Lessons from dipole arrays: what is relevant for dense aperture arrays?

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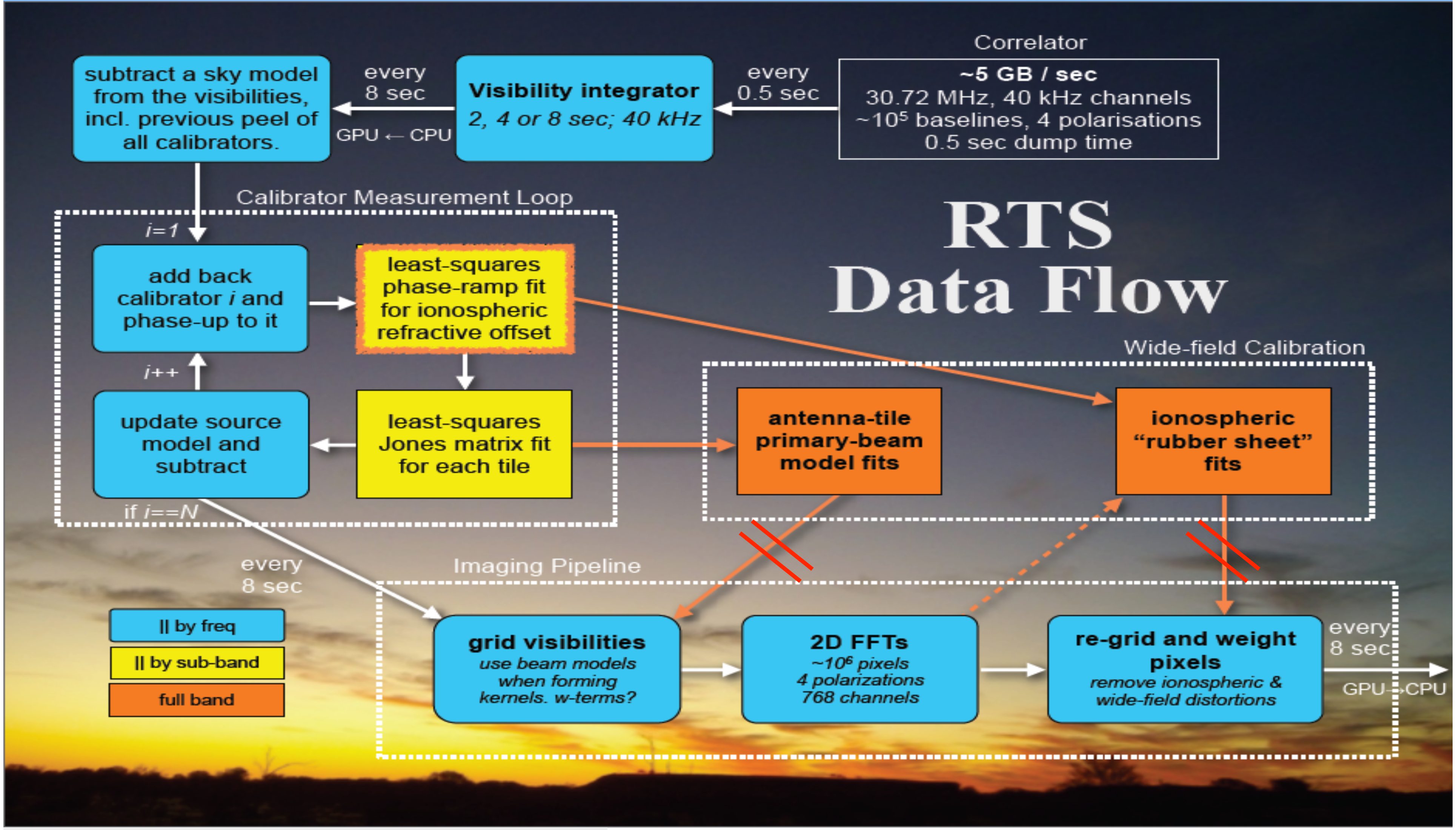
Renaissance of low frequency radio astronomy

Relevant issues at low frequencies

- Wide fields of view: hard to isolate a strong, unresolved point source as a calibrator source;
- Wide fields of view: no single phase solution across the field? Certainly not for long baselines due to the ionosphere;
- Wide fields of view: 3D imaging (computational burden);
- Dipoles often clustered in tiles/stations to increase gain directivity: time an frequency variable station → no such a concept as "observing a calibration source" particularly if the beam forming is analogue;
- Ionospheric modeling required to fix phase corruptions across the field of view (only for long baselines?);
- Correction for dipole projections for each pixel in the image (at each time and frequency) required for full polarimetry;
- Most of the aforementioned effects generate a spatially and time variable PSF: burden on deconvolution;

MWA calibration/imaging: co-addition of warped snapshots



Correlator

~5 GB / sec
30.72 MHz, 40 kHz channels
$\sim 10^5$ baselines, 4 polarisations
0.5 sec dump time

every
0.5 sec

Visibility integrator
2, 4 or 8 sec; 40 kHz

every
8 sec

GPU ← CPU

subtract a sky model from the visibilities, incl. previous peel of all calibrators.

Calibrator Measurement Loop

i=1

add back calibrator *i* and phase-up to it

least-squares phase-ramp fit for ionospheric refractive offset

i++

update source model and subtract

least-squares Jones matrix fit for each tile

if *i*==*N*

RTS
Data Flow

Wide-field Calibration

antenna-tile primary-beam model fits

ionospheric “rubber sheet” fits

every
8 sec

Imaging Pipeline

grid visibilities
use beam models when forming kernels. w-terms?

2D FFTs
$\sim 10^6$ pixels
4 polarizations
768 channels

re-grid and weight pixels
remove ionospheric & wide-field distortions

every
8 sec

GPU→CPU

|| by freq

|| by sub-band

full band

courtesy D. Mitchell

Warped snapshot imaging

(see Griffin Foster’s talk for an application to PAPER)

- Imaging with dipole arrays is always mosaicing;
- The array can be considered instantaneously co-planar → 2D FFT
- Resample to a common reference frame (Healpix) → correction for a ionospheric refraction screen and wide field polarization simultaneously;
- Time integration happens co-adding snapshot images:

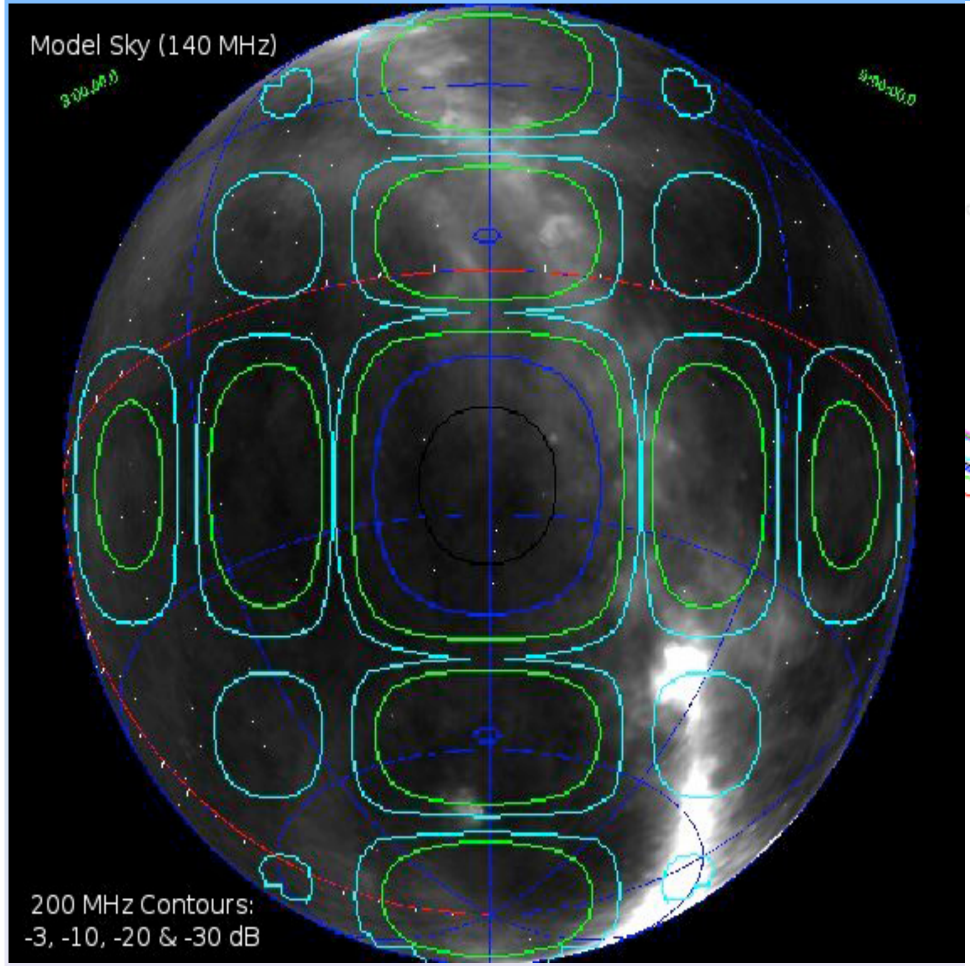
$$b_{HPX}^{S} = [(J_{pix} \otimes J_{pixx})^{\dagger} (J_{pix} \otimes J_{pix})]^{-1} (J_{pix} \otimes J_{pix}^{*})^{\dagger} (J_{pix} \otimes J_{pix}^{*}) S b_{HPX}^{S}$$

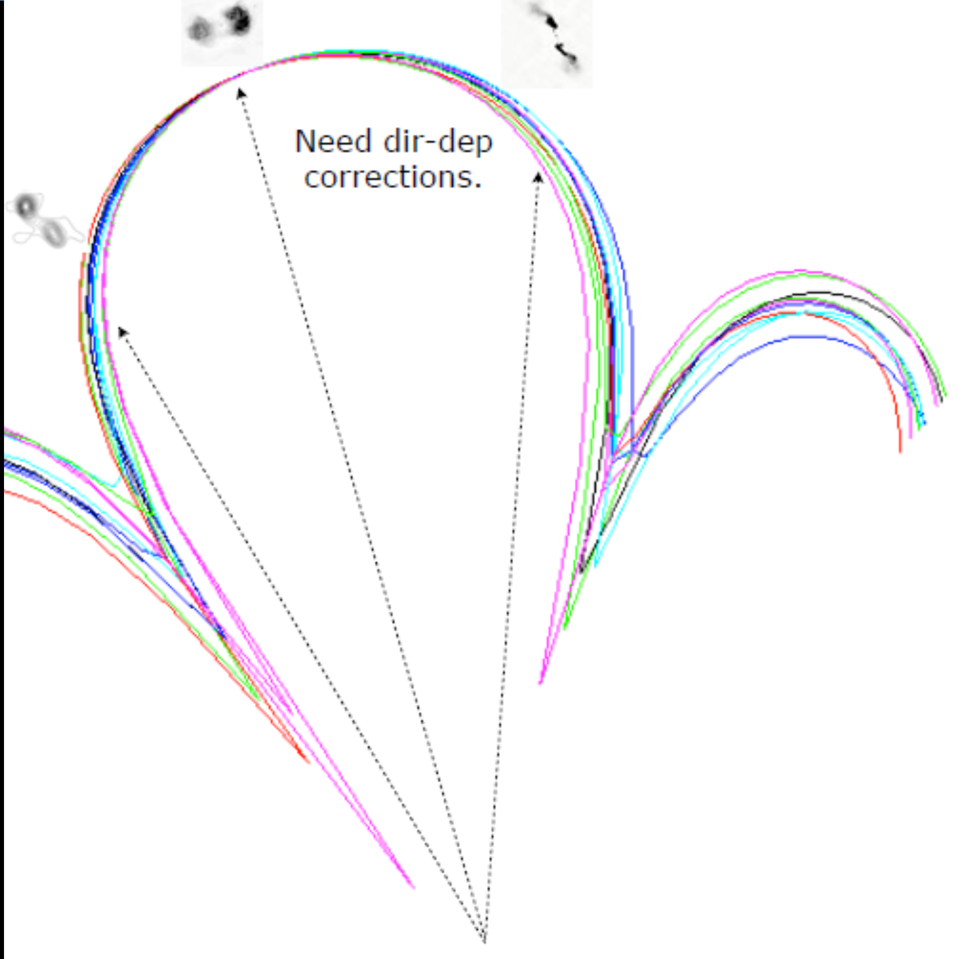
- Long integrations are easily parallelizable in time and frequency;

(Ord et al., 2010, PASP, 122, 1353)

Ord et al. 2010

MWA primary beams

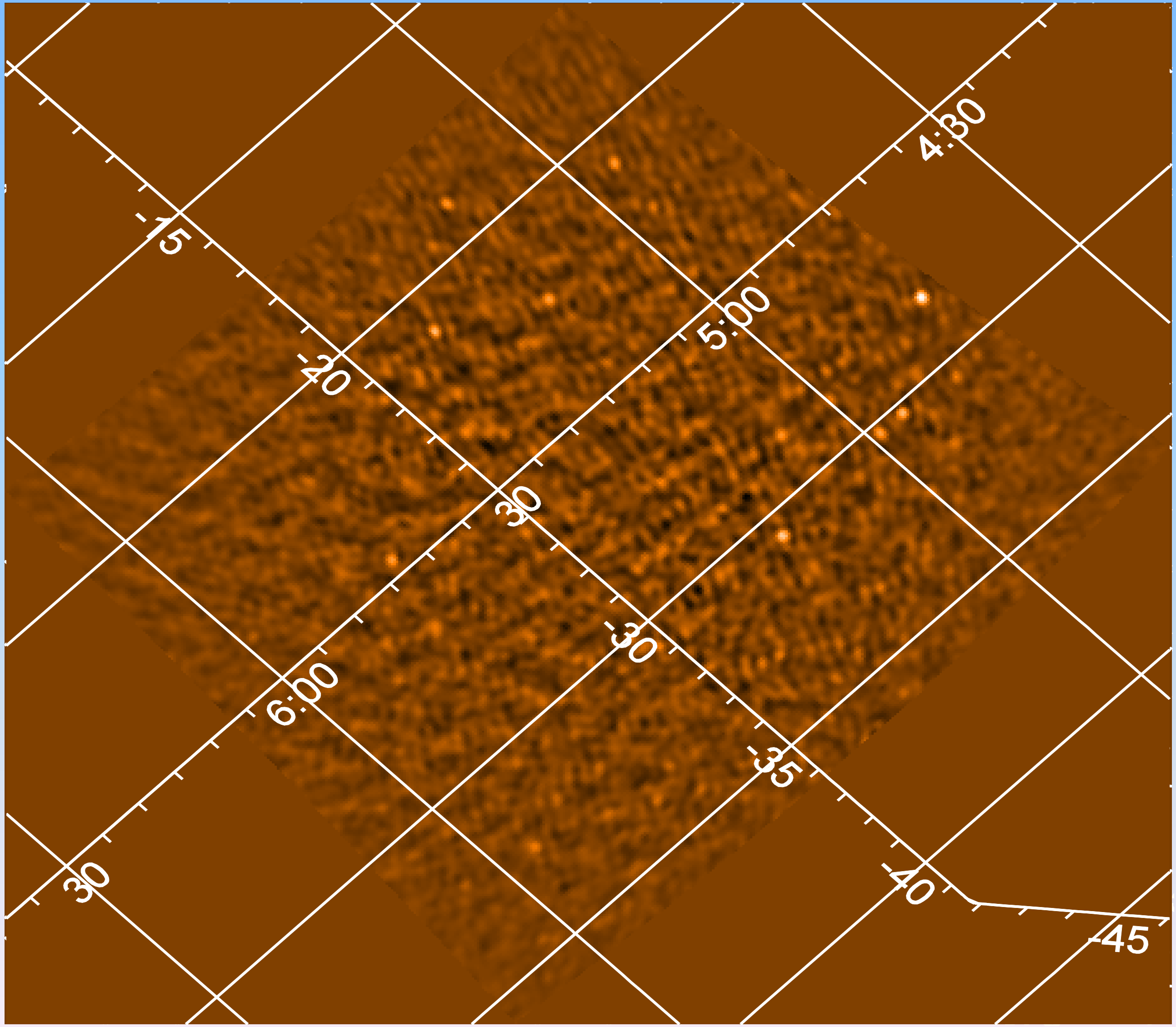




(Ord et al. 2010, PASP, 122, 1353)

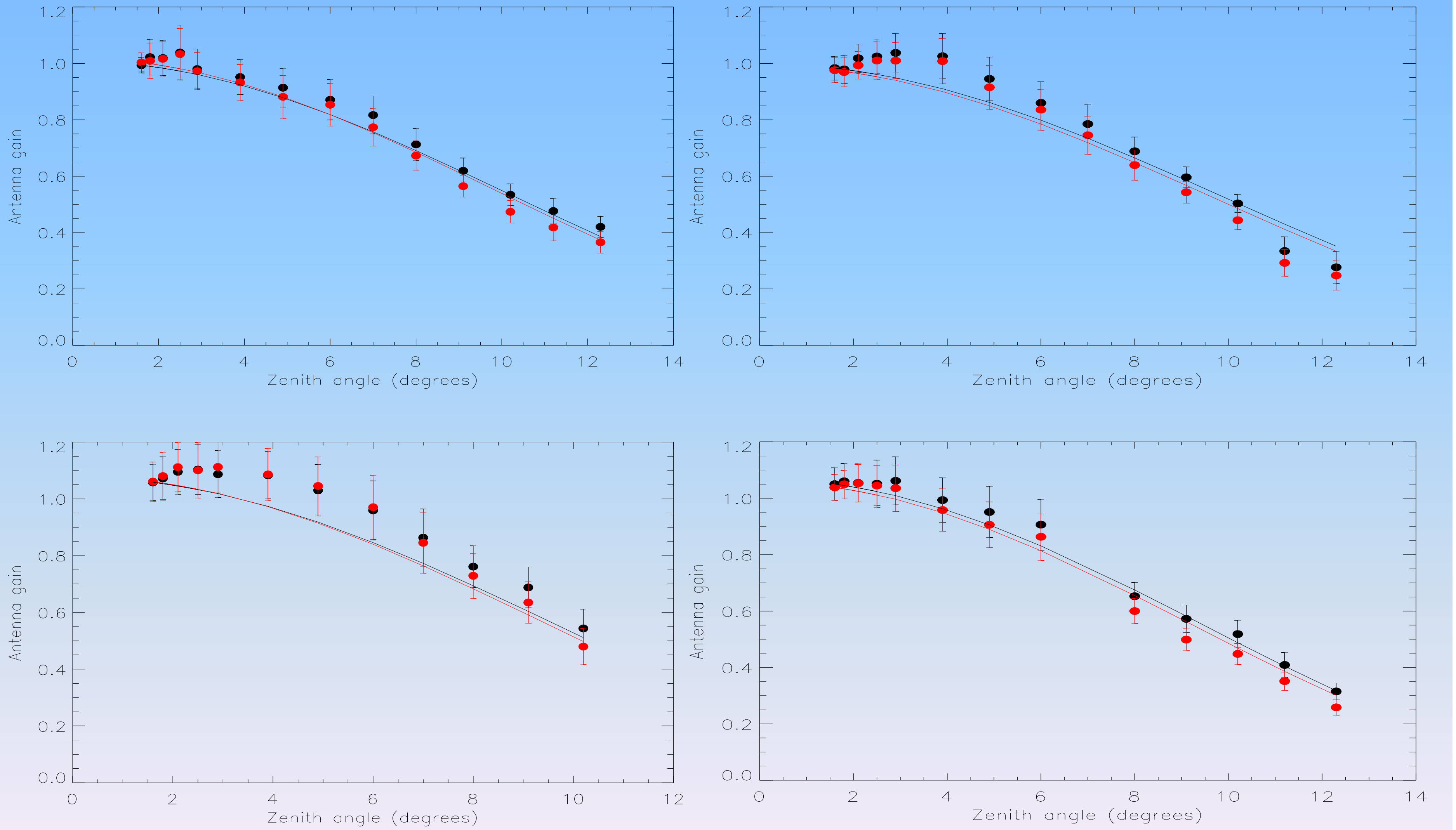
There are methods to grid and image the data using different element beam patterns (Bhatnagar 2008, Morales & Matejek 2009, Mitchell, Wayth, GB et al. 2012, Tasse et al. 2013)… knowing the input beam patterns precisely is still a challenge to date!

Keep the element beam stable in time: turn it into a transit instrument



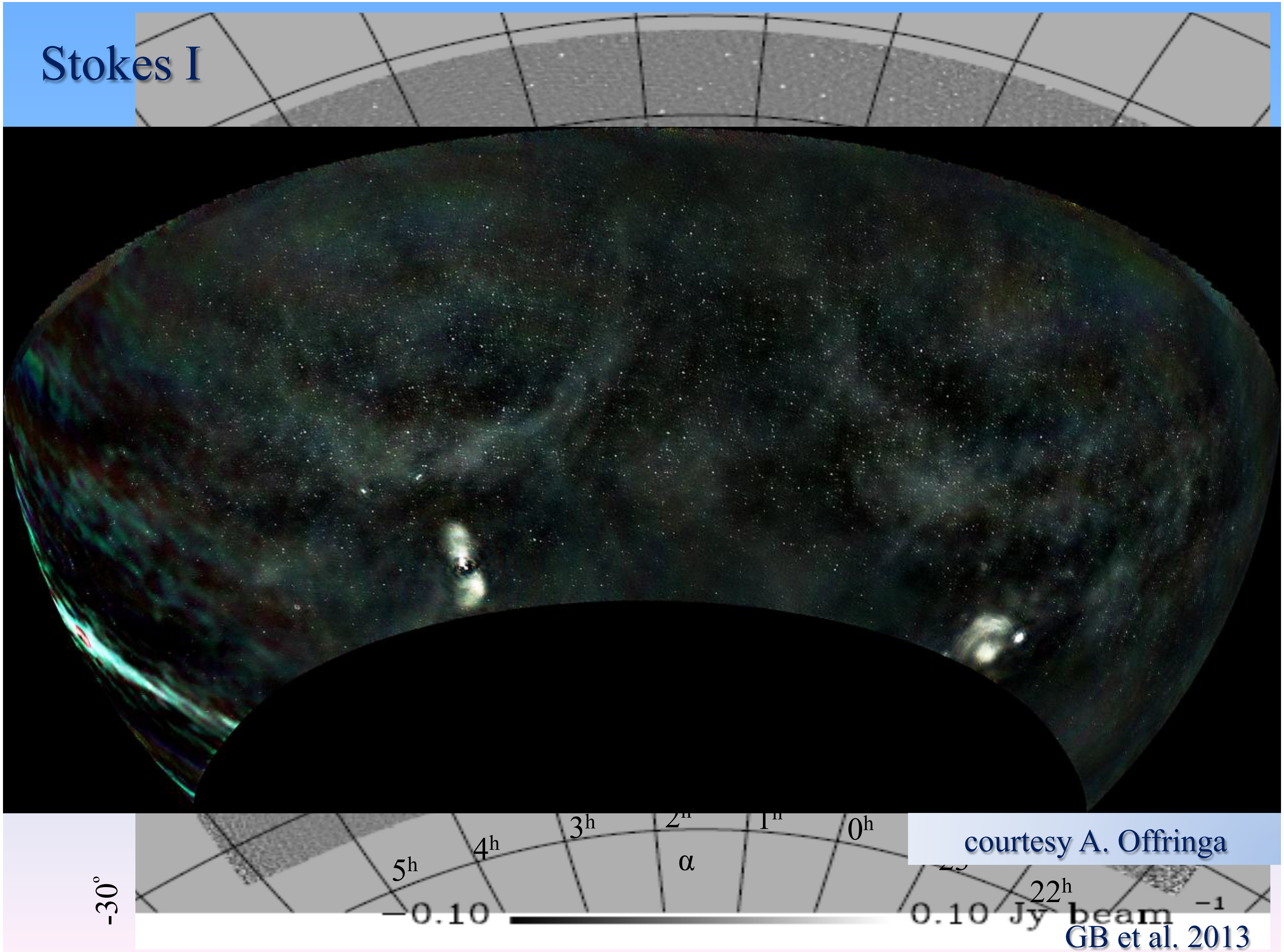
GB et al. 2013

Constraining a beam model with drift scans



GB et al. 2013 (also Pober et al. 2010)

Stokes I

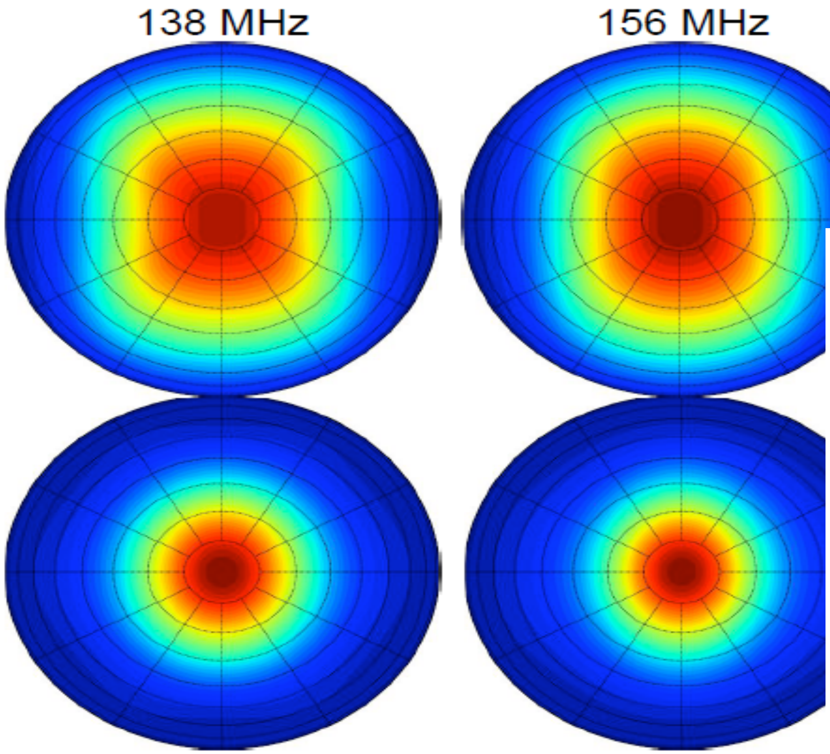


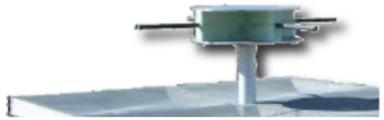
courtesy A. Offringa

GB et al. 2013

Easier problem for individual, non-tracking dipoles (i.e. PAPER)

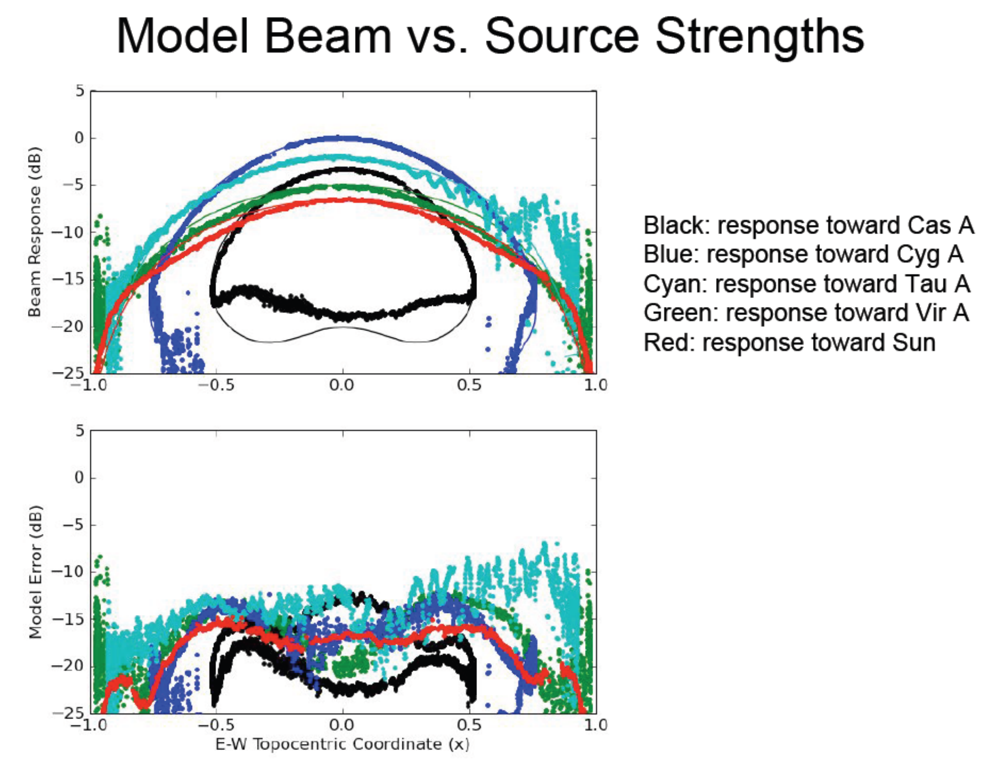
Modeling Beam of Dipole + Flaps





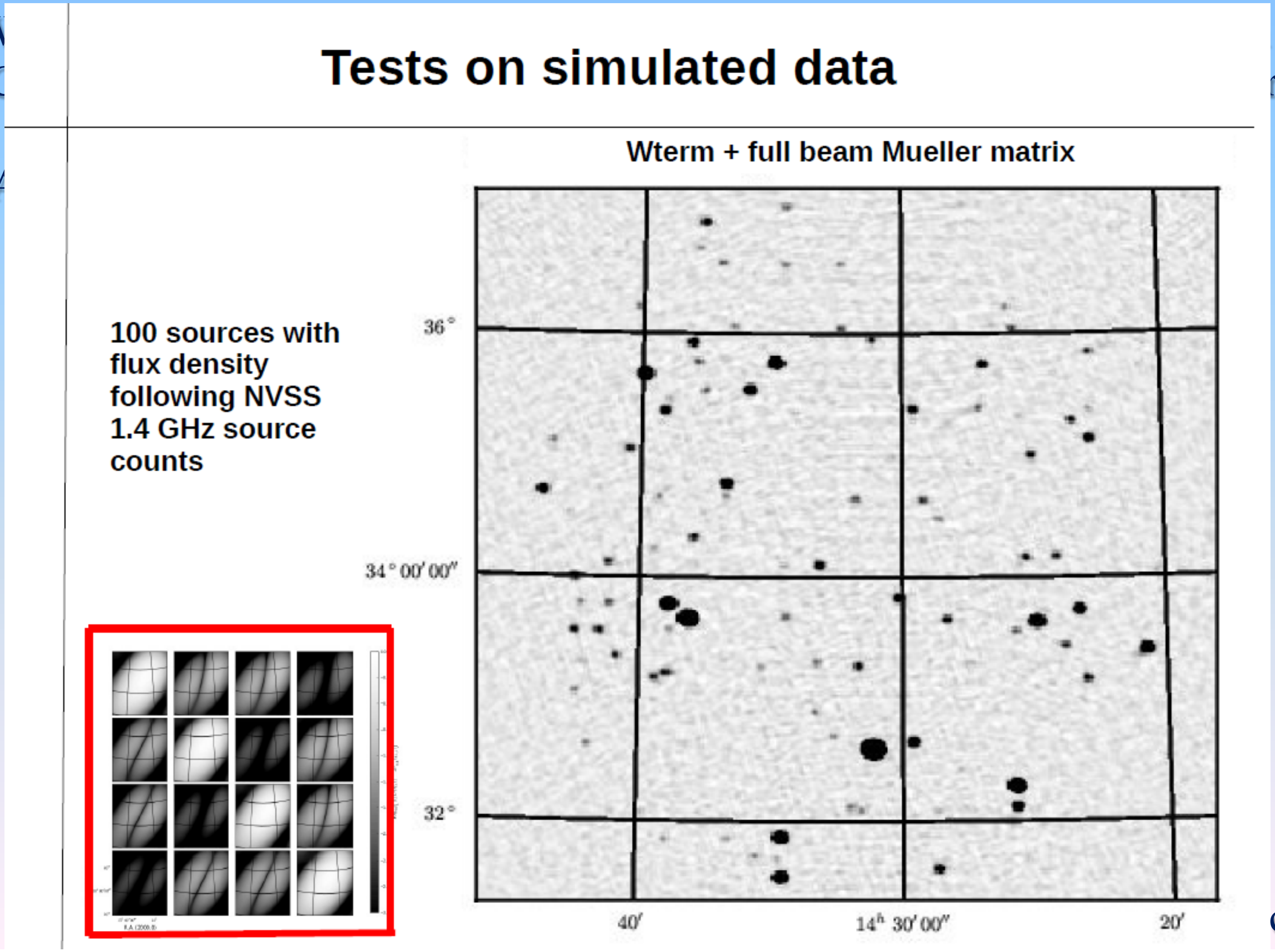
$$a_\nu(\hat{s}) = \sum_{k=0}^{7} \nu^k \left[\sum_{\ell=0}^{8}\sum_{m=0}^{\ell} a_{\ell m}(k) Y_{\ell m}\right.$$

40dB zenith to horizon, 60 degree FW
Smooth spatially and vs. frequency


Model Beam vs. Source Strengths

Deconvolution

- V methods (Hogbom, C riant PSF);
- A



Tests on simulated data

Wterm + full beam Mueller matrix

100 sources with flux density following NVSS 1.4 GHz source counts

courtesy C. Tasse

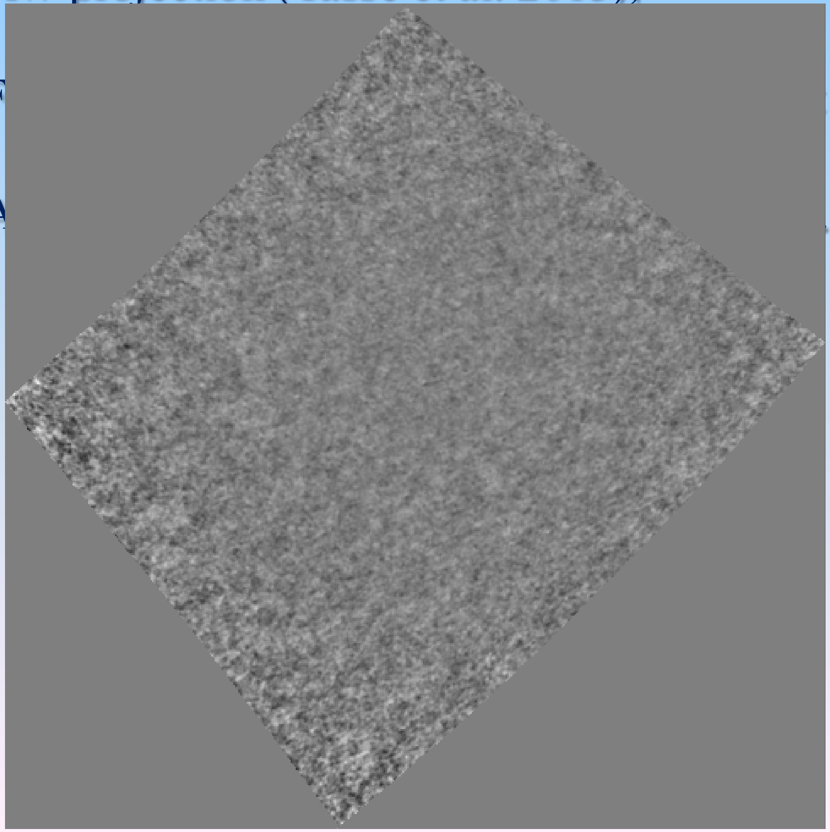
Deconvolution

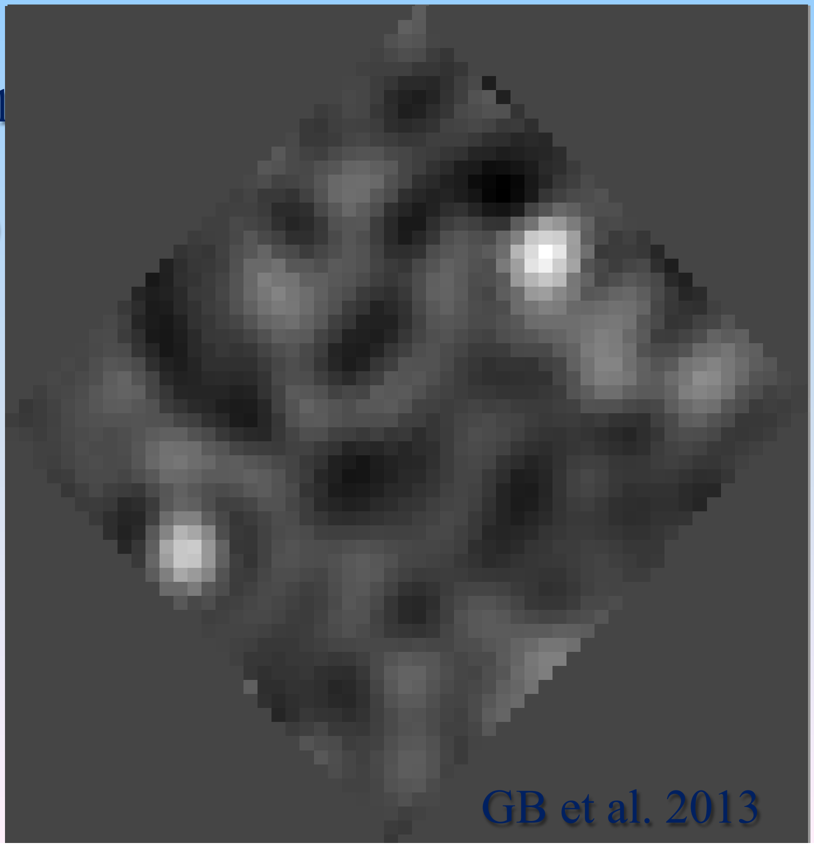
- When the complex gains change across the FoV, traditional deconvolution methods (Hogbom, Clark, Cotton-Schwab etc…) no longer apply (they assume a spatially invariant PSF);

- AW projection (Tasse et al. 2013);

- F al. 201

- A 2011)





GB et al. 2013

Deconvolution

- When the complex gains change across the FoV, traditional deconvolution methods (Hogbom, Clark, Cotton-Schwab etc…) no longer apply (they assume a spatially invariant PSF);
- AW projection (Tasse et al. 2013);
- Fast holographic deconvolution (Sullivan et al. 2013) – image based deconvolution;
- Algebraic forward modeling (Bernardi et al. 2011) – image based deconvolution;
- All the methods are slow and computationally expensive… are there fast, efficient and accurate ways to deconvolve all sky images (including diffuse emission)?

From dipole arrays to MFAAs

- They share very similar (same?) problems → a lot of what was developed for low frequency arrays will be applicable to MFAAs;

- It is best to optimize the array design based on your science goals… but science and technology should meet;

- Cosmology with MFAAs:
  - very short baselines (to detect large scale si
  - large fields of view;
  - extremely accurate calibration for f raction;
  - no station beamforming, just si (PAPER) → accurate beam modeling, beam stability, no W-term in ima imaging (or AW projection);
  - beam constraints from ments of sky sources;
  - lighter deconvolution s with a denser uv-coverage;

THANK YOU

- HI spectral line imaging:
  - long baselines;

- Pulsars and transients:
  - digital beamforming + all sky monitoring (<u>forget about problems in imaging and calibration</u>);