Confusion, the sky model and realistic simulations

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with

“team Greenhill” (Greenhill, Mitchell, Sault)
“team MAPS” (Doeleman, Bhat)

Ashes Update:

England all out for 350. Australia wins the ashes.

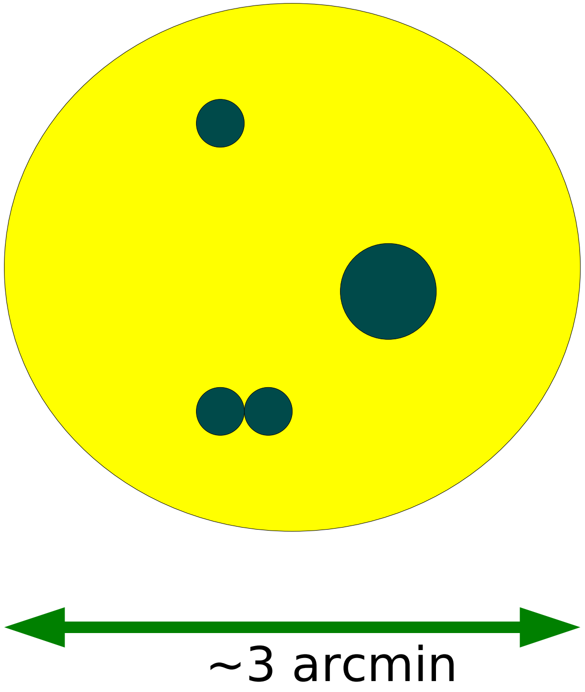
Outline

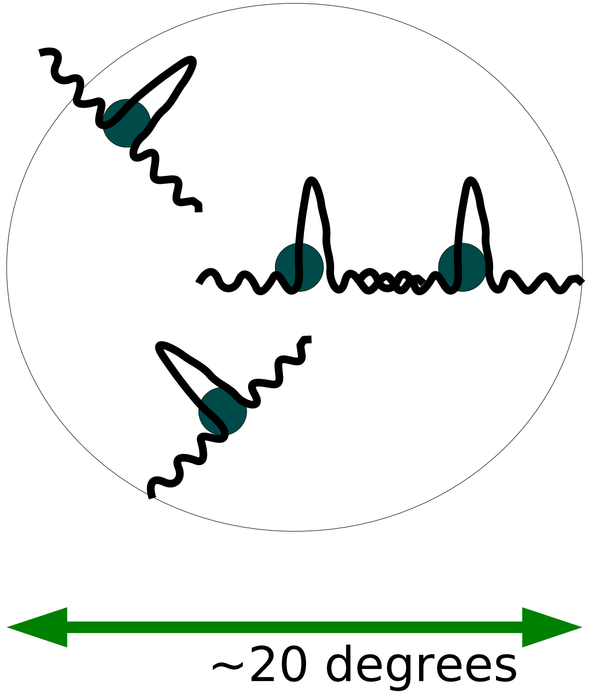
- Context:
  - What's it going to take to calibrate the MWA?
  - What do we need to test the real-time pipeline?

- Part I: Estimating Confusion
- Part II: Generating realistic simulation data

Confusion – basics

- Sources inside *synthesised beam*
  - Depends on size of beam
  - Flux densities add up
- Sidelobes of sources out of synthesised beam
  - S = source strength
  - P = pri beam power
  - ~P*S/N_{ANT} (snapshot)





Confusion – theory

- Factors of interest:
  - Differential source count distribution: $n(S)$
  - Primary beam: $P(\Omega)$
  - Synthesised beam: $B(\Omega)$.
  - Diffuse emission (not included yet)
- Calculate variance in pixels due to all sources in the sky:

$$\sigma^2 = \int_{\Omega=0}^{2\pi} \int_{S=0}^{S_{MAX}} S^2 n(S) B^2(\Omega) P^2(\Omega) \, dS \, d\Omega$$

Confusion – theory

- We want to set a source detection threshold, q, of q sigma, so $S_{MAX} = q\sigma$, q=5 (or more)
- Sources in sidelobes of primary beam are attenuated, so $S_{MAX} = q\sigma / |P(\Omega)|$
- For $B(\Omega)$, assume = 1 in beam, $B_{RMS} = 1/N_{ANT}$ outside

$$\sigma^2 = \int_{\Omega=0}^{2\pi} \int_{S=0}^{q\sigma/|P(\Omega)|} S^2 n(S) B^2(\Omega) P^2(\Omega)\, dS\, d\Omega$$

Confusion

- For $n(S) = kS^{-\gamma}$, with $P(\Omega)$ and $B(\Omega)$ a "tophat" function with width $\theta_{PB}/2$ and $\theta_{SB}/2$, result is analytic:

$$\sigma = \left(\frac{2\pi k}{3-\gamma} \left[B^2_{RMS} \left(1-\cos\theta_{PB}\right) + \left(1-\cos\theta_{SB}\right) \right] \right)^{\frac{1}{\gamma-1}} q^{\frac{3-\gamma}{\gamma-1}}$$

Solid angle of primary beam — Solid angle of synthesised beam

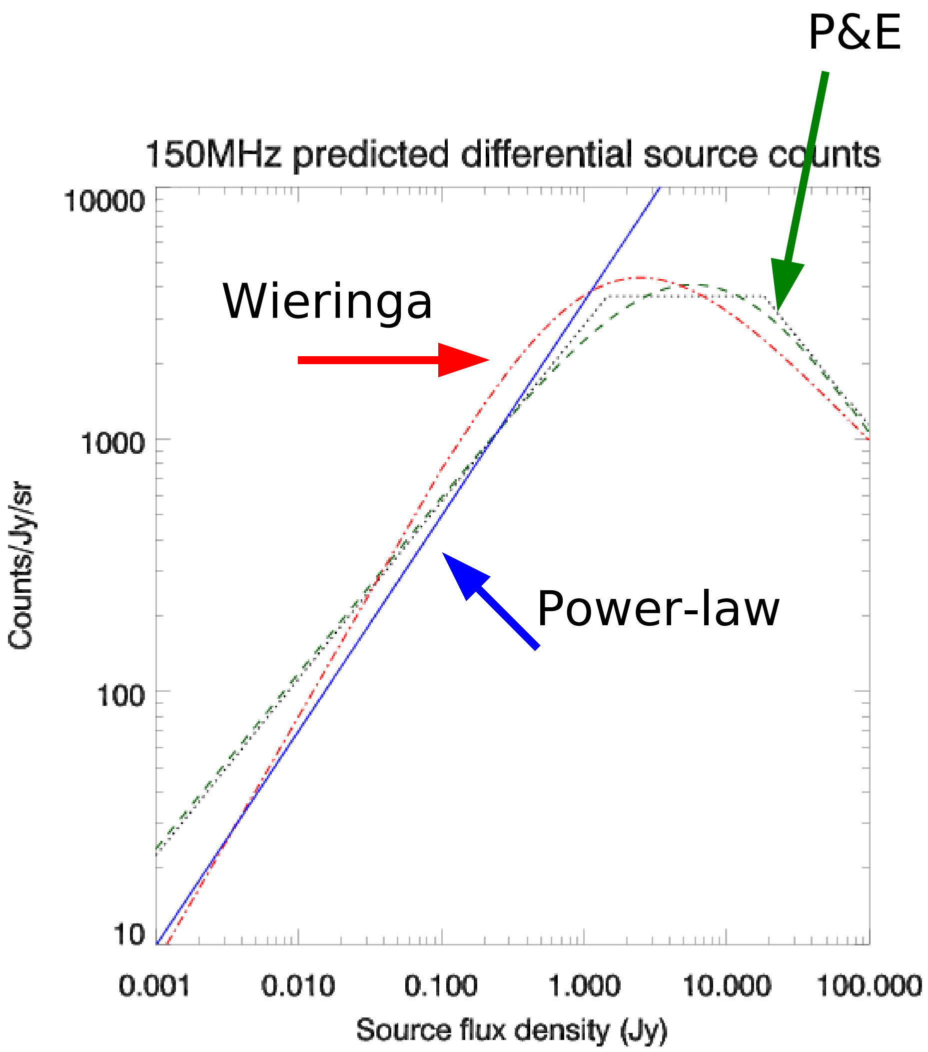
- This is useful to check numerical integration and is a similar result to Condon (1974), extended to suit synthesis images

Source counts (“logN-logS”)

Models for *n(S)*:

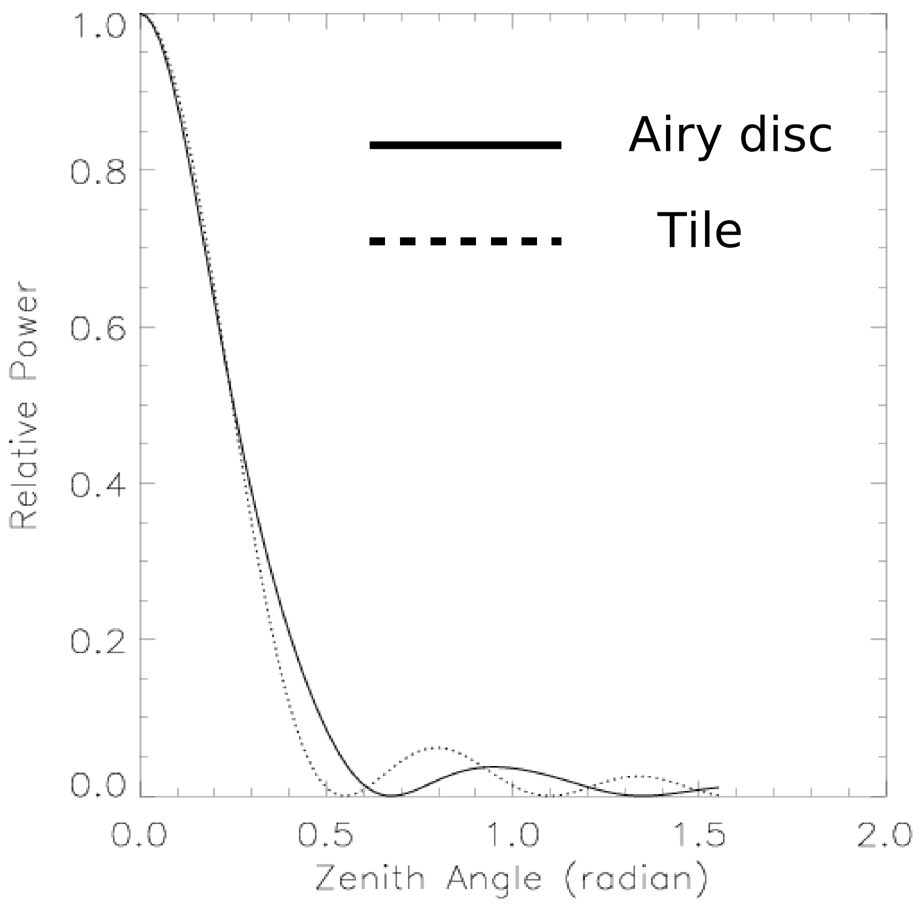
- Power law:
  - $n(S) = kS^{-\gamma}$, $\gamma = 1.65$

  (not realistic for large *S*)
- Perley & Erickson: piecewise linear (VLA memo 146, after Pearson, 1974)
- Wieringa (1991)
- (Scaled to 150MHz)



Primary Beam

- 150MHz
- Primary beam: 30 deg (FWHM) Airy disc
  (rotational symmetry)
- Synth beam: 3.4'
- 2π steradian



Results

- This table shows 5σ confusion limits for different contributors, beam models and source counts.
- 150MHz, 30 deg FWHM primary beam (PB)

Model	*Synth beam only*	*Tophat PB only*	*Real PB only*	*Synth beam + tophat PB*	*Synth beam + real PB*
Power-law	0.042	0.002	0.038	0.052	0.116
Wieringa	0.078	0.003	0.045	0.095	0.133
Perly + Erickson	0.052	0.005	0.031	0.061	0.089

All values in Jy

Shep's work

- X Wieringa total
- X Wieringa synth beam only

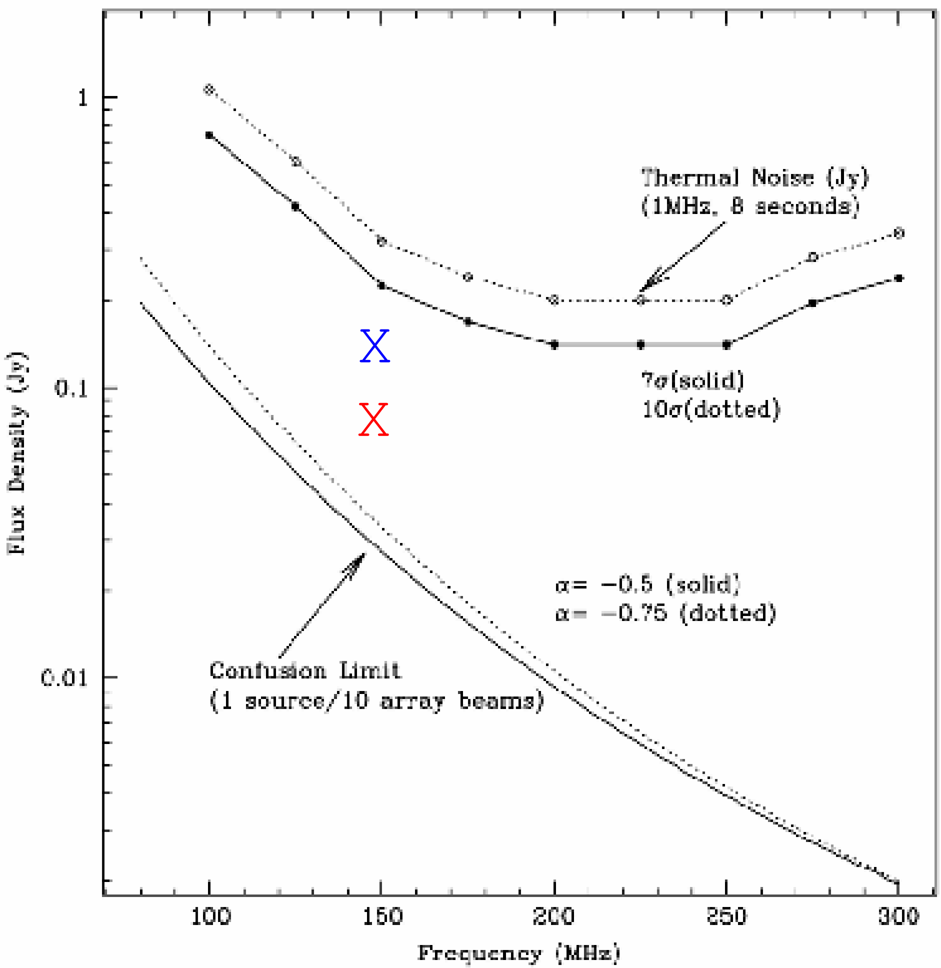


Figure 1: Comparison of continuum confusion limits to thermal noise limits for the MWA. Confusion limits estimated from 327MHz source counts (Wieringa 1991) extrapolated to MWA frequencies assuming the spectral indices shown.

Conclusions – (Part I)

- The confusion limit for the MWA at 150MHz will be around 0.1Jy (with peeling)
  - Results from different approaches agree
- Confusion noise comes partly from sources in synthesised beam and partly from sources in the sidelobes of the tile beams. (does not include diffuse emission!)
  - We can (in principle) reduce the effect of the latter
- Simplified (tophat) models of the primary beam severely underestimate confusion

Part II: GSM & Simulation

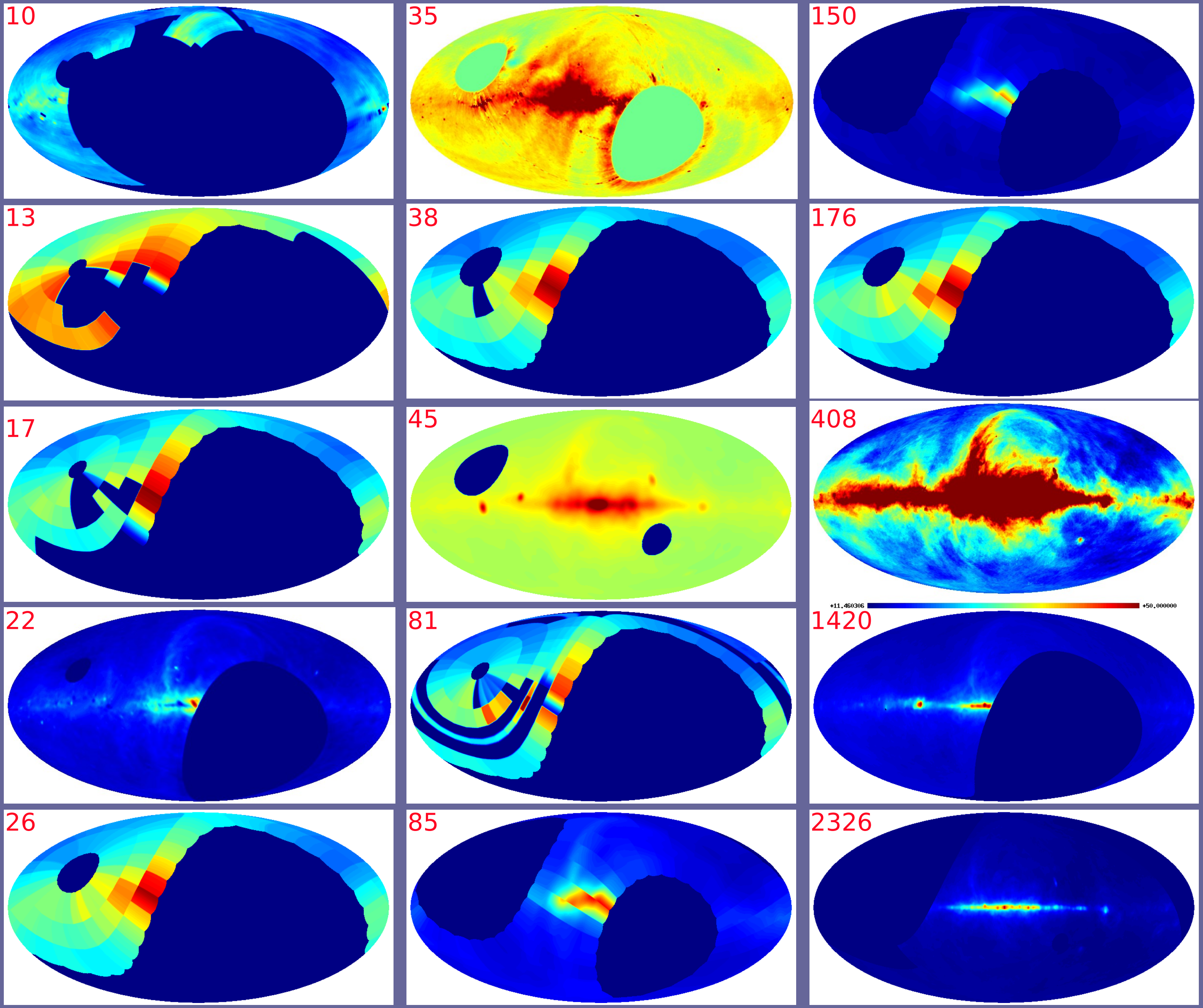
- For simulations
  - We need a “real enough” sky to test the calibration and imaging software
- For the real array: GSM Visibility Predictor
  - Needed to subtract static sky from the data to reduce sidelobe confusion and look for transients

Full sky simulations

- Aim:
  - Realistic model of the sky to test the real-time system including frequency and polarisation
  - Realistic virtual telescope including antenna element (dipole) power pattern, imperfect manufacturing and imperfect gains
- Intermediate goal:
  - Data that are good enough to test the calibration systems
  - Realistic tile response (dipole pattern, gain errors, position errors)

Outline: To improve modeling of foreground emission in the MHz-GHz range.

Work from Angelica de Oliveira-Costa



Making Sims

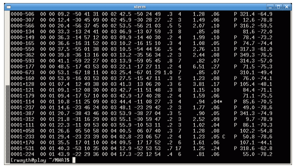
- Ingredients: 1

xterm

```
0000-506  00 00 09.2 -50 41 31 00 02 42.5 -50 24 49  .3  4    1.28  .06      P 321.4 -64.9
0000-307  00 00 12.4 -30 45 09 00 02 45.9 -30 28 27  .2  3    1.49  .06      P  12.6 -78.8
0000-566  00 00 20.4 -56 37 45 00 02 53.5 -56 21 03  .5  5    2.07  .10      P 316.2 -59.5
0000-134  00 00 33.3 -13 24 41 00 03 06.9 -13 07 59  .3  8     .85  .08         81.6 -72.0
0000-149  00 00 36.3 -14 57 12 00 03 09.9 -14 40 30  .2  4    1.99  .10      P  78.4 -73.2
0000-165  00 00 36.6 -16 31 52 00 03 10.2 -16 15 10  .3  4    1.08  .05      P  74.7 -74.4
0000-550  00 00 37.5 -55 01 38 00 03 10.5 -54 44 56  .5  4    2.76  .13      P 317.3 -61.0
0000-362  00 00 39.8 -36 13 16 00 03 13.2 -35 56 34  .2  3    2.44  .08      P 349.3 -76.5
0000-593  00 00 41.1 -59 22 27 00 03 13.9 -59 05 45  .8  7     .82  .07        314.3 -57.0
0000-177  00 00 48.5 -17 43 53 00 03 22.1 -17 27 11  .2  4    6.51  .27      P  71.5 -75.3
0000-673  00 00 53.1 -67 18 11 00 03 25.4 -67 01 29 1.0  7     .85  .07        310.1 -49.4
0000-160  00 00 53.9 -16 03 53 00 03 27.5 -15 47 11  .3  5    1.23  .08      P  76.0 -74.1
0001+128  00 01 07.4  12 49 38 00 03 41.3  13 06 20  .3  6    3.81  .17      P 105.4 -48.1
0001-121  00 01 09.1 -12 08 30 00 03 42.7 -11 51 48  .3  8    1.15  .10         84.4 -71.1
0001-179  00 01 09.4 -17 57 10 00 03 42.9 -17 40 28  .2  4    1.59  .06         71.1 -75.5
0001-114  00 01 10.8 -11 25 09 00 03 44.4 -11 08 27  .3  4     .94  .04*     P  85.6 -70.5
0001-237  00 01 14.6 -23 46 24 00 03 48.1 -23 29 42  .2  3    1.77  .06      P  49.0 -78.6
0001-387  00 01 20.7 -38 43 46 00 03 53.9 -38 27 04  .3  5     .90  .05      P 341.3 -74.9
0001-312  00 01 21.8 -31 16 29 00 03 55.1 -30 59 47  .2  3    2.52  .09      P   9.7 -78.9
0001-111  00 01 22.3 -11 09 53 00 03 55.9 -10 53 11  .2  3    1.02  .04      P  86.1 -70.3
0001+058  00 01 26.6  05 50 58 00 04 00.5  06 07 40  .3  7    1.28  .08        102.2 -54.8
0001-233  00 01 29.4 -23 23 39 00 04 02.8 -23 06 57  .2  4    1.23  .05 C    P  50.8 -78.6
0001+170  00 01 35.5  17 01 10 00 04 09.5  17 17 52  .2  6    1.61  .06        107.1 -44.1
0001-531  00 01 40.3 -53 10 35 00 04 12.9 -52 53 53  .7 17    1.25  .24      P 318.6 -62.8
0001-224  00 01 43.9 -22 29 36 00 04 17.3 -22 12 54  .4  6     .81  .06         55.0 -78.2
[rwayth@play ~/MWA]$
```

Making Sims

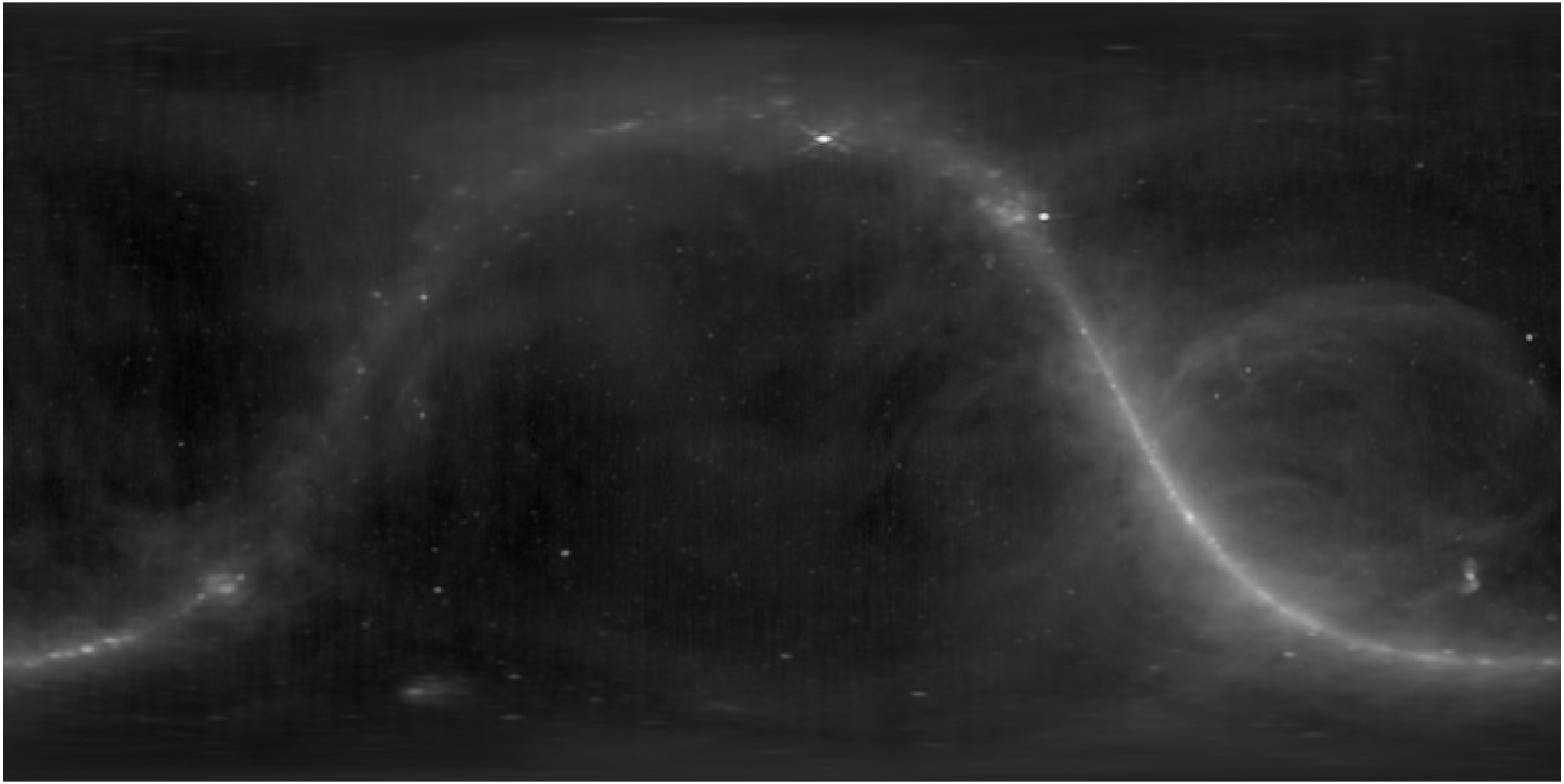
- Ingredients:
  - Molonglo 408 MHz reference catalogue (MRC)



    - Point source catalogue.
    - Resolution: ~arcmin
    - Dec: +18 to -85
    - Sources stronger than ~0.5 Jy

Making Sims

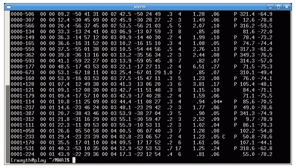
- Ingredients: 2

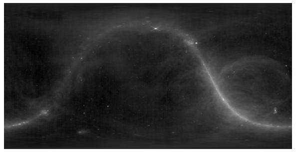


This is a logarithmic scale

Making Sims

- Ingredients:
  - Molonglo 408 MHz (MRC)
  - Haslam 408MHz all-sky map
    - ~1/3 degree resolution
    - Point sources are not well represented (good)
    - Emission dominated by the Galaxy

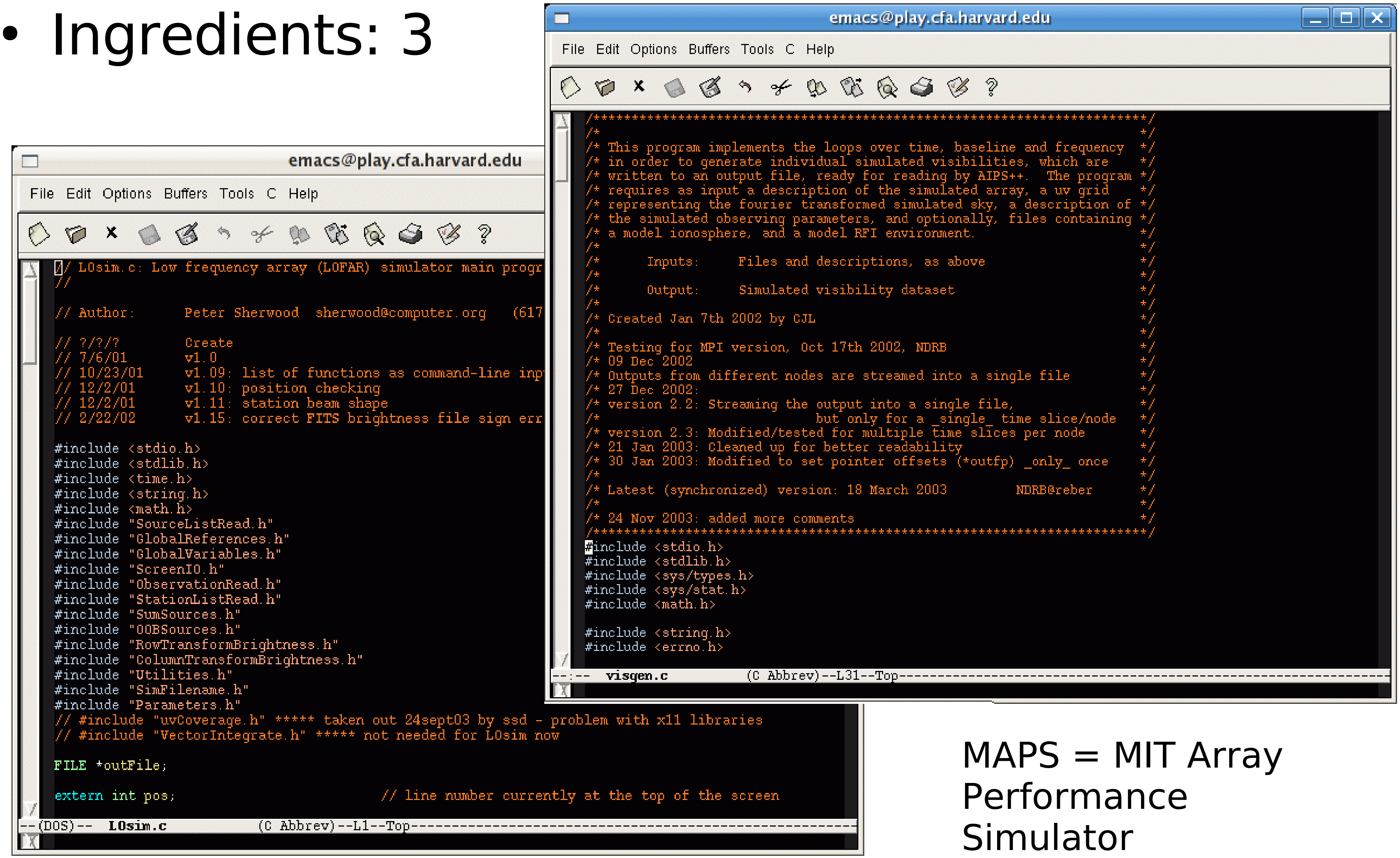




Making Sims

- Ingredients: 3

visgen

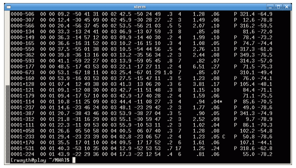


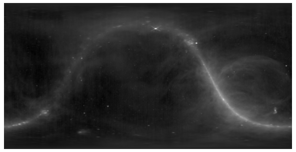
MAPS = MIT Array Performance Simulator

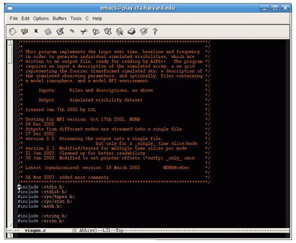
LOsim

Making Sims

- Ingredients: 3
  - Molonglo 408 MHz (MRC)
  - Haslam 408MHz all-sky map
  - MAPS
    - **In**: sky model, array definition, observing parameters
    - **Out**: visibilities “observed” with a simulated telescope

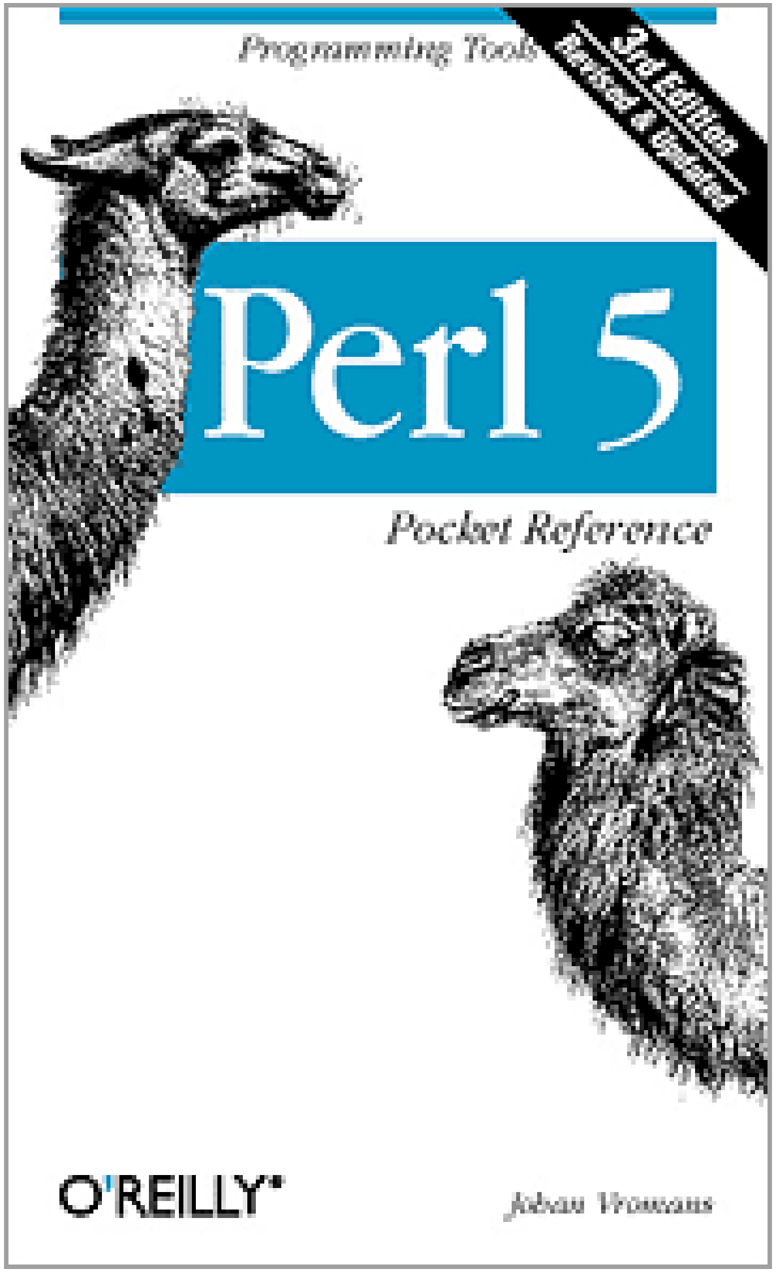






Making Sims

- Ingredients: 4
  - Plus:
    - CFITSIO
    - FFTW
    - SLALIB/C



Making Sims

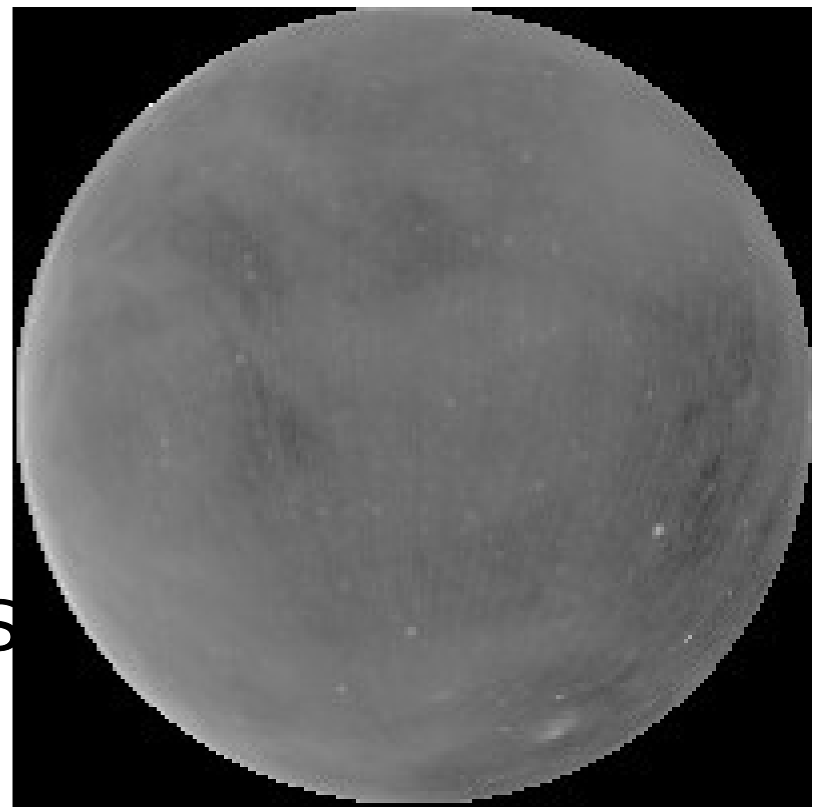
- Ingredients: 4
  - Molonglo 408 MHz (MRC)
  - Haslam 408MHz all-sky map
  - MAPS
  - Glue
- Method:

  1)Make sky

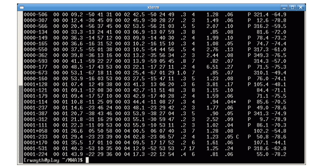
  2)MAPS

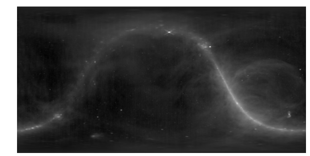
  3)MAPS 2 UVFITS

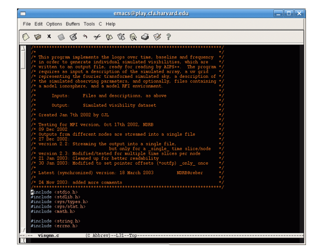
  4)miriad

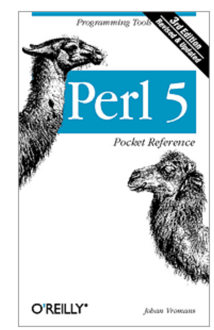


This is a log scale image



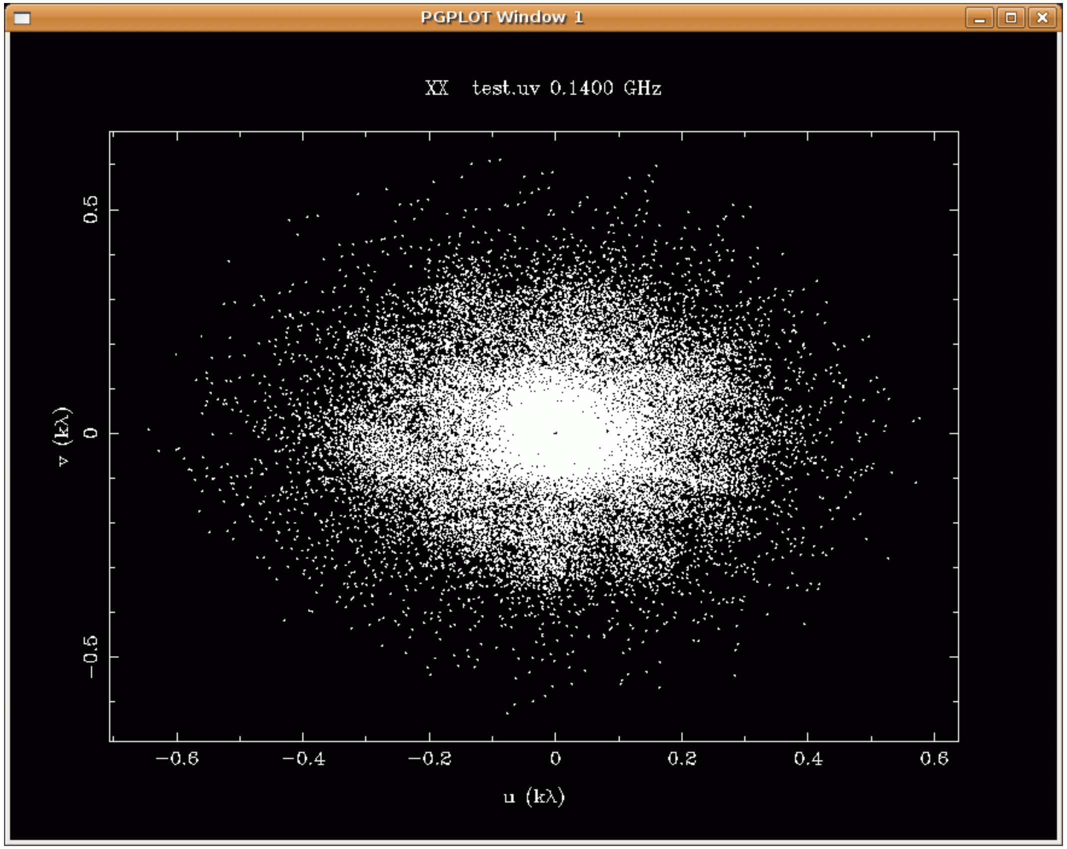




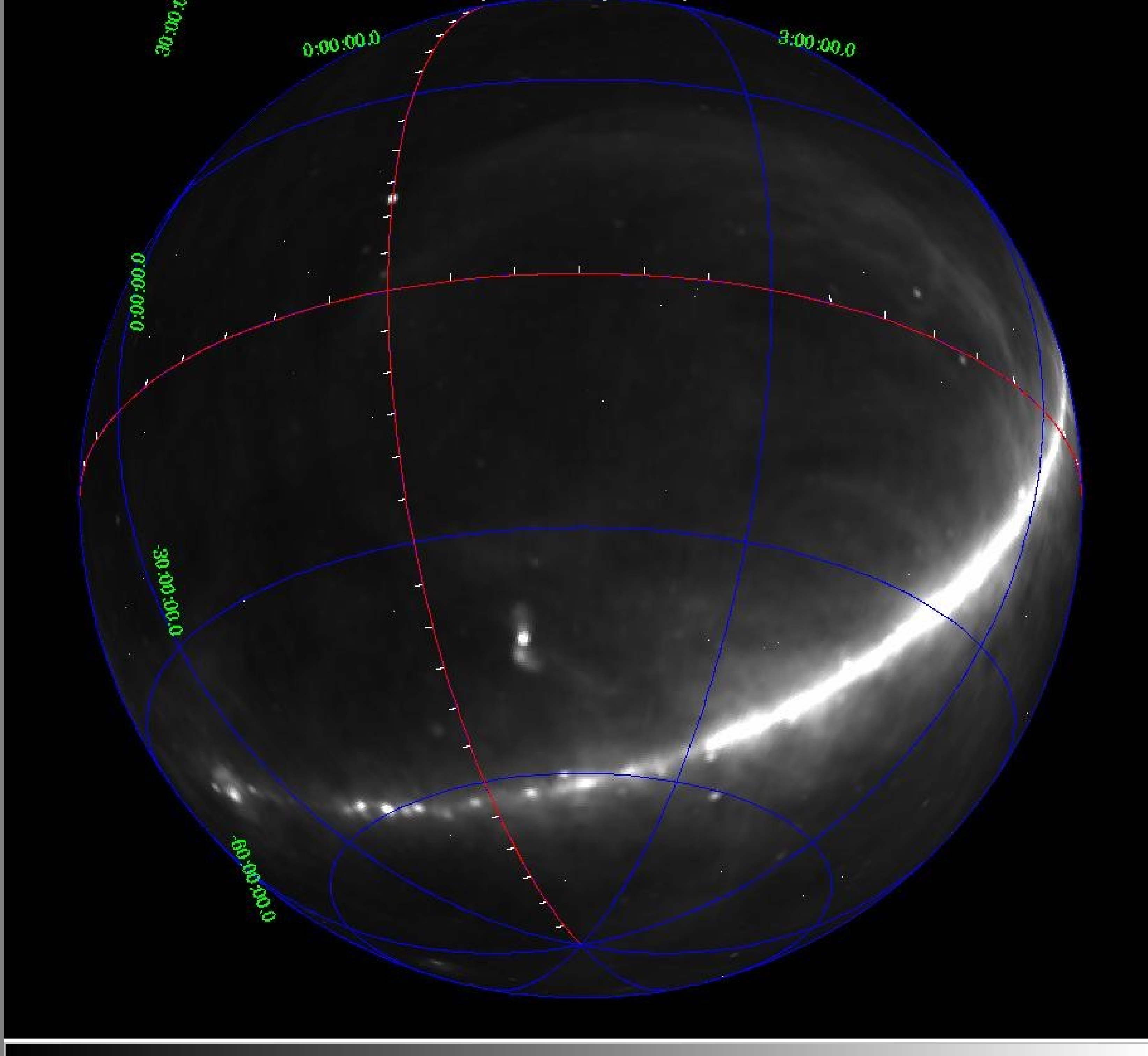


Simulation Specs...

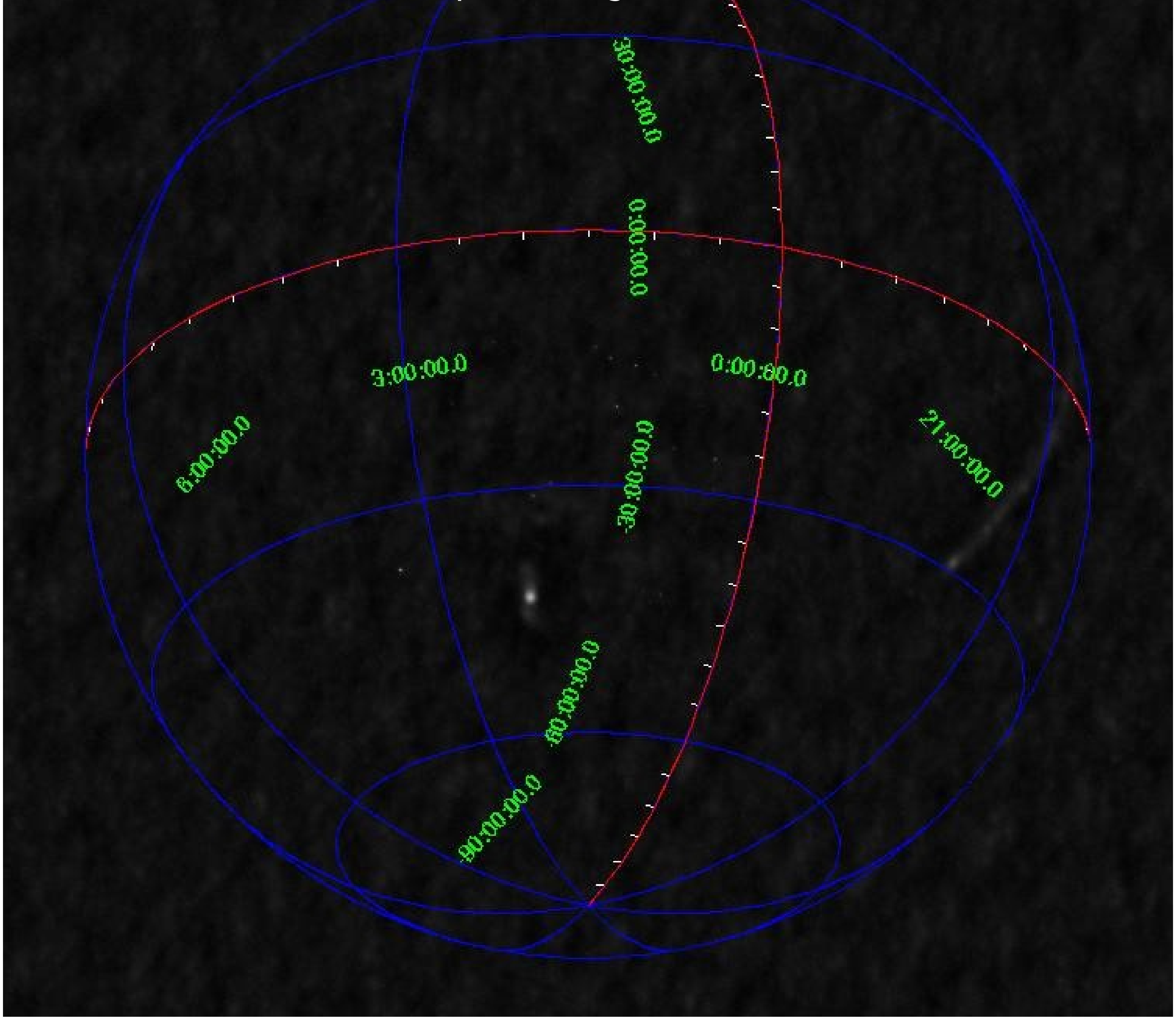
- 250 antennas
- 1.5 km max baseline
- 10m min baseline
- r^{-2} density
- 200 brightest sources from MRC (ex CenA)
- Sky from Haslam
- coplanar
- antennas consisting of 4x4 phased array of isotropic receivers

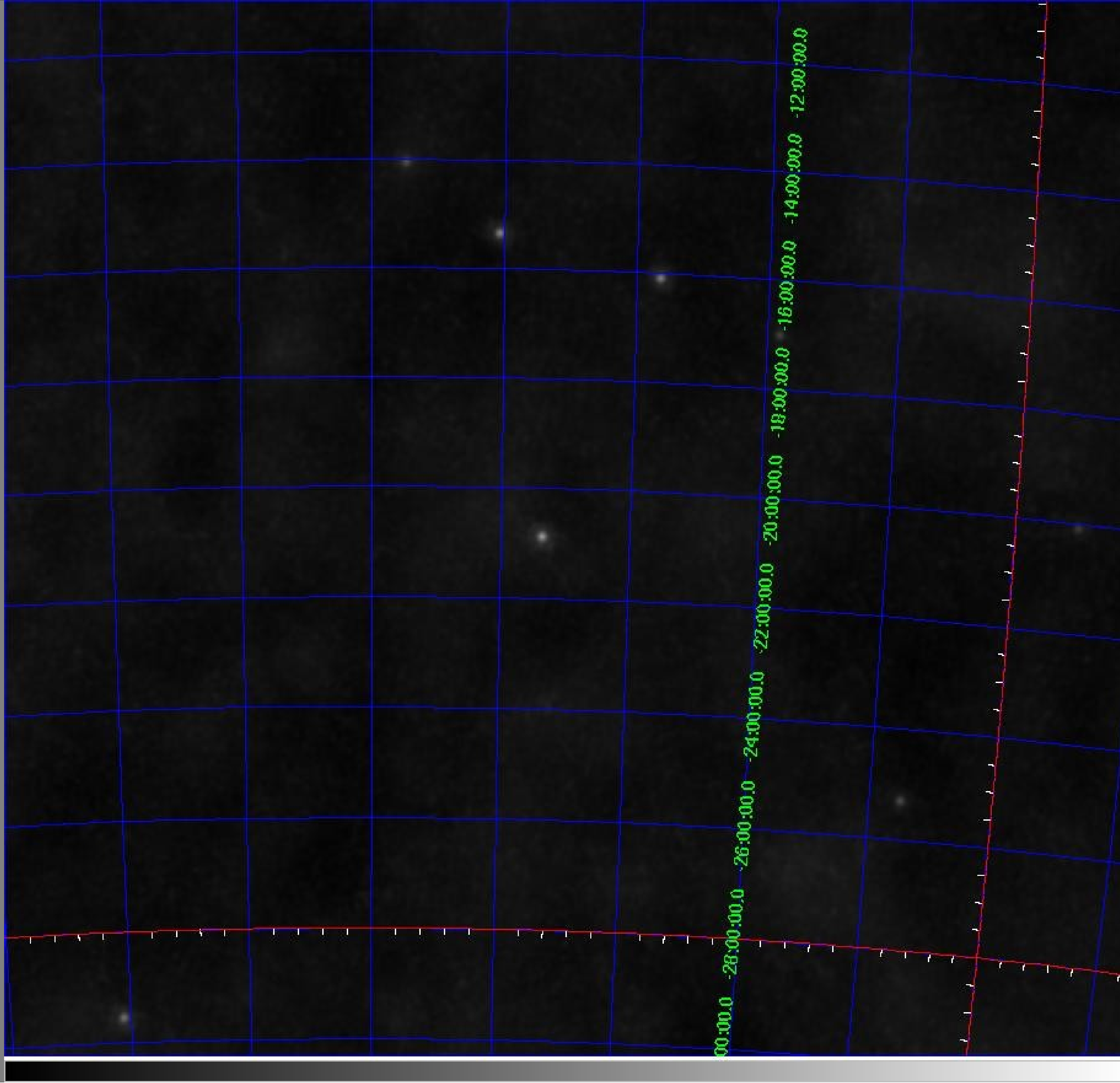


Input sky map



Dirty sky map with tile response
(tile pointing at zenith)

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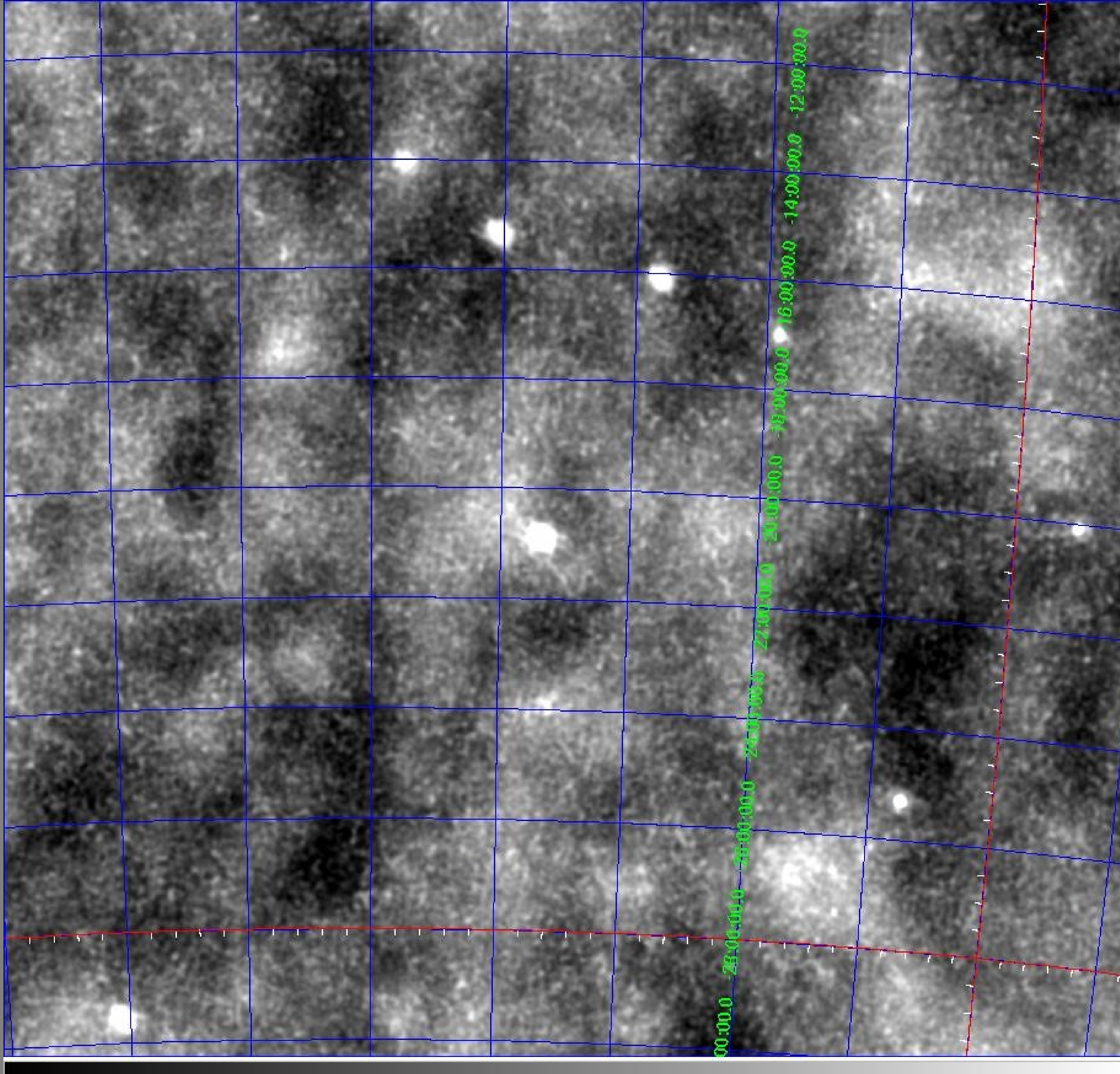

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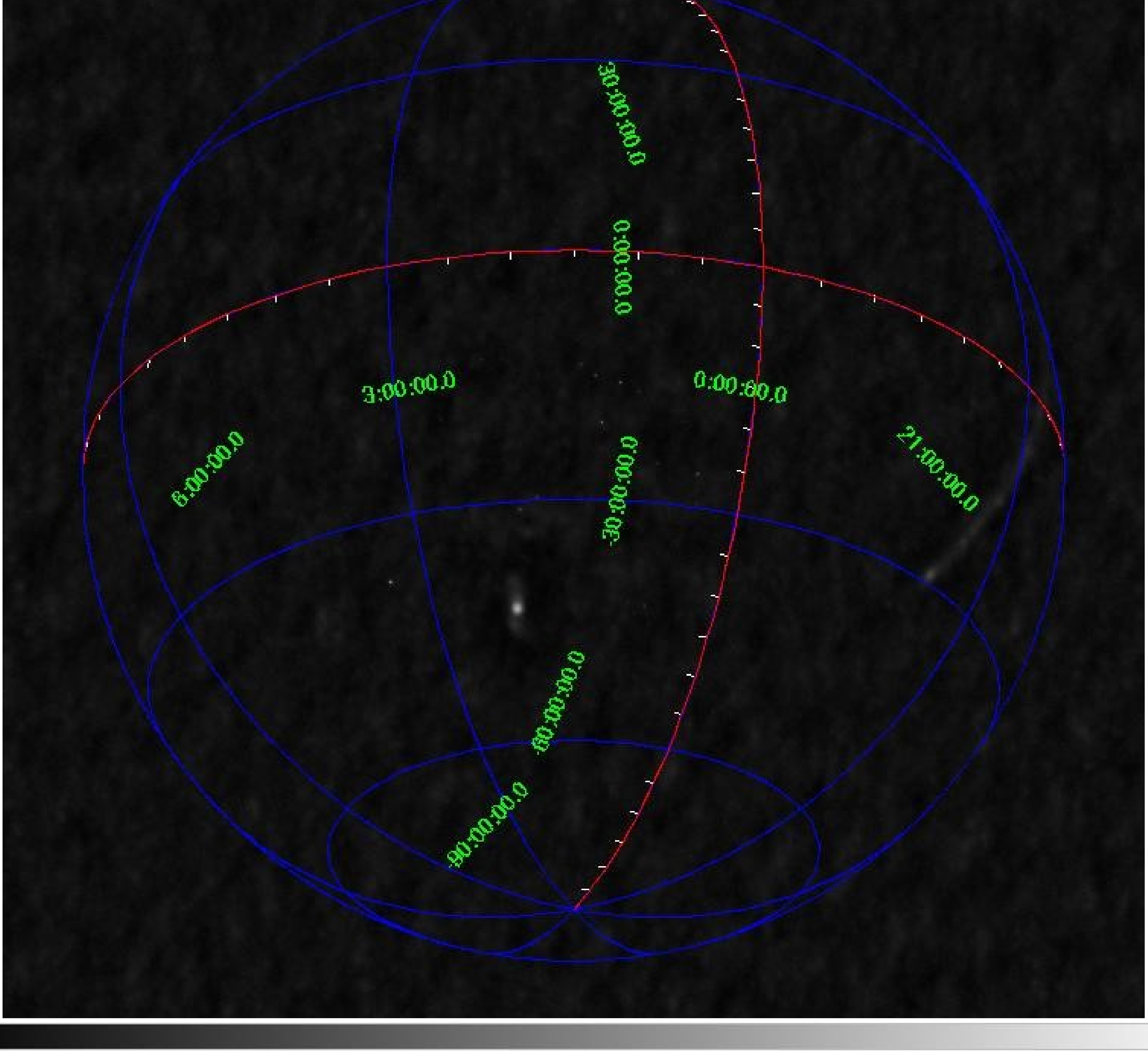
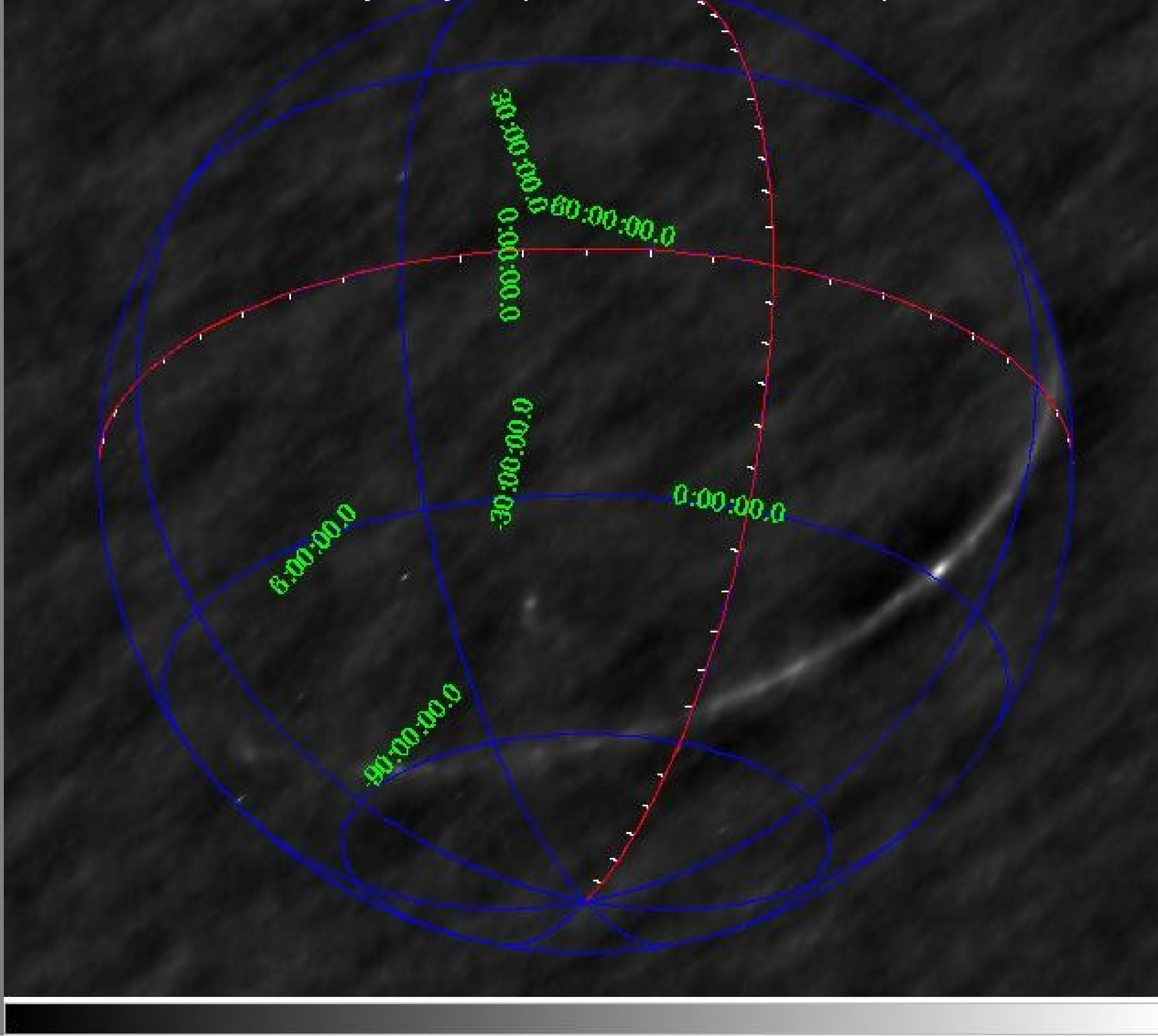
00:00.0

Dirty sky map with tile response



Dirty sky map *without* tile response



Results so far...

- Have generated simulated visibilities for
  - Single freq, single snapshot (any HA, LAT)
  - Takes ~10 mins, requires 2GB memory
  - Pipeline is in place, straightforward to generate long integrations & wide frequencies from here
- Sidelobes from extended sources (gal, Cen A) are significant
  - A few times what was expected from point sources alone
  - caveats: 10m minimum baseline, snapshot, monochromatic
- Data essential for testing, come and get it!

Next...

- non-ideal antenna elements
- Spectral indices on sources, sky
- Polarisation on sources
- Polarisation of antenna response

Fin