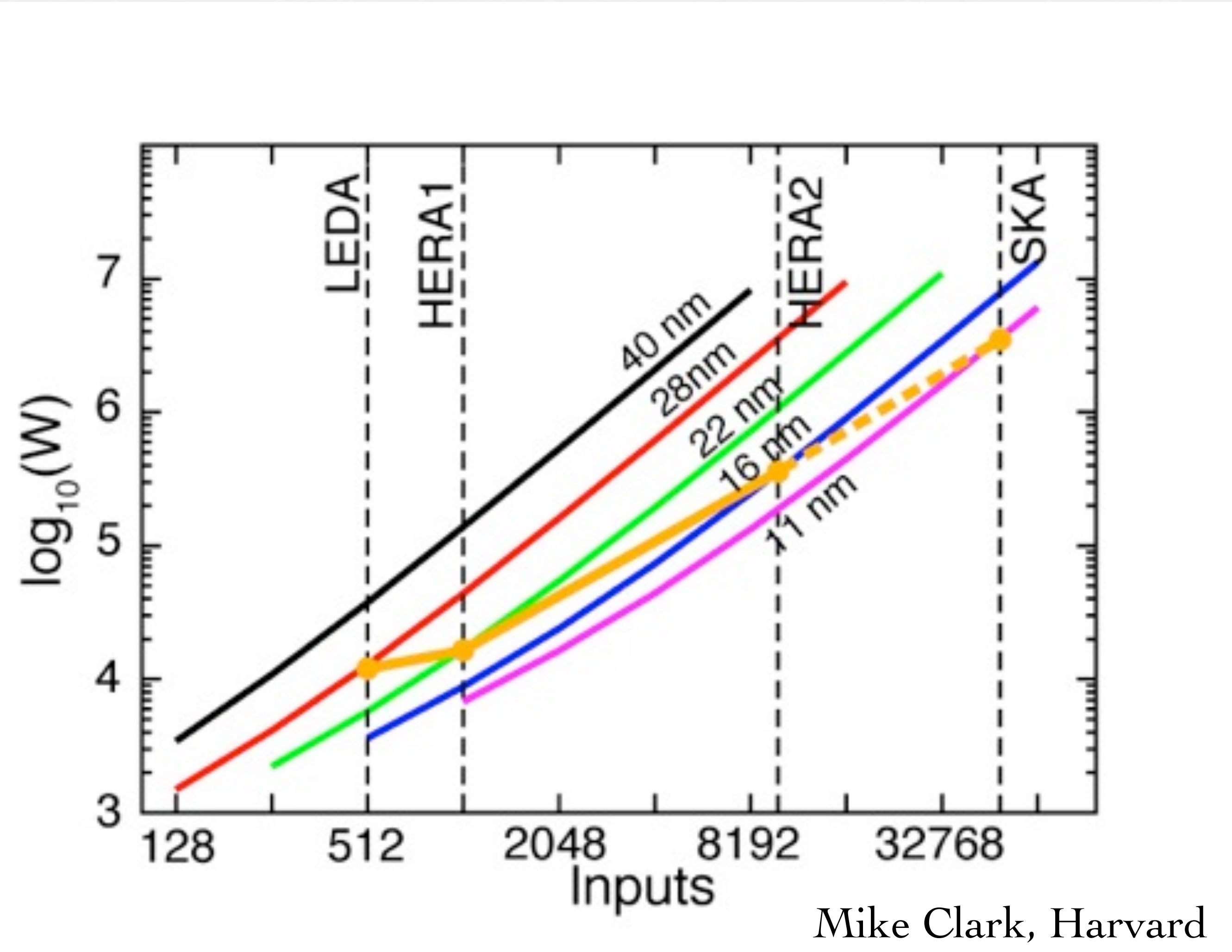
Clark, LaPlante, & Greenhill, arxiv:1107.4264 (source at https://github.com/mikeaclark/xGPU)

Performance of the X-engine as a function of the number of stations and frequency channels (F)



Clark, LaPlante, & Greenhill, arxiv:1107.4264

Power Scaling



Plausible hybrid correlator power scaling with number of inputs and process technology

(100 MHz, BLADE G8264 switches)

- F-engine: ROACH1@40nm and ×2 improvement per Watt per generation.
- X-engine: projections estimated from J. H. Huang GTC 2011 and W. Dally SC11.

Nvidia architecture:

- 40 nm: Fermi
- 28 nm: Kepler (2012)
- 22 nm: Maxwell (2013)
- 16 nm: project Echelon byproducts (2015)

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Residual Images

- OMM/MLE/... gridding is not necessarily best when the residual maps contain the science.
  - Confusion-level sources are not in sky model ⇒ not deconvolved.
  - In general cannot assume J_k is unitary (or even Hermitian).
  - u,v,l,m-dependent Fourier weighting leads to complicated side-lobes.
  - A-projection??? On Monday: JAWS uses pseudo-inverse???
- How well can we normalise the Fourier plane?
  - DD uniform weighting, inverse kernels, ...
- Run simple simulations to test some simple cases.
  - Stick to a single polarisation to avoid complication.

EoR Foregrounds

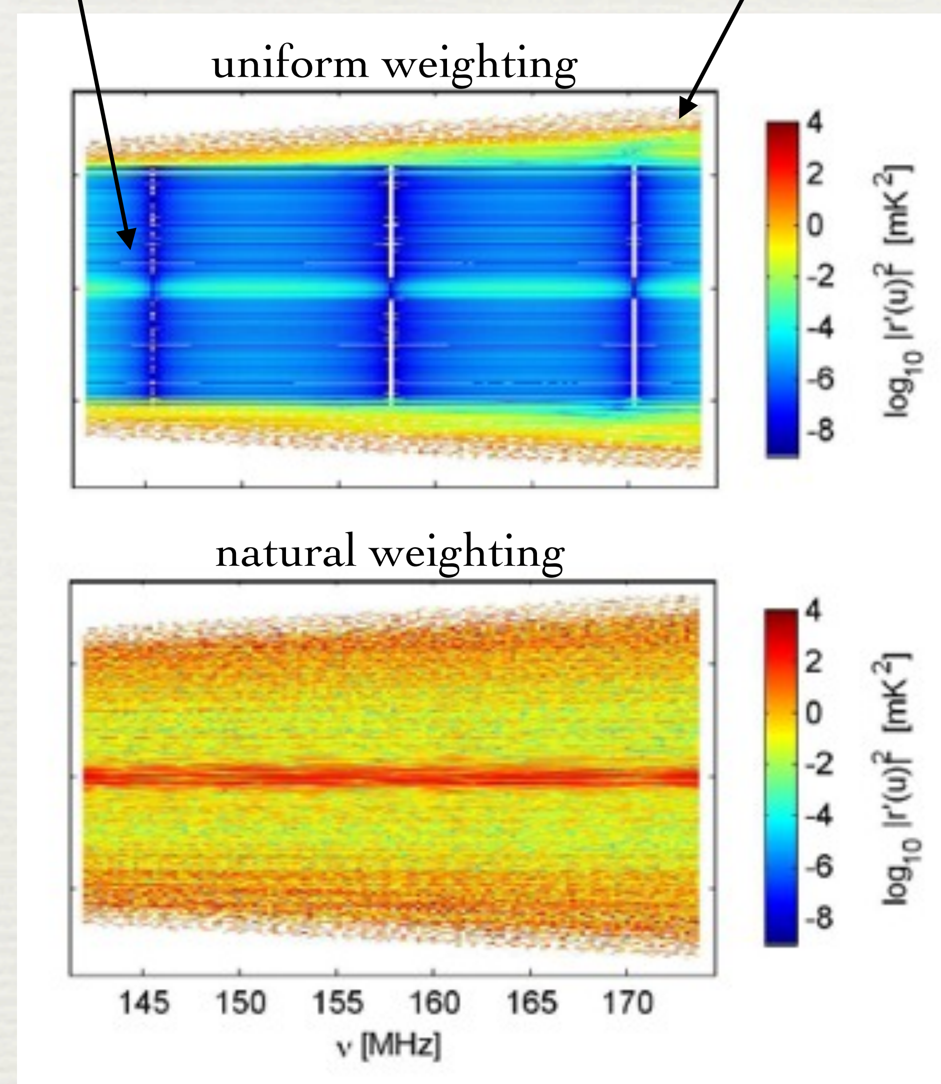
- Remove compact sources using carefully deconvolution.
- Remove diffuse structure by removing low-order spectral structure.
- What about confusion-level compact sources?

Residuals (in the Fourier domain) after subtracting a fitted polynomial to each pixel in the image domain.

Bowman, Morales & Hewitt 2008 (arXiv:0807.3956)

Spatial scales with filled UV cells.

Spatial scales in poorly filled regions contain most of the residual power.



SNR versus side-lobes

$$g_{jk}\, e^{-i2\pi\phi_{jk}}$$

$$V_j = n_j + \sum_k^M a_k A_{jk}$$

LSq

FT

if possible

$$\mathrm{MIN}\left\{\chi^2 = \sum_j^N \sigma_j^{-2}\left|V_j - \sum_k^M \hat{a}_k\, A_{jk}\right|^2\right\}$$

$$\hat{a}_k^{(d)} = \sum_j^N g_{jk}^{-1}\, V_j\, e^{i2\pi\phi_{jk}} - \ldots$$

$$\vec{a} = \left(\underline{A}^H\, \underline{W}\, \underline{A}\right)^{-1} \underline{A}^H\, \underline{W}\, \vec{V}$$

$$\vec{a} = \underline{A}^{-1}\, \vec{V} + \text{deconvolution}$$

If the a_k lie on a regular grid, the summing and phasing can be done by an FFT, and the gain can be dealt with while gridding the visibilities.

The Kernels

- replace $|g_j|^2$ weighting with $|g_{ref}|^2$
- retain ~gain^2 weighting
- suppress 1/null regions
- can make freq-indep.

$$K_j(u,v) = \mathcal{F}\left\{g_j^*(l,m)\,\varphi_j(l,m)\right\}\Pi(u/u_0, v/v_0) \quad \text{(OMM/MLE/...)}$$

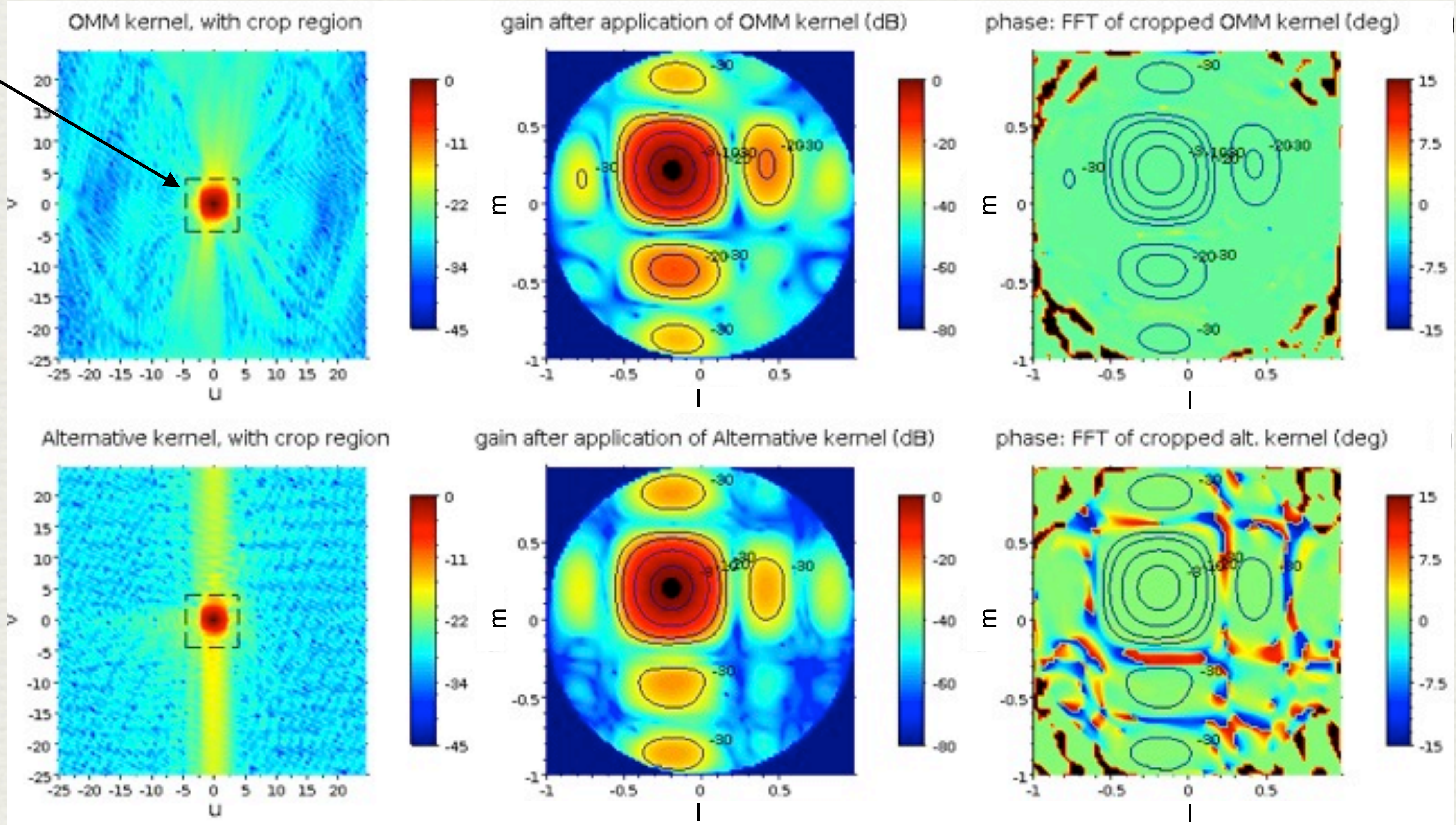
$$K_j(u,v) = \mathcal{F}\left\{\frac{|g_{ref}(l,m)|^2}{g_j(l,m)}\,\varphi_j(l,m)\right\}\Pi(u/u_0, v/v_0) \quad \text{(ALT)}$$

+const

crop region

Attempt to give each gridded visibility the same DD response.

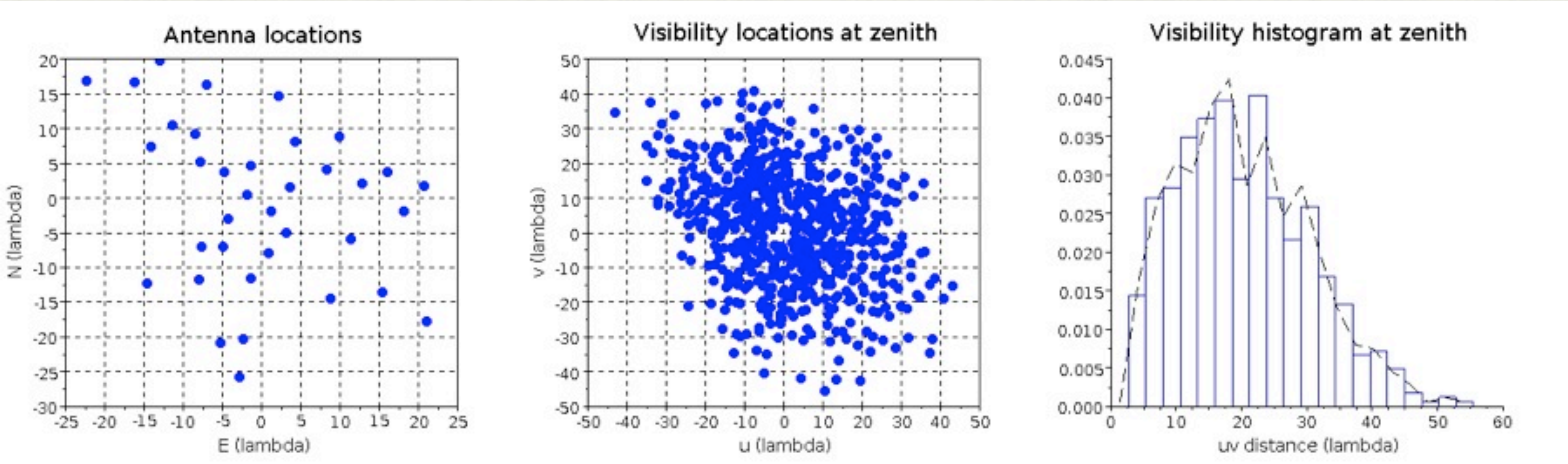
Retain ~visibility response squared weighting for optimal snapshot integration.



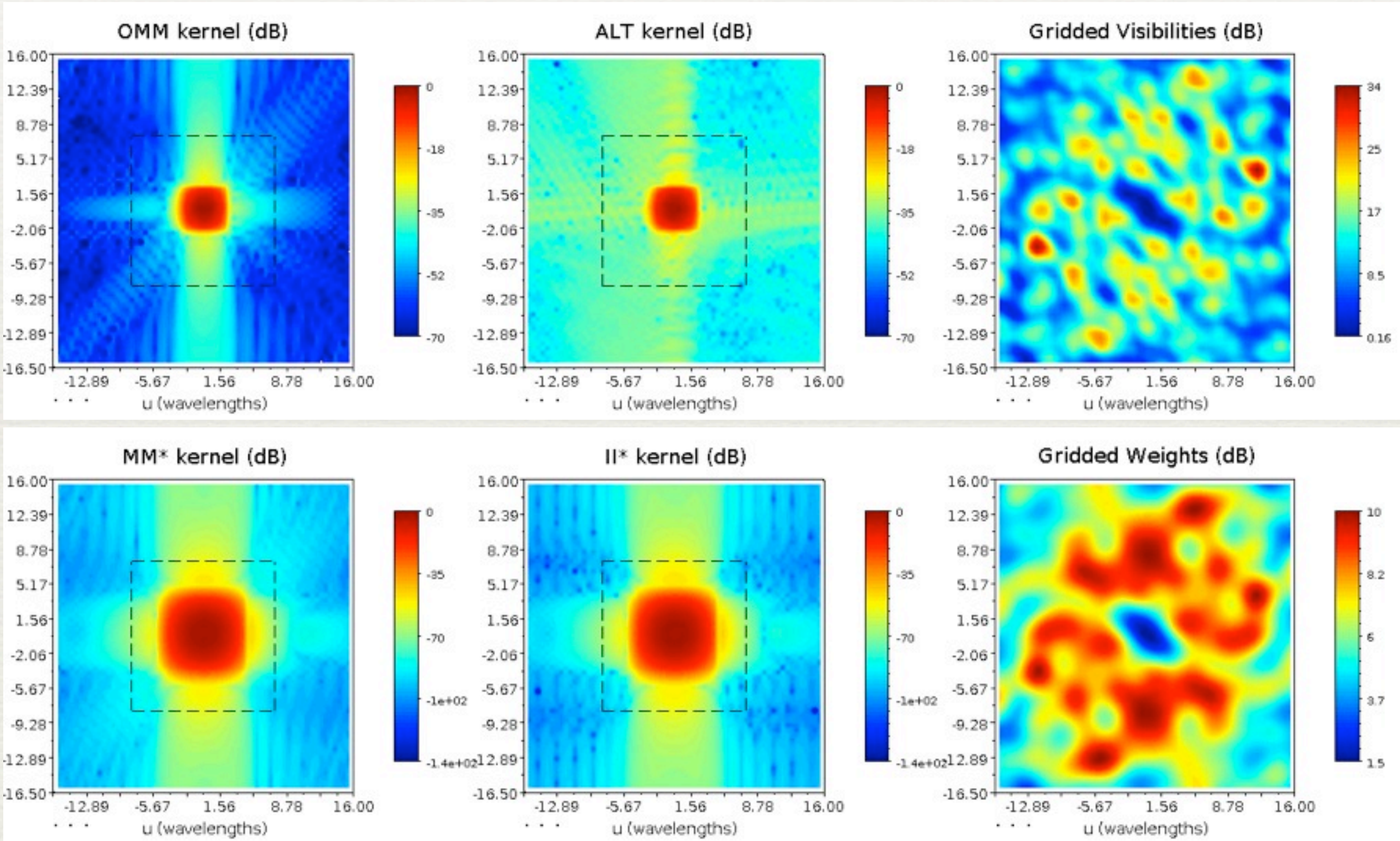
Simulation Setup

A compact array is desirable for signals like the EoR, both to maximise the surface brightness sensitivity and to fully sample the uv plane (reducing side-lobes and mode mixing).

- 36 MWA-like antennas.
- Maximum baseline ≲ 100 λ.



uv grids

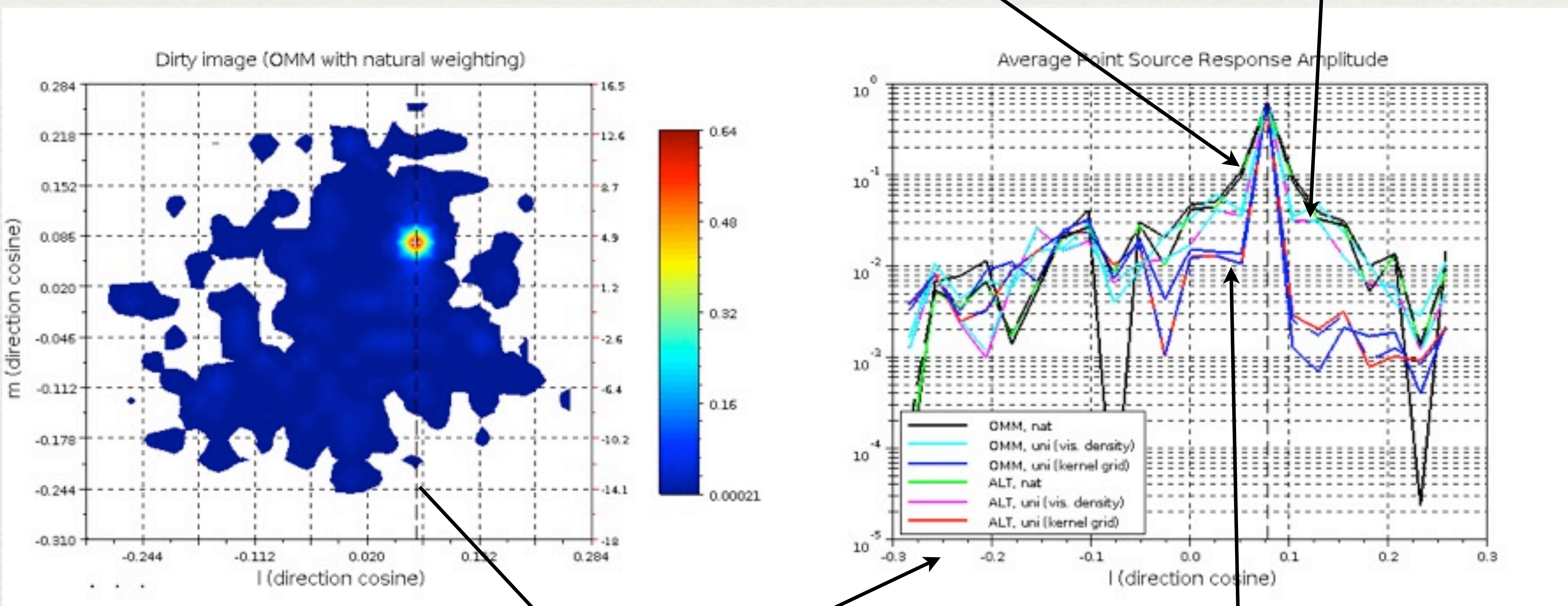


OMM kernel (dB)
ALT kernel (dB)
Gridded Visibilities (dB)
MM* kernel (dB)
II* kernel (dB)
Gridded Weights (dB)
16.00
12.39
8.78
5.17
1.56
-2.06
-5.67
-9.28
-12.89
-16.50
-12.89
-5.67
1.56
8.78
16.00
u (wavelengths)
0
-18
-35
-52
-70
34
25
17
8.5
0.16
-1e+02
-1.4e+02
10
8.2
6
3.7
1.5

Example of plots

Cyan and magenta: standard uniform weighting using local visibility density

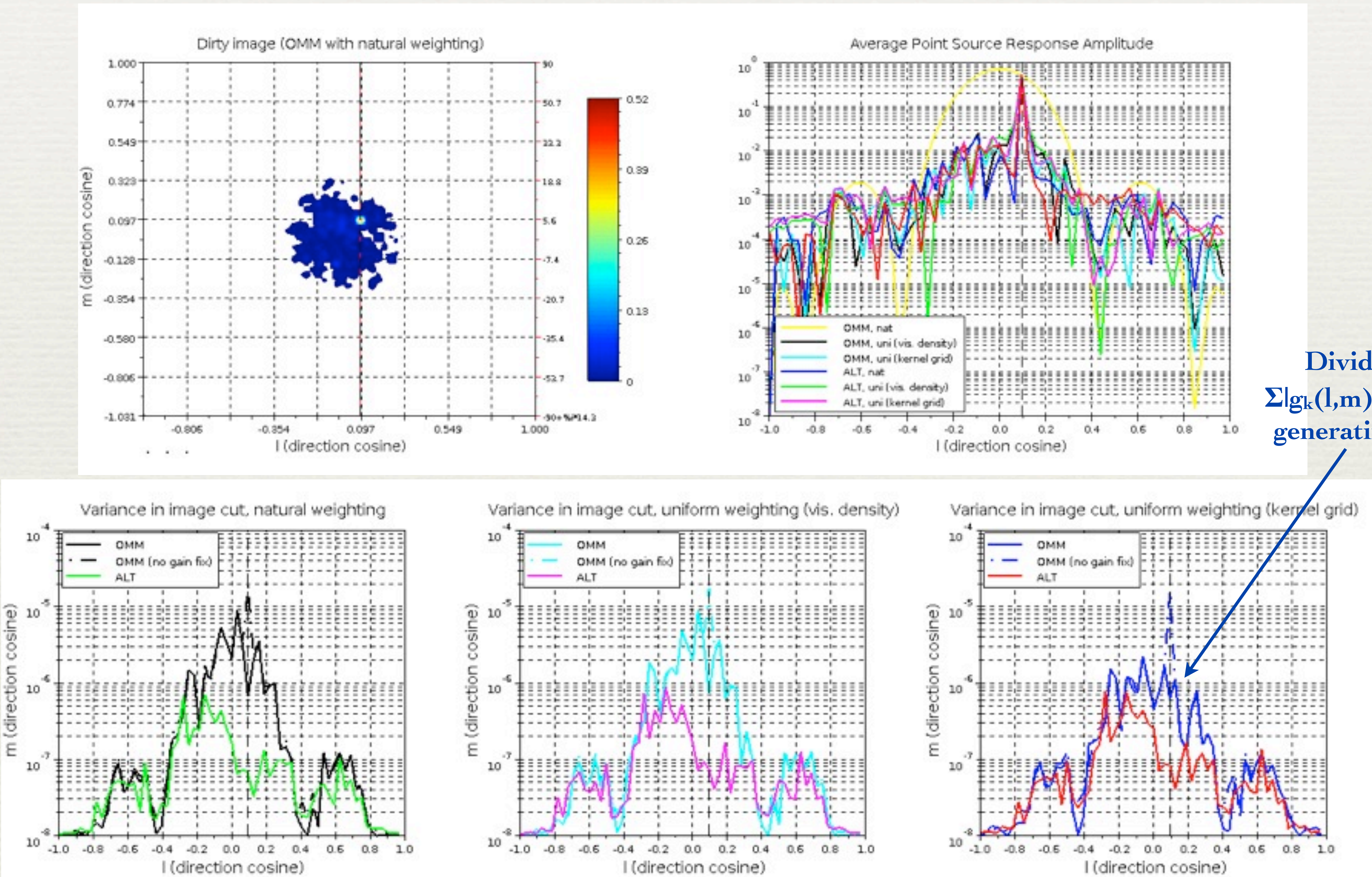
Black and green: natural weighting



Cut through the point source

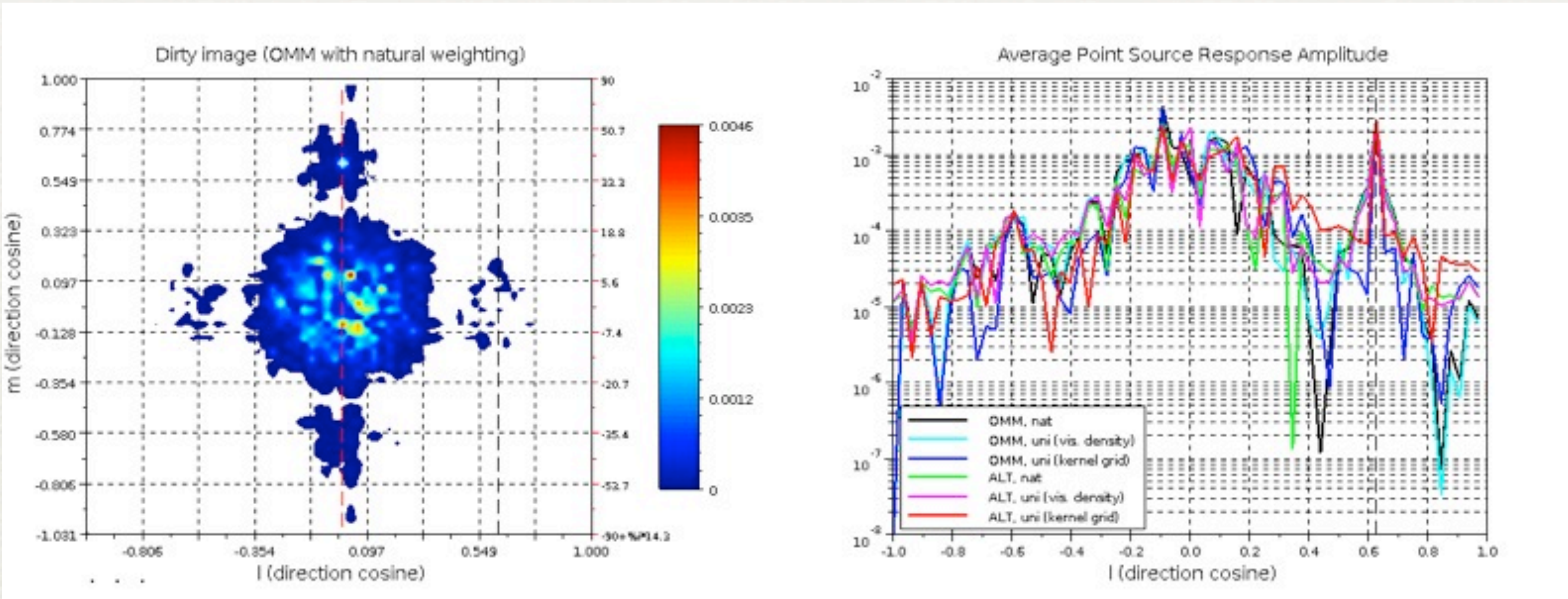
Blue and red: uniform weighting using the gain^2 kernel grid

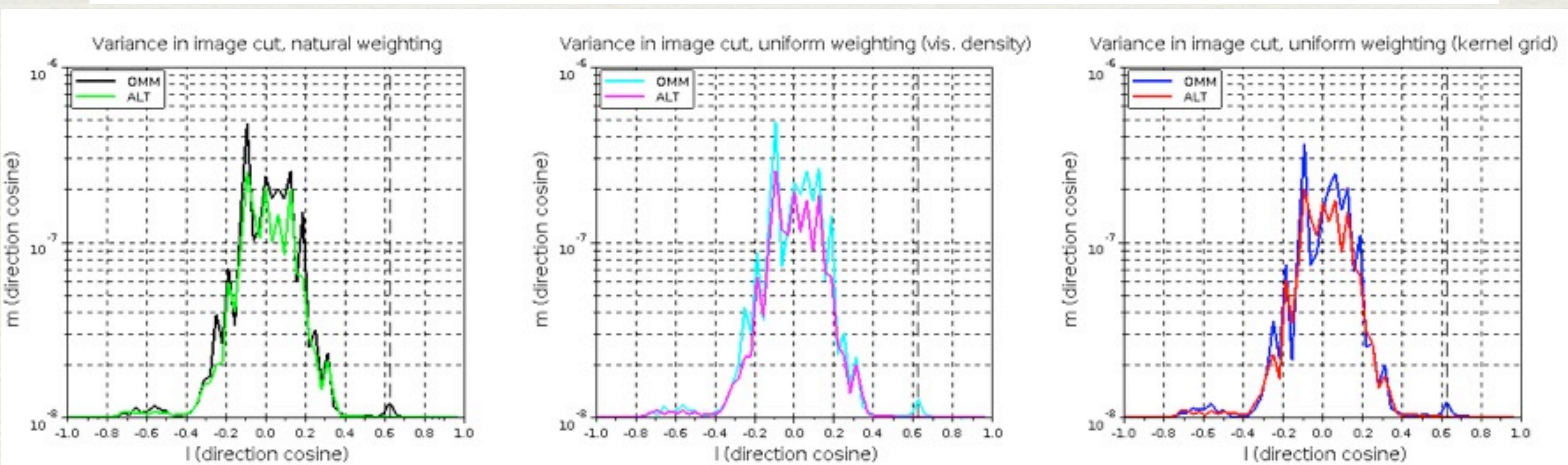
1 point source in the main-lobe



Divide out $\Sigma|g_k(l,m)|^2$ before generating stats

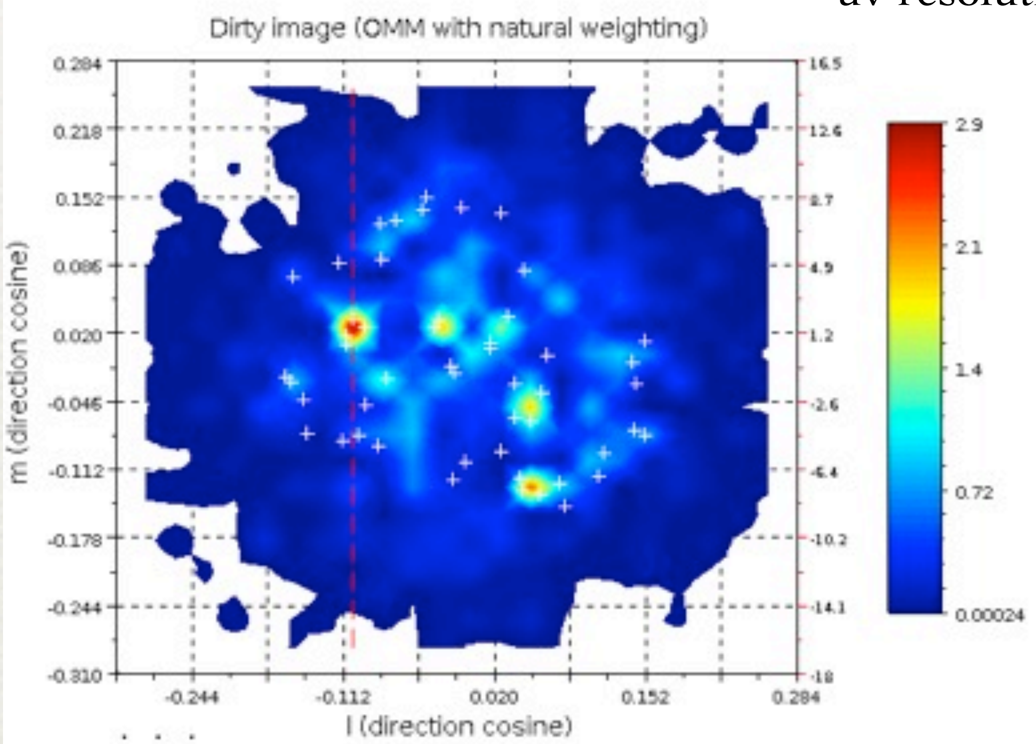
1 point source in a side-lobe

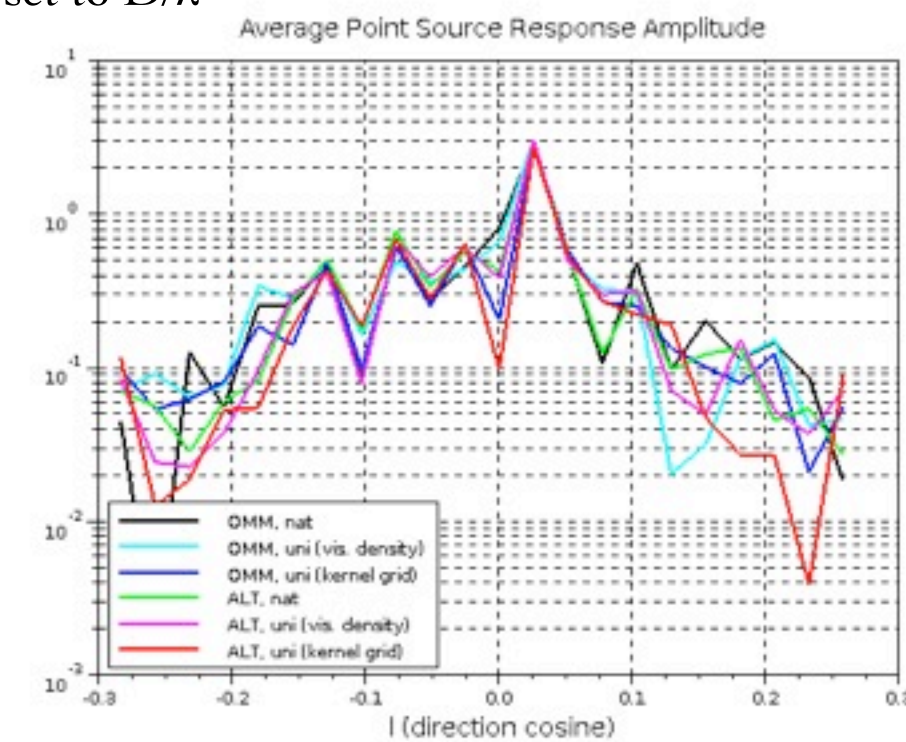


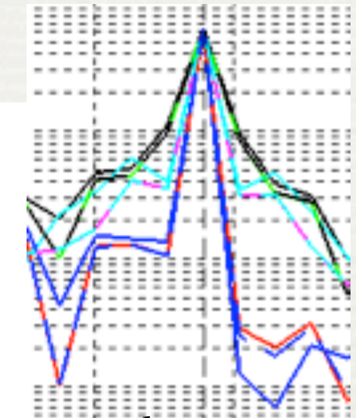


50 random sources

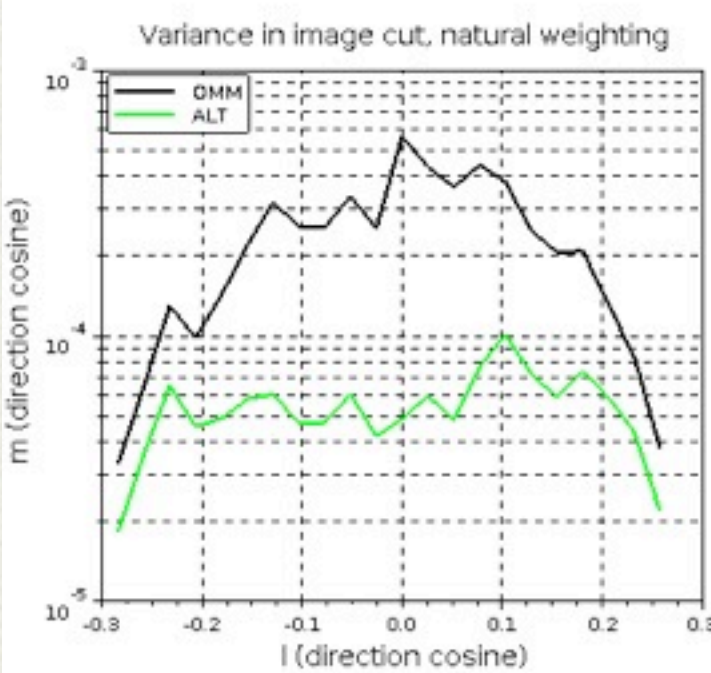
uv resolution set to D/λ

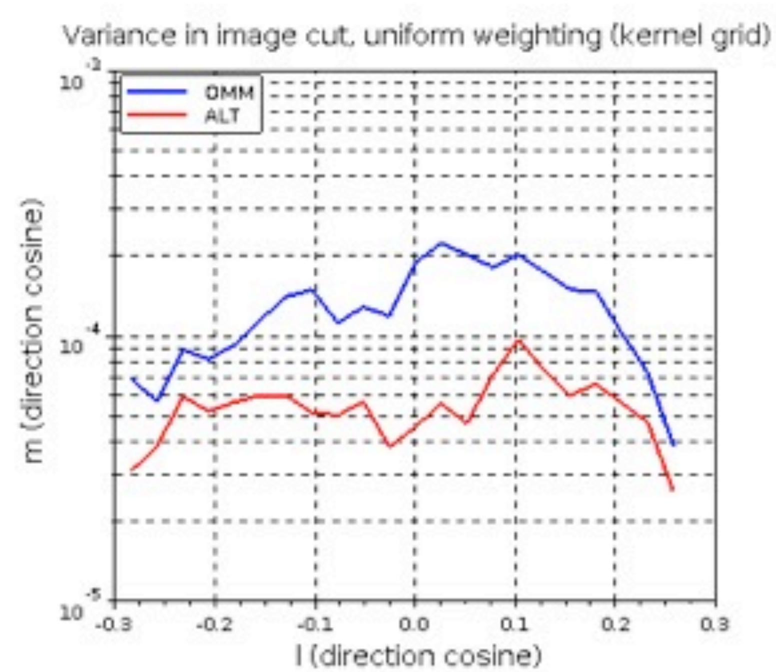






single source





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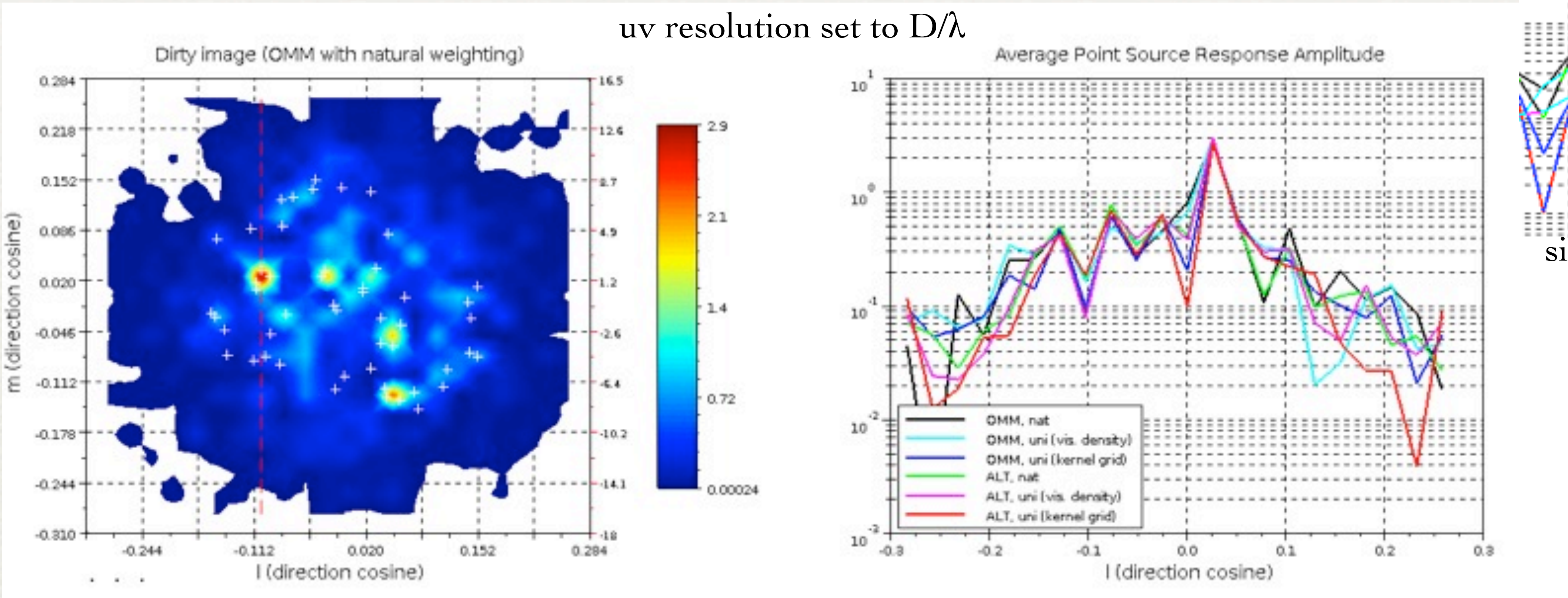
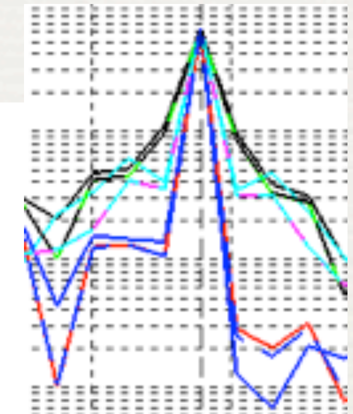
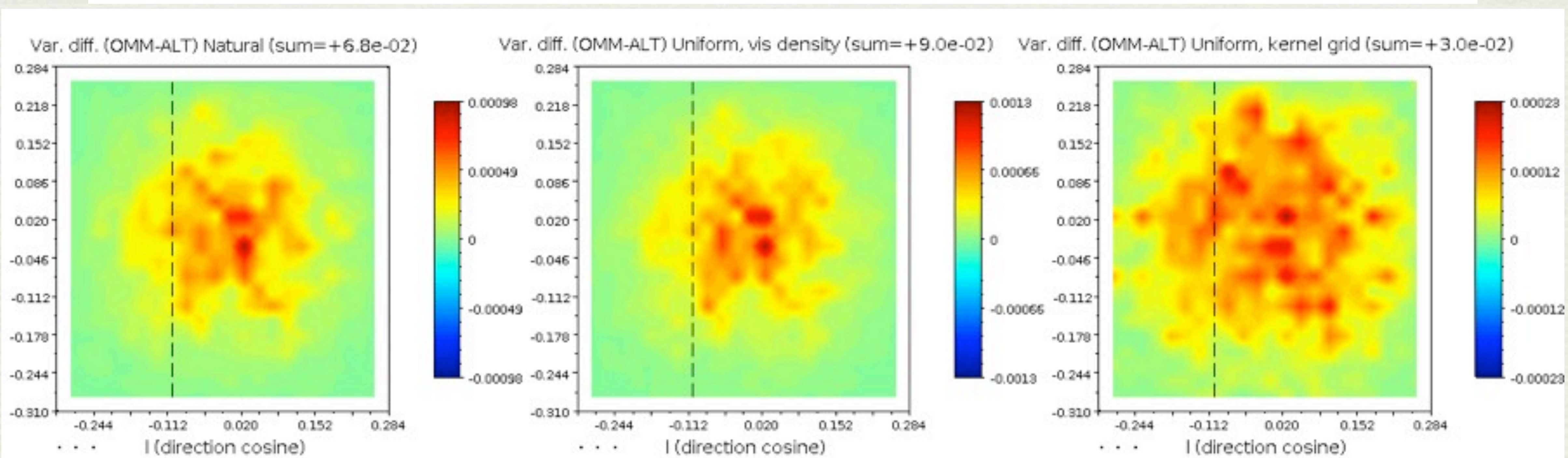
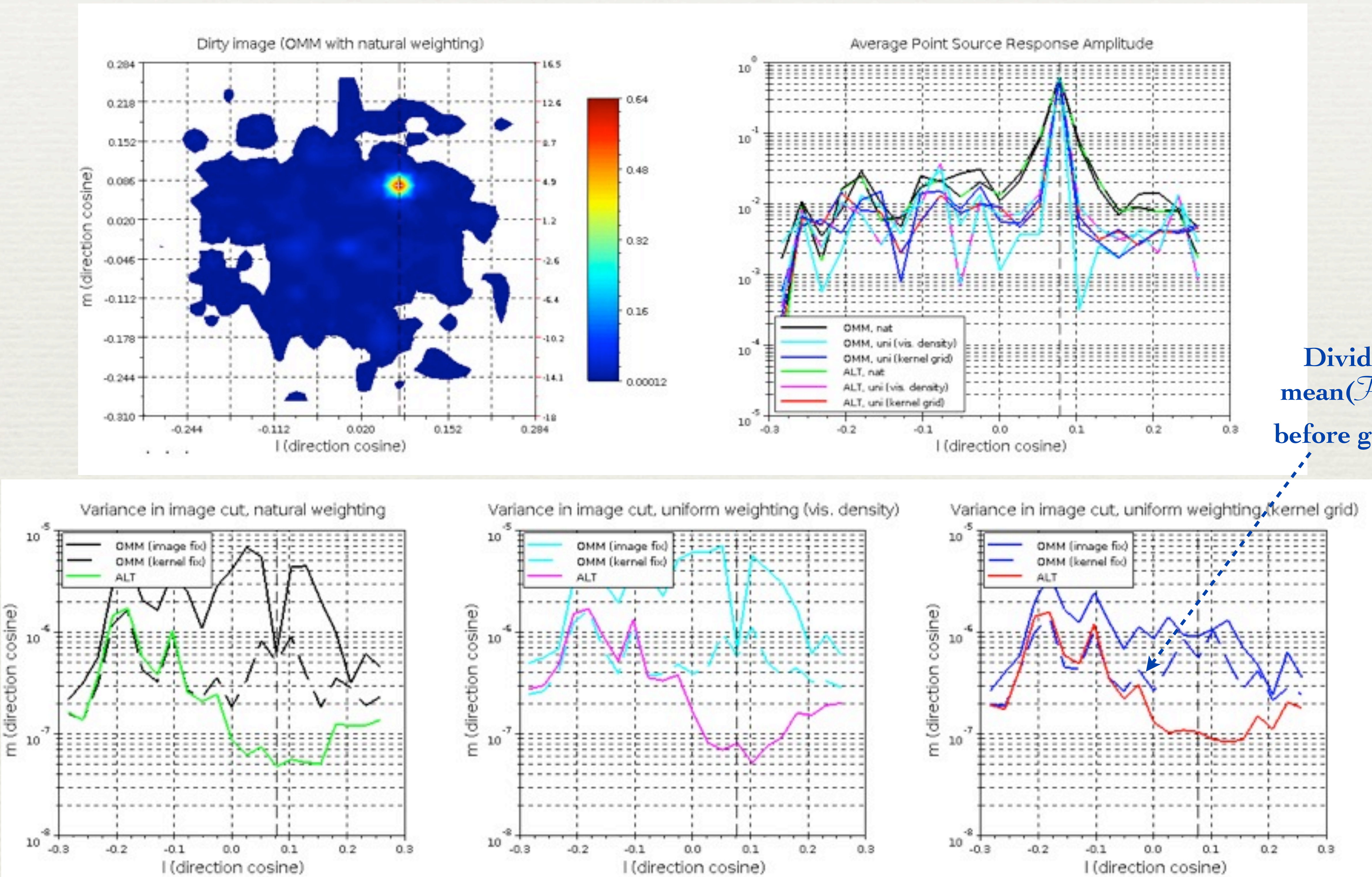




single source

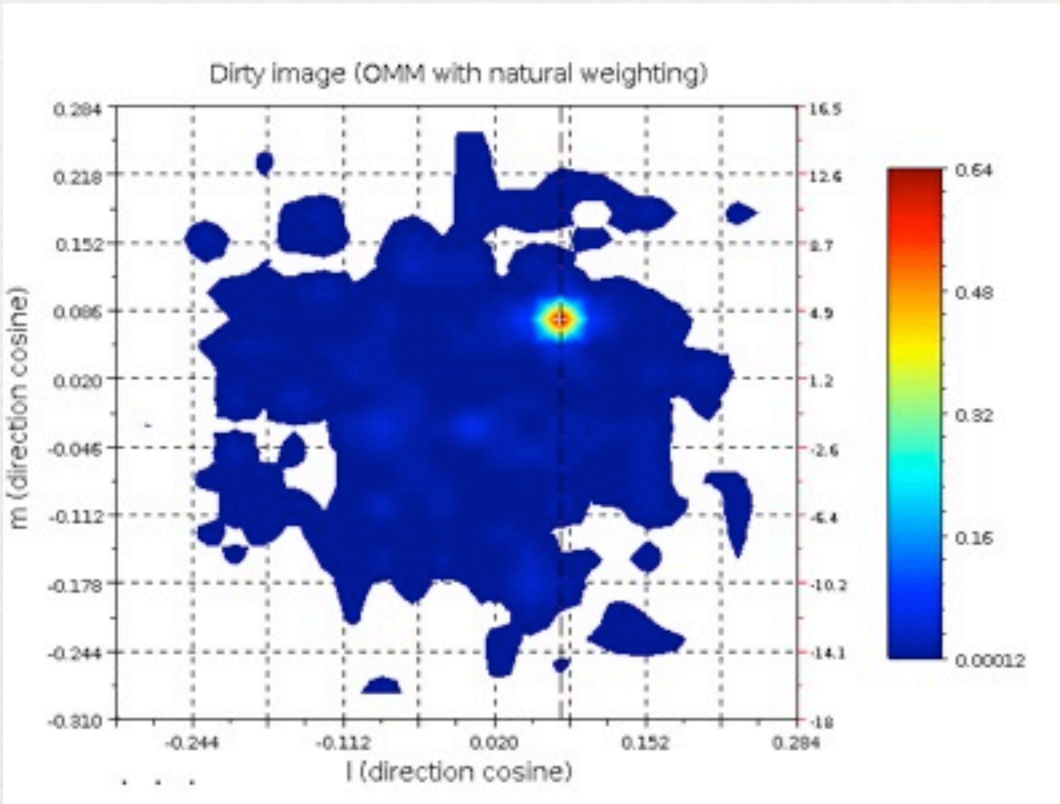


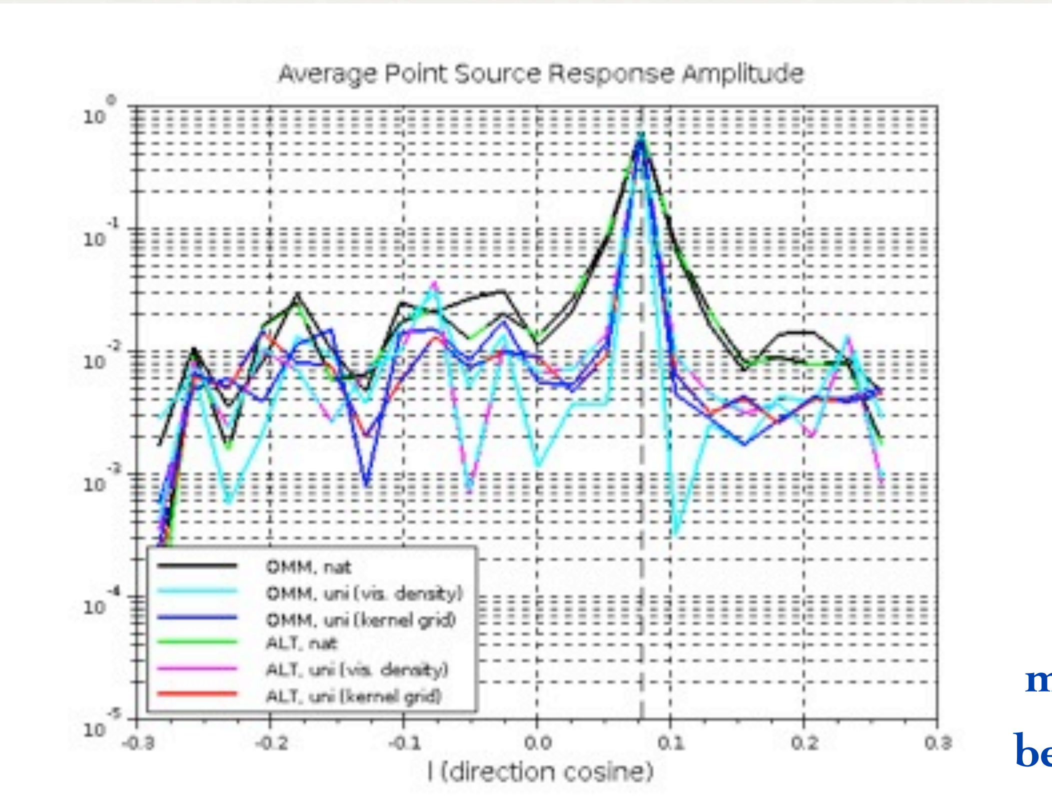
Normalise Kernels



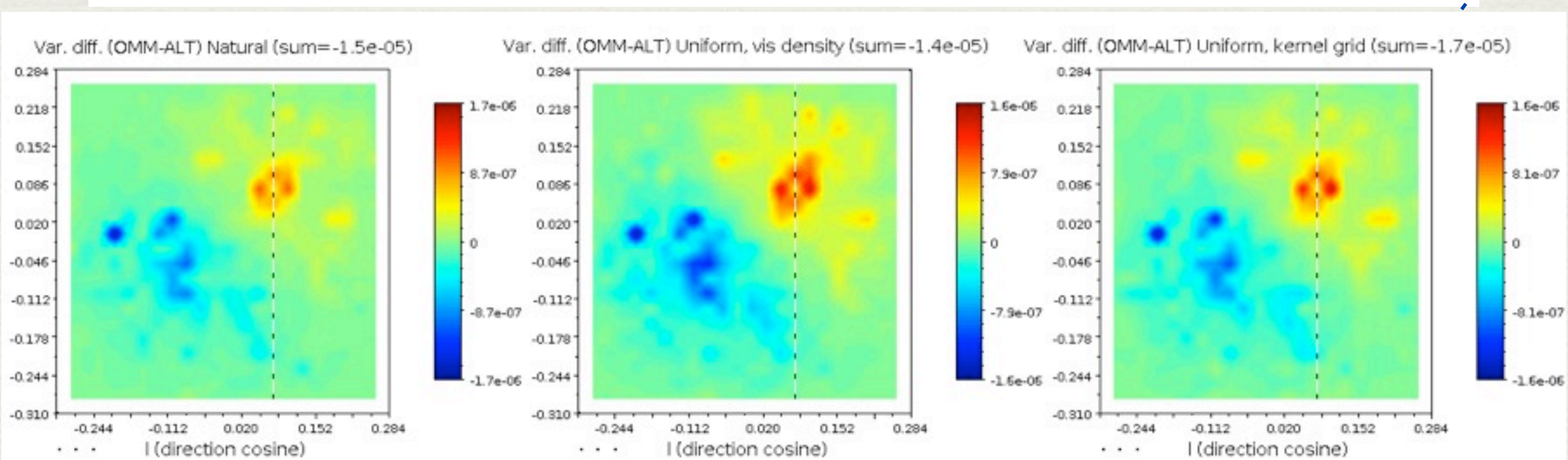
Divide out mean($\mathcal{F}\{|g_k|^2\}$) before gridding

Normalise Kernels





Divide out mean($\mathcal{F}\{|g_k|^2\}$) before gridding



Summary

- CUWARP
  - The MWA RTS can be used as an off-line stream processor (wide-field calibration and imaging).
  - It will be used for MWA 128T and LEDA, and very useful for testing the real-time version.
- Gridding & weighting
  - When interested in residual maps, gridding kernels that maximise SNR may not minimise confusion noise.
  - There is much to be gained from determining the best way to grid & weight the uv plane (perhaps differently at different times in the imaging process).