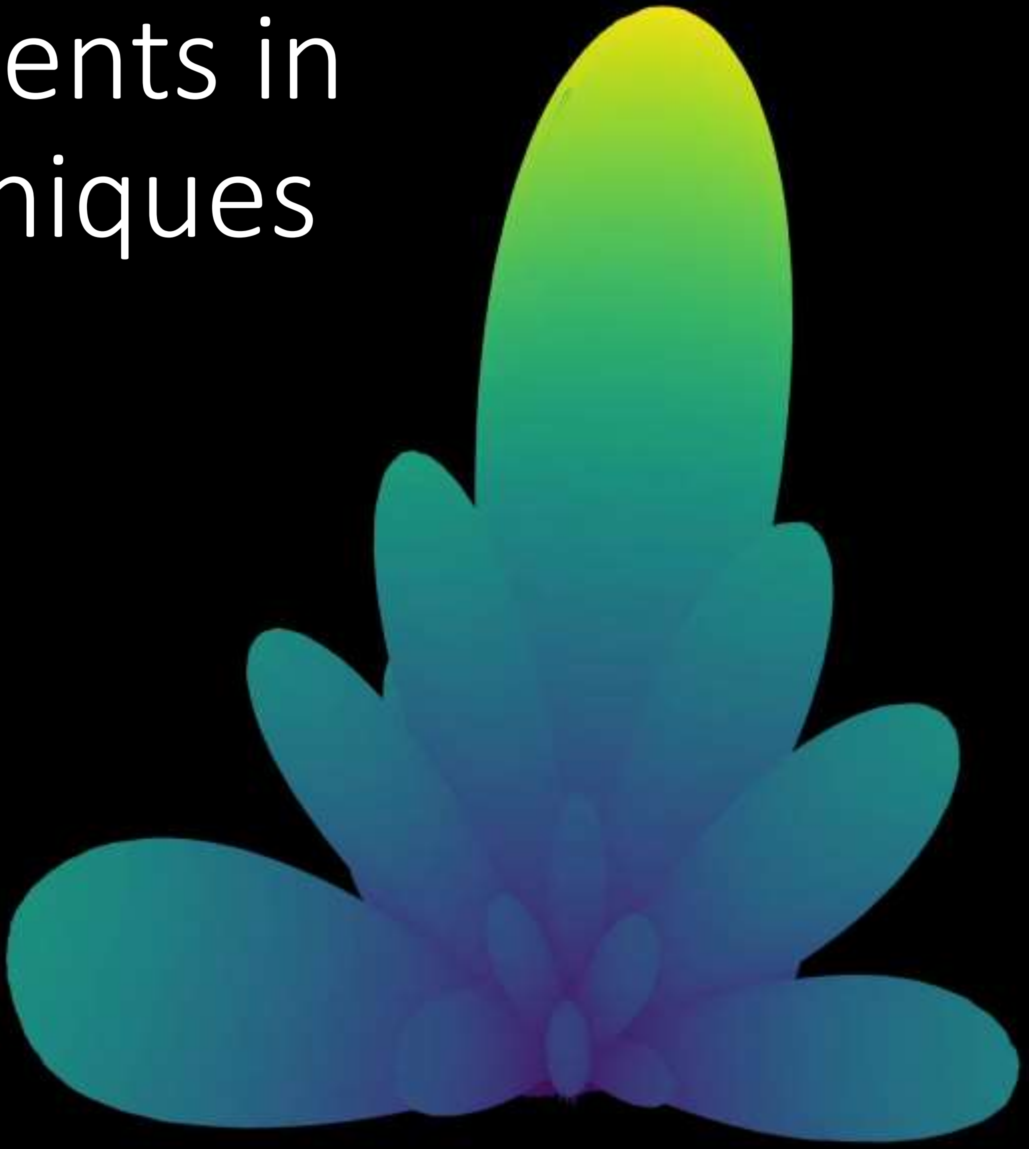
A Decade of Advancements in MWA Calibration Techniques

Dev Null

MWA Operations / EoR

aus | SRC

SKAO Regional Centre Australia



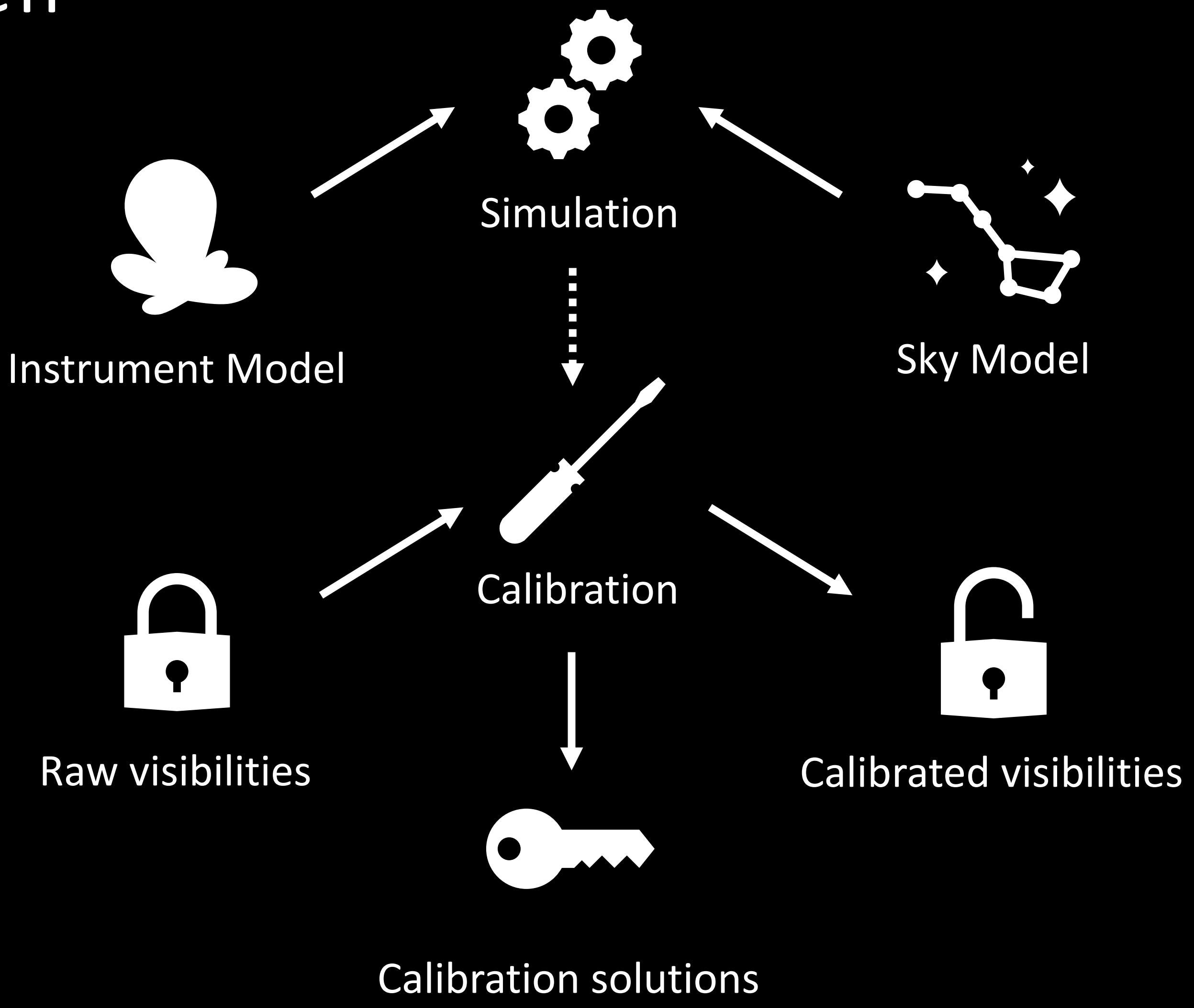
MWA FEE beam @238MHz via mwa_hyperbeam

Motivation

- Real-time calibration is the “holy grail” for MWA
- Calibration is still a challenge after 10+ years.
- ASVO calibration pipeline (Sokolowski et. al. 2020) was a big step forward, but we can do better!
- Better first-pass calibration solutions:
  - More accurate cable lengths => Improved MWAX fringe stopping
  - QA for flagging and fault finding
  - Enables basic imaging and self-calibration
  - Average data that would otherwise be deleted to save space
  - Make MWA data more accessible

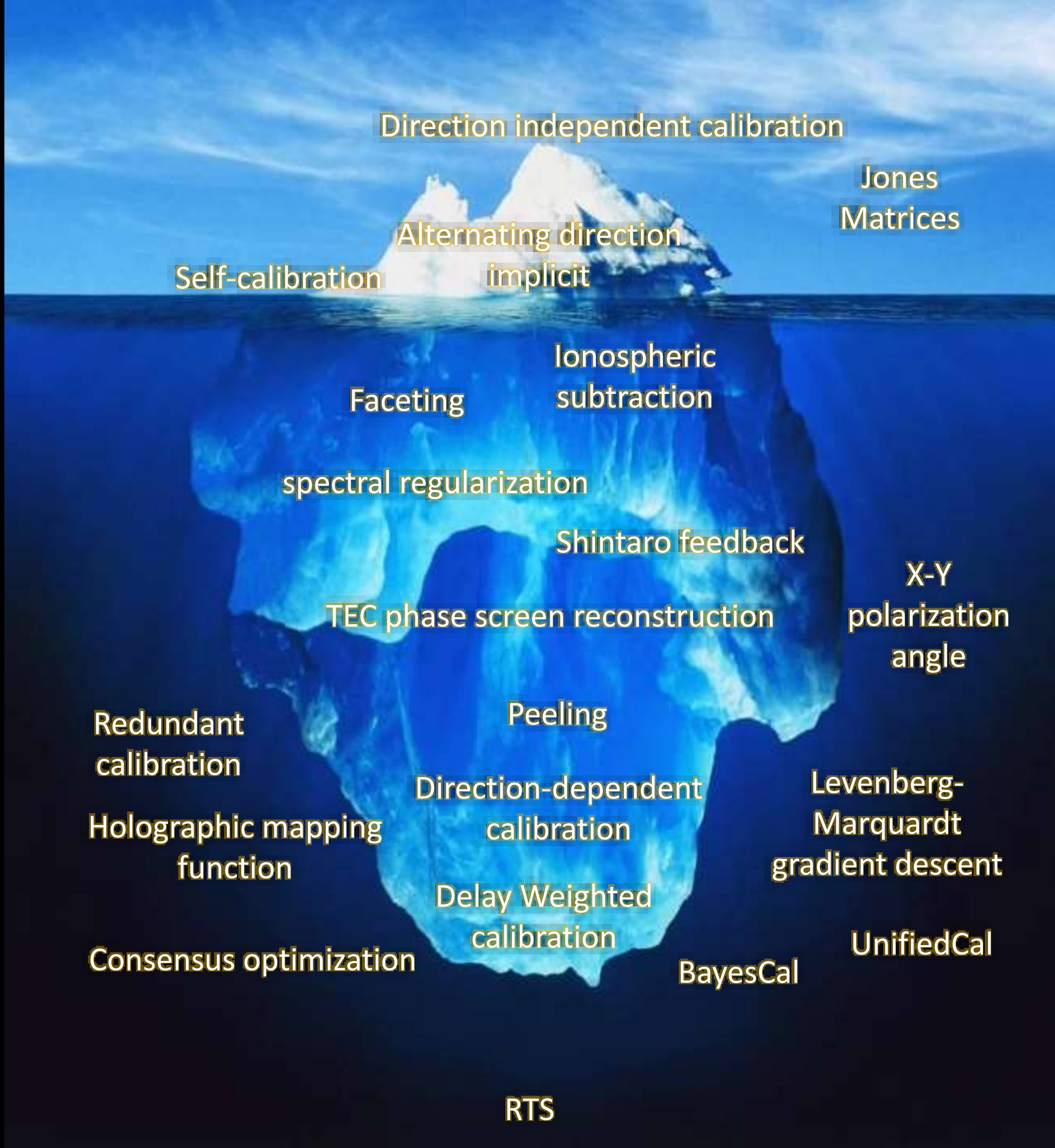
Calibration in a nutshell

- Simulate expected visibilities
- Solve for corrections to remove instrumental effects.
- Sounds simple right?



The reality

- Many challenges to solve
- Efforts are split across multiple bespoke calibration pipelines
- There’s no way to fit every technique into a 20 minute talk



MWA Calibration Challenges

Low frequency (80-300MHz)

→ionospheric effects ∝ λ^2, direction dependent

→RFI from satellites, aircraft, DTV,DAB,FM

Wide field of view

→need detailed sky / instrument models

Heterogeneous signal chain

→variability in calibration solutions

MWAX: 20GB/s, >10k baselines

→Need efficient algorithms and supercomputers

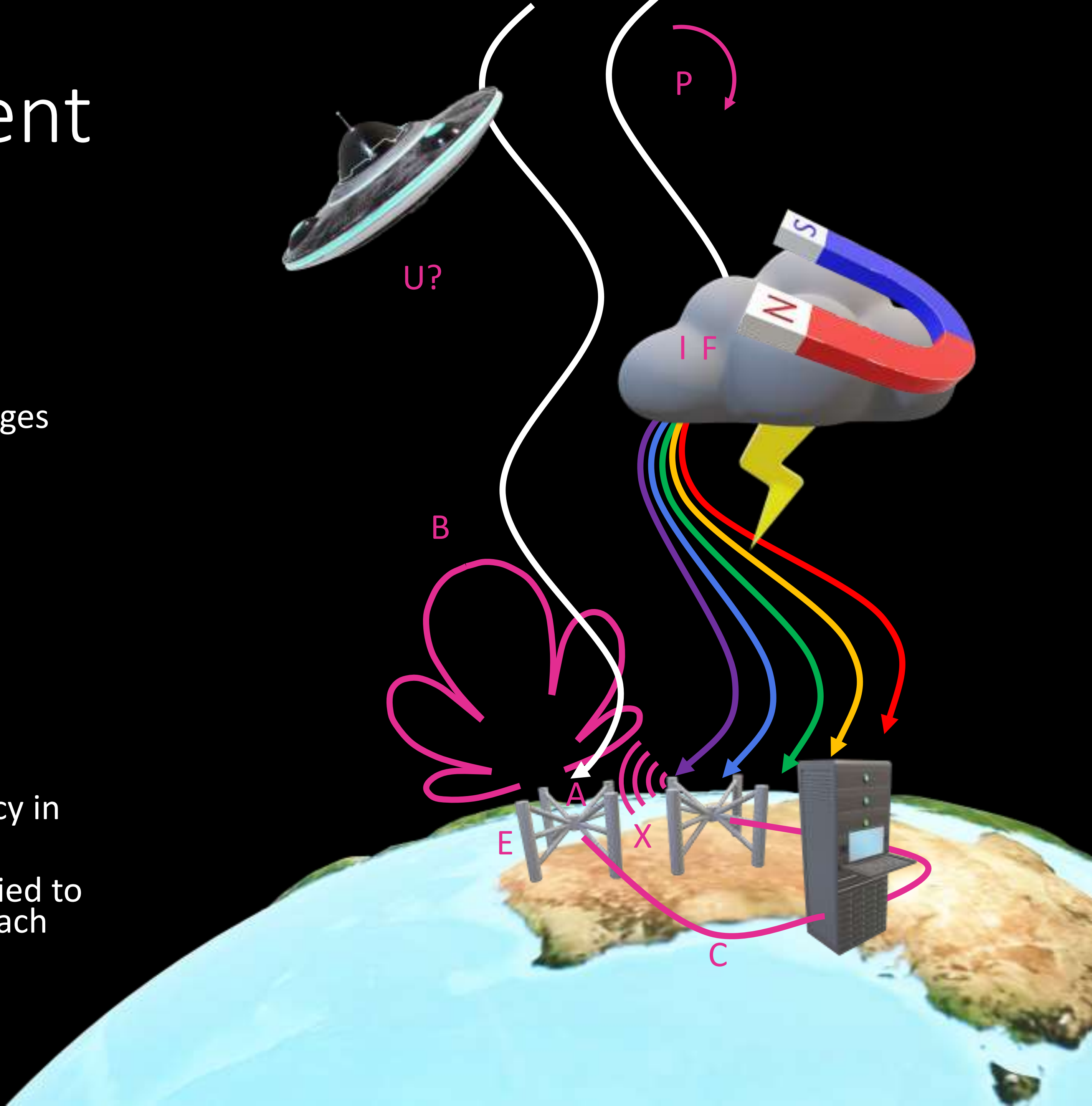
Direction Independent Calibration

A. Thermal effects in amplifiers
B. Beam response
C. Cable reflections at kinks or impedance changes
E. Electromagnetic properties of antenna and environment: moisture level, temperature
F. Faraday rotation
I. Ionospheric refraction
P. Parallactic rotation
U. Other, un-modelled effects
X. Cross-talk between antennas or tiles

Some effects can vary over time and/or frequency in ways that are difficult to model.

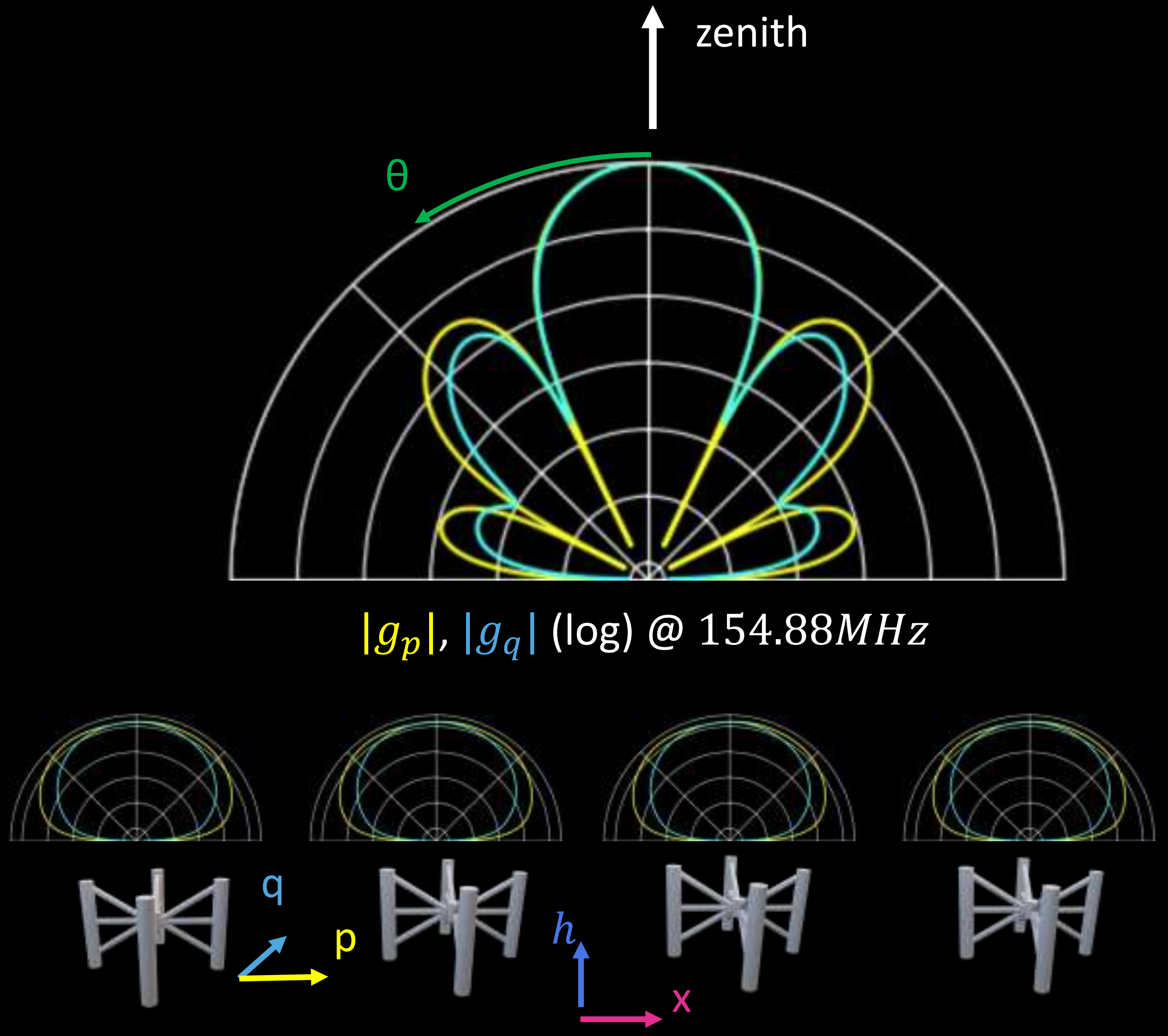
Solutions are a single complex Jones matrix applied to the two polarizations measured by each tile at each frequency

$$\begin{bmatrix} g_p & D_q \\ D_p & g_q \end{bmatrix}$$



Beam Models - Analytic

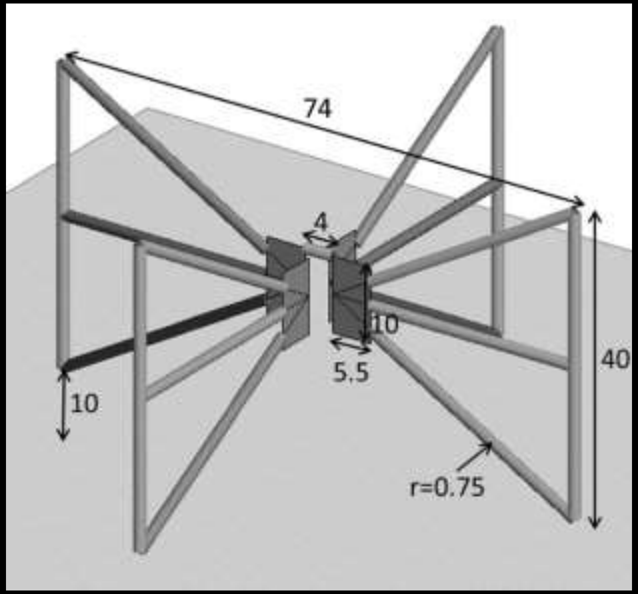
- Sutinjo et. al. 2015
- Hertzian (ideal) dipole elements
  - $J_e(\theta, \phi) = \begin{pmatrix} \cos\theta\cos\phi & -\sin\phi \\ \cos\theta\sin\phi & \cos\phi \end{pmatrix}$
- Sum with Array factor
  - $\sum_{n=1}^{16} v_n e^{j(k_x x_n + k_y y_n)}$
  - x_n, y_n - position
  - $k_x = \frac{2\pi}{\lambda}\sin\theta\cos\phi\,, k_y = \frac{2\pi}{\lambda}\sin\theta\sin\phi$
  - v_n from beamformer delays
- Add ground plane term
  - $g(\theta) = \sin\left(2\pi\frac{h}{\lambda}\cos\theta\right)$

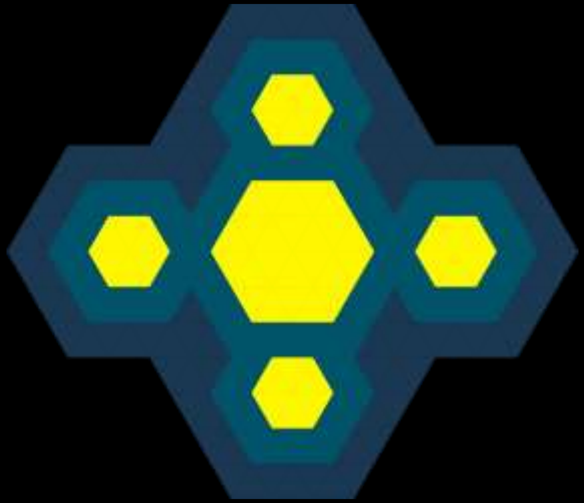


Plots made with hyperbeam (FEE), not analytic

Average and Full Embedded Element

- Sutinjo et. al. 2015, Sokolowski et. al. 2017
- Average embedded element: more accurate dipole model simulated with FEKO
- Full embedded element models mutual coupling between dipoles
- hyperbeam (Chris Jordan) provides an interface for FEE hdf5 spherical harmonic coefficients
- Line et. al. 2018 validated the beam with the ORBCOMM constellation down to elevation 10°
- Katherine Elder's talk shows that even FEE may not have the full picture

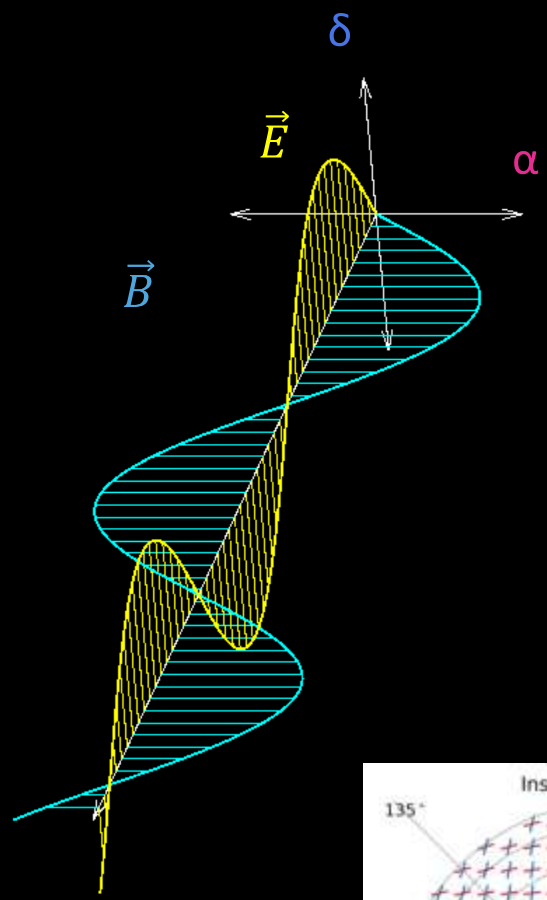


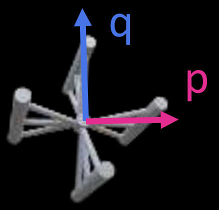


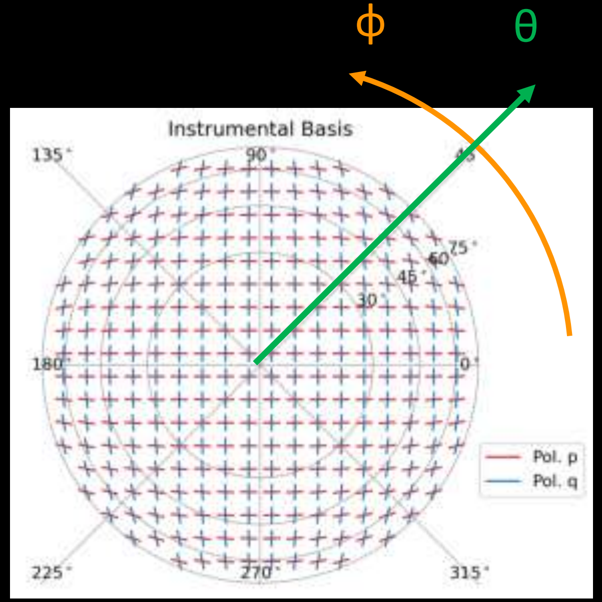
Credit: Sammy McSweeney, MWA Project Meeting 2022B

Beam Models - Polarimetry

- Polarization of electric field $\vec{E}$ defined in orthogonal sky basis (α, δ)
- Projection onto instrument basis (p, q) depends on incident angle (ϕ, θ)
- False polarization seen if basis transform is not accounted for

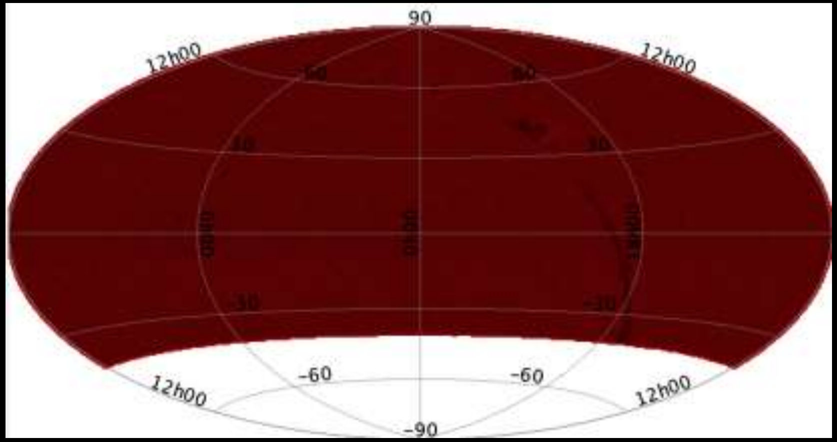




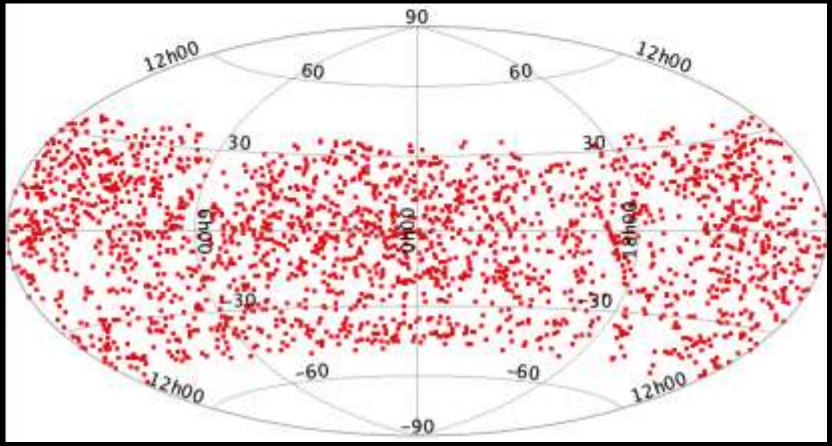


Credit: Byrne et. al. 2022, fig 5

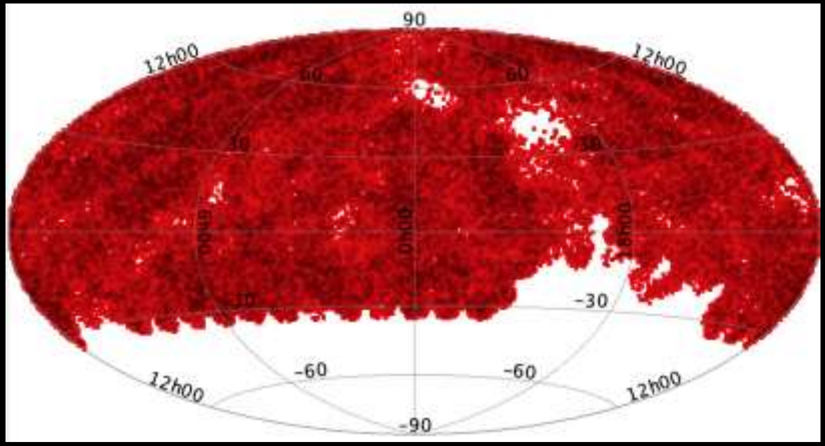
Catalogues in 2013



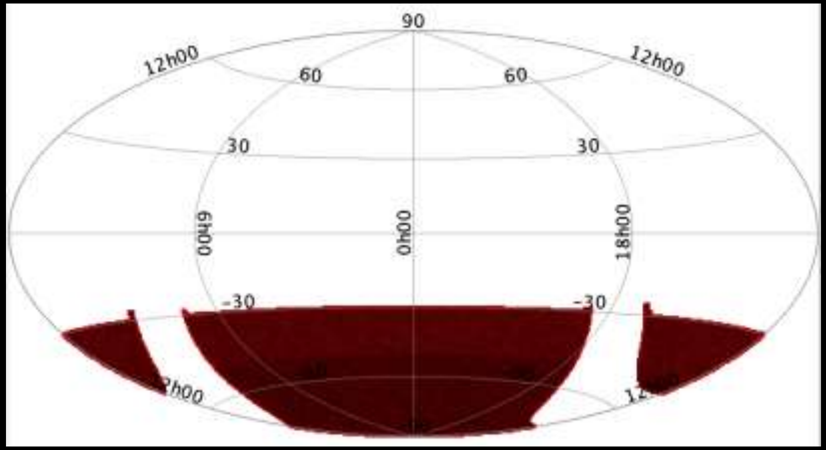
NVSS @ 1400MHz



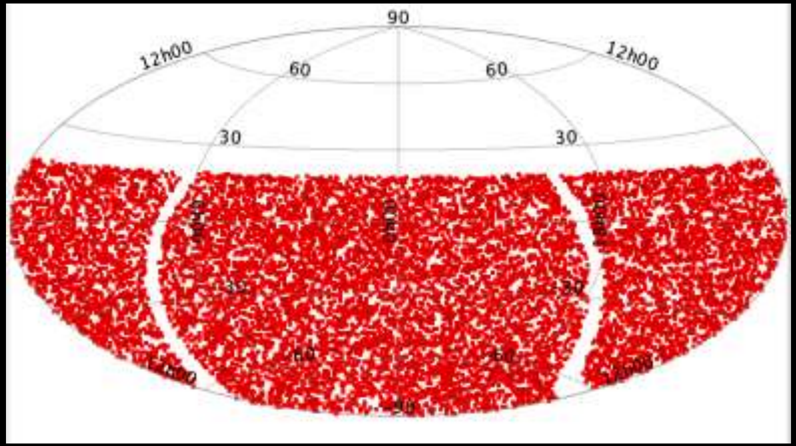
Culgoora @ 160MHz



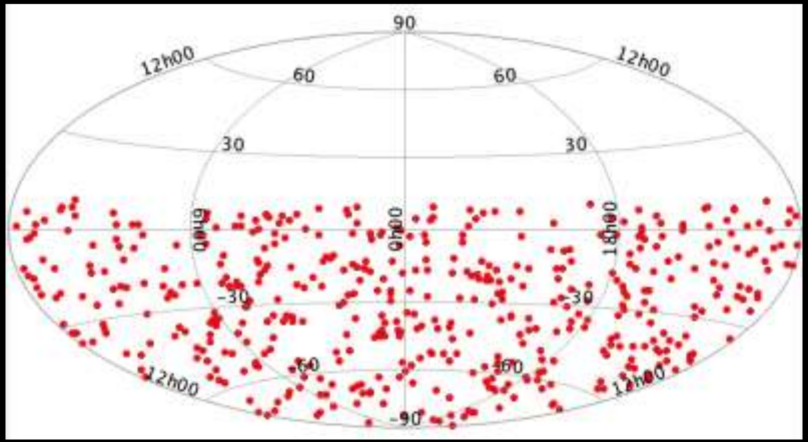
VLSS @ 74MHz



SUMSS @ 843MHz



MRC @ 408MHz



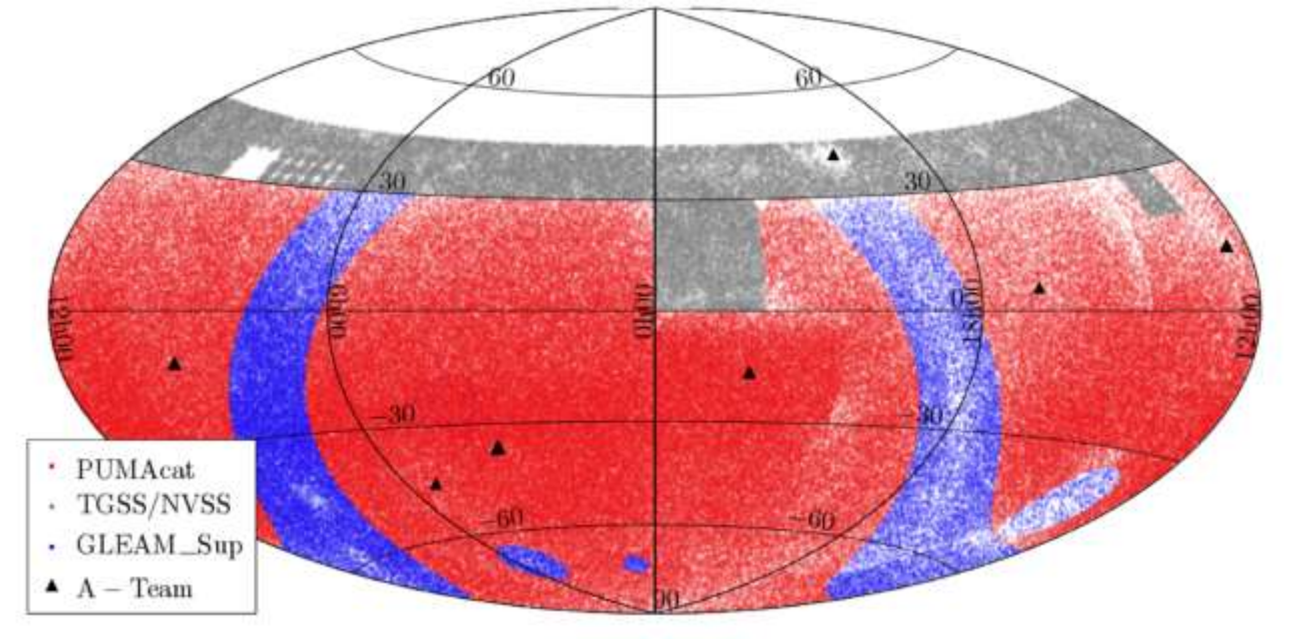
PAPER @ 145MHz

MWA's contribution

- Surveys like GLEAM, GLEAM-X and others have filled in many of the gaps in our point source models
- LoBES provides extended source models resolved by shorter baselines around EoR0, EoR1 fields
- Detailed models enable advanced calibration techniques

One catalogue to rule them all?

- Cook et. al. 2021
- Polylogarithmic fitting
- Cross-match with PUMA:
  - GLEAM and friends
  - LoBES
  - TGSS
  - NVSS
- Why not these?
  - POGS-II
  - GLEAM-X
  - ${YOUR_CATALOGUE_HERE}



RTS - Real-time system

- 2007: first commit
  - MWA 512T Planned
  - Massive data rates require 25x (~300GFLOPS) GPUs
  - Real-time calibration, wide-field imaging by coarse channel
  - unknown beam model, incomplete sky model: direction dependent calibration
- 2010: MWA De-scoped to 128T
  - Alternative DI calibration software competing for researcher time
- 2020: Last commit to main
  - Massive usability issues never addressed
  - Largely undocumented outside of Mitchell et. al. 2008
- Its many innovations live on in hyperdrive:
  - MitchCal (Alternating Direction Implicit)
  - Position-based source finder (Sault 2007)
  - GPU-accelerated peeling

Git Contributors:
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Miguel Morales
Michael Clark
Pietro Procopio
Christopher Jordan
Steve Ord
Jack Line
Bradley Meyers
Christopher Williams
Gianni Bernardi
Ben McKinley

FHD - Fast Holographic Deconvolution

- 2012: First demonstrated
- Major differences from RTS:
  - Holographic approach to deconvolution
  - Full-band calibration
  - Use autocorrelations for bandpass calibration
  - Fit cable reflections
- No overlap with RTS authors*
  - Independent pipelines give more confidence in EoR results
- Open source but written in IDL – Can't run on Pawsey
- PyFHD is showing promising results

Git Contributors:
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Wenyang Li
Dara Storer
Pyxie Star
Danny Jacobs
Matthew Kolopanis
Jon Ringuette
Miguel Morales
Jonnie Pober

https://github.com/EoRImaging/FHD

MWA-reduce / Calibrate

- 2012: first commit
- André Offringa’s C++ implementation of MitchCal/ADI
- Based on mwa_tools (32T_tools) 2009
- GPU-acceleration never completed
- Early 2022: Most recent commit

Git Contributors:
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Franz Kirsten
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Chen Wu
Dave Emrich
Christopher Jordan
Bradley Meyers
Cath Trott
…

CASA

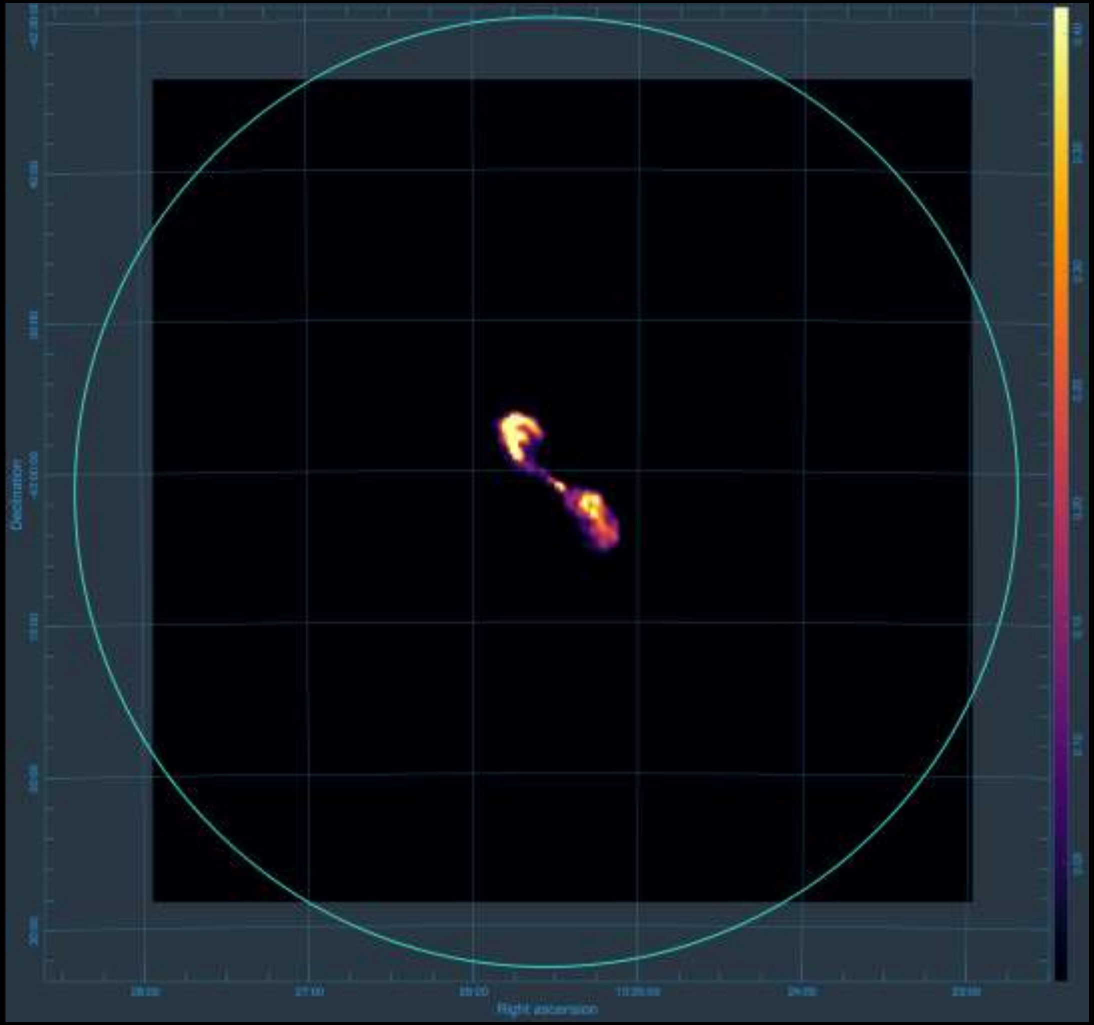
- A workhorse of radio astronomy
- Slow, buggy
- Can sometimes produce calibration solutions for A-team sources

hyperdrive

- 2020: first commit, Chris Jordan
- Well-tested, well-documented
- Works on SKA-Low simulations (SDC3)
- GPU-accelerated Rust: Runs on NVIDIA, HIP, CPU. Tested on Setonix
- Full-band calibration
- Rich Quality Analysis metadata
- Late 2022: Initial Ionospheric subtraction work
- Peel branch in progress

ASVO Calibration pipeline

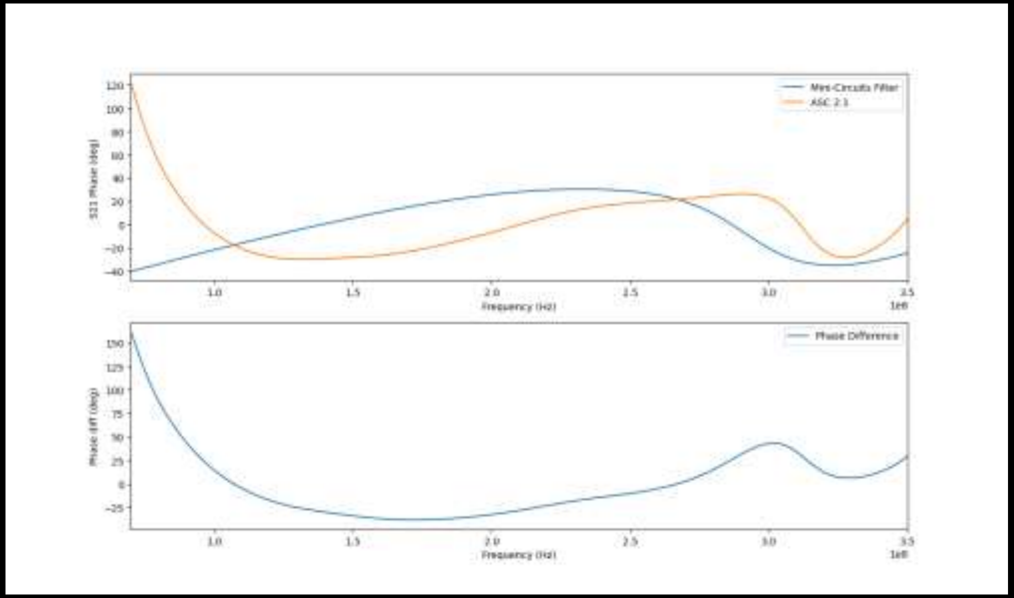
- Sokolowski et. al. 2020
- Similar calibration to MWACS:
  - Apply Spectral index to calibrator images (MOST, VLA)
  - FT and calibrate with CASA
- Store solution in MWA database
  - Linear phase fit on unwrapped phases
  - 2nd order polynomial gain for each coarse channel
  - Quality analysis metrics used by the operations team for fault finding
- How does it do?
  - 16k of 79k calibrator observations have solutions
  - 11k “good” solutions (>100 tiles with >50% channel convergence)

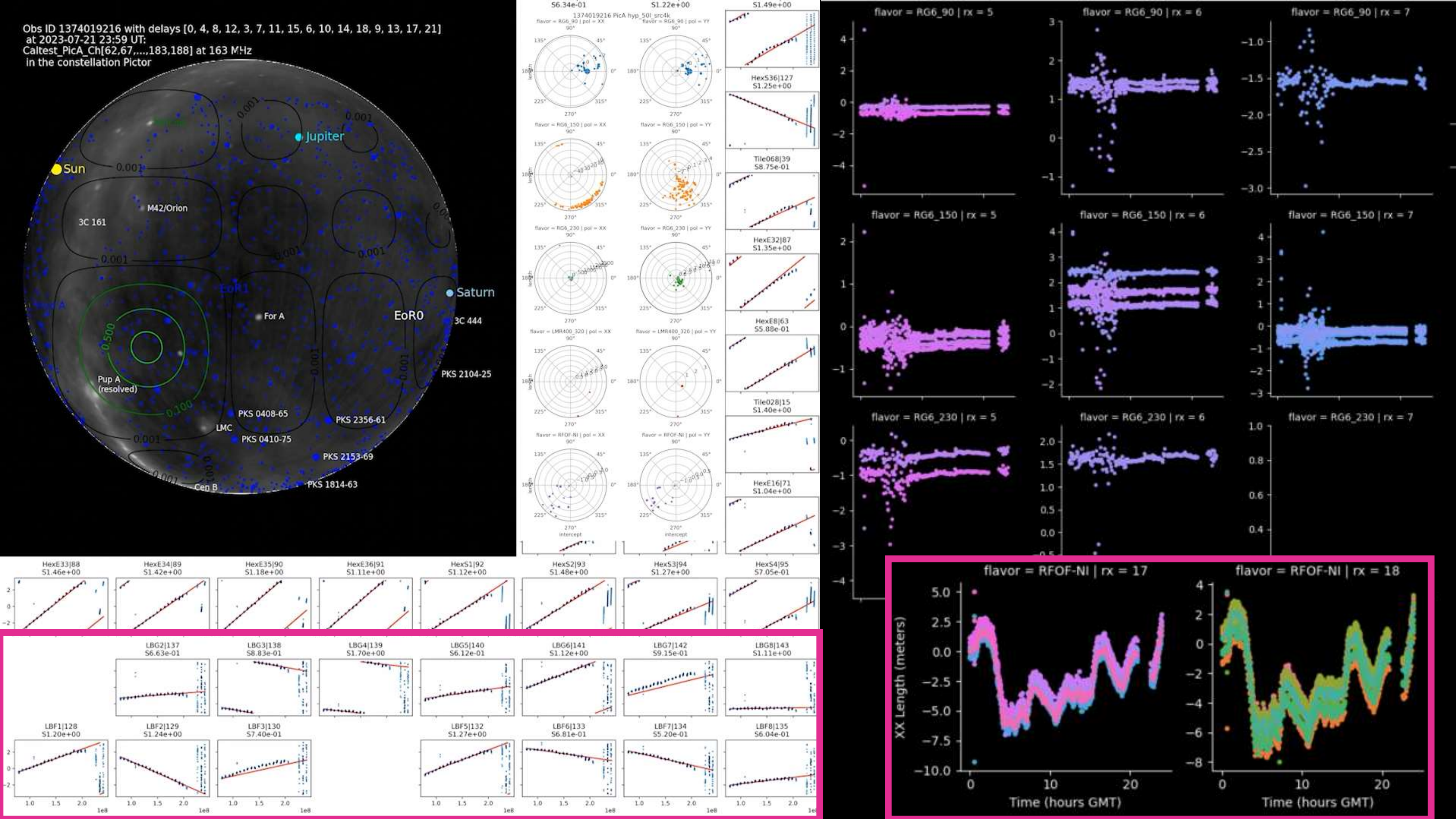


MOST image of CenA @ 150MHz
Angular extent of moon for comparison

Improving the ASVO Calibration pipeline

- Replace CASA with Hyperdrive
- Use a modern calibration catalogue:
  - Currently Gleam GSM (Thanks Kat Ross)
- Greg Sleap: near real-time preprocessing of raw visibilities on-site
- Fourier magic to fit delay (thanks Sammy McSweeney)
- Phase offset between RRI and NI receivers (thanks Jake Jones)
- How does it do?
  - 2 minute Calibrator every 5 minutes for 24 hours
  - Picket-fence: ch62-188 (79 – 240MHz)
  - Compact configuration with 2x NI receivers of RFOF long baseline tiles
  - Uvw cutoff: 50λ
  - 4k sources modelled from GSM





Obs ID 1374019216 with delays [0, 4, 8, 12, 3, 7, 11, 15, 6, 10, 14, 18, 9, 13, 17, 21]
at 2023-07-21 23:59 UT:
Caltest_PicA_Ch[62,67,...,183,188] at 163 MHz
in the constellation Pictor
Sun
Jupiter
Saturn
M42/Orion
3C 161
EoR1
EoR0
For A
3C 444
Pup A (resolved)
PKS 2104-25
PKS 0408-65
PKS 2356-61
LMC
PKS 0410-75
PKS 2153-69
Cen B
PKS 1814-63
1374019216 PicA hyp_50l_src4k
flavor = RG6_90 | pol = XX
flavor = RG6_90 | pol = YY
flavor = RG6_150 | pol = XX
flavor = RG6_150 | pol = YY
flavor = RG6_230 | pol = XX
flavor = RG6_230 | pol = YY
flavor = LMR400_320 | pol = XX
flavor = LMR400_320 | pol = YY
flavor = RFOF-NI | pol = XX
flavor = RFOF-NI | pol = YY
HexS36|127
Tile068|39
HexE32|87
HexE8|63
Tile028|15
HexE16|71
HexE33|88
HexE34|89
HexE35|90
HexE36|91
HexS1|92
HexS2|93
HexS3|94
HexS4|95
LBG2|137
LBG3|138
LBG4|139
LBG5|140
LBG6|141
LBG7|142
LBG8|143
LBF1|128
LBF2|129
LBF3|130
LBF5|132
LBF6|133
LBF7|134
LBF8|135
flavor = RG6_90 | rx = 5
flavor = RG6_90 | rx = 6
flavor = RG6_90 | rx = 7
flavor = RG6_150 | rx = 5
flavor = RG6_150 | rx = 6
flavor = RG6_150 | rx = 7
flavor = RG6_230 | rx = 5
flavor = RG6_230 | rx = 6
flavor = RG6_230 | rx = 7
flavor = RFOF-NI | rx = 17
flavor = RFOF-NI | rx = 18
XX Length (meters)
Time (hours GMT)

Thank you!

- Thanks to everyone who has made the MWA possible
- Corrections please! What did I miss?

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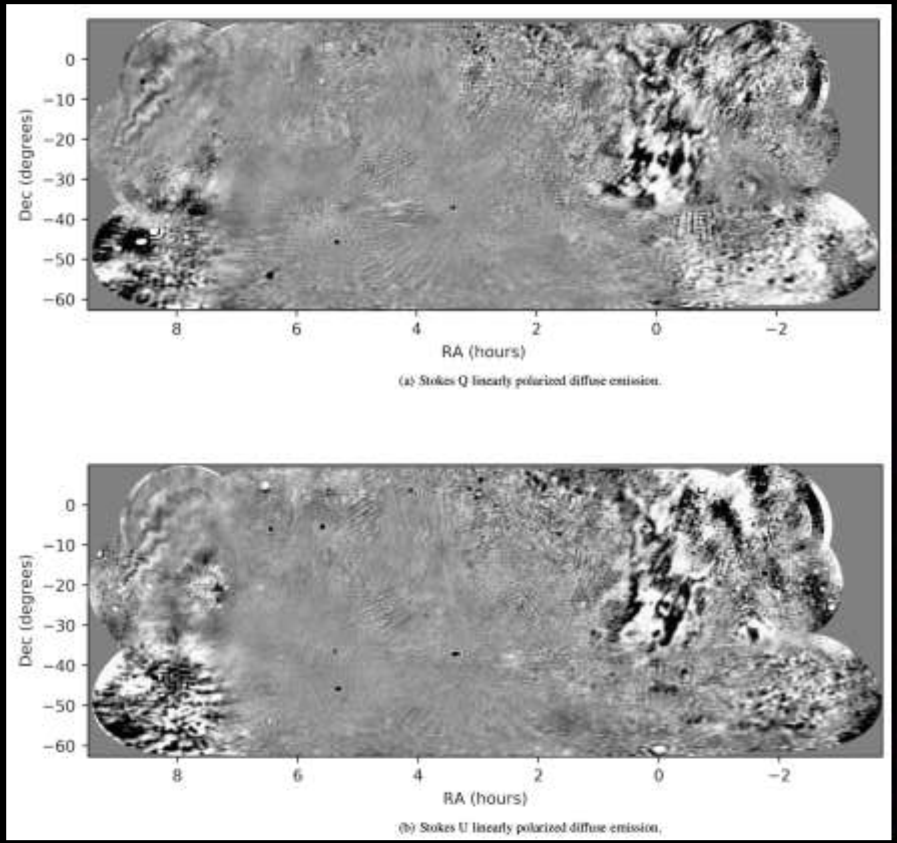
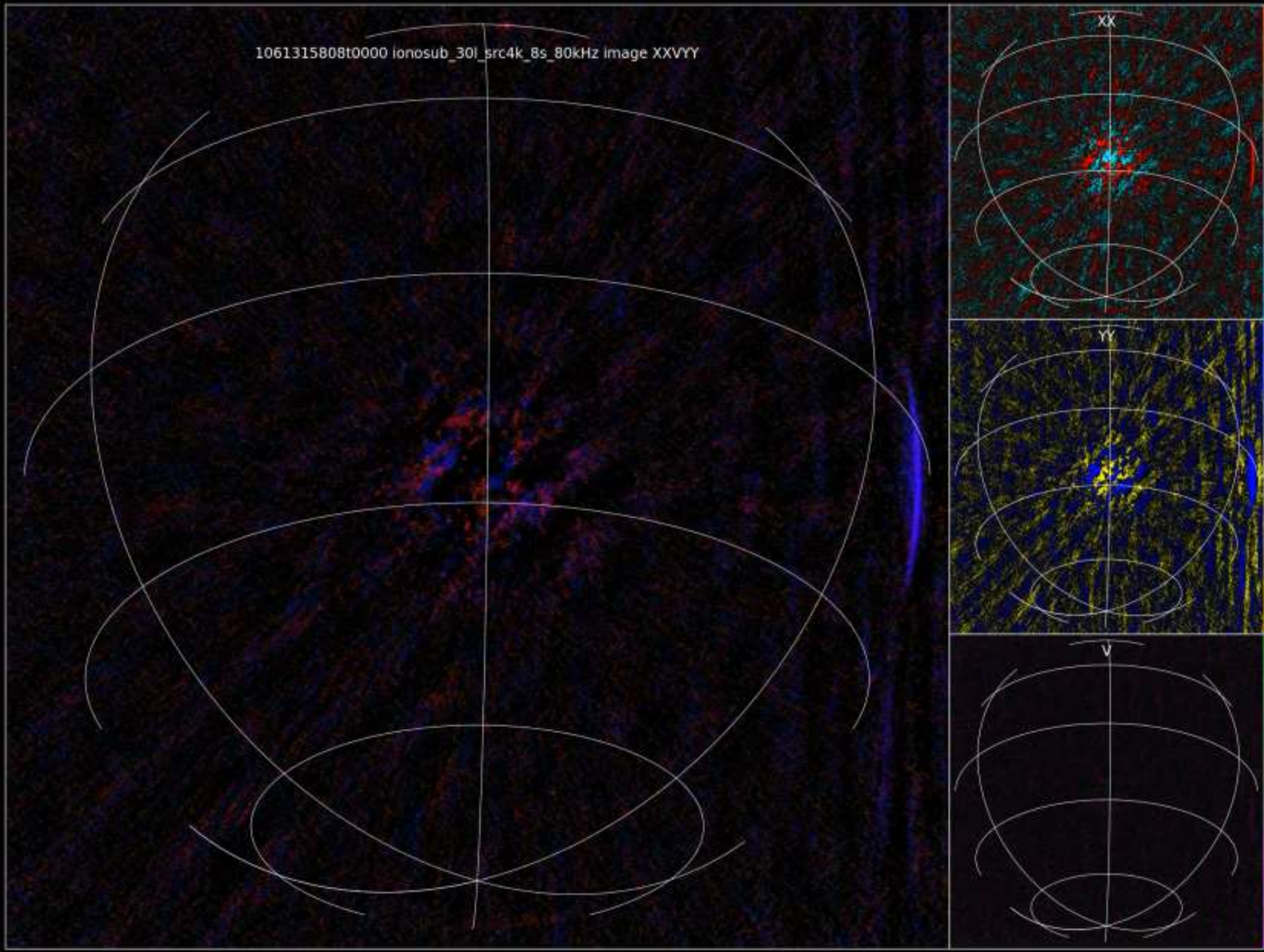
Side note: Faraday rotation



(a) Stokes Q linearly polarized diffuse emission.

(b) Stokes U linearly polarized diffuse emission.



Credit: Byrne et. al. 2021