Algorithms R&D: Updates

Jan. 15th, 2020

S. Bhatnagar

Algorithms R&D Group

NRAO

Algorithms R&D Group (ARDG)

- Rational
  - Longer term focus for algorithms R&D
  - Recognize R&D as a distinct step in software development cycle
  - Identify algorithms R&D work necessary to full-fill long term NRAO goals
  - Formalize the way AR&D is done at NRAO
  - Work on unforeseen issues that require AR&D (e.g. VLASS imaging)
- Under DMSD: ARDG Lead reports to Head of DMSD
- Develop a road map in collaboration with DMS, SSR, EVLA, ALMA, SCG, Sc. Staff reps. Update ~yearly.
- Disperse information about its activities

Algorithms R&D Group (ARDG)

- Current membership
  - S. Bhatnagar (Scientist), Group Lead (0.75 FTE)
  - P. Jagannathan (Assistant Scientist) (0.75 FTE)
  - M. Pokorny (Software Engineer-IV, 2-year term position for ngVLA) (1 FTE)
  - B. Kirk (PhD student)
  - Mingyu (Genie) Hsieh (Software Engineer-IV); New hire (starting Feb. 03,2020) (1FTE)
  - Srikrishna Sekhar, Joint NRAO-IDIA/SA PDF; New hire (starting Feb. 2020)

- Total effort:
  - 2.5 FTE from 3 full-time staff members
  - 1 FTE from one 2-year term position
  - 1 PDF + 1 student

Algorithms R&D Group (ARDG)

- Primary deliverables
  - Scientific publications demonstrating the working of the algorithm/technique
  - Technical description, limitations, limits of applicability, etc.
  - A software prototype implementation, regression with test data and reference products
  - Software interface description
  - Assistance in integration with production software, commissioning, (re-)training support staff

- CASA code base as the development platform (by choice)
  - Minimize development overheads in the R&D stage
  - Minimize cost of integration with the production package

ARDG Road Map

- Items broadly categorized as
  - Planned for delivery
    - Proof-of-concept demonstrated
    - Usually in the stage of prototype implementation
  - In active R&D stage
    - R&D in progress
    - First goal usually is a PoC demo
  - Potential R&D topics
    - Exploratory projects
    - Often parts of PhD or Masters level projects
  - Consulting/Maintenance
    - Support staff, CASA staff, others...
    - Maintenance support for algorithmic issues once in production

ARDG Road Map 2019

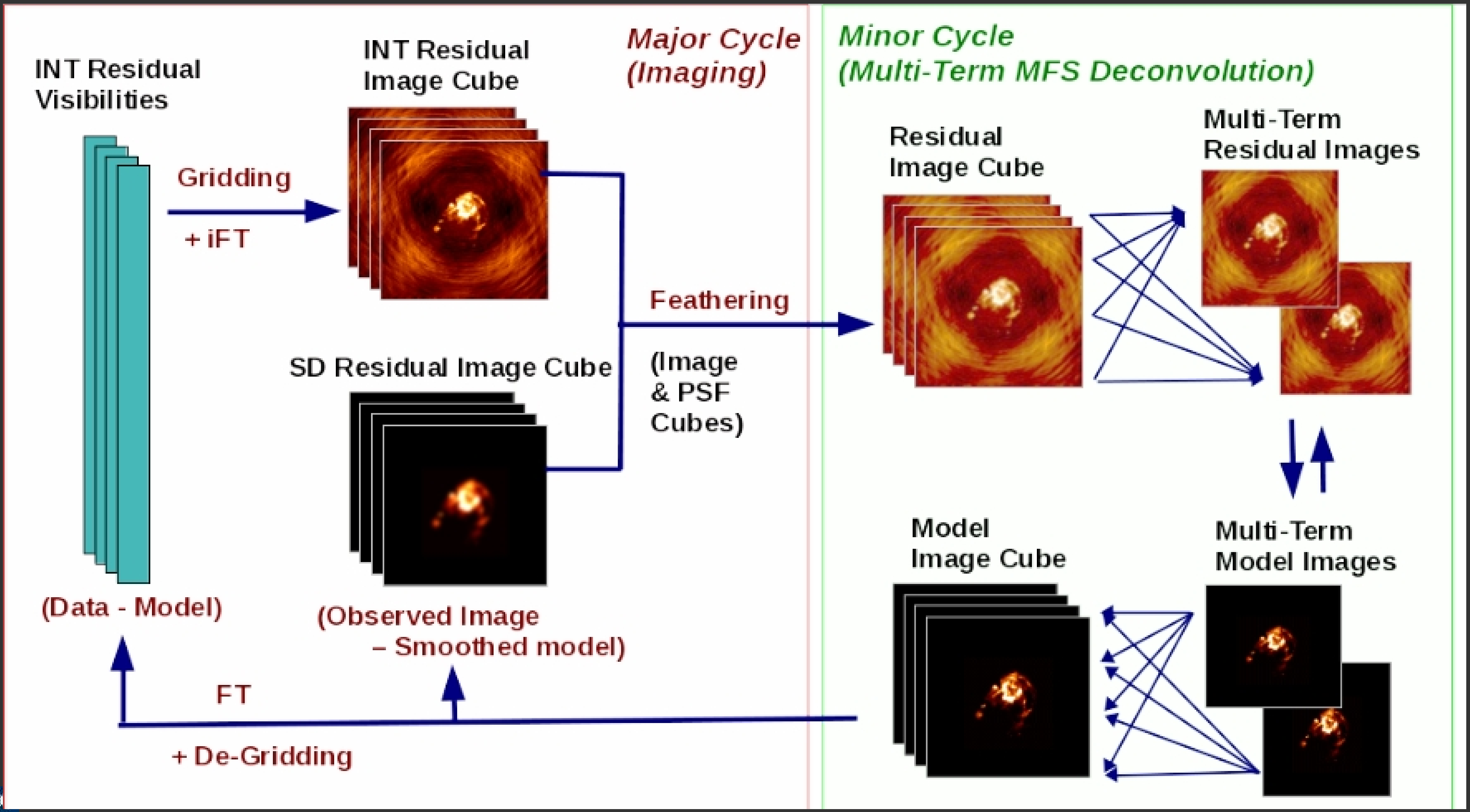
- Joint SD-Interferometric imaging
- Scientific commissioning of AW-Projection
- Wide-field full-pol. Imaging (ALMA Study Project)
- Full-Stokes imaging
- Asp-Clean (port from AIPS++!) + new ideas
- ngVLA
  - Size of computing
  - Algorithms
- ML/AI Application to RA (B. Kirk's PhD)
  - As a start, detect and classify artifacts in images from pipelines

What we actually ended up doing?

- Joint SD-Interferometric imaging [Done]
- Scientific commissioning of AW-Projection [Done]
- Work on VLASS imaging (a report now exist) [Done]
  - Deep-dive into imaging problems
  - PB models, Pointing corrections, HPC
- Follow-up VLASS work [Done]
  - CFCache Lazy Fill
  - Corrections for antenna pointing offsets
- Size-of-computing estimates for the ngVLA [Done/In progress]
- Wide-field full-pol. Imaging (ALMA Study Project) [Done/In progress]
  - New holography data, A-term models

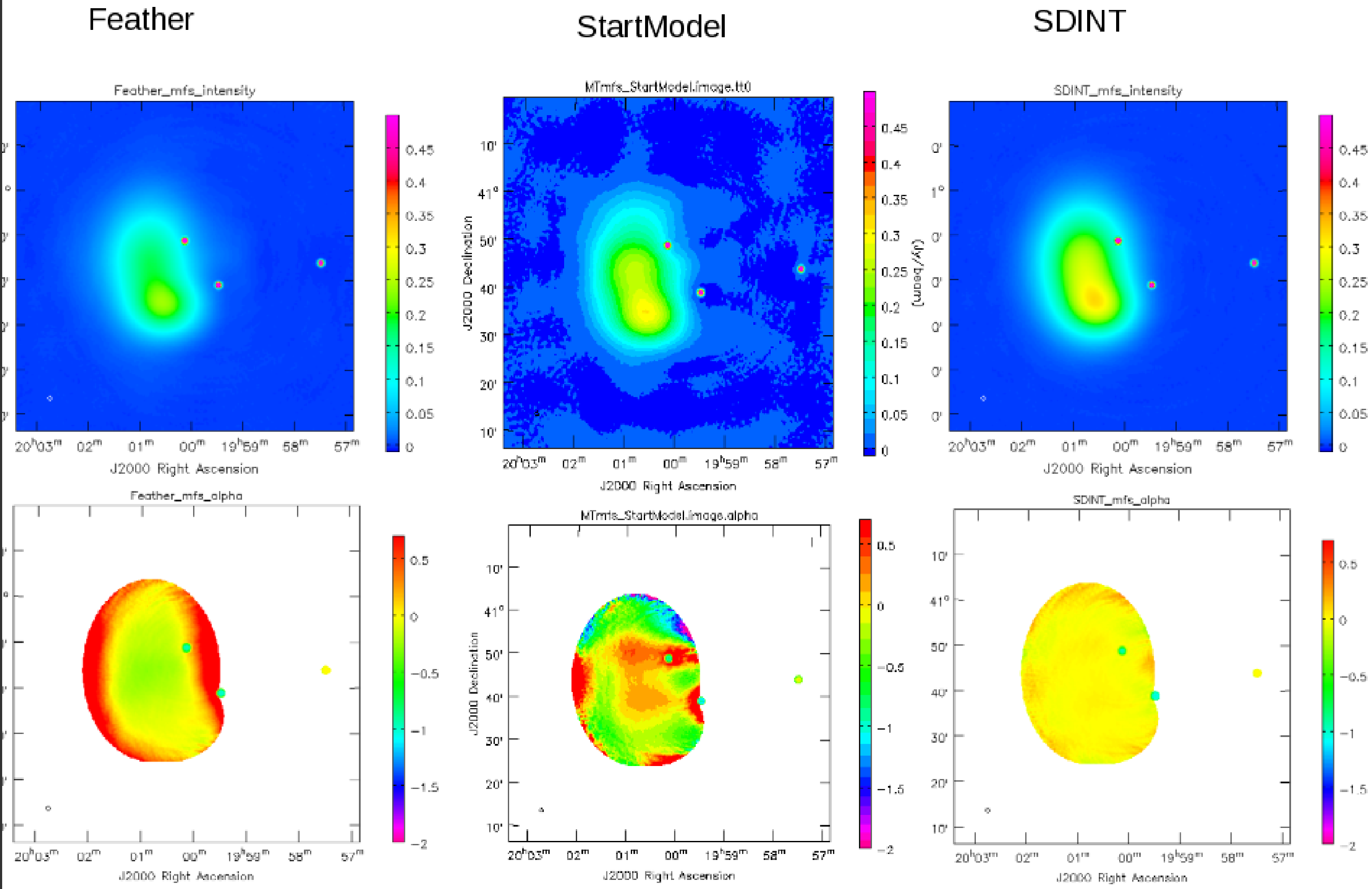
SD-Int Joint reconstruction

Examples for SD+INT joint reconstruction.



Rau

SD-Int Joint reconstruction



Top : Intensity Bottom : Spectral Index (should be 0.0/yellow for extended emission
-1.0/green for point sources)

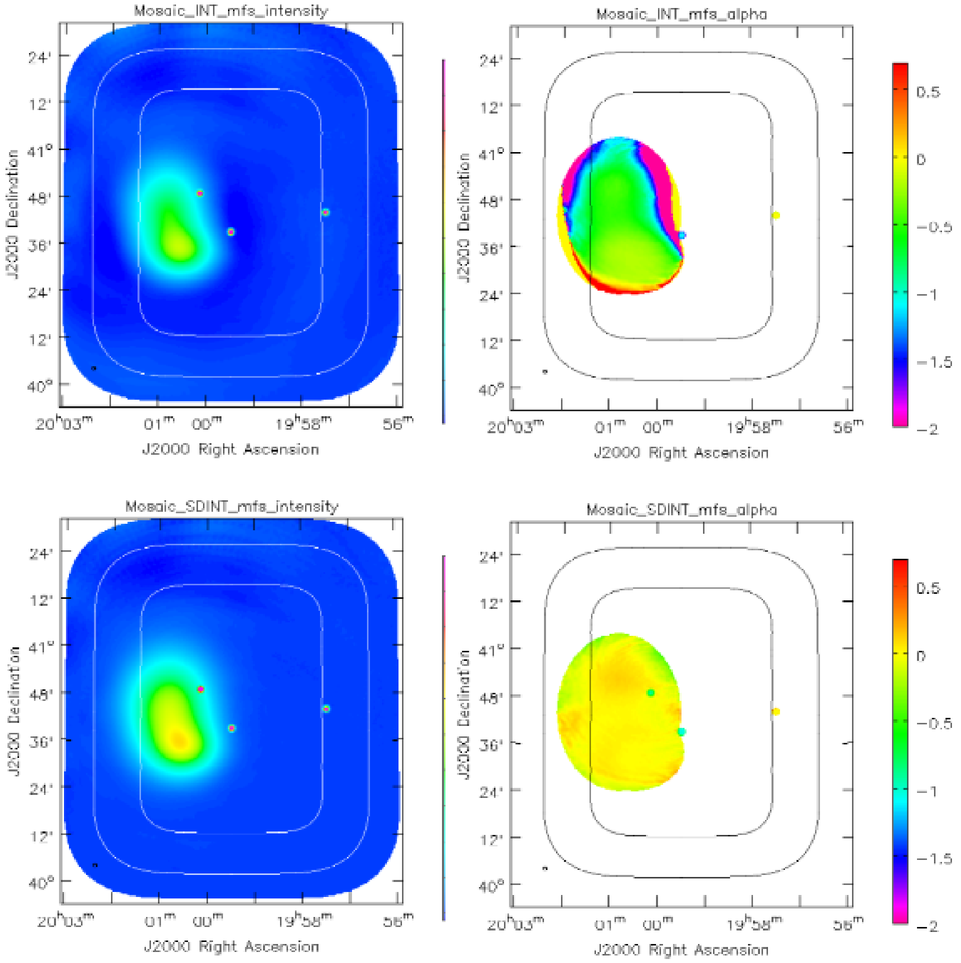
SD-Int Joint reconstruction

Wideband
Mosaic

INT only

Wideband
Mosaic

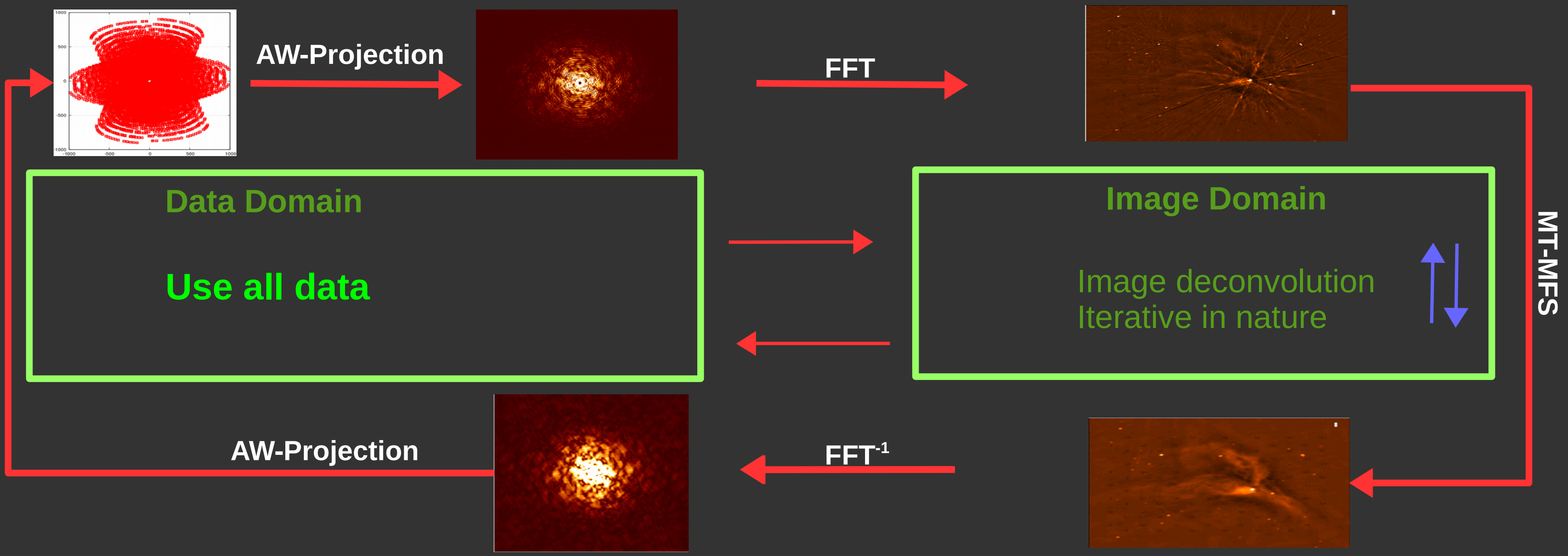
SDINT



Wideband Mosaic : gridder='mosaic' with specmode='cube' and deconvolver='mtmfs' with specmode='mfs' with conjbeams=T implemented as part of the SD+INT merging process (in python). [[Used PySynthesisImager prototyping interface]]

WB AW-Projection Commissioning

- Joint WB AW-Projection + MT-MFS for wide-band wide-field continuum imaging



AW-Projection

FFT

Data Domain

Use all data

Image Domain

Image deconvolution
Iterative in nature

MT-MFS

AW-Projection

FFT^{-1}

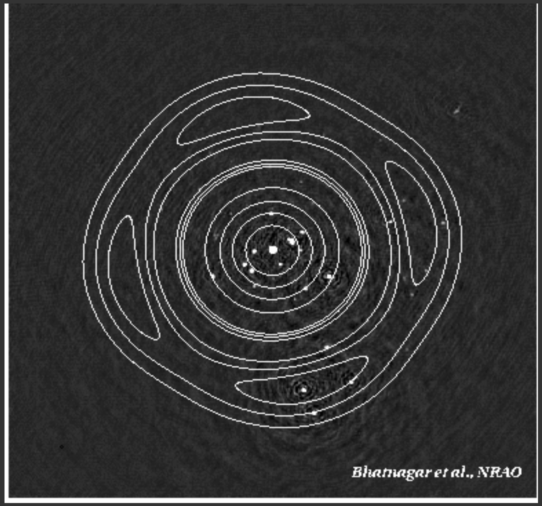
WB AW-Projection:
Make image free of PB- W-term effects

MT-MFS:
Images corrected for instrumental effects
Reconstruct WB sky model

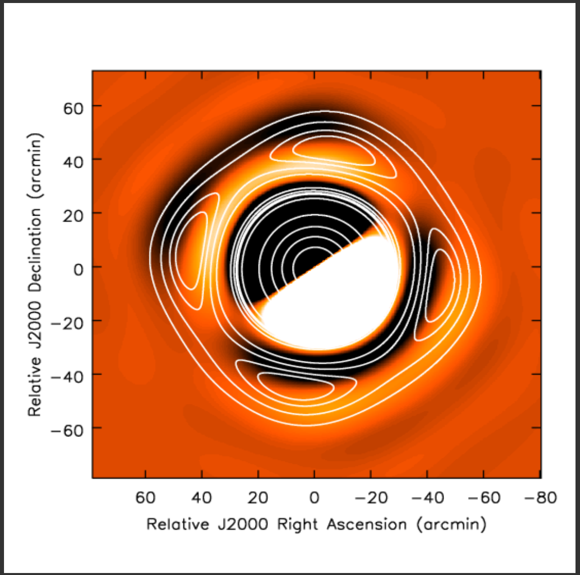
Project-out PB effects before transforming to the image domain

Image domain algorithms then need to model only the (WB) sky emission

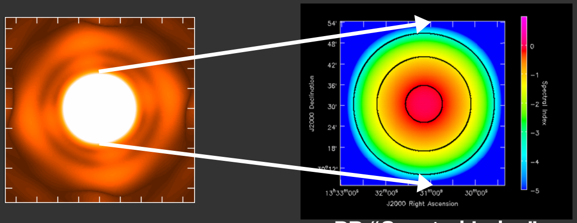
WB AW-Projection Commissioning



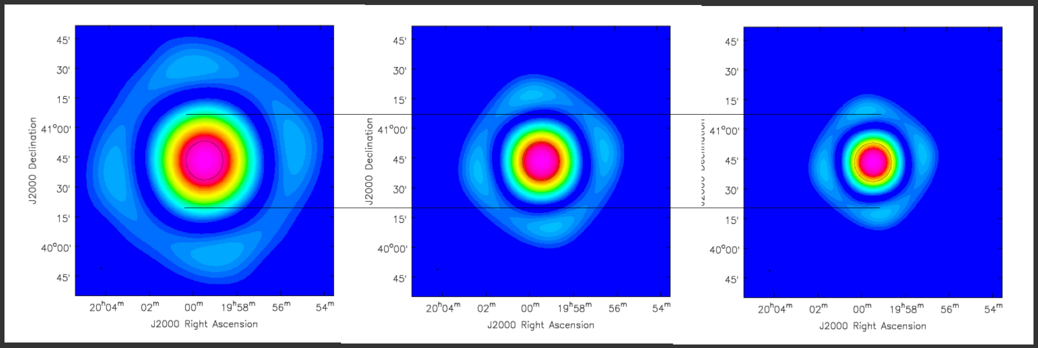
Time dependence



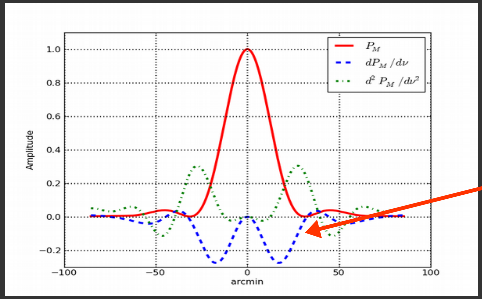
Polarization dependence



PB "Spectral Index"

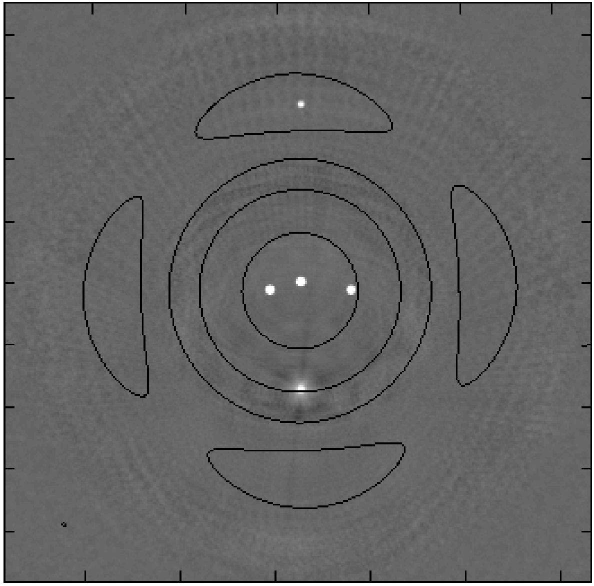


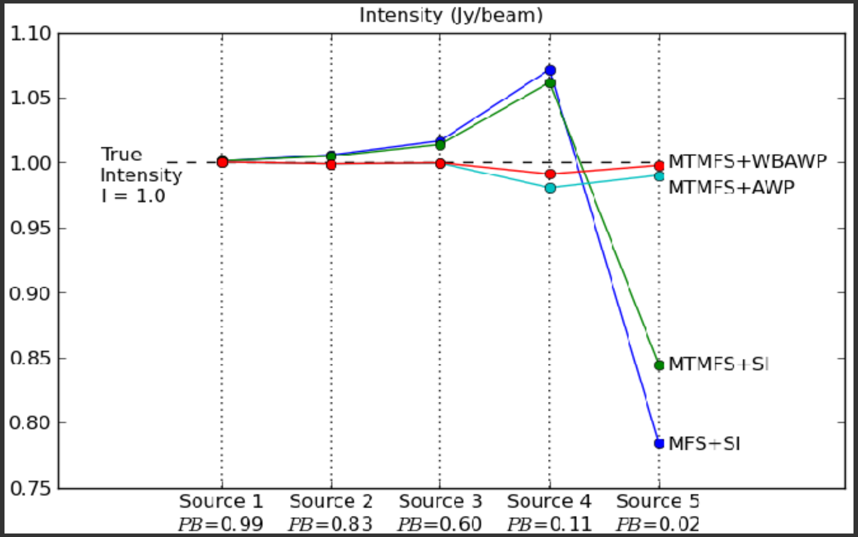
Frequency dependence

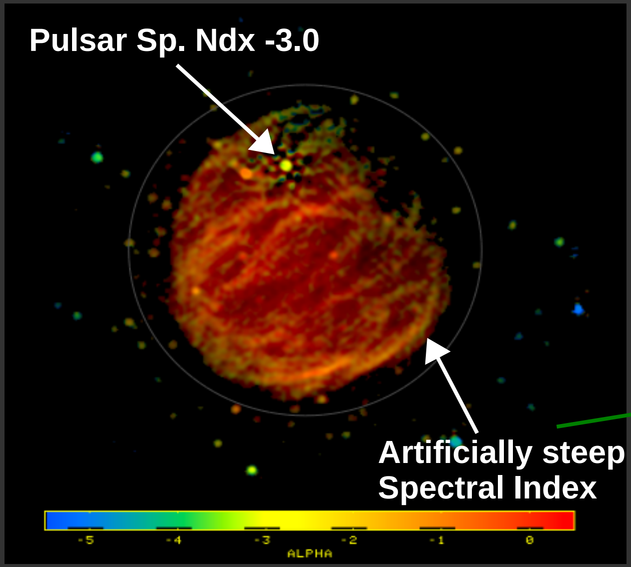


PB Frequency dependence (blue curve)

WB AW-Projection Commissioning

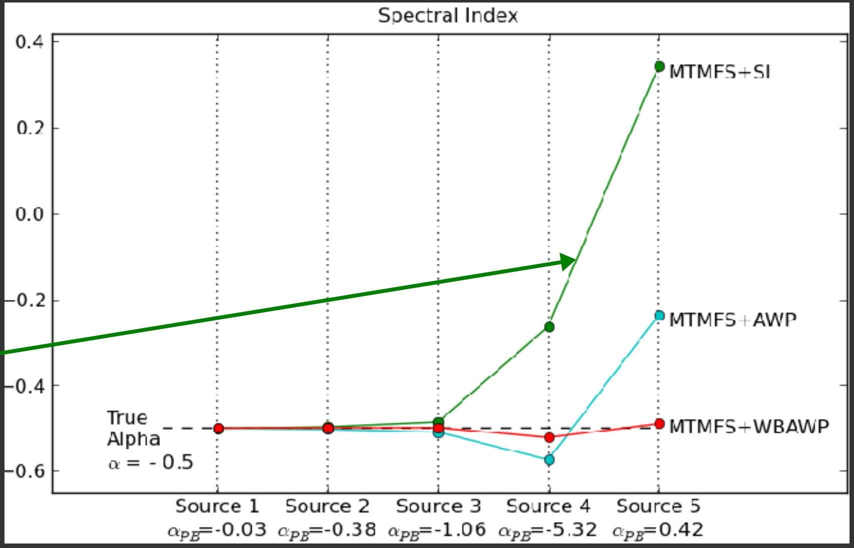






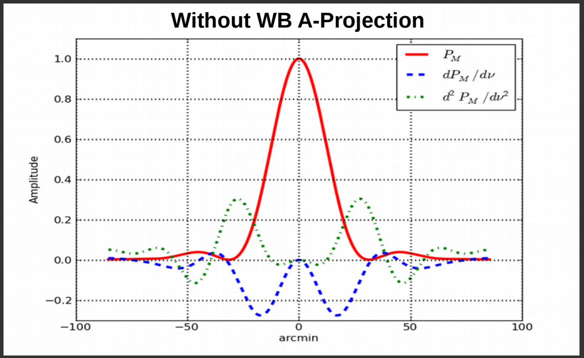
Pulsar Sp. Ndx -3.0

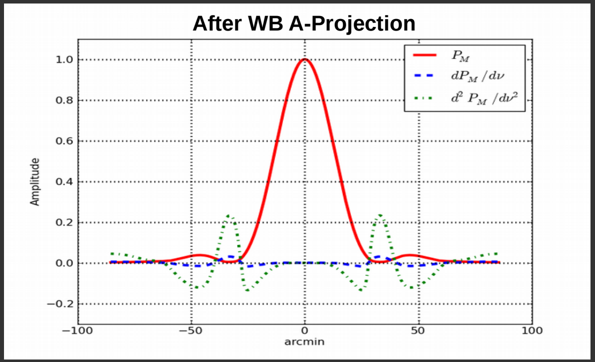
Artificially steep Spectral Index



WB AW-Projection Commissioning

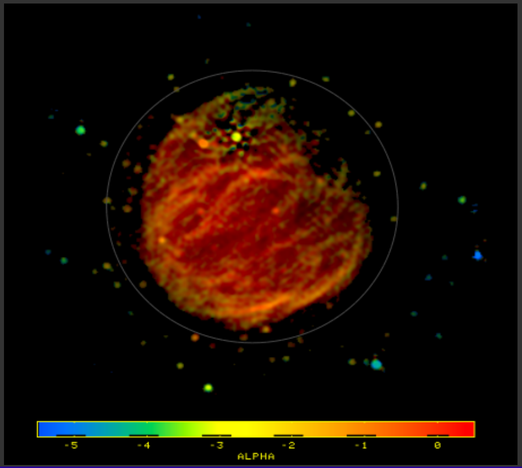
- WB A-Projection + MT-MFS
  - WB A-Projection for PB



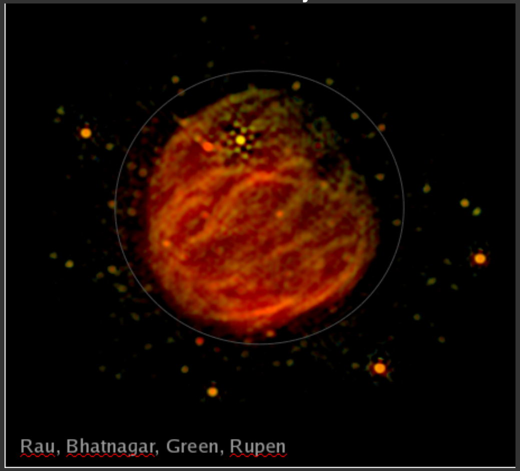


  - MT-MFS for sky
  - **Without PB correction the reconstructed spectral index increases with distance from the center**

Without WB PB Correction

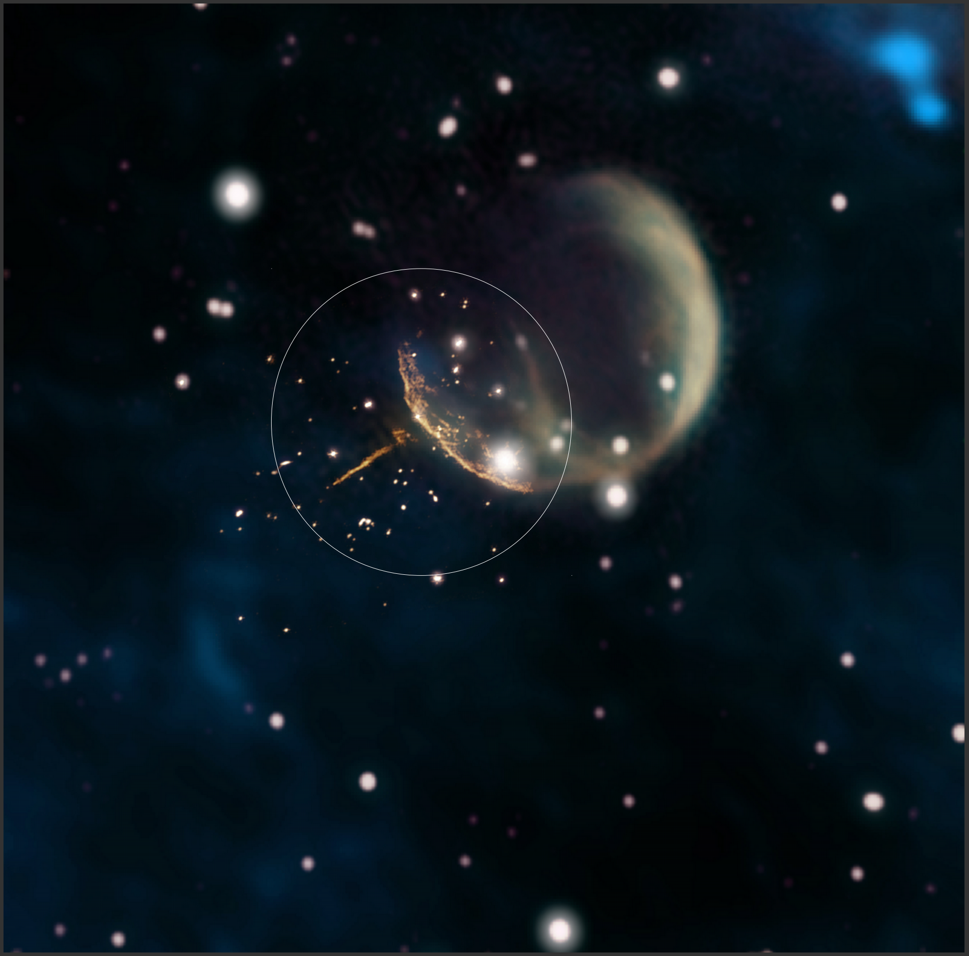


With WB A-Projection


Rau, Bhatnagar, Green, Rupen

Wide-band Wide-field Imaging

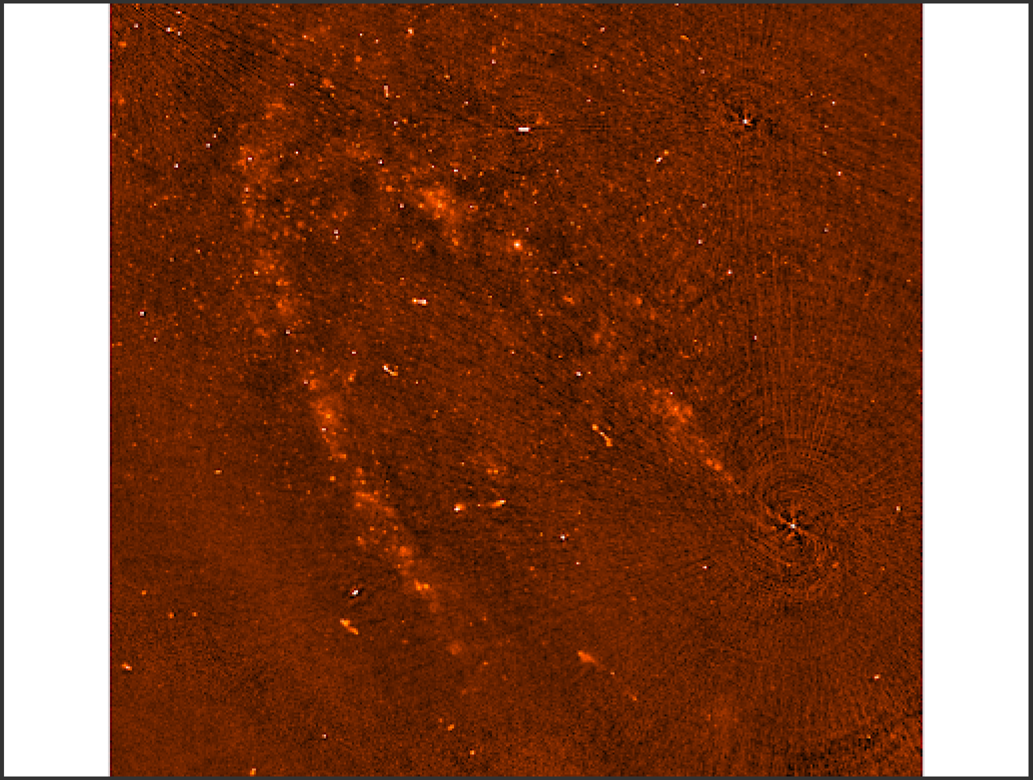
- Wide-band full-beam imaging at L-Band



L-Band, B,C-array mosaic: 512 W-Planes + WB PB rotation

7 uJy/B, 11 uJy/B near strong source (6% PB): DR ~500,000

11 cores x 4 nodes, ~1 TB data: 4 days / major cycle

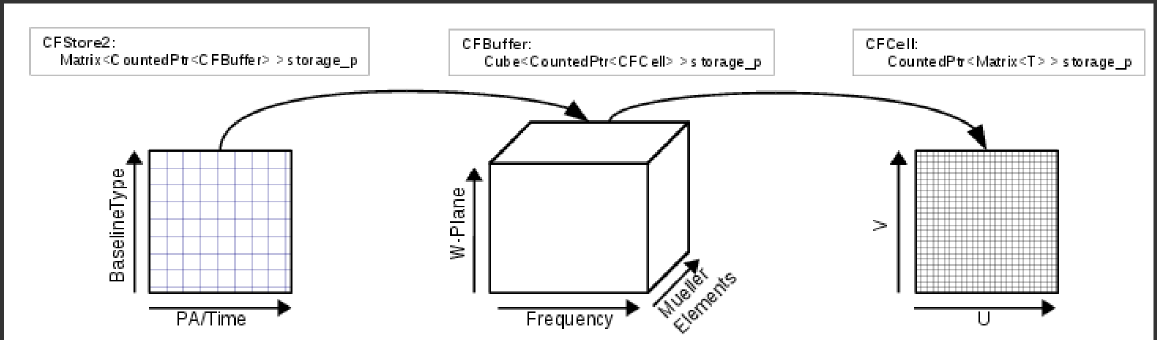


Wide-band Wide-field Imaging

- Generalized CF: CF = PSTerm * ATerm * Wterm
  - Can be configured for Std, W-, A-, AW-Projection
  - Mosaicking, correction for pointing offset
  - Full pol, WB corrections

Operation	aterm	psterm	wprojplanes	CF
AW-Projection	True	True False	>1	PS*A*W A*W
A-Projection	True	True False	1	PS*A A
W-Projection	False	True	>1	PS*W
Standard	False	True	1	PS

- On-disk CFCache; re-usable
  - Easily parallelized, or deployed on special h/w [32K CFs in O(1hr)]
  - Lazy Fill mode: CF Paging algorithm to control memory footprint
  - Usable for managing pointing offset correction, Hybrid-Mueller,...



CFStore2:
Matrix<CountedPtr<CFBuffer> > storage_p

CFBuffer:
Cube<CountedPtr<CFCell> > storage_p

CFCell:
CountedPtr<Matrix<T> > storage_p

WB Mosaicking with the EVLA

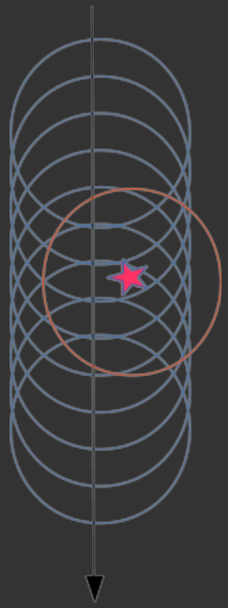
- VLASS as an example of OTF
  - Continuum imaging in the 2 – 4 GHz band (fractional BW ~67%)
  - Imaging 1 x 1 sq deg at a time using 40 pointings
  - OTF: Continuous antenna motion: 3.31 arcmin/sec, 0.45 sec integration per pointing
  - Correlator phase-center updates quantized in time
  - ~100 uJy/b noise limit
  - Resolution: ~2 arcsec

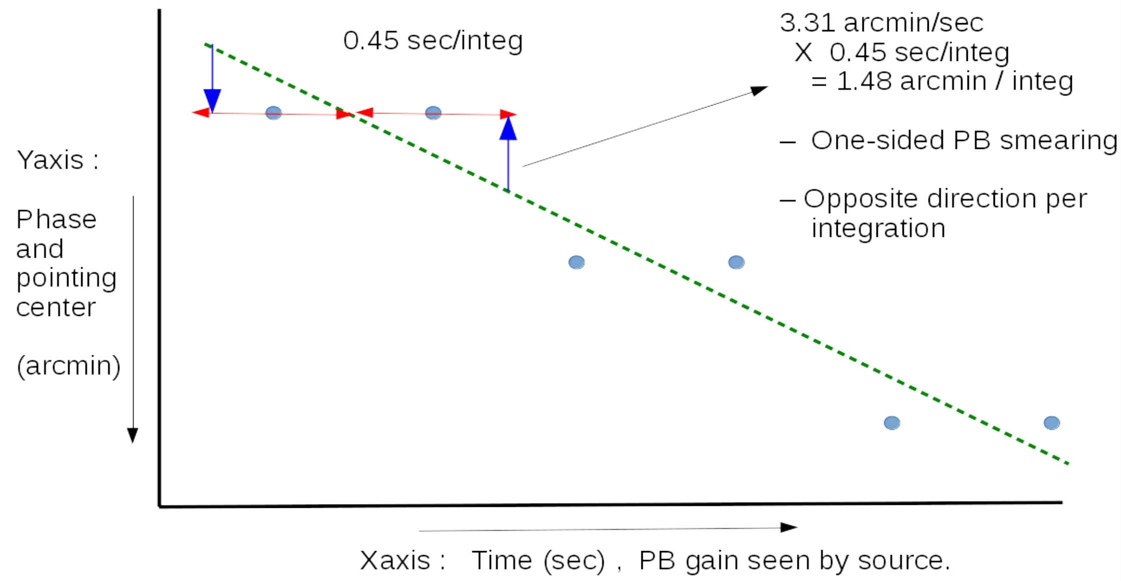
- Primary continuum scientific products
  - Source positions, flux, spectral indices, images

- Image size:
  - Wide-band sensitivity pattern about 2x2 sq deg.
  - 5400 pixels on a side (desired: 12K pixels on a side)

- Imaging
  - MT-MFS for image reconstruction
  - Algorithms for imaging still being evaluated

WB Mosaicking with the EVLA



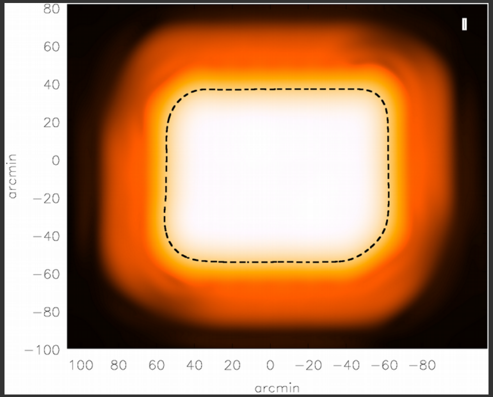

0.45 sec/integ
3.31 arcmin/sec
X 0.45 sec/integ
= 1.48 arcmin / integ
– One-sided PB smearing
– Opposite direction per integration
Yaxis :
Phase and pointing center
(arcmin)
Xaxis : Time (sec) , PB gain seen by source.

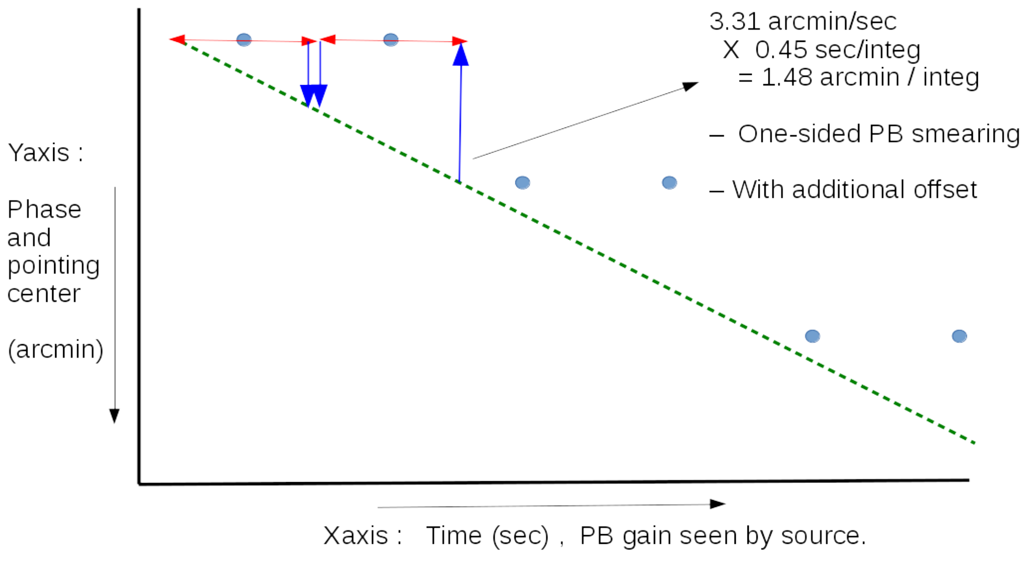
- Error in fluxes, positions and spectral indices was too large
  - No W-correction: To reduce computing load, memory footprint
    - » Leads to position errors → flux and spectral index errors!
  - Narrow-band A-Projection: Minimize computing load and s/w complexity
    - » Ignore PB frequency dependence
  - Ignore pointing offsets: Was expected to "average out"
    - » Errors in flux and spectral index

[ARDG Memo, Rau&Bhatnagar, 2018]

WB Mosaicking with the EVLA

- Error in the reconstructed flux was dominated by errors in source positioning in the PB (pointing errors) and on the sky (W-term)
  - Pointing errors due to OTF mode + a software bug
  - Gain errors: PB sidelobe span ~2x antenna FoV





3.31 arcmin/sec
X 0.45 sec/integ
= 1.48 arcmin / integ

– One-sided PB smearing

– With additional offset

Yaxis :

Phase and pointing center

(arcmin)

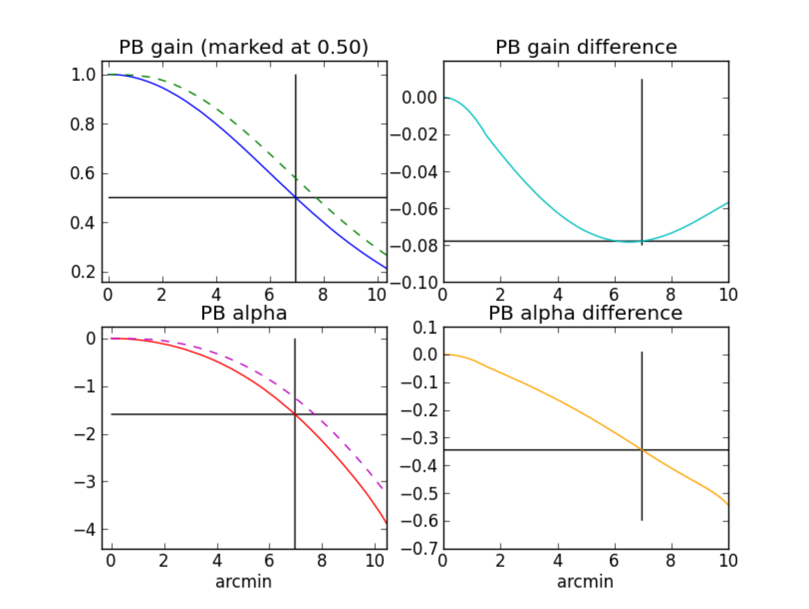
Xaxis : Time (sec) , PB gain seen by source.

- Each pointing is a snapshot observation. W-term leads to radially-dependent source position offsets.
  - Actual position offset in a joint mosaic image is more complicated

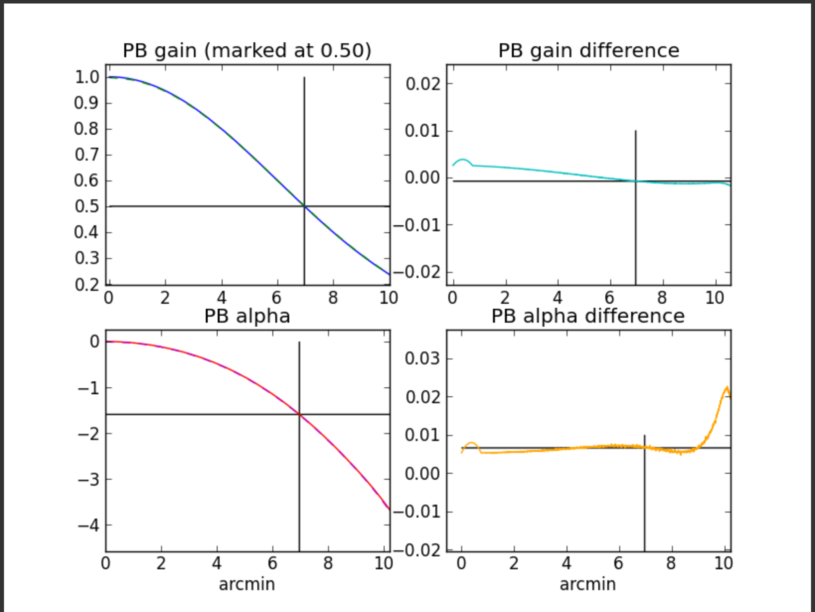
WB Mosaicking with the EVLA

- Effects of pointing errors and w-term do not in general “average out”
  - Source positioned in different parts of the PB of overlapping pointings
- Spectral index is extra sensitive to pointing and source position offsets
  - Systematic error of >100%

Actual data



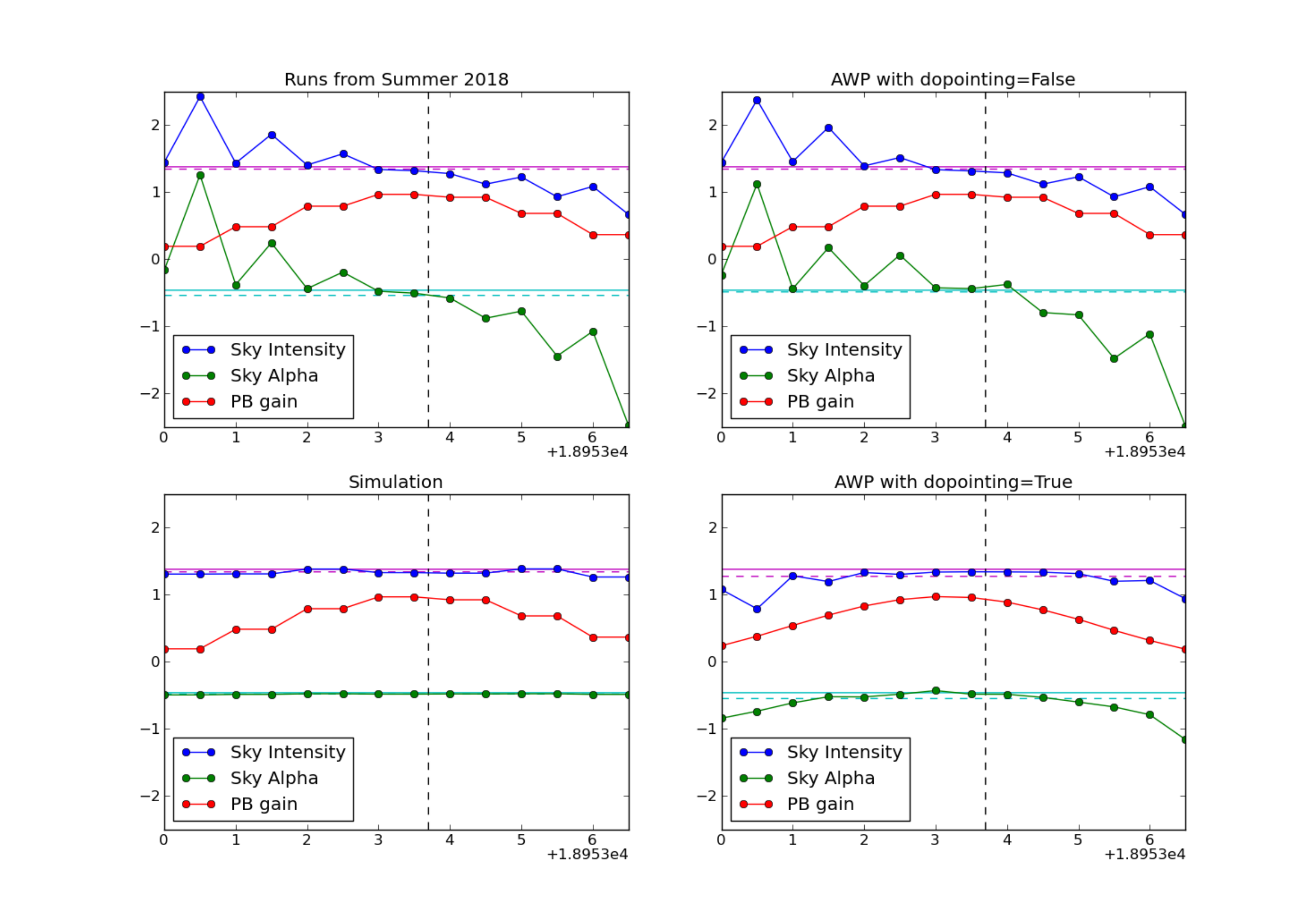
Intended data



- Computing load *10-100x* larger

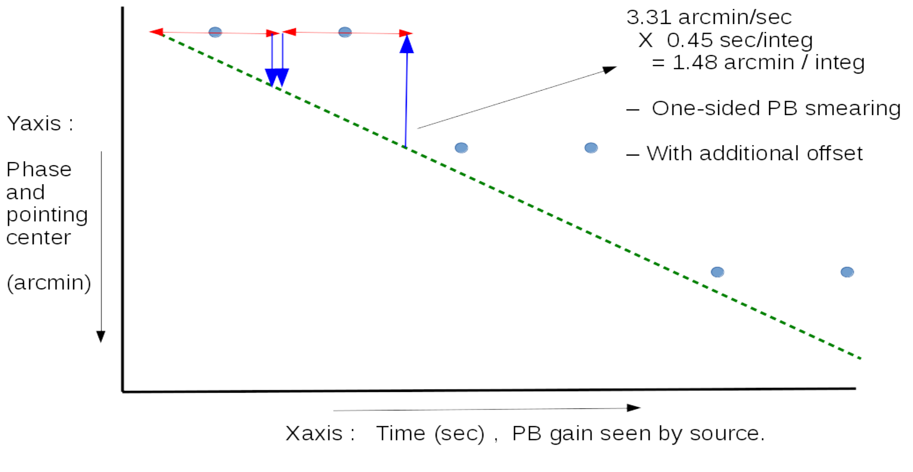
WB Mosaic imaging with EVLA

- WB AW-Projection with corrections for antenna pointing offsets



Correction for antenna pointing

- Proof of concept demo:
  - Imaged each integration in VLASS observation independently for a strong source (ARDG Memo)



- Homogeneous pointing correction
  - Apply same pointing correction for all antennas in the array

$$A_{ij}=A_{ij}^{o}[e^{(l_i-l_j)^2\alpha^2/2}][e^{\iota u(l_i+l_j)}]$$

  - Lower complexity, faster, but insufficient in general

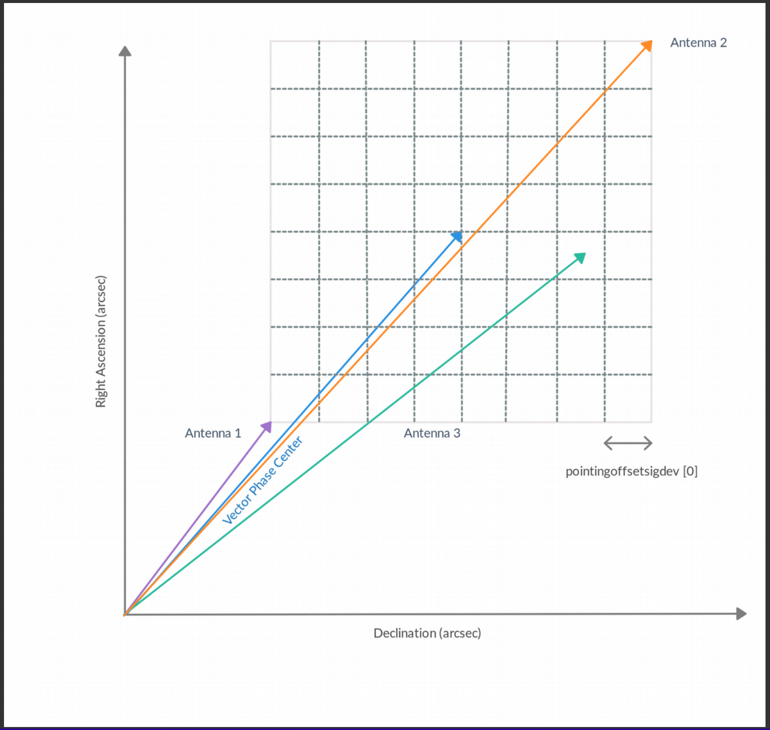
Jagannathan Bhatnagar

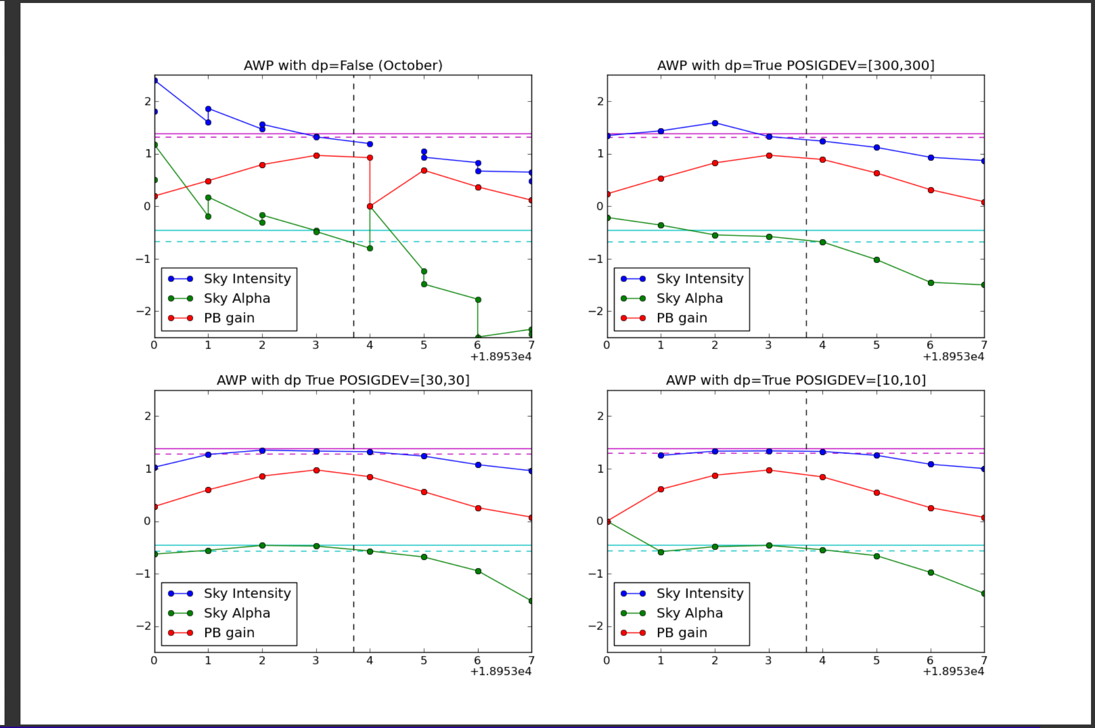
Correction for antenna pointing

- Heterogeneous pointing correction; deeper implementation

$$A_{ij} = A^o_{ij}[e^{(l_i - l_j)^2 \alpha^2/2}][e^{\iota u(l_i + l_j)}]$$

  - Detect antenna groups with same pointing offset
    - » Needs to be computationally cheap
  - Cache phase gradients for groups of baselines
    - » Can become a compute bottleneck [N + N(N-1)/2 scaling]
    - » Can become a memory footprint bottleneck for fully heterogeneous case





Correction for antenna pointing

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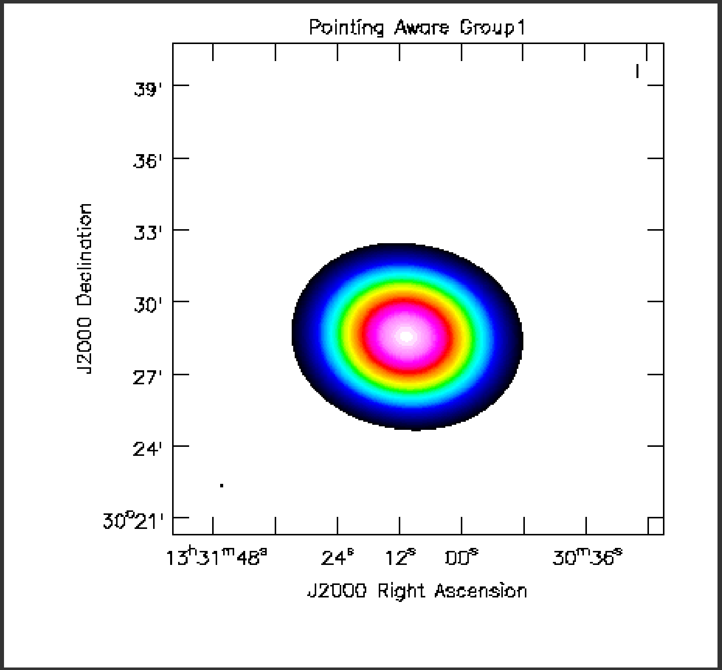

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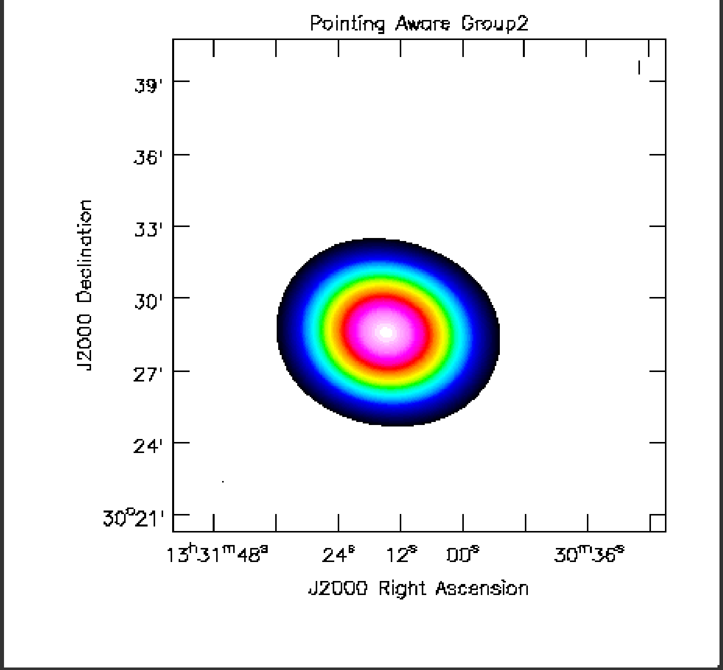

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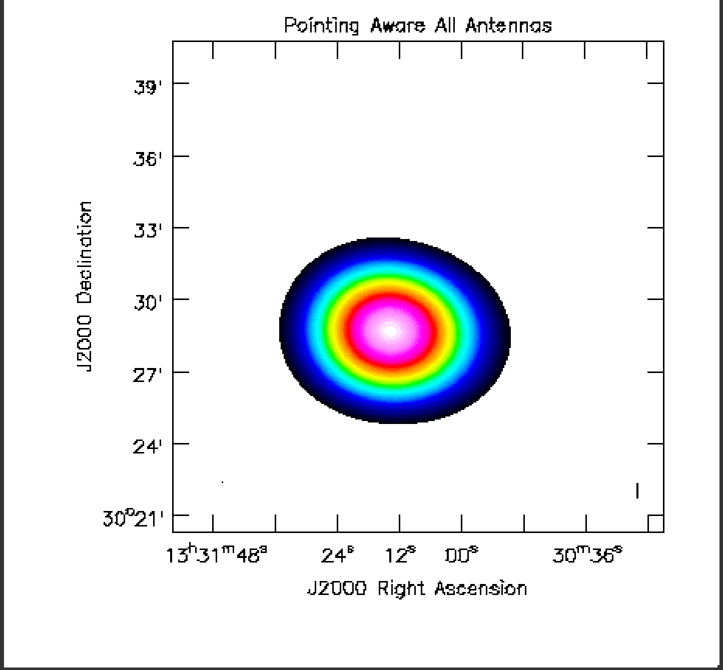

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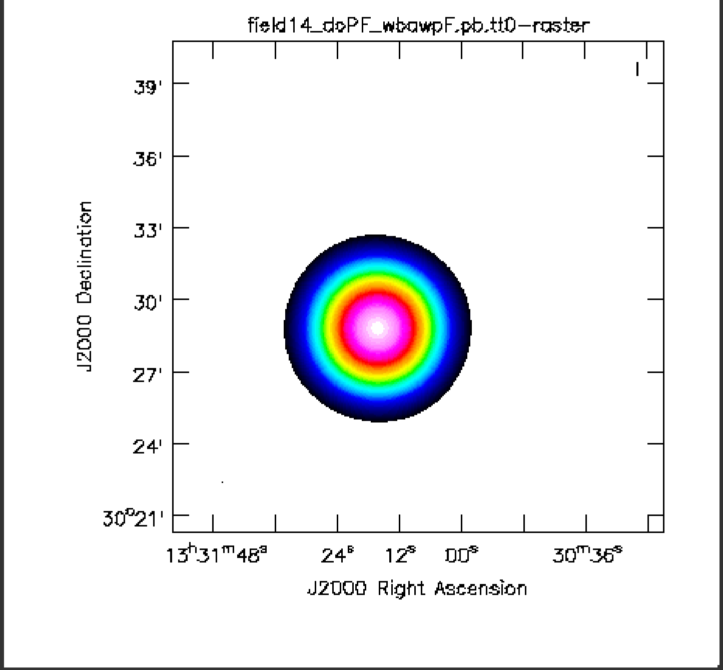
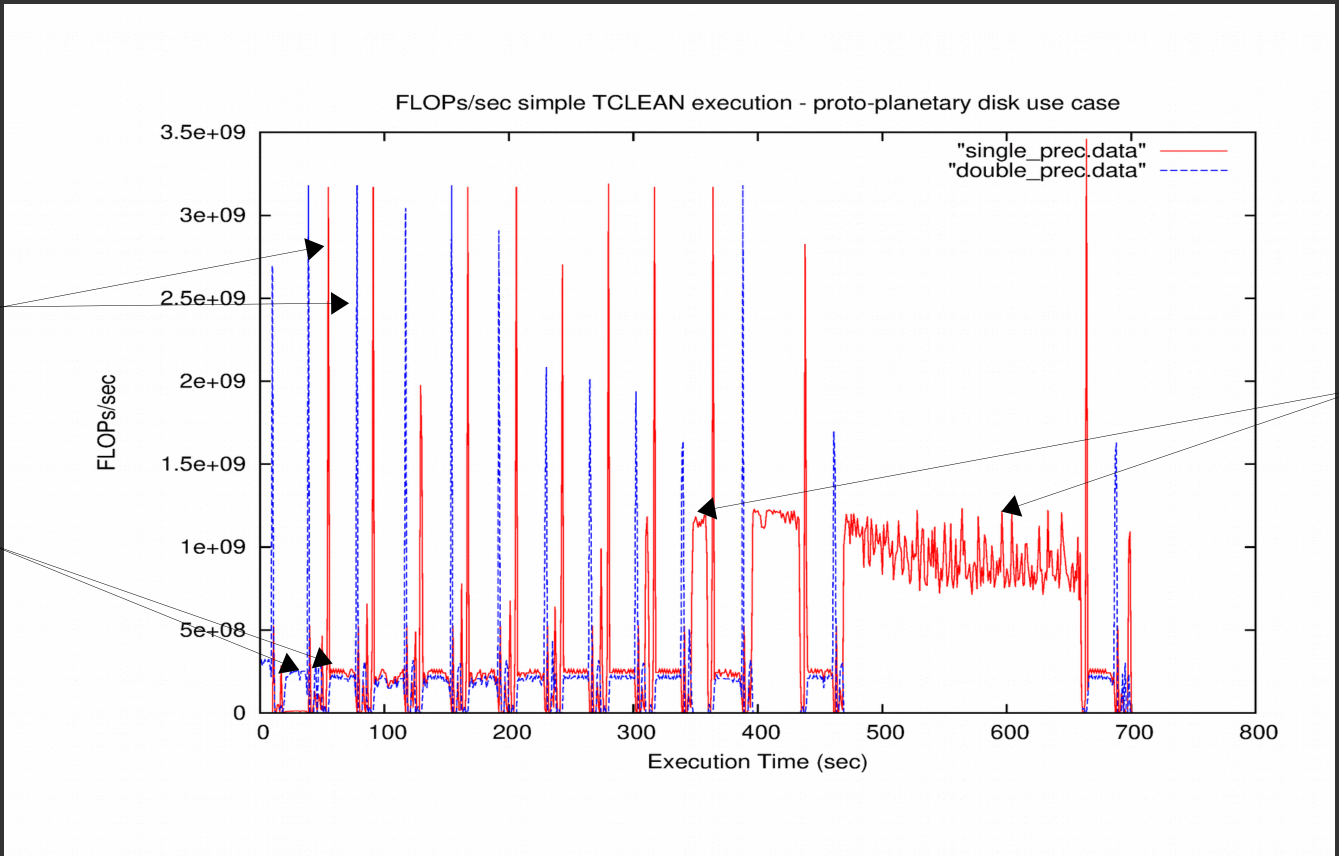


Size-of-Computing for ngVLA

- Goals:
  - Make realistic estimate of SoC, assuming current algorithms and implementations are sufficient
  - Measure run-time performance in serial and parallel
  - Use scaling laws to predict required SoC for cost estimates



FFT

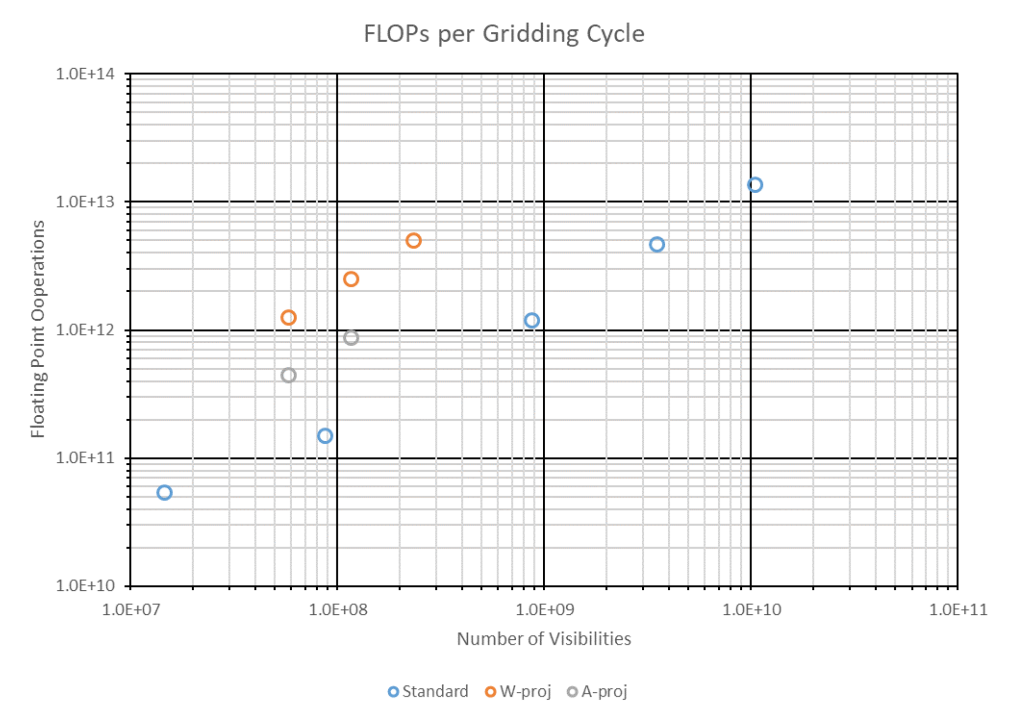
Minor Cycle

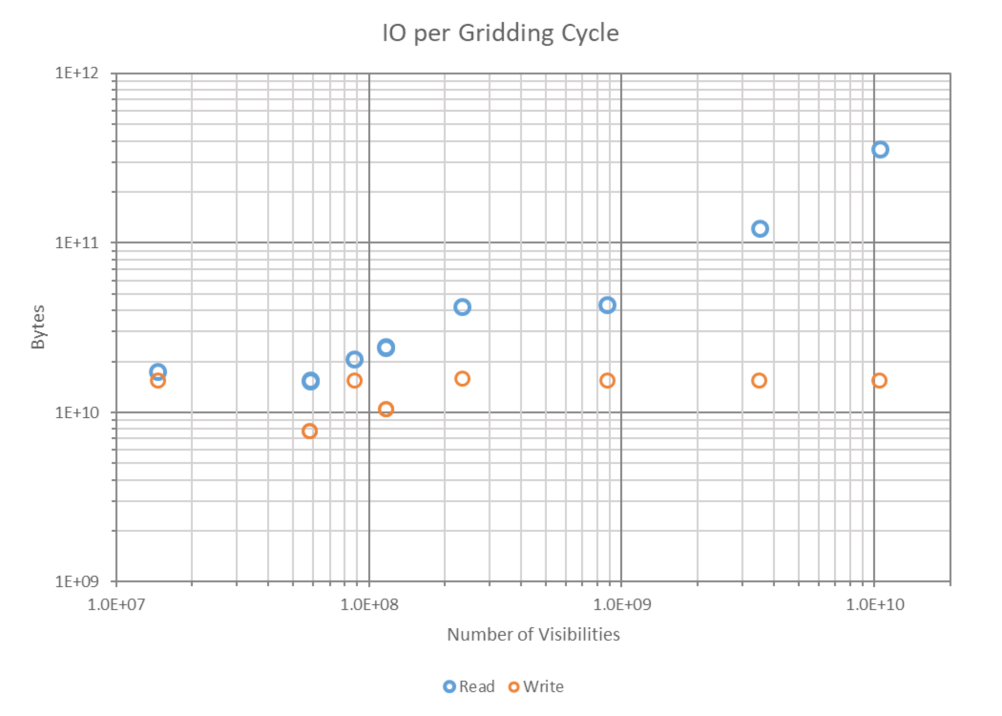
Gridding De-gridding

Pokorny
Hiriart
Bhatnagar

Size-of-Computing for ngVLA

- Identify a smaller set of Key Science Goals (KSG) that covers algorithms parameter space
- Instrument the imaging code for run-time measurements (Score-P)
  - Used a stand-alone application in C++ to directly use CASA C++ libraries





Arithmetic Intensity (FLOPS/byte):
Std: 40 A-Proj.: 233 W-Proj.: 670

Projected SoC for ngVLA: ~60 PFLOPS

ALMA Full-Stokes Imaging

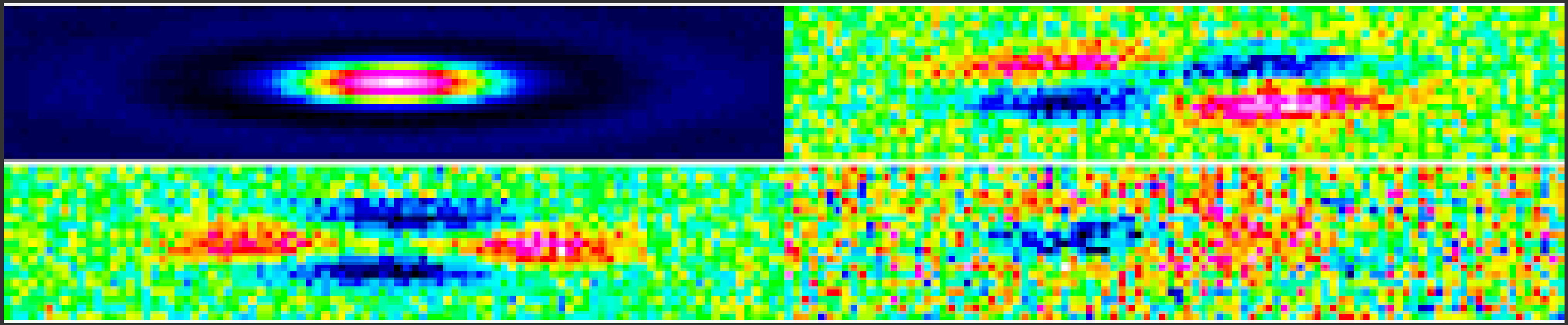
- ALMA Study Project to understand the issues with full-Stokes mosaic imaging (BK, PJ, UR, CH, PC (Chile))
  - Measured PB in Stokes-Q and -U did not show the Clover Leaf pattern! This is un-physical
  - Imaging tests (Stokes-V) remained inconclusive

- Characterize full-Stokes PB
  - Reprocess holography measurements at that time (early 2018)
  - Star/Radial scanning pattern
  - We could see the expected leakage patterns in all Stokes, but SNR was too poor
  - Radial pattern puts highest sensitivity at the center of the PB
  - Need high sensitivity in the **outer** parts of the PB
  - Under-sampled aperture
  - Position information was not recorded, added distortions

ALMA Full-Stokes Imaging

- New holography data acquired in Nov. 2018
  - Standard holography observing method
  - Standard CASA tools for data processing using standard ALMA calibration procedure

- Initial test observation with existing ALMA holography script produced “squashed” beams
  - Involved PJ@NM and CH@Chile debugging in real-time!



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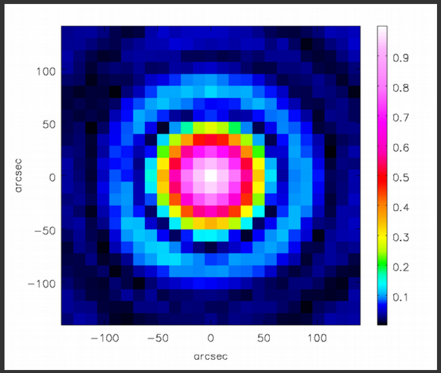
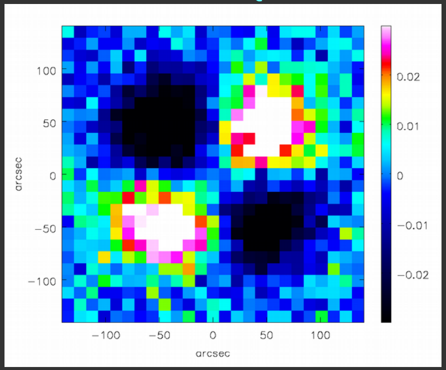
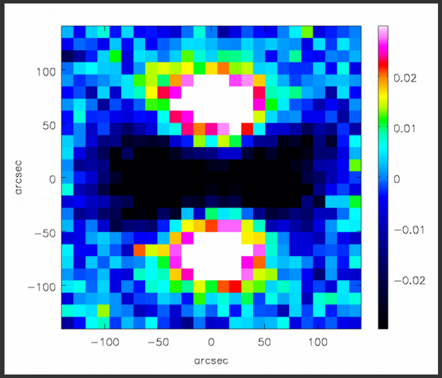
Stokes-I



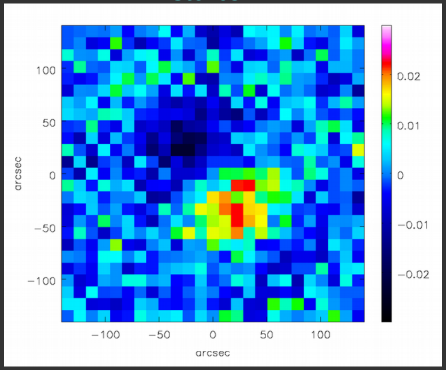
Stokes-Q



Stokes-U



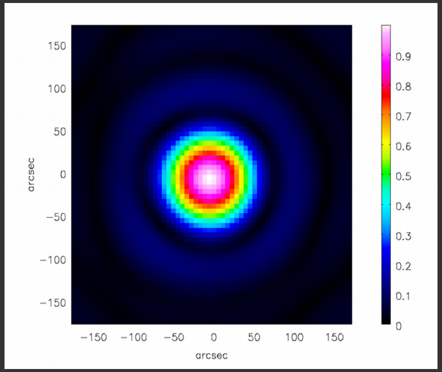
Stokes-V



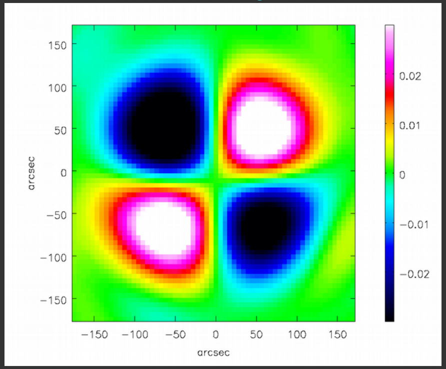
ALMA Full-Stokes Imaging

- Produced Zernike polynomial models using the holography data (shown below as PBs in Stokes-I, -Q, -U and -V)
- Work is in progress to integrated these models with A-Projection in CASA to enable full-pol mosaic imaging with ALMA

Stokes-I

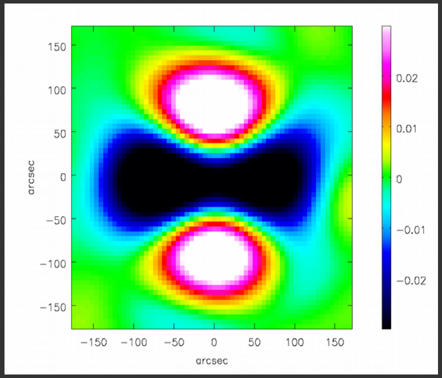


Stokes-Q

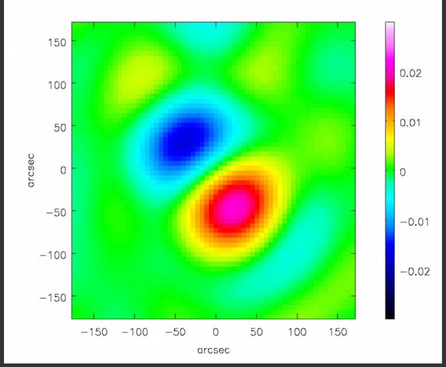


Stokes-Q, -U leakage
~3-5% in the main-lobe
Higher in the first side-lobe

Stokes-U



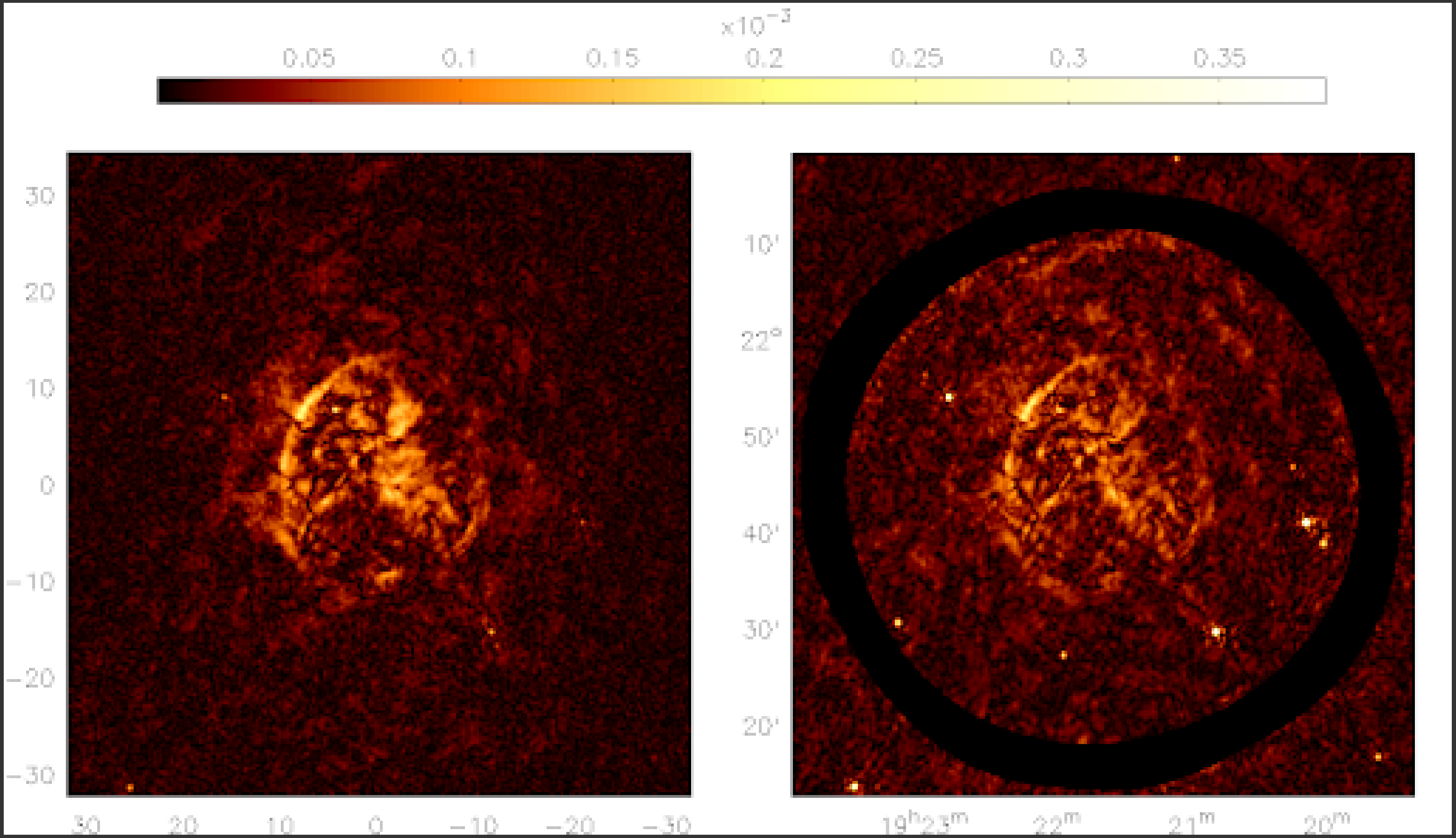
Stokes-V



Stokes-V leakage
~3-4% in the main-lobe
Higher in the first side-lobe

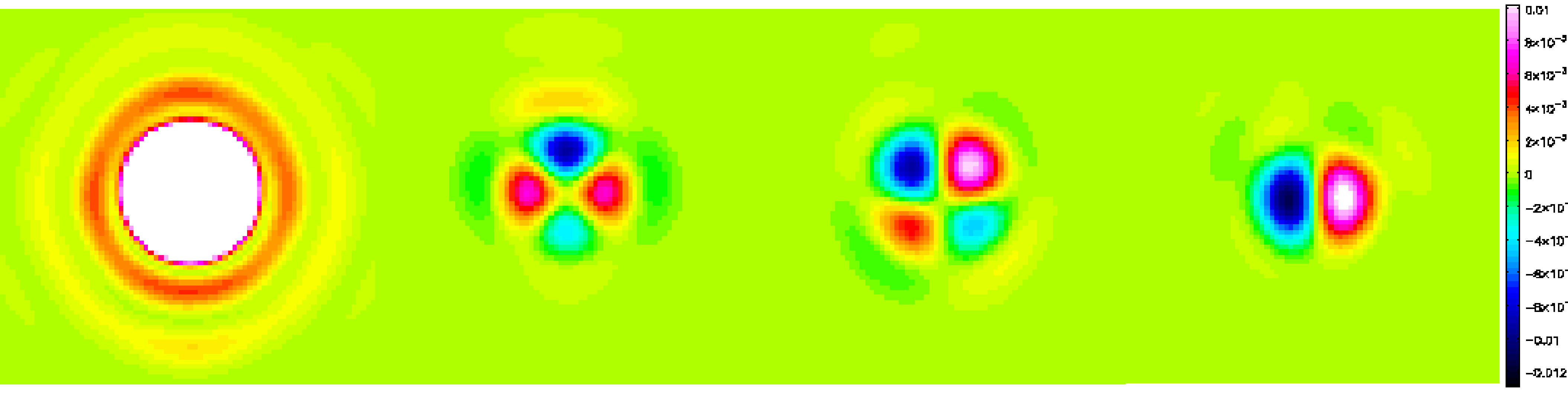
Full-Stokes Imaging

- Produce polynomial models for the A-term (shown below as FT(A))
- Use these models in A-Projection to test mosaic imaging with ALMA



NRAO-IDIA, SA Collaboration (MeerKAT)

- The A-to-Z solver (Aperture-to-Zernike)
  - Holography (full-Stokes) → Antenna Jones matrix (the A-term)

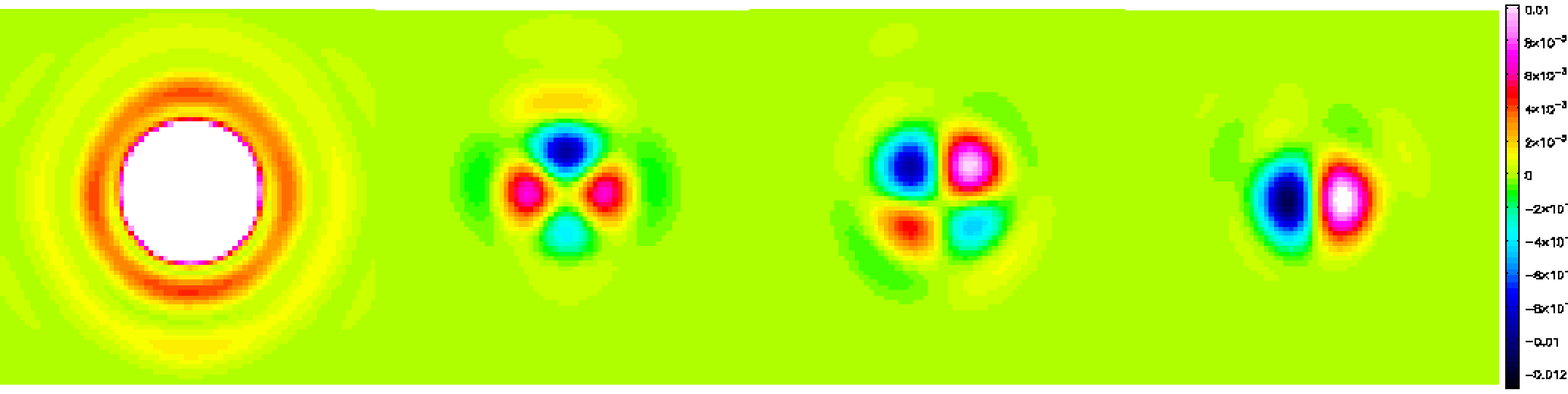


- Easy to generate A-term for any telescope, given holography data

Srikrishna
Jagannathan
Bhatnagar

NRAO-IDIA, SA Collaboration (MeerKAT)

- Collaboration with NRAO-IDIA, SA
  - Holography (full-Stokes) → Antenna Jones matrix (the A-term)



Road Map 2020

- Finish the ALMA Study Project: Finish the report!
- Hybrid-Mueller Imaging: Phase-I
  - Hybrid-Mueller imaging framework in CASA
- Hybrid-Mueller Imaging: Phase-II
  - Full-pol PB model, use for full pol imaging
  - Test image-plane full pol PB correction (VLASS)
- SoC estimate for ngVLA
  - Finalize the report on current work
  - Measurements for parallel execution
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Plans are worthless, but planning is essential.

Dwight D. Eisenhower