Towards MWA phase II Calibration & Imaging

Huib Intema

On behalf of: Melanie Johnston-Hollitt, Torrance Hodgson, Stefan Duchesne, Ben McKinley

Curtin Institute for Radio Astronomy

Gurlgamarnu

~Outline

Scope

MWA has evolved into a large(r) array (phase I → II), complicating the data processing

MWA archive is filling up quickly

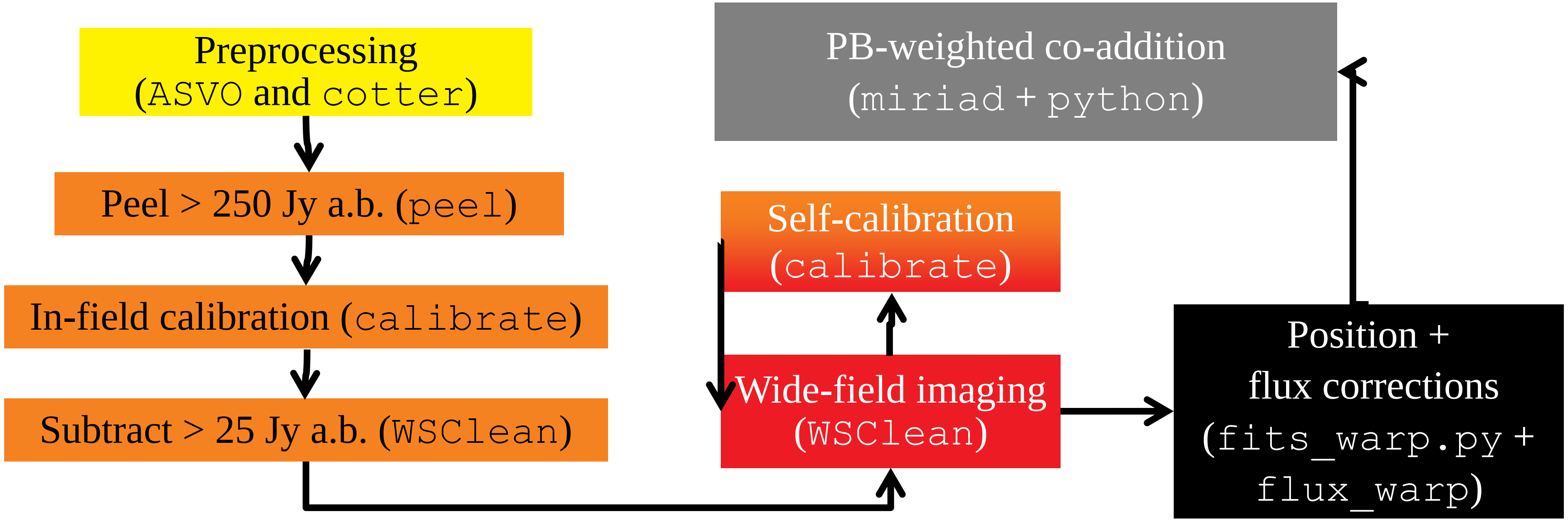
MWA user base is largely limited to domain experts

These issues can be addressed by developing a (largely) automated processing pipeline that generates (near) science-ready data products

Proof of concept for low-frequency radio telescopes is given by pipelines for e.g., LOFAR and GMRT.

Challenges: wide field-of-view, wide bandwidth, variable complex beams, ionosphere, …

Standard MWA Pipeline (Stefan Duchesne)



Standard MWA phase II pipeline:

- Source-subtraction as a function of frequency using multiscale CLEAN component models.
- In-field calibration using full-sky model from GLEAM, NVSS, SUMSS, and TGSS.
- Final flux-scale corrections required to account for residual PB leakage, CLEAN bias, and initial flux-scale set by poorly modelled bright sources in the field (e.g. PicA at low frequencies).

Standard MWA Pipeline

In-field calibration with an all-sky model

- Sky-model generated from a cross-match between GLEAM, NVSS, SUMSS, and TGSS.
- Include sources above some apparent brightness threshold. Use 2017 MWA primary beam model to determine apparent brightness. Sky model most effective where GLEAM is present, but can be used for regions of the sky without GLEAM coverage (e.g. North of declination +30°)
- Usually at least one bright (> ~ 25 Jy at 216 MHz) source available within primary beam

Compared to traditional calibration methods:

Pros

- Less observing/data-management overhead – no dedicated calibrator scans
- Typically overall better results (especially prior to CLEAN-based selfcal)
- Including bright off-axis sources in initial models allows direct subtraction after calibration

Cons

- Low-elevation pointings have less sensitivity, so fewer sources are suitable for calibration
- Computational cost of predicting >200 source model is high with current software

Standard MWA Pipeline

Final flux-scale corrections

We expect the final flux scale to be consistent with the input sky model, however...

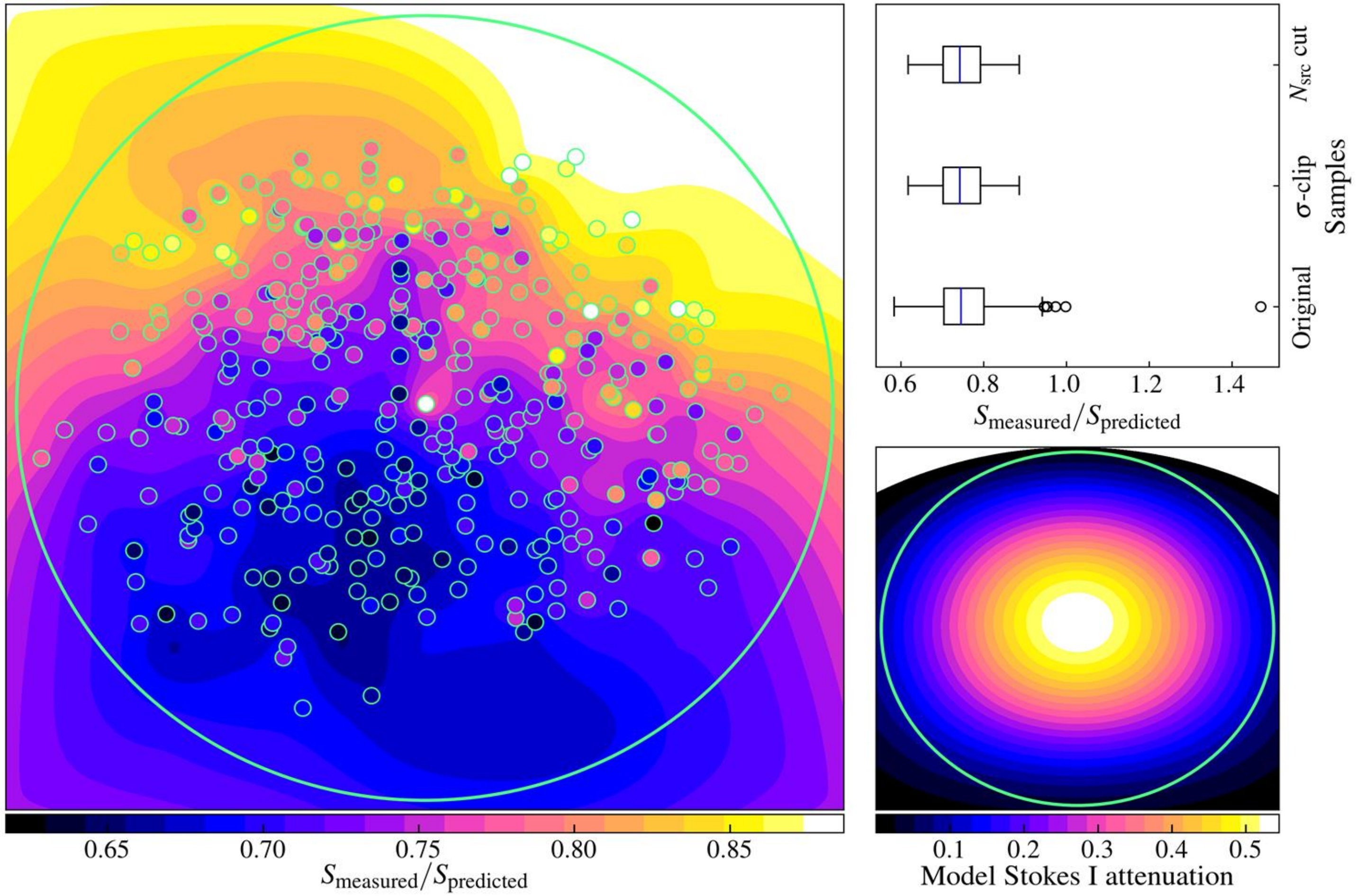
Errors in final flux scale:

- CLEAN bias
- Residual leakage from PB (worse at low elevation)
- Initial model not quite right, especially when flux-scale is largely set by certain bright sources like PicA at low frequency
- Other effects?

Position-dependent flux-scale corrections:

- Use sky model (minus specific bright sources – usually extended/multi-component) to predict fluxes of sources in image
- Derive ratio of S_measured to S_predicted flux density for compact sources
- If no large-scale structure to S_measured / S_predicted, take an SNR-weighted mean ratio and apply to image
- Else if large-scale structure, correct flux-scale via some interpolation method:
  - Smoothed (2-5 degrees) 2-D linear radial basis function
  - Fitting 1-D polynomial as a function of elevation
  - 2-D quadratic screen (though less effective) generally)

Gradient in flux



MWA stokes I image:

- 88 MHz
- ~40 deg.
- Dec ~ +14 deg.
- Low-elevation = large instrumental leakage
- Constant offset + largely elevation-dependent flux scale variation

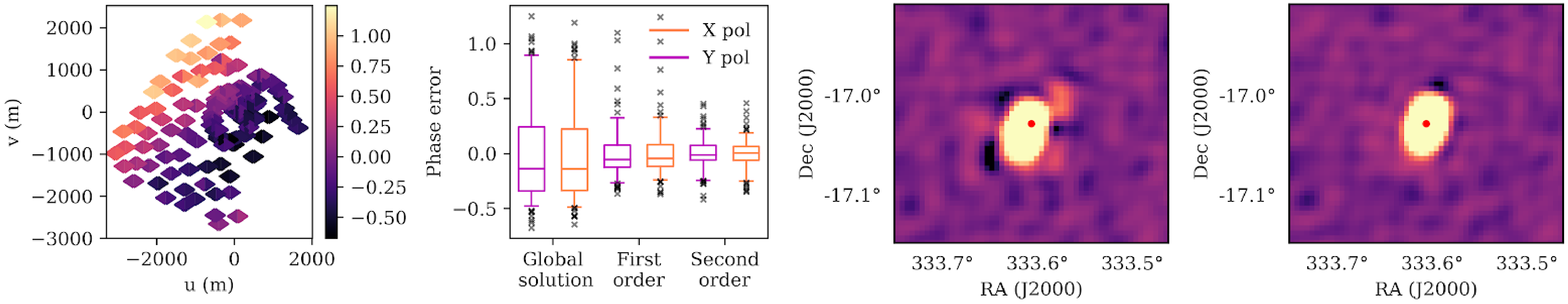
Going deep has revealed calibration errors (Torrance Hodgson)

- Traditional MWA imaging involved stacking (in images space) of 2 min snapshots
- This pushes down noise, but suffers from in-field sidelobe noise (due to insufficient cleaning depth)
- Stacking also masks calibration errors
- Joint deconvolution techniques using Image Domain Gridding (van der Tol, Veenboer & Offringa 2018) have revealed a new class of calibration errors.

Cause 1: Ionospheric variation

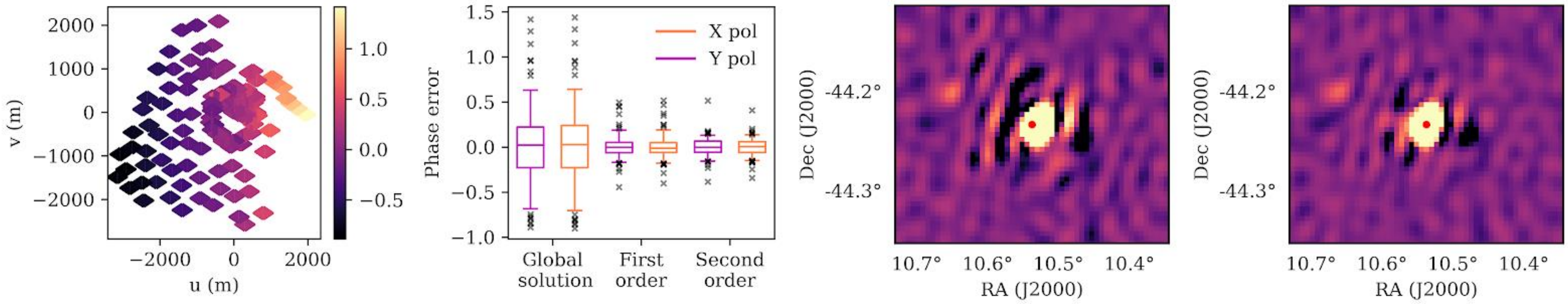
- Introduces (primarily) directional phase changes across the sky
- Global calibration gives a ‘compromise’ solution across all sources, weighted most strongly towards the brightest source(s)
- At low frequencies (~150 MHz) with 6km baselines, these residual phase errors can amount to > 1 radian
- The phase error is primarily ‘first order’ - meaning position offset - but second and high order errors (‘lensing’, ‘split array’) occur with higher occurance at lower pointing elevations
- Though in principle these phase variations are on the order on ~15 seconds, in practice we mostly get away with calibration intervals of 2 minutes.

A 'good' source



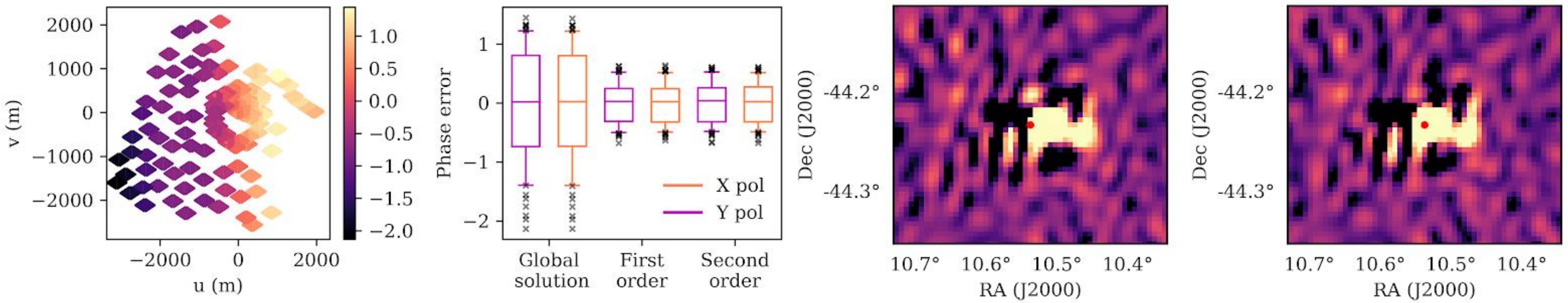
- Smooth phase variation across array
- Easily captured by a 2nd-order polynomial sheet
- Corrected image (on right) fixed with just 5 degrees of freedom which avoid errors from overfitting, with a single solution for full 2 minute interval

A ‘bad’ source



- Smooth phase variation across array
- Not well captured by a 2nd-order polynomial screen
- Corrected image (on right) improved, but 5 degrees of freedom across 2 minutes not enough

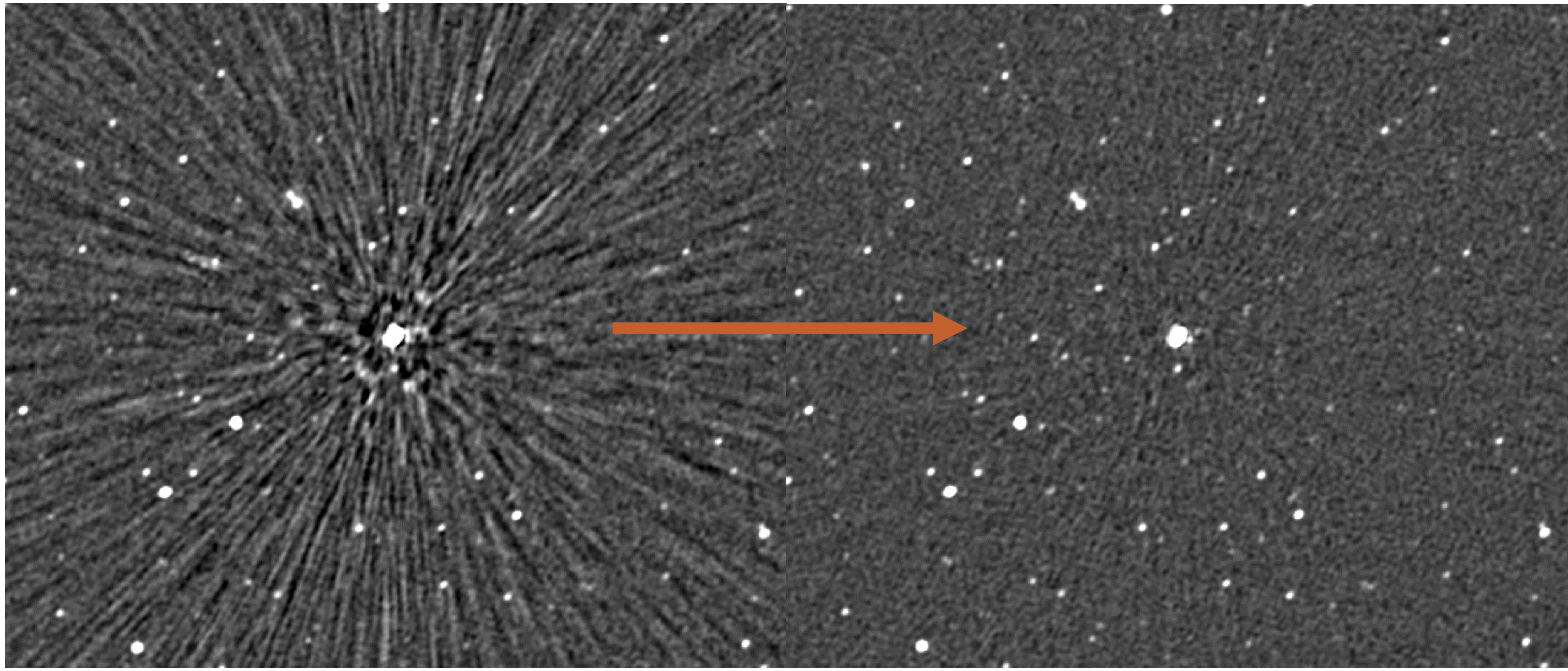
A ‘terrible’ source



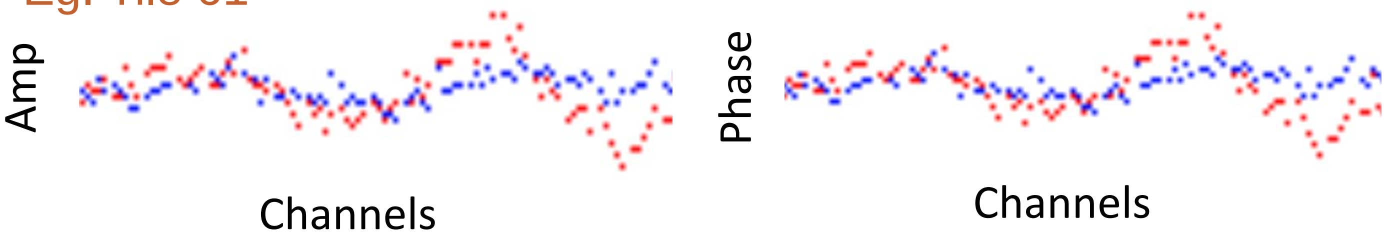
- Yes, this is a point source
- Suffers from high-order phase structure across the array - ‘split array’
- 2nd-order polynomial screen fails to capture any of this structure
- Corrected image (on right) has only been corrected for position offset
- Needs at least 4th order phase screen (14 degrees of freedom)

Frequency-dependent, directional solution

- We excluded errors from multiple other sources (MFS errors; gridding errors; PSF sidelobe errors; beam errors…)
- Only a full, directional, bandpass calibration on all tiles could resolve the radial spikes
- (Some) tiles exhibit strong frequency-dependent amplitude errors
- Physical cause currently a mystery, but most likely cause is non-uniform beam patterns between tiles



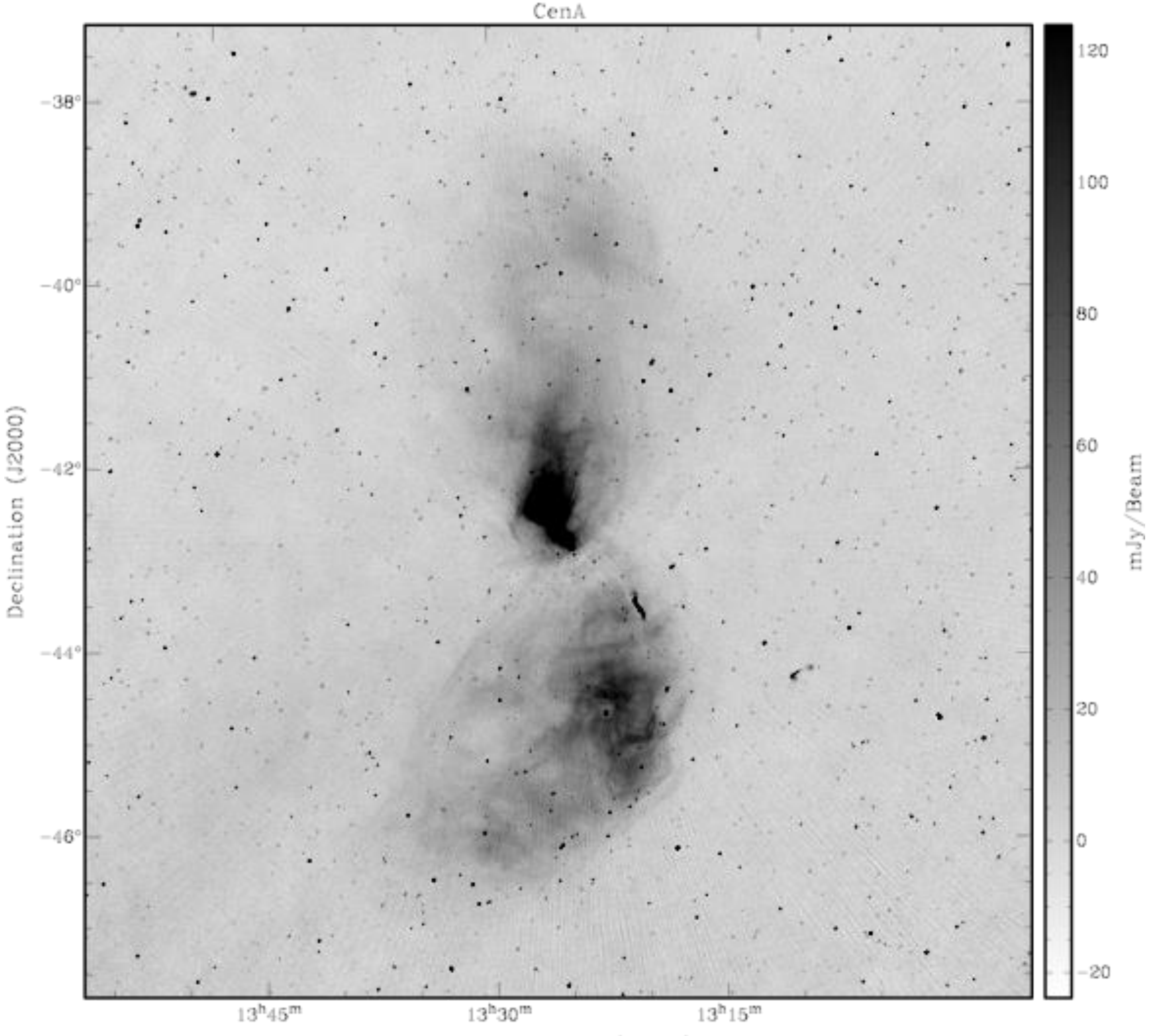
Eg. Tile 61



Faceted Calibration

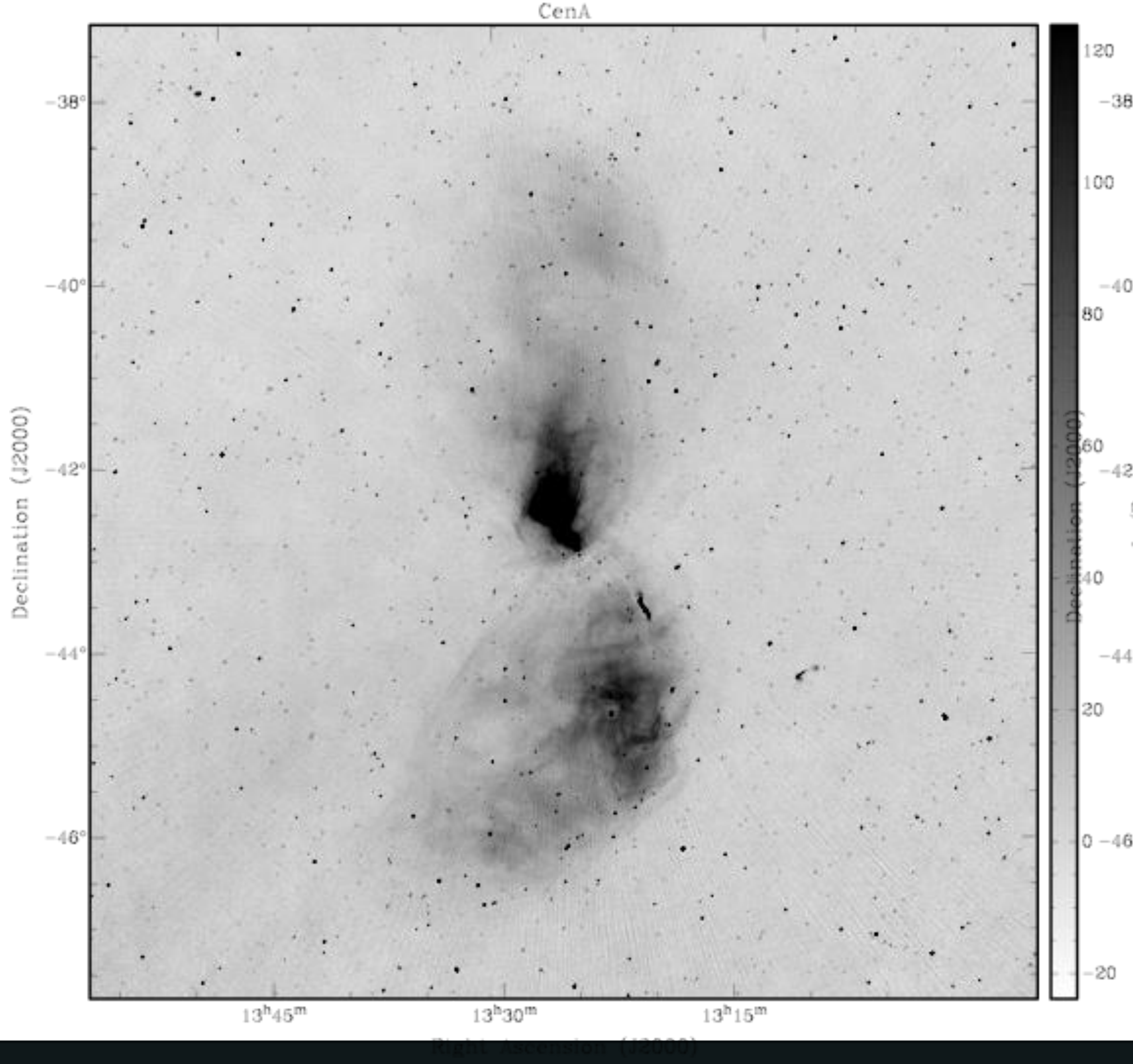
- Bespoke process (read: bash monster) involving WSClean[2], MWA's calibrate (Mitchcal/Stefcal), and a whole lot of glue
- Typically use ~30 facets across 40 square degrees, with each facet seeded by a bright source
- Concerns about overfitting, particularly if this means suppressing extended, diffuse emission
- Slow and expensive process, but room to partially parallelize
- Results look very promising (more to come…)

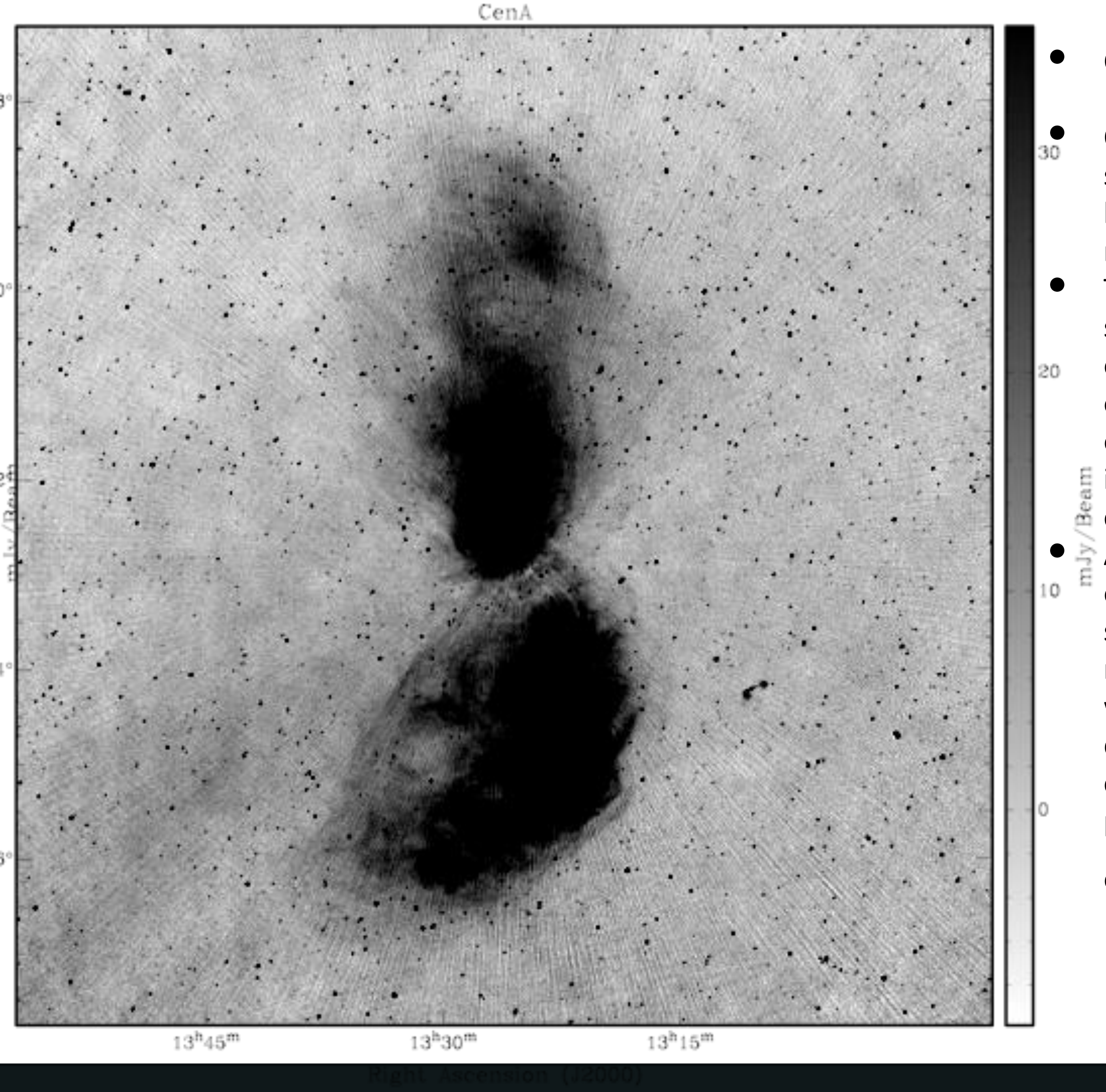
A difficult source (Ben McKinley)



- Centaurus A at 185 MHz
- ~20 mins data, combination of MWA phase I and II (extended)
- Looks good on this color stretch
- Dynamic range ~10,000

Techniques don't always work…

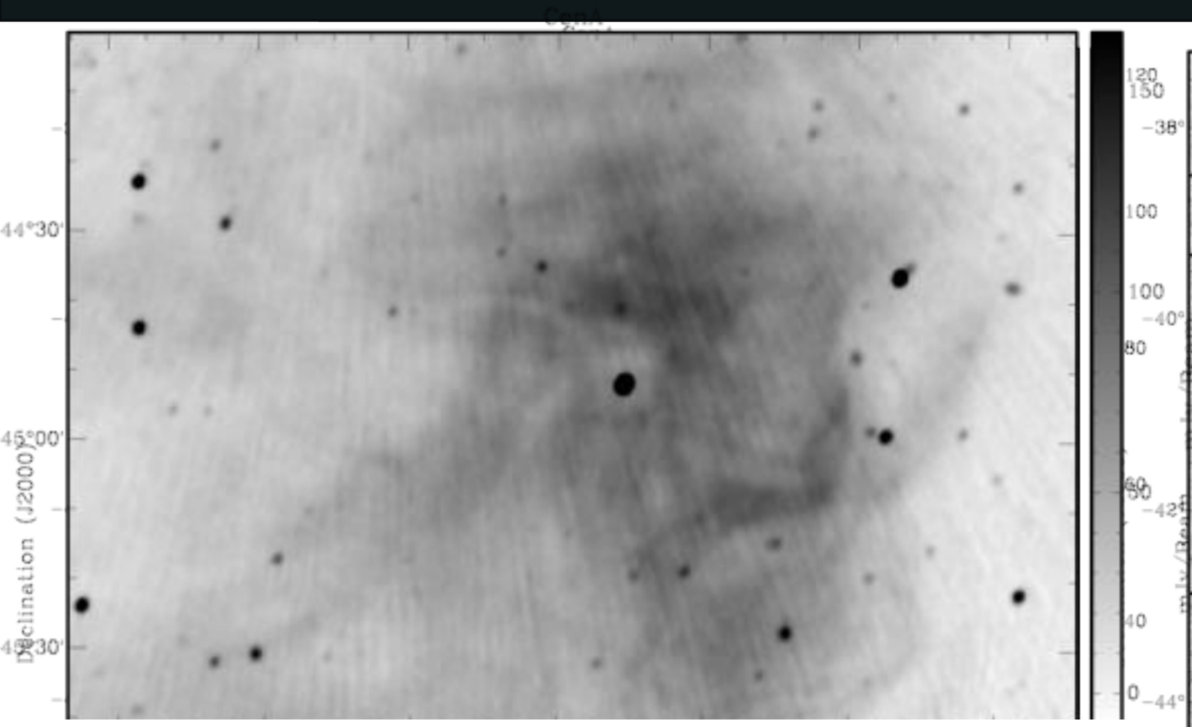




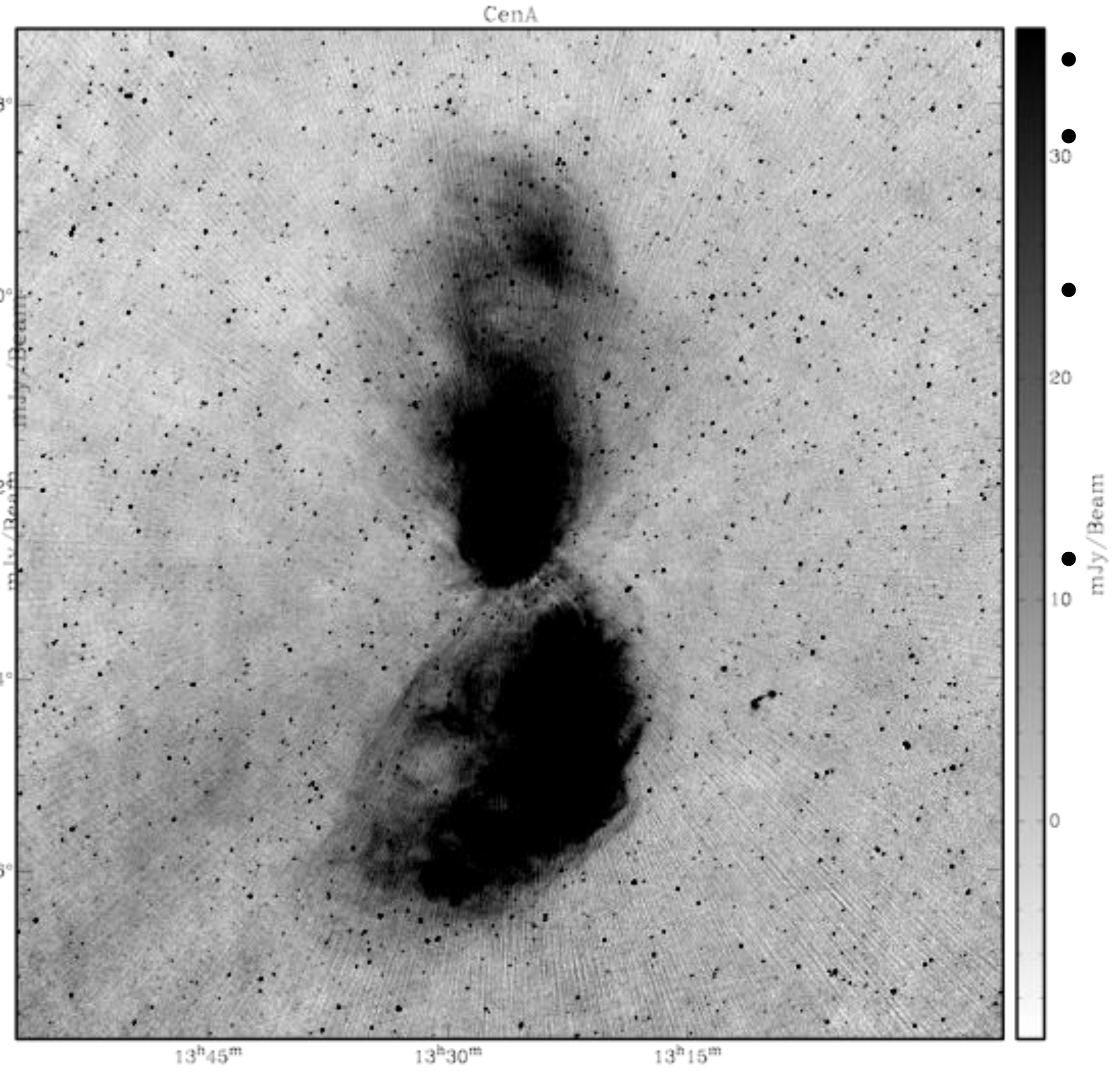
- Centaurus A at 185 MHz
- On different color stretch faint radial line artefacts are more obvious
- Thought to be small calibration errors, made obvious by the extremely bright inner lobes at the center of Cen A.
- Also appear in each single snapshot. Can't get rid of them, even with direction-dependent calibration / peeling the core

etc.

Techniques don't always work…



- Part of the Cen A southern lobe A at 185 MHz
- Radial artefacts are on the same level as the diffuse filamentary features (~5 mJy/beam), this affects the science we can do with the image.
- Still working on ways to improve the image!



- Centaurus A at 185 MHz
- On different colour stretch faint radial line artefacts are more obvious
- Thought to be small calibration errors, made obvious by the extremely bright inner lobes at the centre of Cen A.
- Also appear in each single snapshot. Can't get rid of them, even with direction-dependent calibration / peeling the core etc.

Summary

Developments for a generic MWA phase II continuum pipeline are underway:

Pushing MWA towards higher resolution and better sensitivity introduces new challenges, requiring different data processing steps

Ongoing tests and developments are continued, many challenges still to be overcome

Aim is to re-use existing tools, and only develop/measure what is missing

Steps will be integrated into a broadly applicable data processing pipeline