MWA real-time imaging

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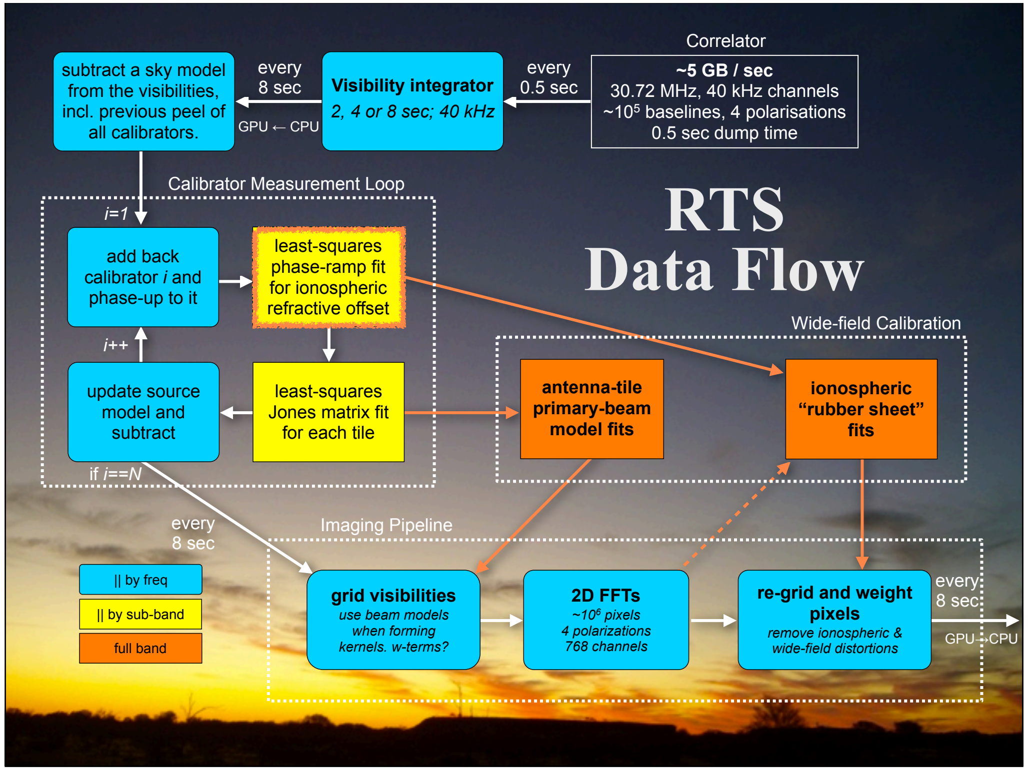
Outline

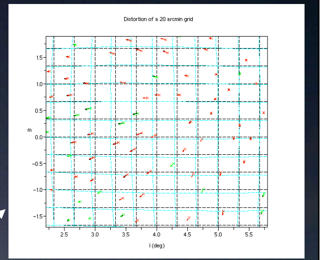
- Quick overview
- Real-time calibration
- Real-time imaging
- GPU performance
- 32-tile results

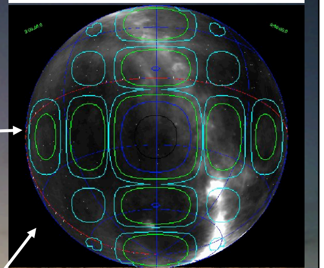


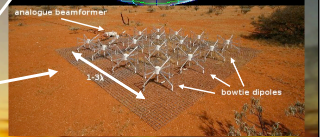
Correlator
~5 GB / sec
30.72 MHz, 40 kHz channels
~10⁵ baselines, 4 polarisations
0.5 sec dump time
every
0.5 sec
Visibility integrator
2, 4 or 8 sec; 40 kHz
every
8 sec
GPU ← CPU
subtract a sky model from the visibilities, incl. previous peel of all calibrators.
RTS
Data Flow
Calibrator Measurement 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
Wide-field Calibration
antenna-tile primary-beam model fits
ionospheric "rubber sheet" fits
every
8 sec
Imaging Pipeline
|| by freq
|| by sub-band
full band
grid visibilities
use beam models when forming kernels. w-terms?
2D FFTs
~10⁶ pixels
4 polarizations
768 channels
re-grid and weight pixels
remove ionospheric & wide-field distortions
every
8 sec
GPU → CPU

Calibration

- Solve for the location of, and gain towards, many point sources.
- Use position offsets to constrain a 2D ionospheric phase screen.
- Use the Jones matrix measurements to constrain a primary beam model for each antenna tile.
- Use the ~ wavelength^2 dependency of the ionosphere to isolate the models.







Simple, but time variable primary beams (including ~ 5 minute drifts between pointings)

Visibility Model

V, I, F, J & N are 2x2 complex matrices

All variables are functions of time and frequency

Keep as 2x2 matrices so that the Jones matrices can be extracted

$$V_{jk} = \sum_{s=1}^{N_c} \left\{ J_{js}.[e^{i\phi_{jks}}.F_s.I_s].J_{ks}^{\dagger} \right\} + N_{jk}$$

Phase shift, including ionospheric refraction

Ionospheric Faraday rotation

Source covariance matrix

Instrument response

Visibilities.

Noise
thermal (receivers), other sidelobes ($s>N_c$), confusion sources, diffuse emission, ...

Peel loop: calibrate & subtract

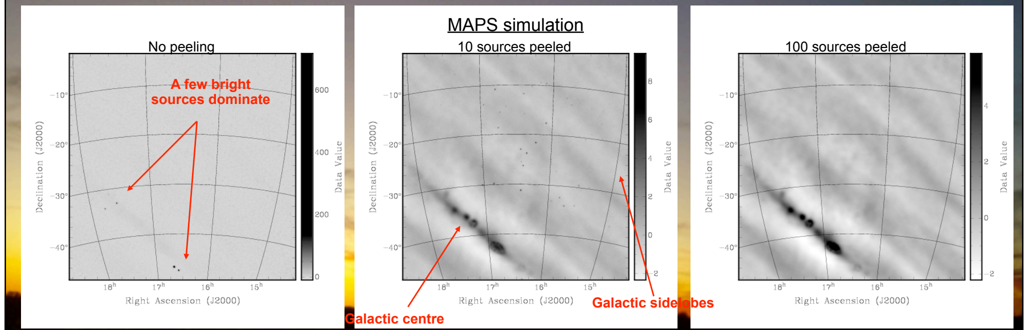
V′ : phased to old position
V″ : phased to new position

- Subtract sky model to reduce side-lobes, etc.
- Loop over sources, *s*:
  - Fit for ionospheric offsets over baselines & frequency.

$$J_{js}^{-1}.V'_{jk}.J_{ks}^{\dagger-1} = I_s e^{i(u_{jk}\alpha_l + v_{jk}\alpha_m)\lambda^2} + N_{jk}$$

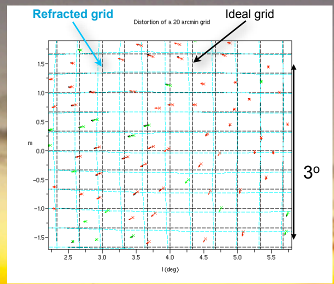
  - For each antenna, *j*, fit J_{js} over $k \neq j$.

$$J_{js} = \left(\sum_{k\neq j} V''_{jk}.J_{ks}.I_s^\dagger\right).\left(\sum_{k\neq j}.I_s.J_{ks}^\dagger.J_{ks}.I_s^\dagger\right)^{-1}$$



Ionospheric Rubber Sheet

- Use the measured calibrator offsets to relabel pixel boundaries and tweak the re-gridding.
- Interpolation function: At each vertex fit a 2×2 matrix, M, by minimising $\sum_i w_i |M\,p'_i - q'_i|^2$
- $w_i = d^{-a}$ ($w_i = 0$ if $d > d_{max}$)
- Fast: only sum over local calibrators
- Scales as the number of pixels and density of calibrators.

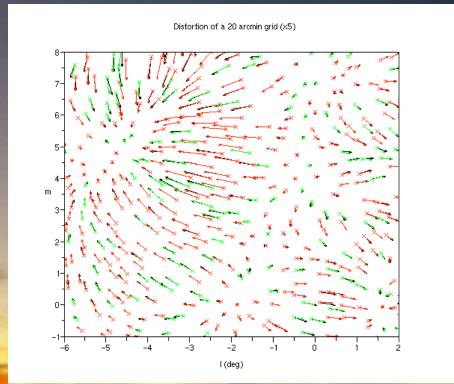


"Image Deformation Using Moving Least Squares",
S. Schaefer, T. McPhail & J. Warren

Globally smooth interpolation function

$M^TM = cI$ (minimise local shear)

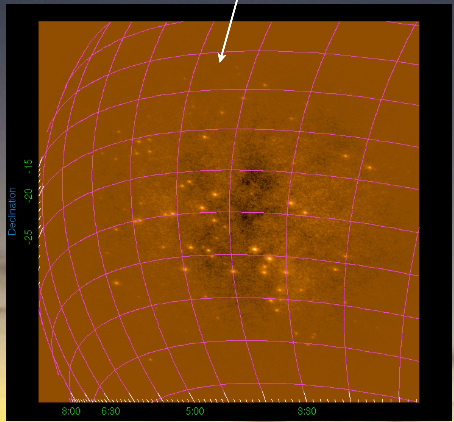
$M^TM = I$ (minimise local scaling)

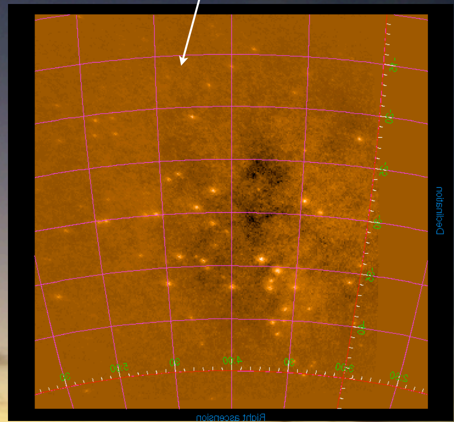


Warped Snapshots (-3.5 hrs to +3.5 hrs)

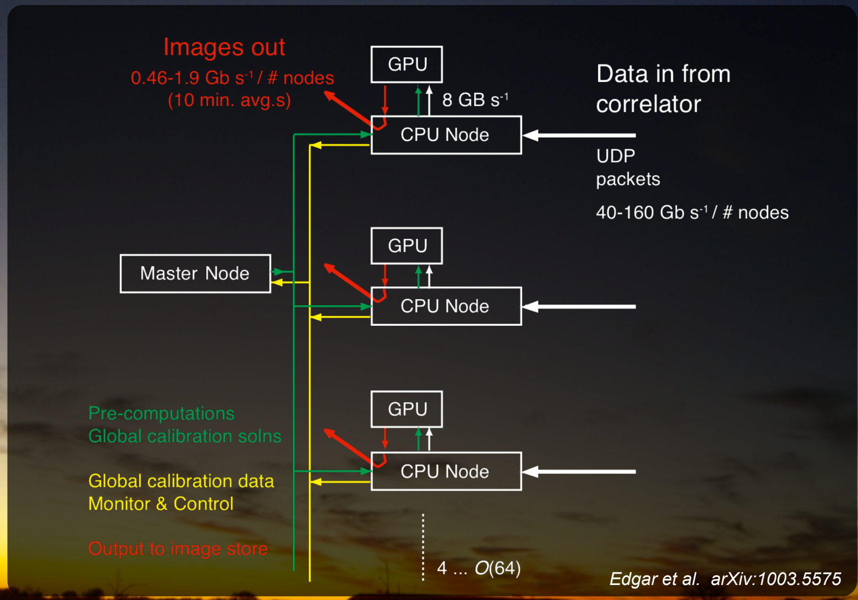
determine grid (wide-field effects & ionosphere) and weights (primary beams & potentially FR) for snapshots

re-sample to a constant frame for integration





MWA: Heterogeneous Architecture



GPUs for MWA

RTS on GPU cluster at Harvard (Richard Edgar & Mike Clark)

- 12 frequency channels per RTC node
- 21 degree FoV
- 50 sources calibrated & peeled
- Does not include all-sky primary beam and ionospheric phase fits

2.66 GHz quad core Nehalem + NVIDIA C1060 Tesla GPU

AcquireData	1.08 seconds (can reduce by 1 second)
Send data to GPU	0.03 seconds
Receive data from GPU	0.05 seconds
Calibration Loop	3.58 seconds
Gridding prep.	0.17 seconds (not including new kernels)
Gridding	1.40 seconds (can reduce by 10s of %)
Imaging	0.36 seconds
Grid/Conv fn	0.01 seconds (simple kernels)
Stokes	0.10 seconds
Re-gridding	0.47 seconds
Cleanup	0.13 seconds
Entire Cadence	**7.37 seconds**

Fixed! Related to a cfitsio POSIX thread issue

First 32 antenna tiles (32T)
~ 5% demonstrator

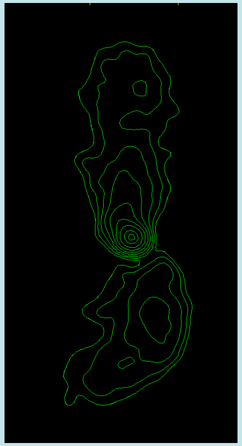
Pipeline tested on site in real time in 2009 & 2010.

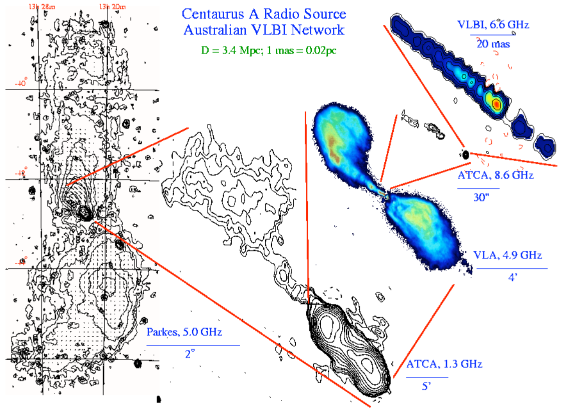
- Mini Real Time Computer ($^{1}/_{24}$ or $^{1}/_{16}$)
  - 1+4 nodes equipped with GPUs (8800GTS)
  - CPUs communicate via MPI
  - Use hardware on site (slight mods)
- Modified Real Time System
  - Simplifying assumption: identical beam shapes

Centaurus A

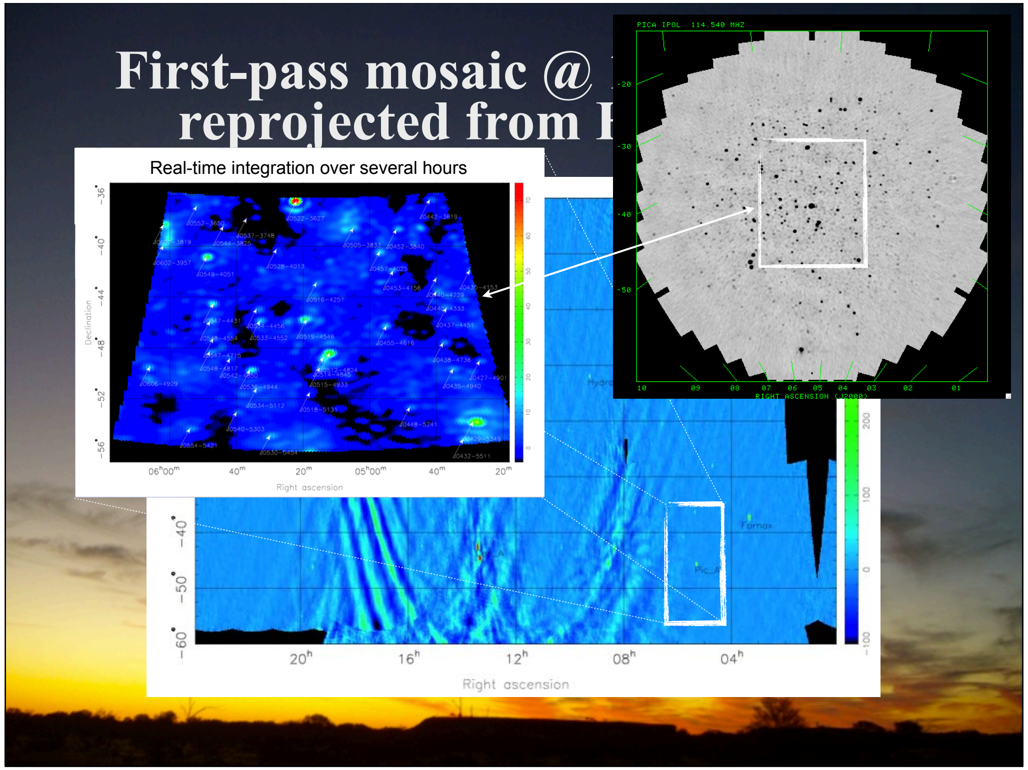
Optical

MWA @2.6m wavelength.
30' resolution

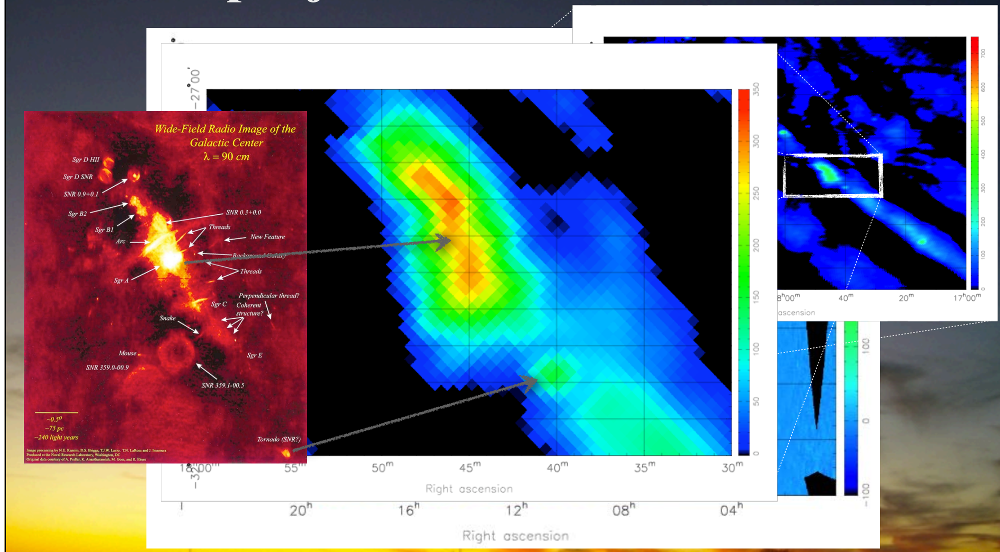




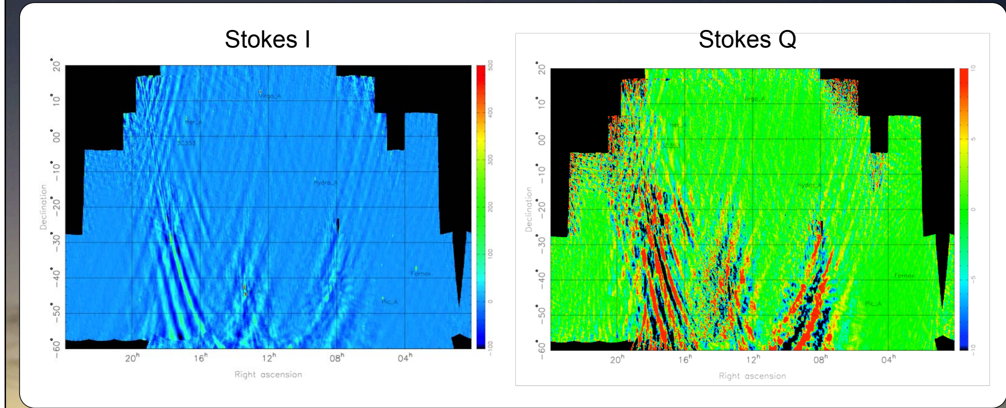
F. Briggs & S. Tingay


First-pass mosaic @
reprojected from
Real-time integration over several hours
Declination
Right ascension
PICA IPOL 114.540 MHZ
RIGHT ASCENSION (J2000)
Fornax
Right ascension

First-pass mosaic @ 103±15 MHz reprojected from HEALPIX



Polarised Sidelobes



Summary

- The MWA faces many of the same challenges as the SKA, and will deal with them using a high-throughput, real-time calibration and imaging pipeline.
- Most of the solutions are built into the snapshot imaging framework.
- MWA will not store all of the visibilities and will reply forward modelling for deconvolution.

- C. Lonsdale, et al., “The Murchison Widefield Array: Design Overview”, *Proceedings of the IEEE*, **97** (8), 1497--1506, 2009. [arXiv:0903.1828]
- D. Mitchell, et al., “Real-Time Calibration of the Murchison Widefield Array”, *IEEE Journal of Selected Topics in Signal Processing*, **2** (5), 707--717, 2008. [arXiv:0807.1912]
- R. Edgar, et al., “Enabling a High Throughput Real Time Data Pipeline for a Large Radio Telescope Array with GPUs”, accepted by *Comp. Phys. Comm*. [arXiv:1003.5575]
- B. Pindor, et al., “Subtraction of Bright Point Sources from Synthesis Images of the Epoch of Reionization”, submitted to *PASA*. [arXiv:1007.2264]
- G. Bernardi, et al., “Subtraction of point sources from interferometric radio images through an algebraic forward modeling scheme”, submitted.