Results from the MWA

Rachel Webster, University of Melbourne
& EoR collaboration

Outline

- MWA status and plans
  - Phases II and III
- What have we learned?
- Some 2016-17 developments
- Next steps

What are we trying to do?

Statistically detect the EoR signal $6 \lesssim z \lesssim 10$

- Determine the instrumental limitations
- Detect and remove RFI
- Measure ionospheric effects, and resolve
- Optimise the calibration model
- Characterise the foreground emissions
- Process huge complex datasets; manage software pipelines

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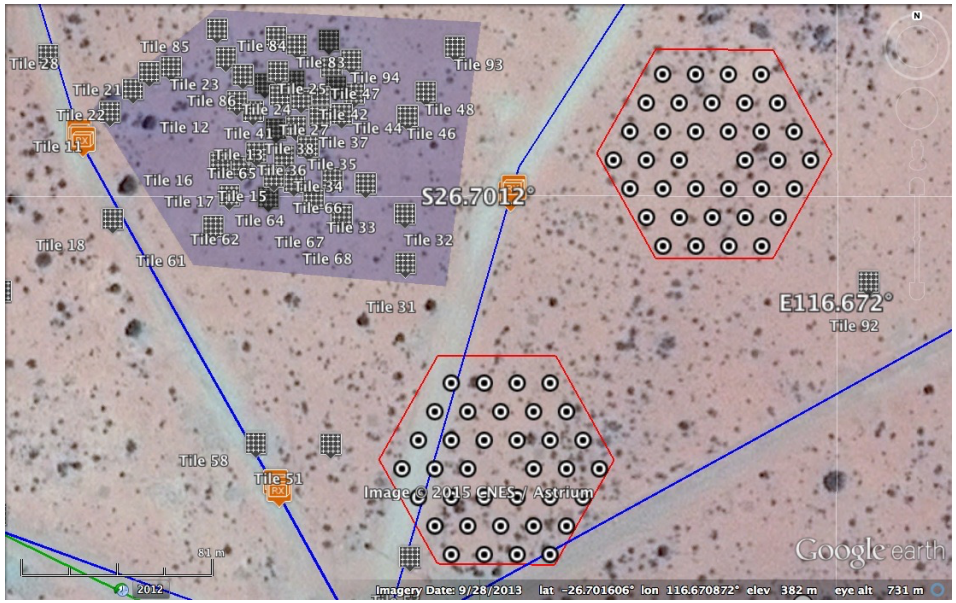
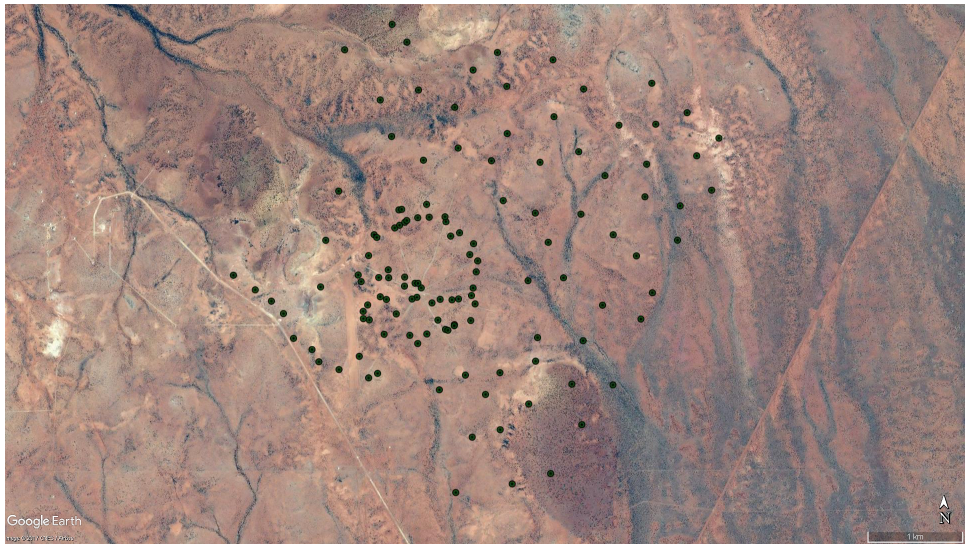
Realistically: understand and design the SKA EoR experiment

MWA Phase II



Enhanced Core:
72 tiles in 2 redundant hexagonal arrays



Extended baselines:
56 tiles in baselines from 3km up to 5 km

BUT only 128 tiles available at one time

MWA Phase III

- Design and build new receivers
- Funding not secured
- New partners in Phase II
  - Japan
  - China
  - [India, changed US collaboration]
- New partners will be required for Phase III

Implications for EoR

- Phase II
  - Extended baselines → higher resolution → improved sky model
  - Redundant hexagons → hybrid calibration → optimising the array configuration
- Phase III
  - Removal of instrumental ‘features’
  - Full 256 tiles

What have we learned?

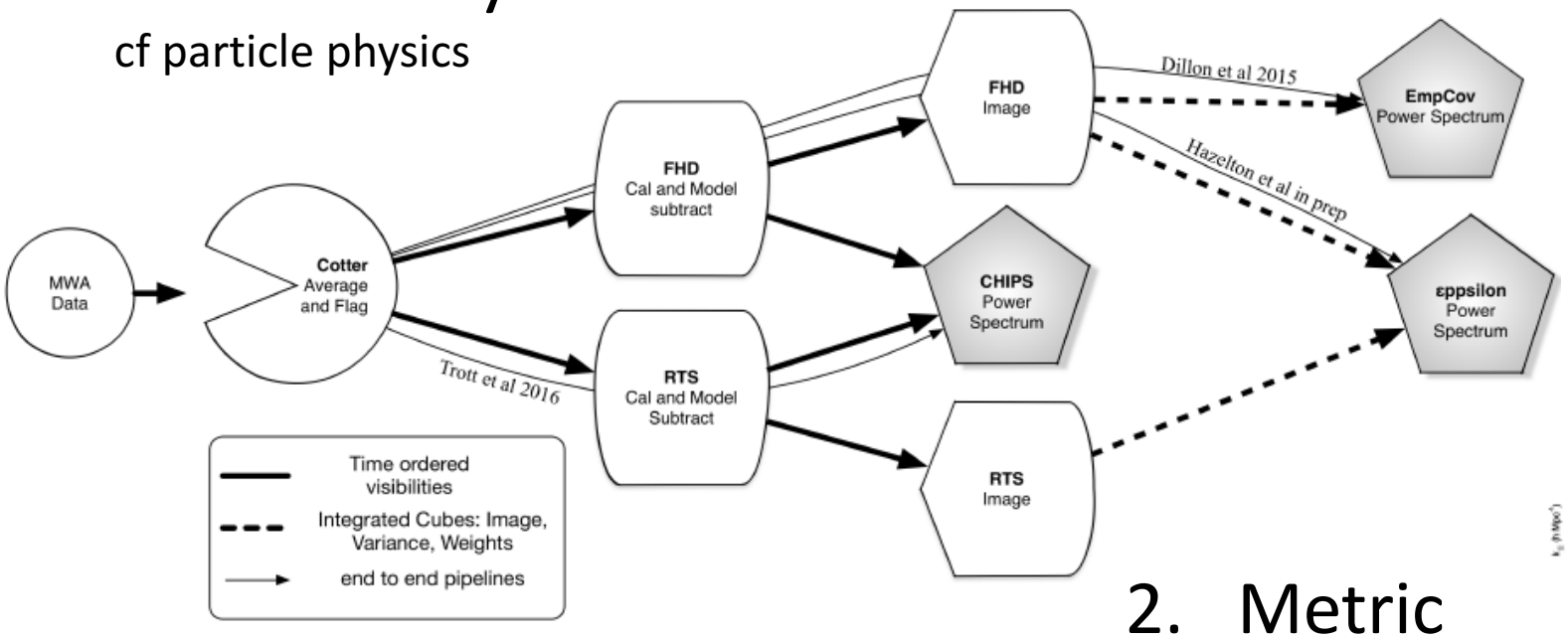
- Redundant pipelines – Jacobs+16
  - End-to-end→ metric → iteration
- Polarisation leakage: self-calibration?
  - Lenc+16
- Know the beam: measure it
  - Neben+15
- Systematics in the signal path

MWA Pipeline Strategy

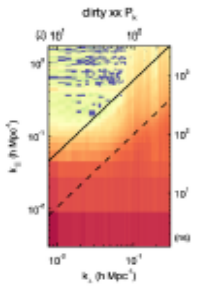
1. Redundancy

   cf particle physics

Jacobs + 2016



2. Metric



Short Name	Name	Citations
Cotter	AOFlagger + Averaging	Offringa et al. (2010)
RTS	Real Time System	Mitchell et al. (2008); Ord et al. (2010)
FHD	Fast Holographic Deconvolution	Sullivan et al. (2012)[1]
εppsilon	Error Propagated Power Spectrum with InterLeaved Observed Noise	Hazelton et al. 2016, *in prep*[2]
CHIPS	Cosmological HI Power Spectrum	Trott et al. (2016)
EmpCov	Empirical Covariance Estimator	Dillon et al. (2015)

[1] github.com/miguelfmorales/FHD
[2] github.com/miguelfmorales/eppsilon

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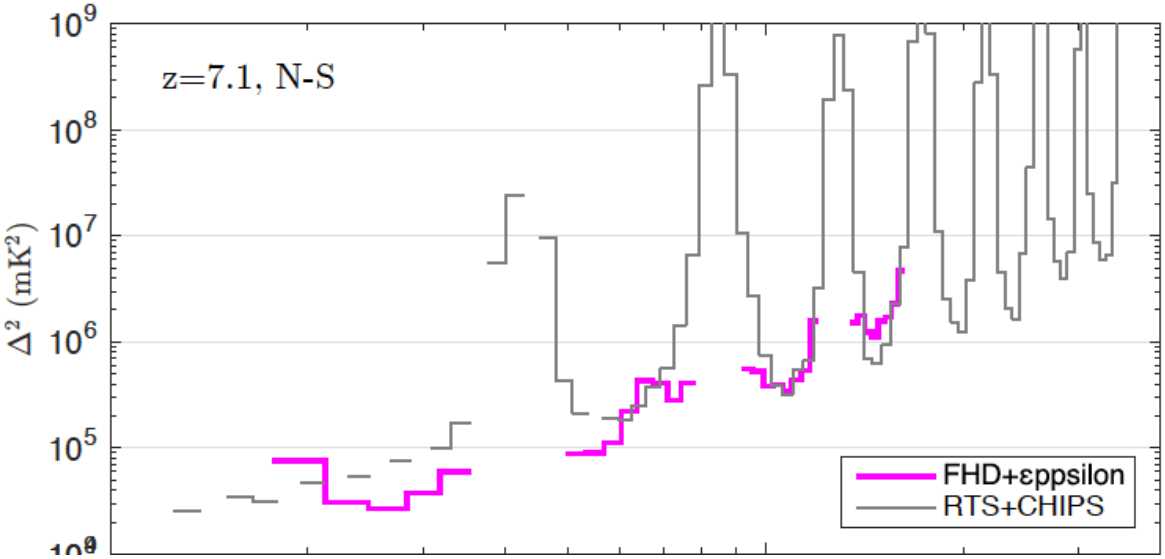
- FOR EoR EXPERIMENT, INCREMENTAL BUILDOUT

Best limits from MWA

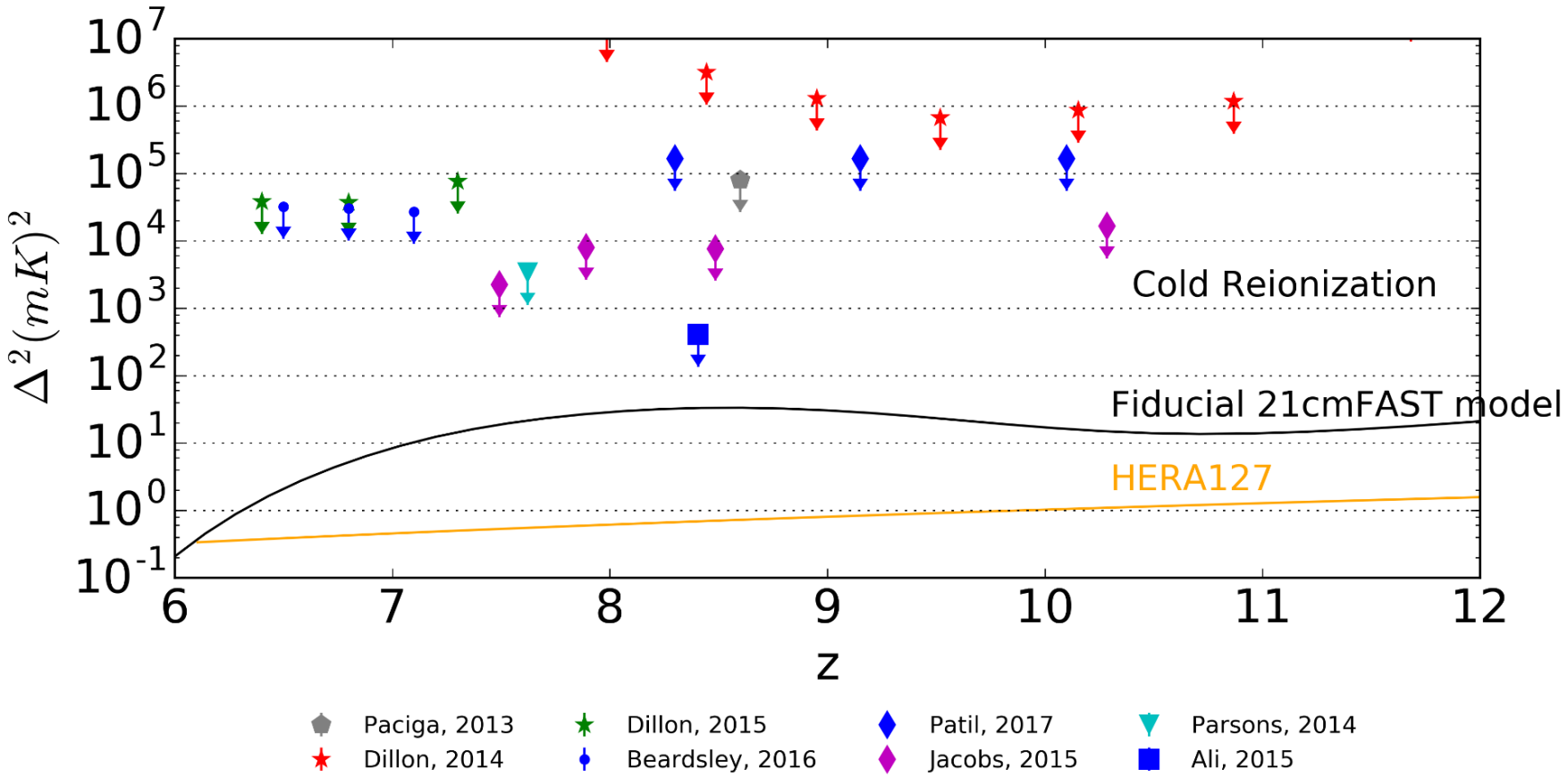


- 32 hours quality data
- 6.5<z<7.1
- Foreground limited

Sub-band	z_0	Pol	FHD+εppsilon k	FHD+εppsilon Δ^2_{UL}	RTS+CHIPS k	RTS+CHIPS Δ^2_{UL}
Low	7.1	E-W	0.231	3.67×10^4		
Low	7.1	N-S	0.27	2.70×10^4	0.16	3.2×10^4
Mid	6.8	E-W	0.24	3.56×10^4		
Mid	6.8	N-S	0.24	3.02×10^4	0.14	2.6×10^4
High	6.5	E-W	0.20	4.70×10^4		
High	6.5	N-S	0.24	3.22×10^4	0.14	2.5×10^4

Beardsley+16

Best limits


$\Delta^2(mK)^2$
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
6
7
8
9
10
11
12
z
Cold Reionization
Fiducial 21cmFAST model
HERA127
Paciga, 2013
Dillon, 2014
Dillon, 2015
Beardsley, 2016
Patil, 2017
Jacobs, 2015
Parsons, 2014
Ali, 2015

Peeling Onions
by Adrienne Rich

Only to have a ~~grief~~ joy
equal to all these tears!

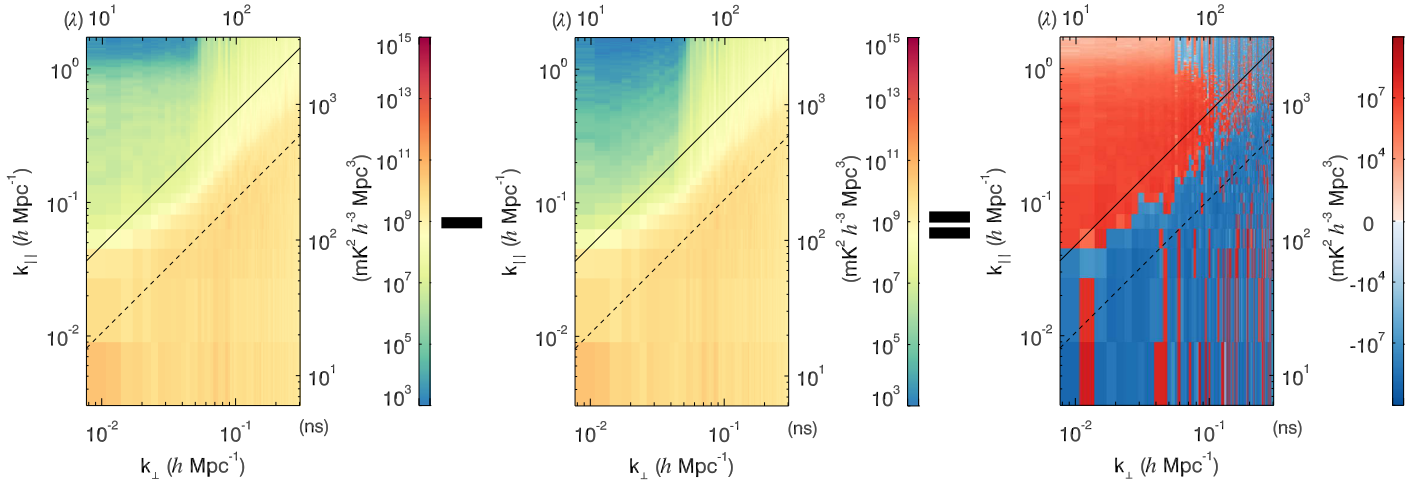
....

First published in Snapshots of a Daughter-in-Law *(NY: Harper & Row, 1963*

What have we learned

- Determine the instrumental/calibration limitations
- Detect and remove RFI: Offinga+15
- Measure ionospheric effects, and resolve
- Optimise the calibration model*
- Characterise the foreground emissions
- Process huge complex datasets; manage software pipelines
    - *Bart Pindor's talk after the break
    - *Ronniy Joseph's talk after lunch

Just how good does our calibration need to be?



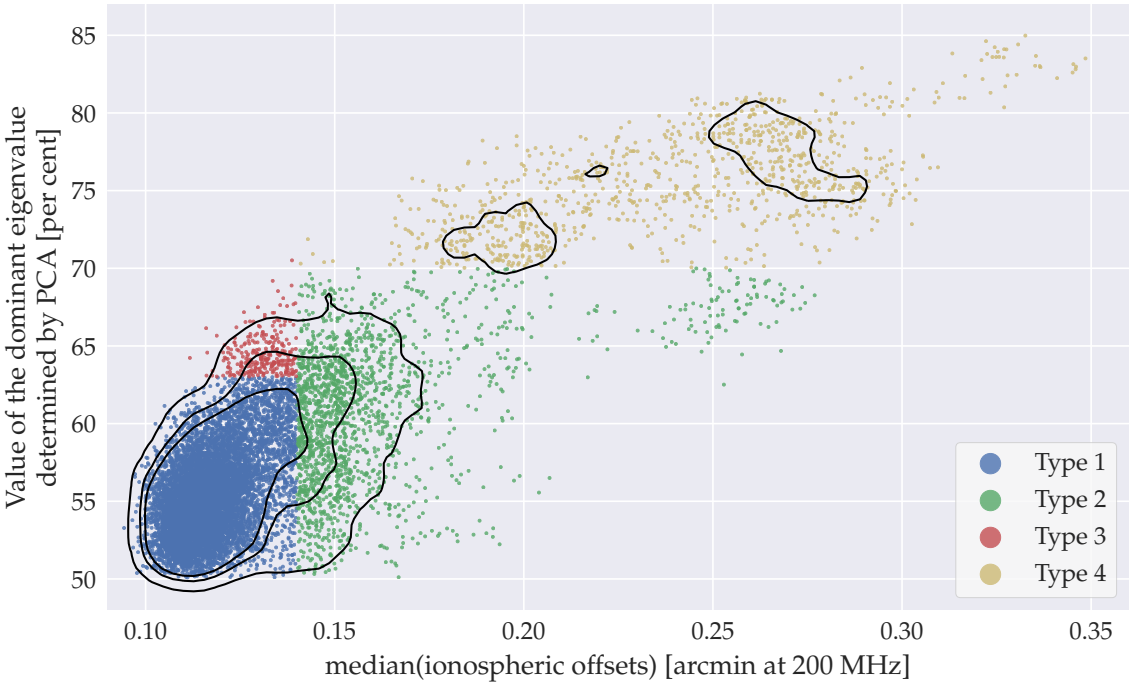
An idealised model of the effect of calibrating on 4000/6950 sources (left) and all sources (middle) giving the difference on the right.

Requirements for detection of EoR signal:

- High fidelity calibration catalogue
- Very smooth instrumental spectral response:
  - 1 part in 10^5 across 8MHz
- Identical antennae

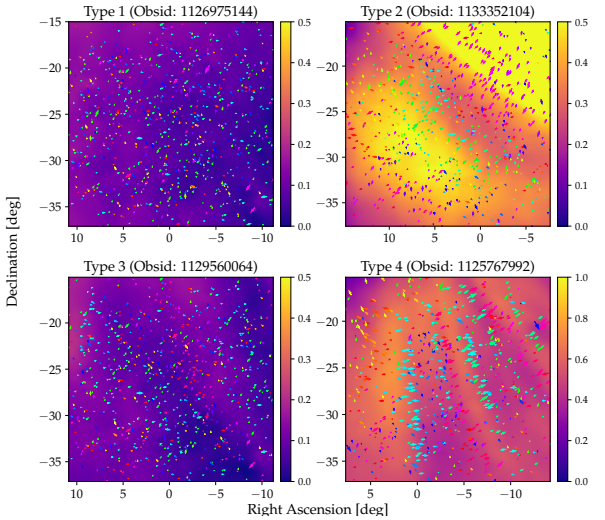
Barry+2016

Characterise the ionosphere
→ ‘Clean’ data



Jordan+17

Examples of 4 types of structure



Two statistics are sufficient to characterise the ionosphere
Sufficiently quiet ionosphere ~74% of the time
100-200 pierce points sufficient for real-time measurement
Ionospheric activity *tends* to remain stable across a night

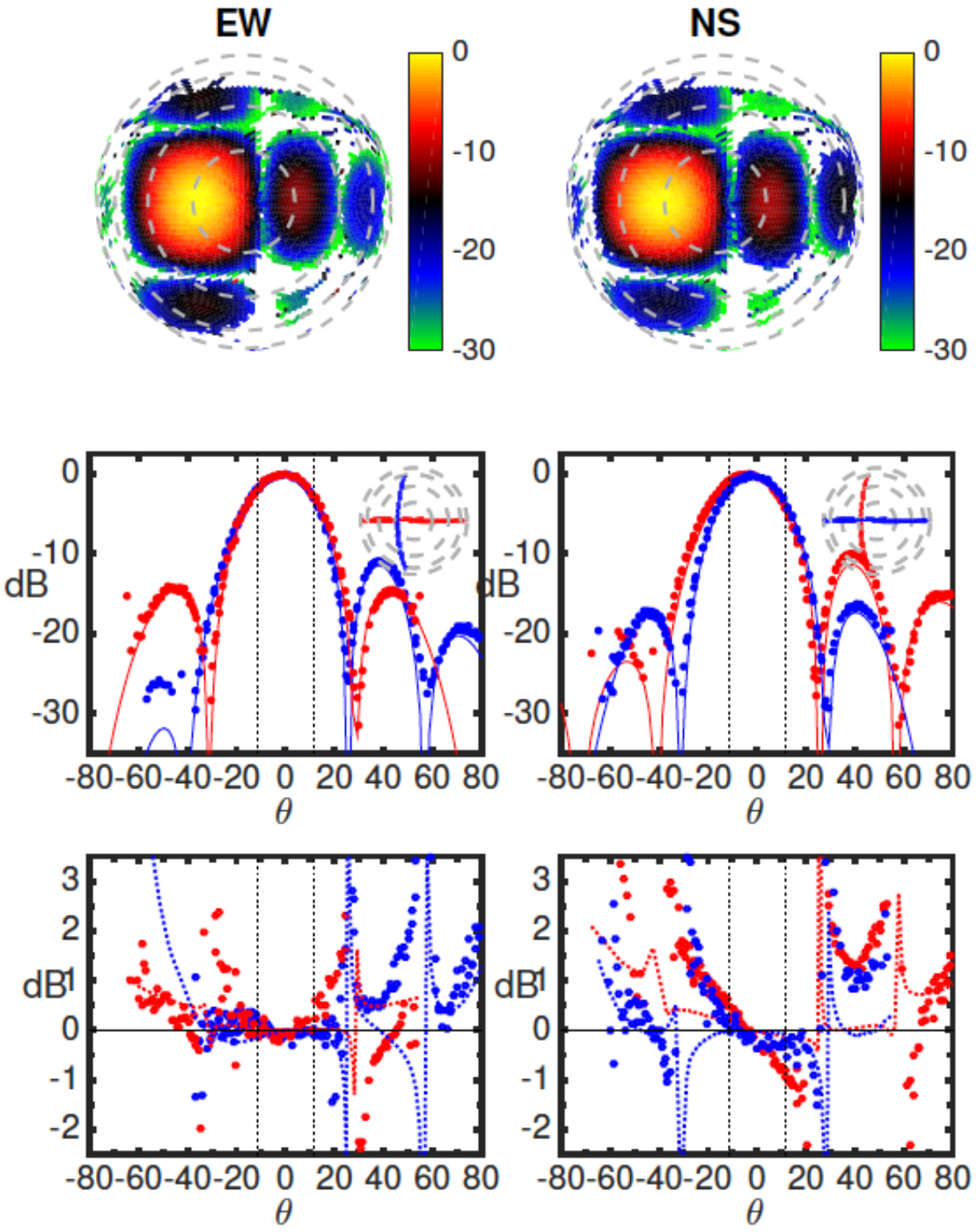
The Beam

Neben+ 2015

- Test tile at Greenbank & ORB-COMM
- Measured & Model (solid lines)

- Difference

(vertical lines → FWHM ~23 deg @137MHz)



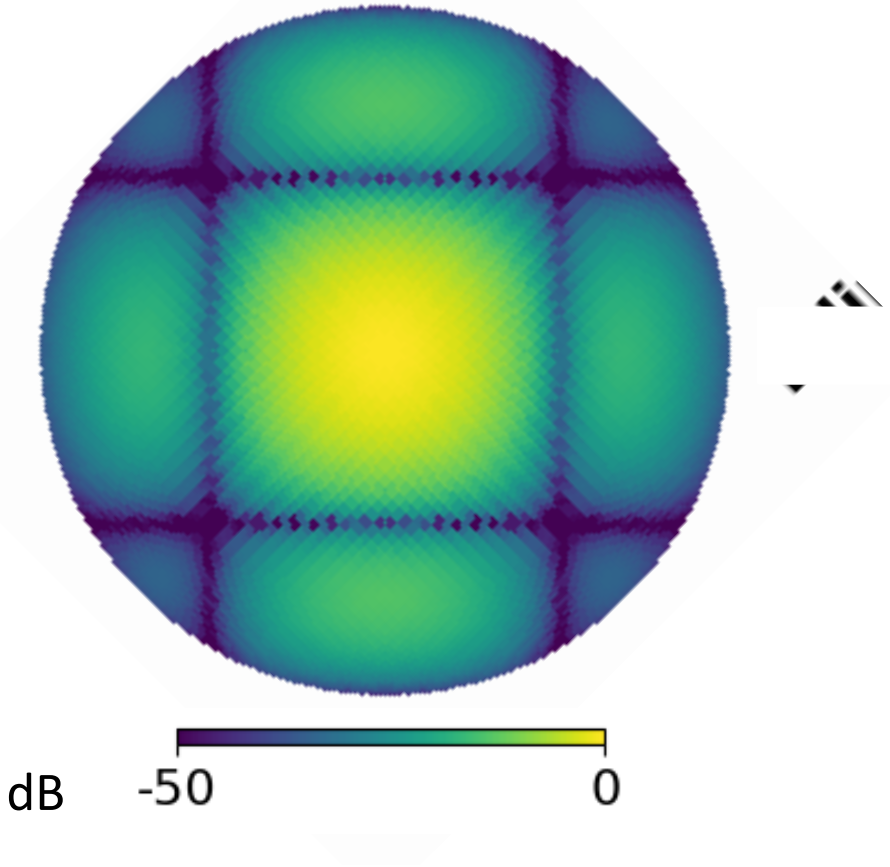
An MWA tile

Jack Line, Ben McKinley,
Jarryd Rasti, Mohit Bhardwaj

Tile S23 (used in this experiment)

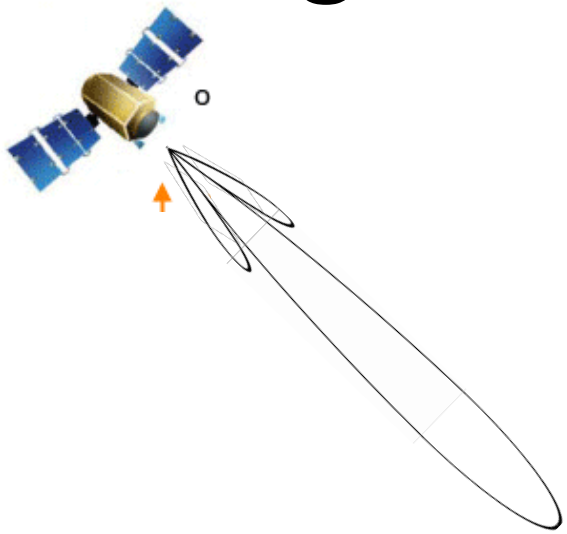
- **4x4 grid of cross-dipole antennas**
- **Electronically beam-formed to create a primary beam response**
- **Accurate modelling requires mutual coupling (Sutinjo et al. 2015)**
- **Regular spacing of antenna gives grating sidelobe pattern (plotted down to 10° altitude here)**

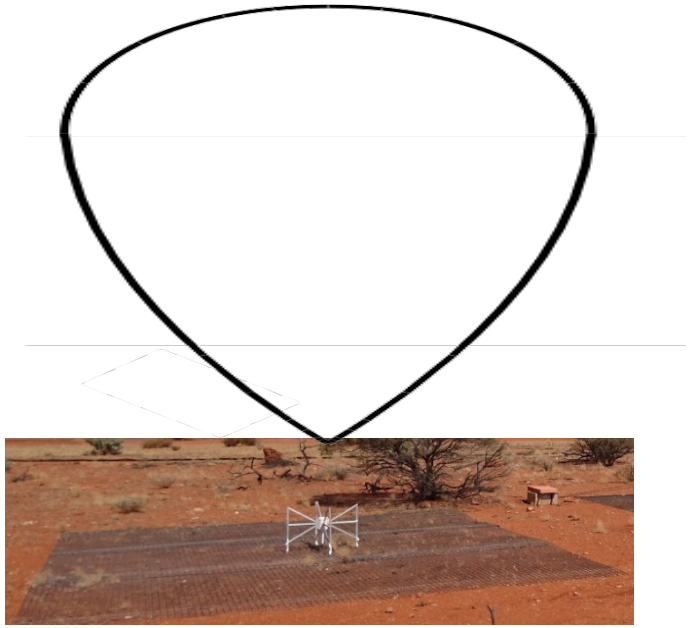
Zenith pointing at 137 MHz



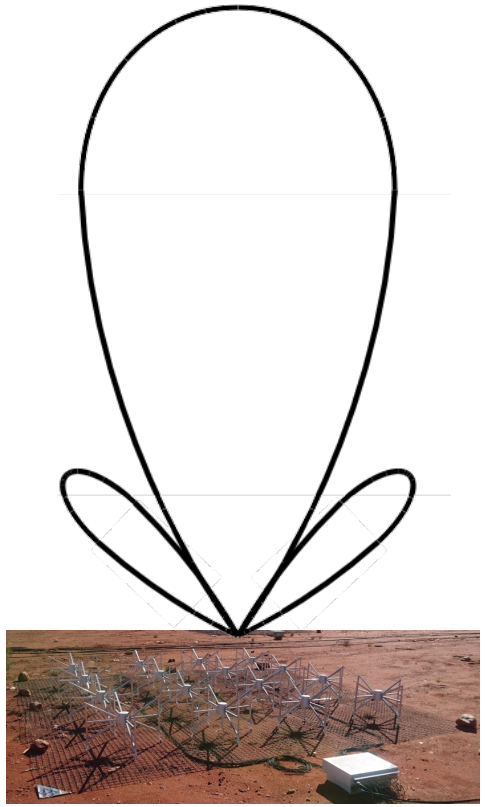
Measuring a beam shape

- **Need a locatable radio emitter (satellite)**
- **Must account for beam shape of satellite**
  - **Use a reference antenna with known beam response (single MWA dipole)**
- **Divide reference by model, and apply to antenna under test**





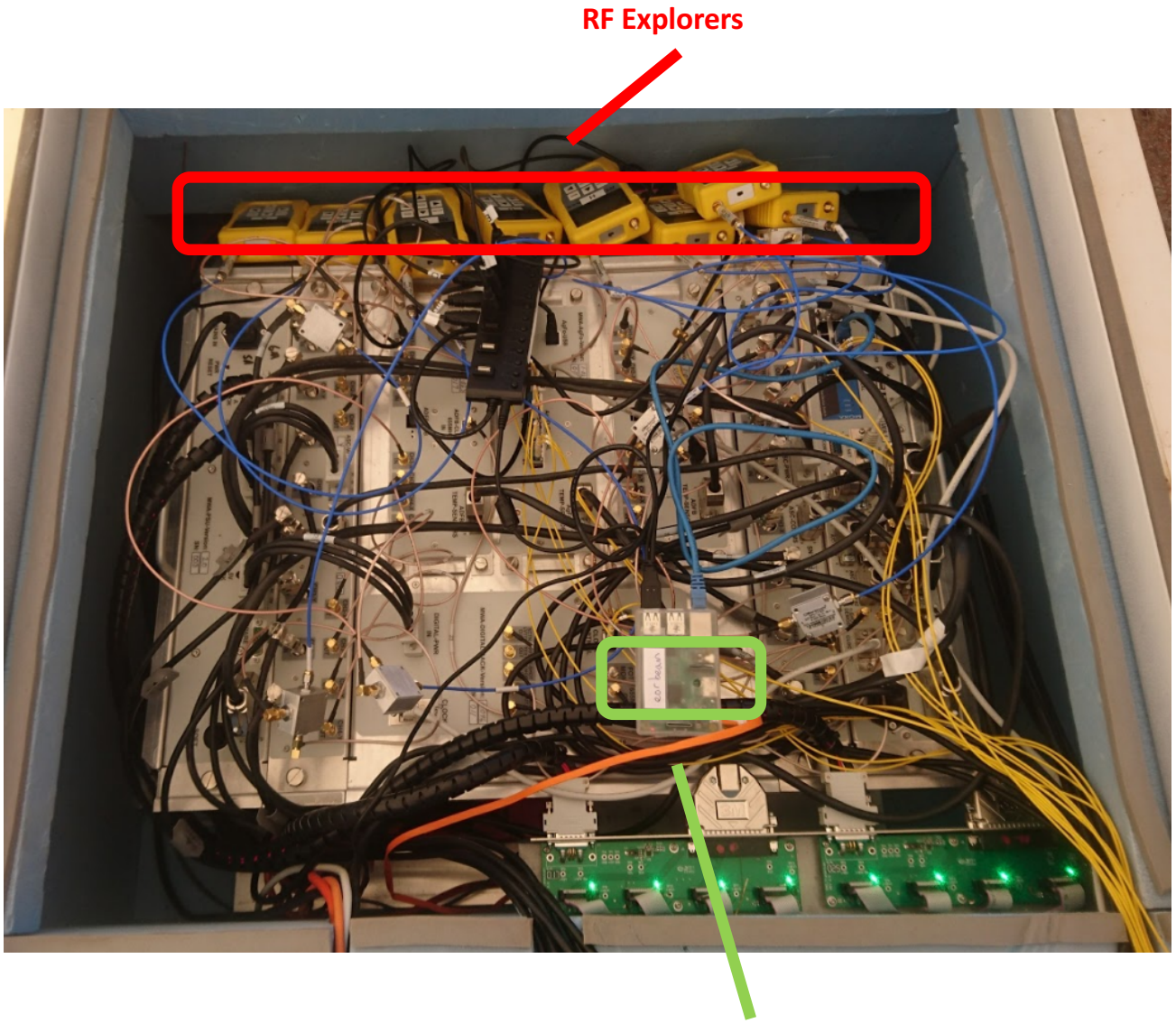
Reference



Tile

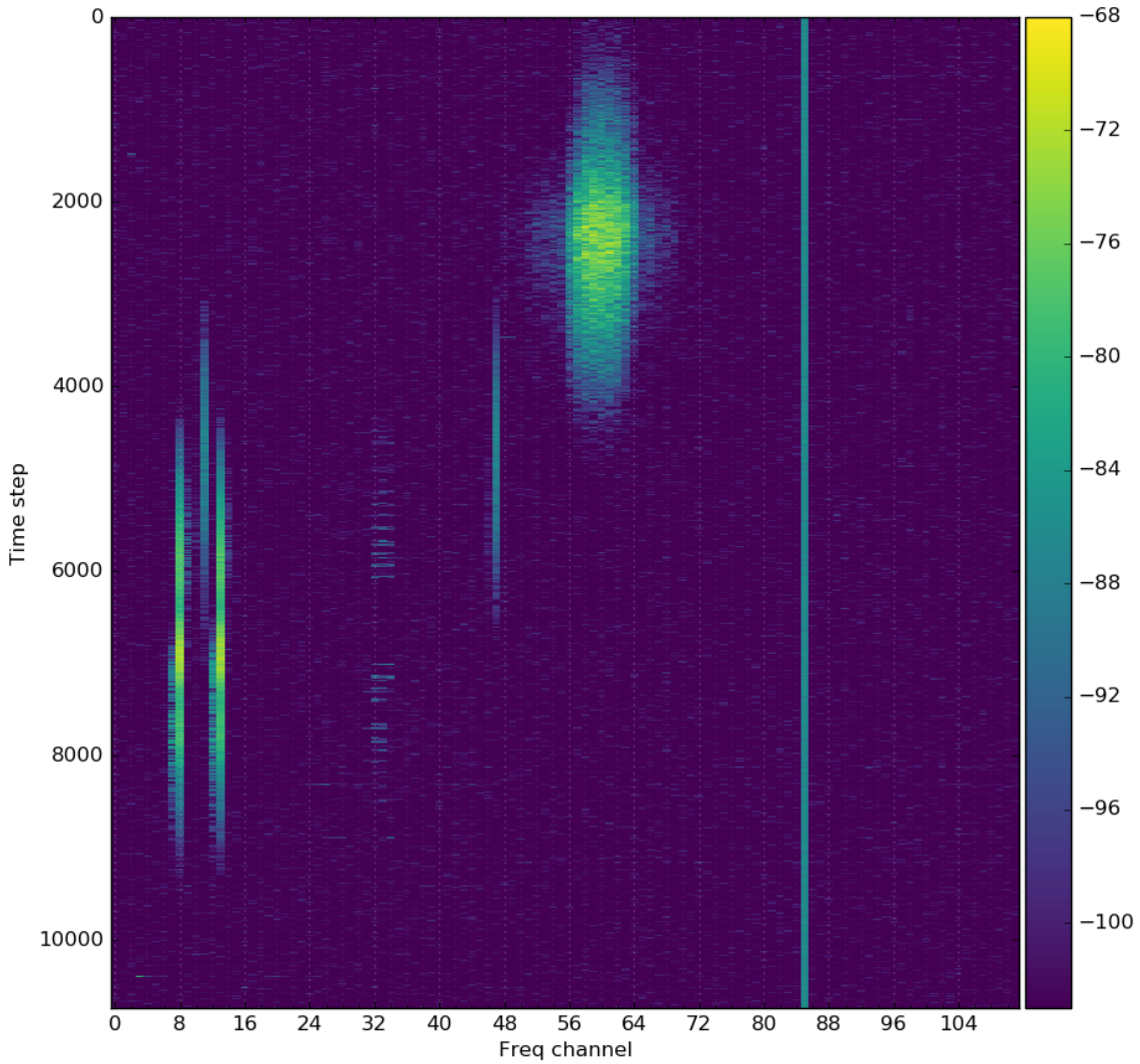
Experimental setup

- One receiver box connects to 8 tiles
- Tap into raw output of each beam former directly using RF explorers
- Happens before any digitisation of signal path
- Record data from RF explorers using Raspberry pi
- Similar setup for 2 reference antennas



Challenges

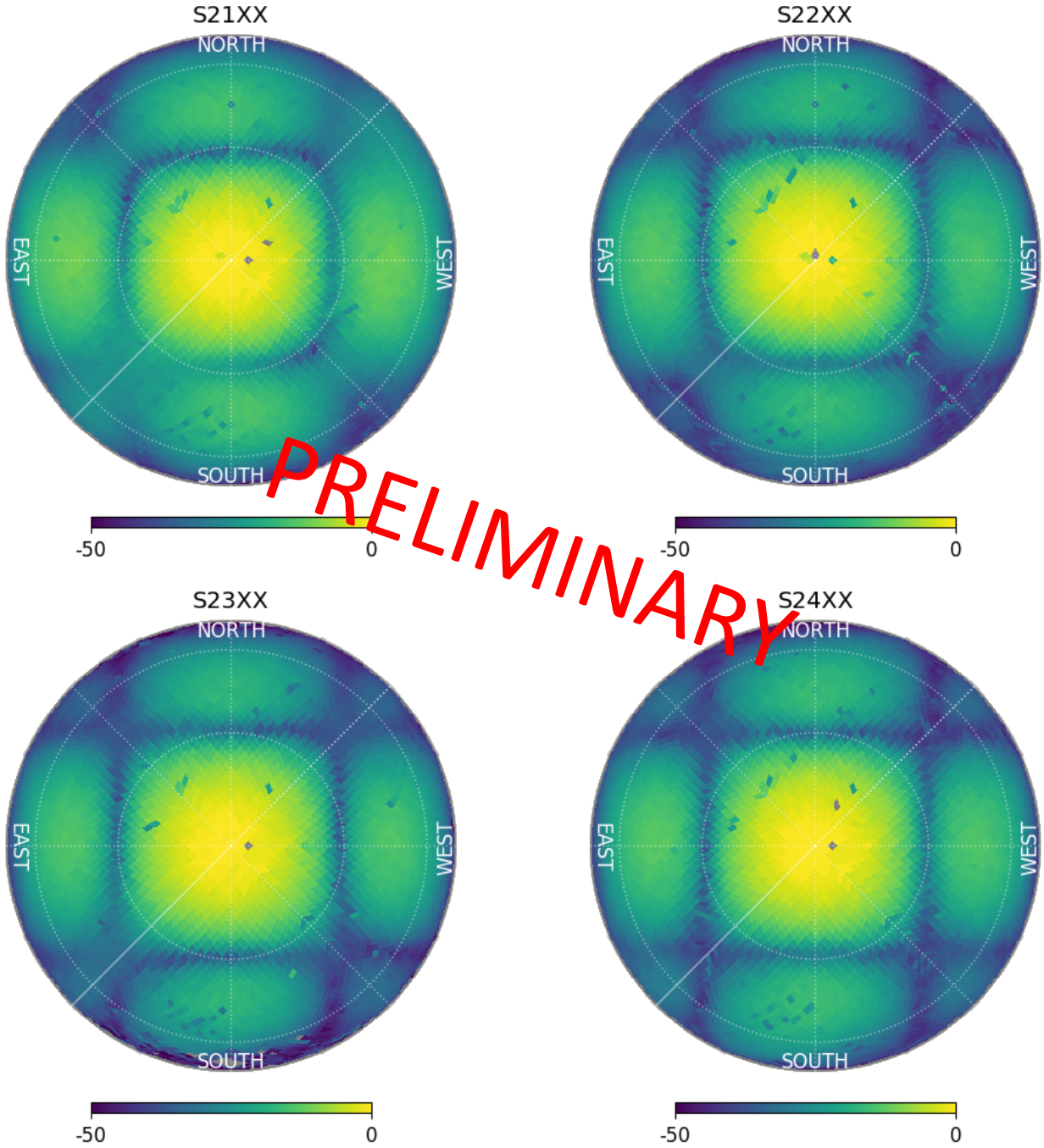
- **Must match all satellites to a frequency channel using ephemeris only**
- **Satellites can sometimes pulse**
  - **Pi recording reference and tile data are not perfectly time matched**
- **Make data quality cuts to match time steps – lose ~15% of data**



Waterfall plot of 20 mins of data – shows time versus frequency. Each channel has a bandwidth of 10 kHz

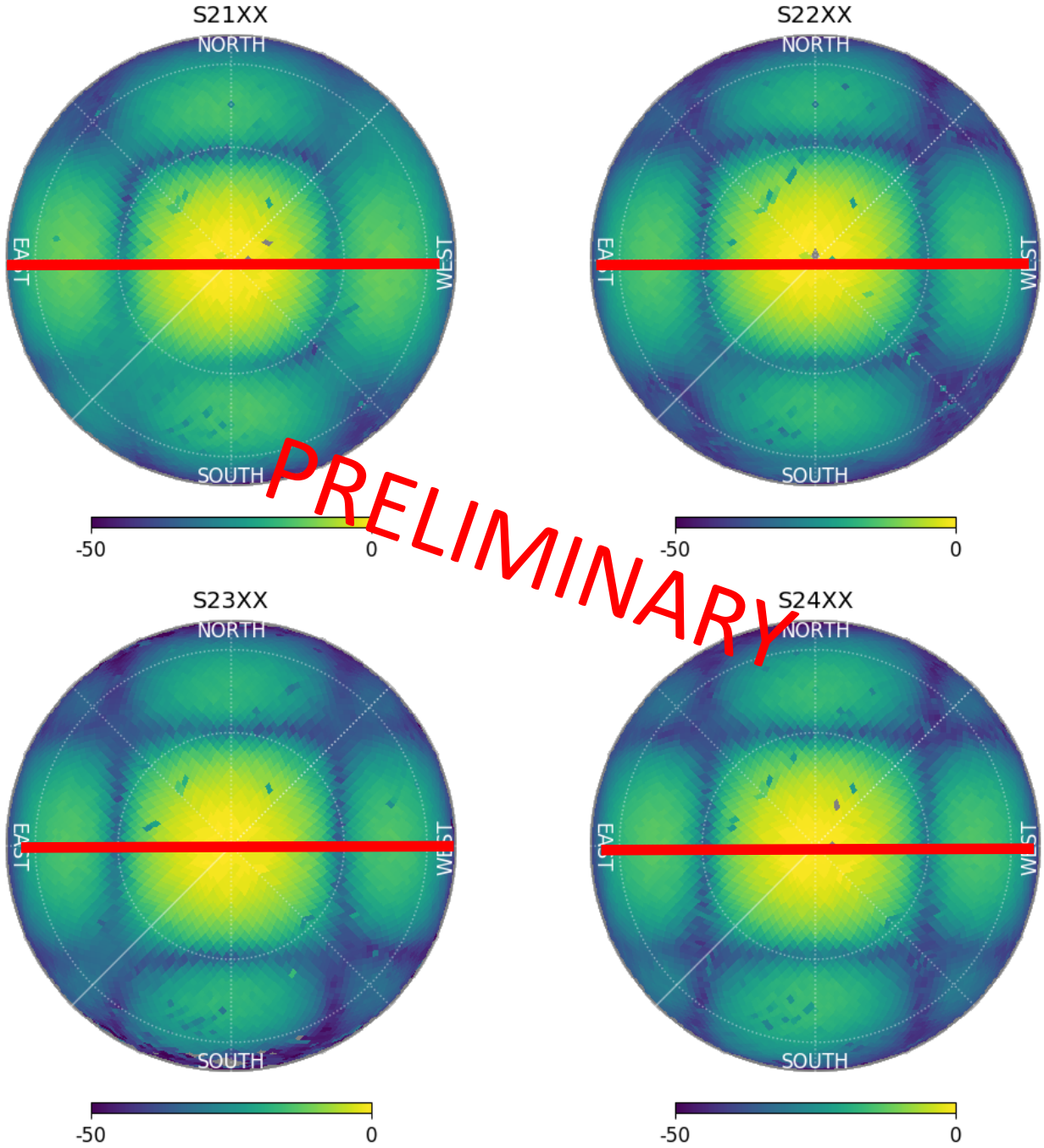
Measured beam shape for 4 tiles

- **Map each satellite pass onto regular healpix grid and correct tile data by reference antenna/model**
  - **Take median of each healpixel**
- **Normalise beam to zenith**
- **Data taken between 17th Aug and 5th September 2017**



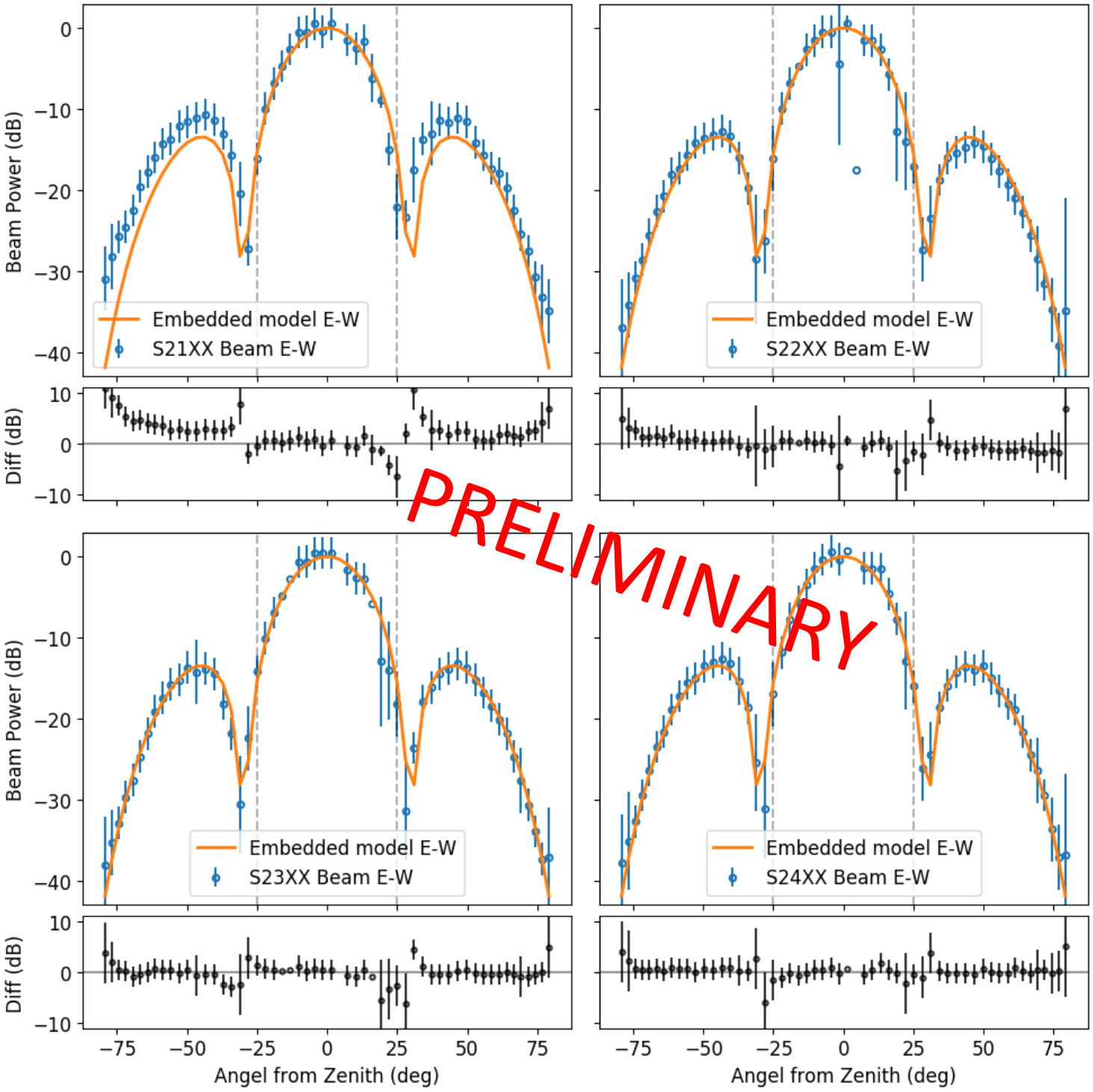
Measured beam shape for 4 tiles

- **Take a slice across the beam from East to West and compare to the Sutinjo et al. 2015 model**



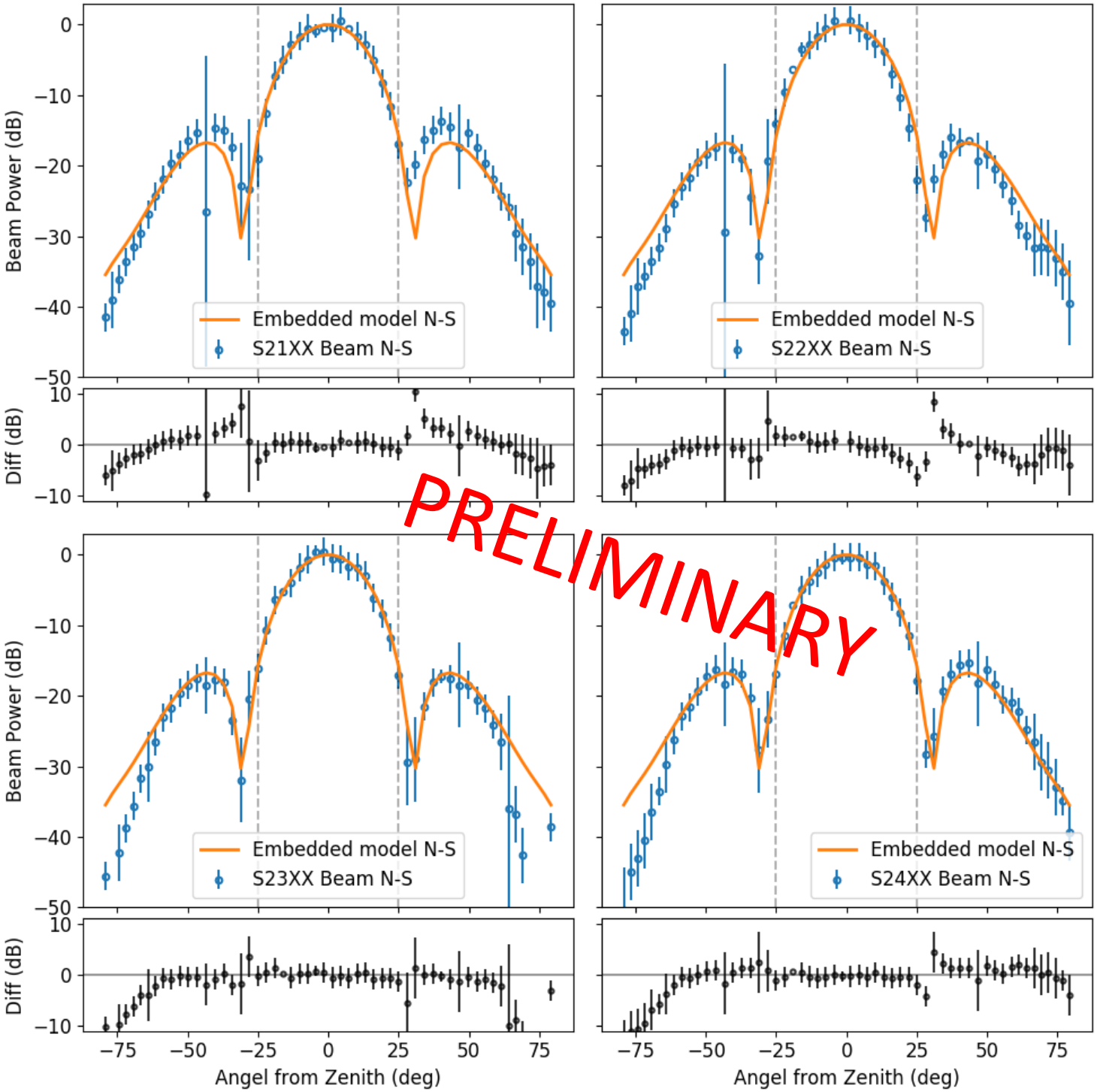
Embedded model comparison

- **Overall good agreement shown – error is the median absolute deviation of each healpixel**
- **Tile S21 sidelobes differ by >= 10dB – this is big!**
- **Need to check reference antenna is behaving**



Embedded model comparison

- **Same comparison but North to South slice**
- **Similar difference in left sidelobe**
  - **Possibly due to reference – under investigation**



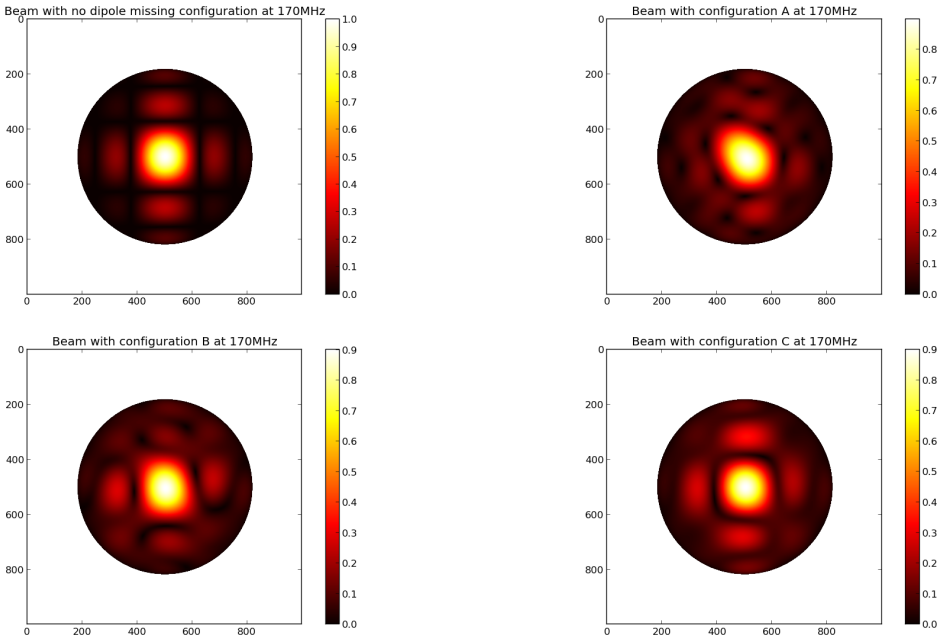
Questions

- Does the beam model match the data?
- Is the beam the same from tile to tile?

Caveats

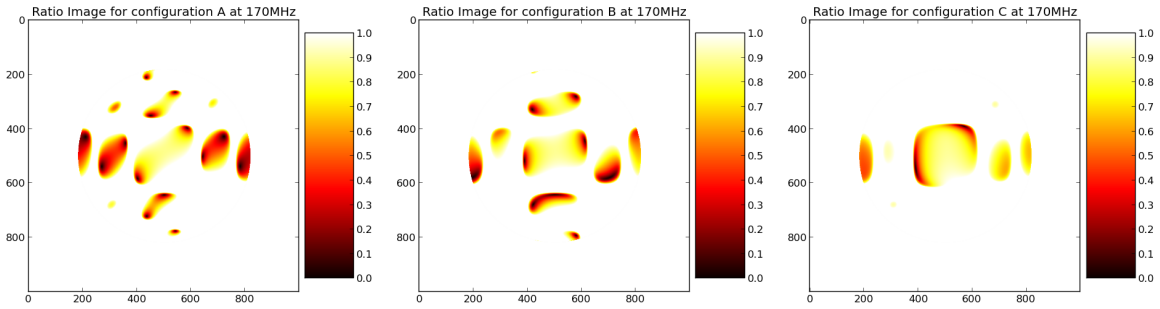
- Measured at ~137MHz – not where we are taking data
- So far, only zenith pointings

What happens if a dipole dies?



- 3 configurations
- Persistent perturbation

- Ratio cf regular tile



Bhardwaj

Sky model

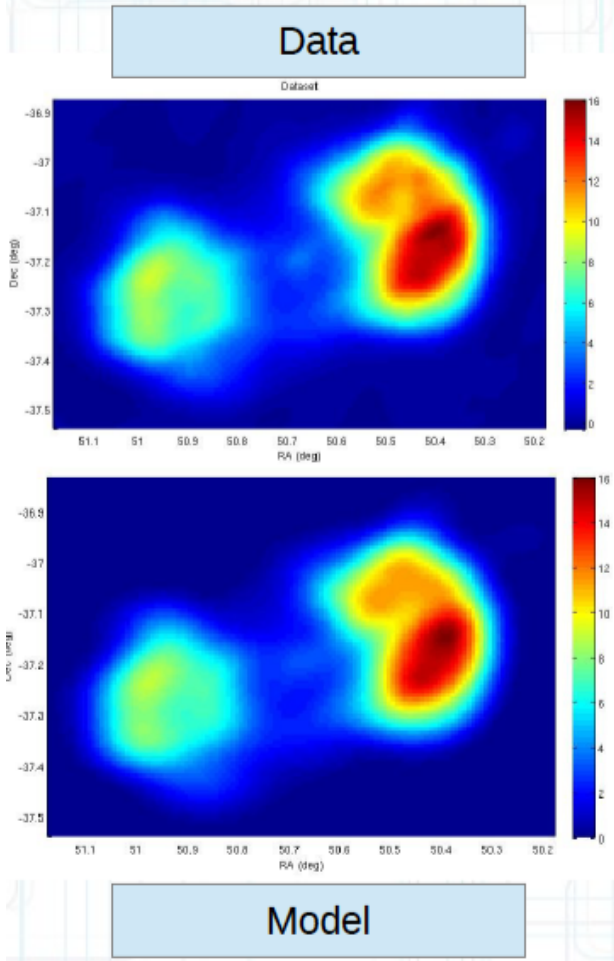
- Fidelity of sources – both in field and in the sidelobes
- Modelling extended sources
- Diffuse backgrounds
- Effect of unresolved source clustering – note Steven Murray's talk on Friday
- (Super-)Resolution

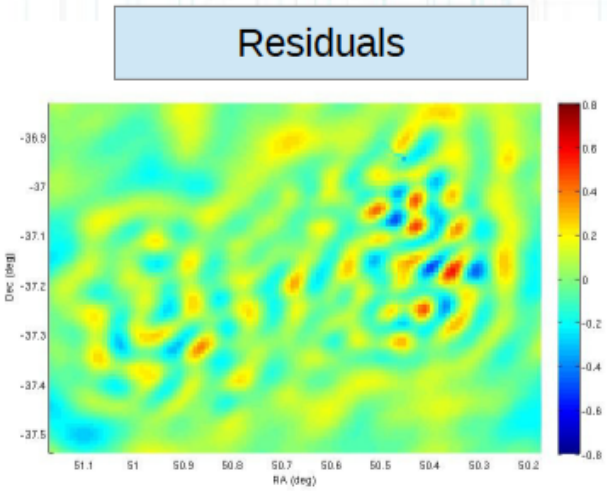
Resolution – super-resolving

- Is the resolution of our telescope sufficient?
- Can we use higher resolution data to improve source characterisation?
- What are the optimum scales?
- Can we determine optimal scales analytically?

- Use other telescopes or other frequencies?

Dealing with extended sources

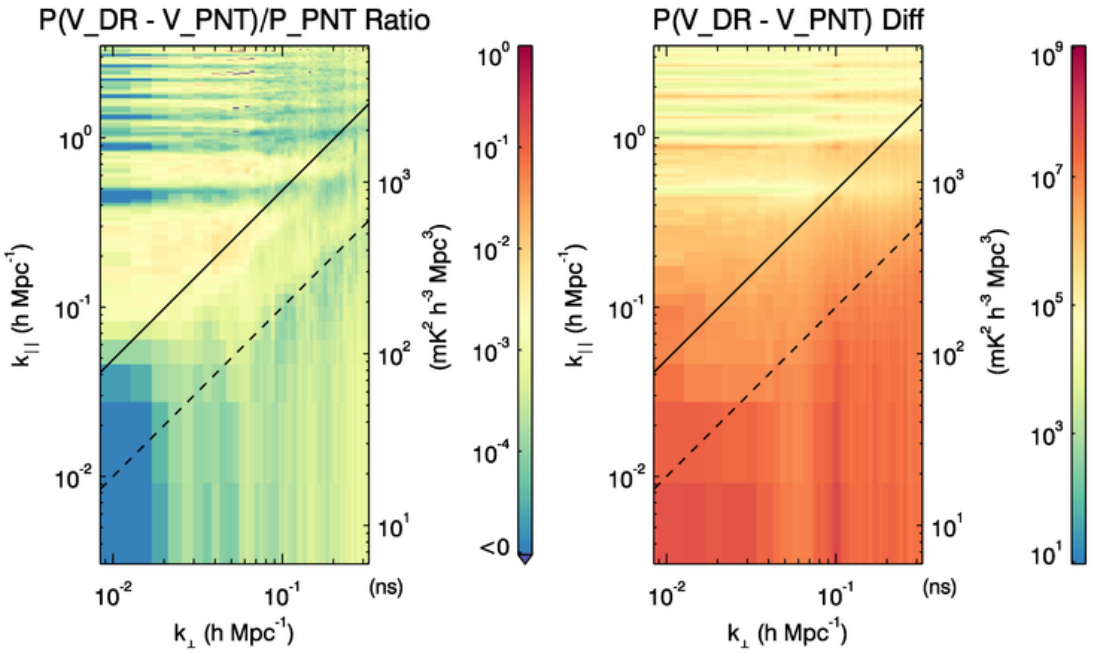




Shapelets are being used to model extended sources; subtraction either in the image or UV plane. And then there's the Milky Way!
Based on Hi-res GMRT images.

Jenny Riding

MWA (GLEAM) sources matched to higher resolution TGSS catalogue → 87% Singles + doubles & complex



Ratio and difference plots: higher resolution modelling v. point source modelling
→ Quantitaive estimate

Procopio+ 17

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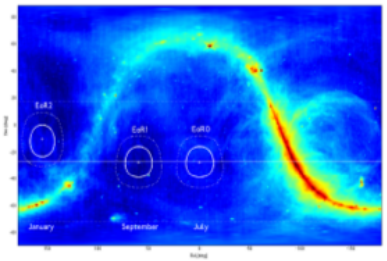
Next steps for MWA EoR

- QA implementation
- Improved sky model
- Improved calibration model, including hybrid
- More data processed



DATA
- 2 Observing Bands
  - Low 139 – 169 MHz
    - 1800 Hrs
  - High 168 – 197 MHz
    - 1600 Hrs
- 2+1 Fields
  - Driftscan 600 Hrs

- Many more detailed end-to-end simulations

Thank you

MWA
MURCHISON
WIDEFIELD
ARRAY

Gurlgamarnu

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SYDNEY

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National
University

Curtin University

ASU

CfA

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