Full-Mueller Mosaic Imaging with ALMA

Jan. 5th 2018, Boulder, CO

Impact of in-beam (PB) effects

S. Bhatnagar

P. Jaganathan, U. Rau, ALMA Polarization Team (P. Cortez, S. Kameno-san, C. Hull, T. Hunter, C. Brogan) + B. Kirk

Plan for the talk

- Characterization of the problem
  - Theory of Full-Mueller imaging
  - Effect of PB: Apparent sky-polarization varies with time, direction and frequency
  - Effect of PB: Limits full-Stokes mosaic imaging performance
- Results from investigations with the EVLA
  - Effect of in-beam leakage on WF Stokes-Q, -U and -V imaging
  - Effect of Parallactic Angle (PA) coverage
  - Full-Mueller (WB) A-Projection
- ALMA Study Project: Full-Mueller Mosaic Imaging
  - Goals
  - Plan for the work and current status

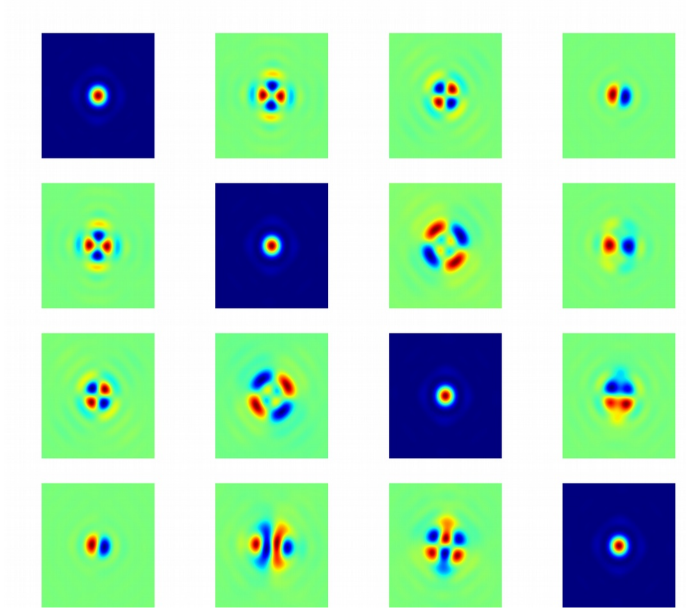
Full-Mueller (-Polarization) WF Imaging

- Direction Dependent (DD) imaging equation

$$I^{Obs} = [M]\cdot[I^o]$$

- Diagonal: "pure" poln. products
- Off-diagonal: poln. leakage

$$\begin{bmatrix} I_I^{Obs} \\ I_Q^{Obs} \\ I_U^{Obs} \\ I_V^{Obs} \end{bmatrix} =$$



Stokes Basis

$$\cdot \begin{bmatrix} I_I^o \\ I_Q^o \\ I_U^o \\ I_V^0 \end{bmatrix}$$

- ***I*^obs^: *Observed image***
- ***I*^o^: *True image***
- ***M:** DD Mueller Matrix*
  DD Full-pol. Response of the antenna
  Gives the precise off-axis Pol. mixing

$$M_{ij} = E_i \otimes E_j^*$$

Full-Mueller (-Polarization) WF Imaging

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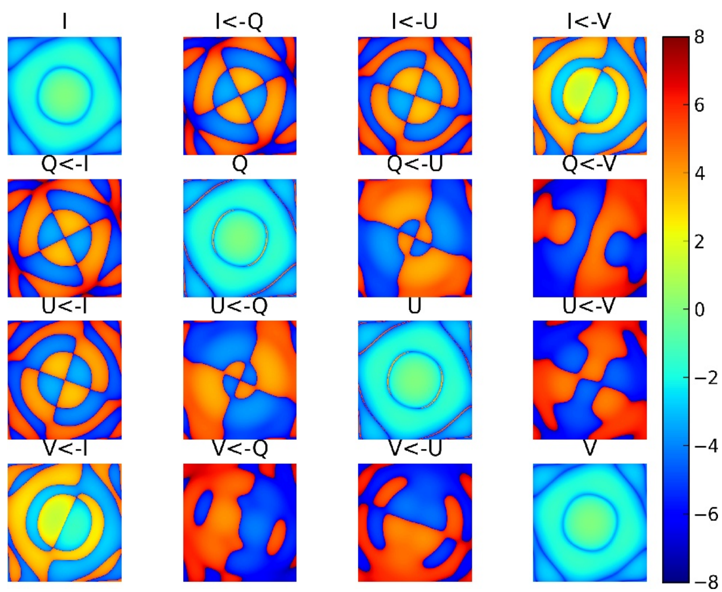

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  DD Full-pol. Response of the antenna
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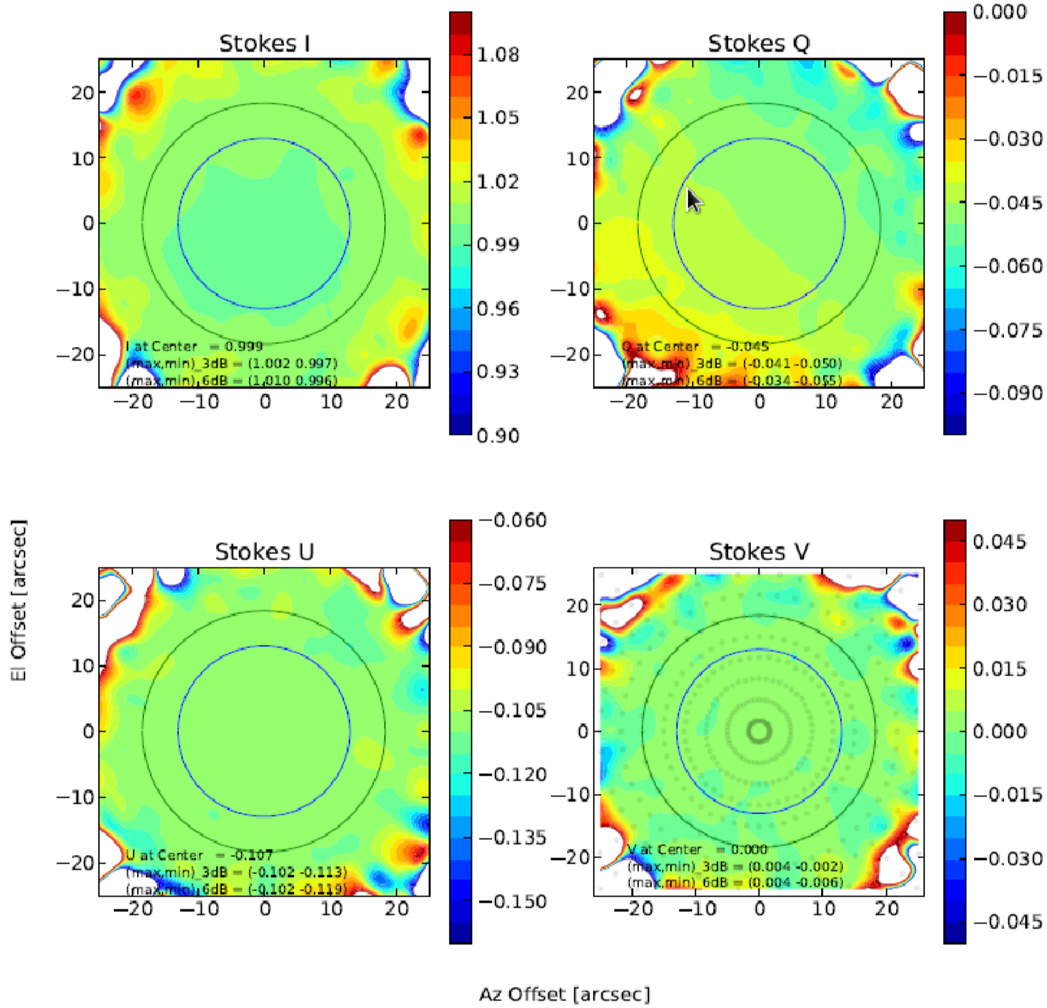
$$M_{ij} = E_i \otimes E_j^*$$

- Affects fidelity at the $10^{3\text{-}4}$ level
- PB Stokes-Q, -U is few% of Stokes-I

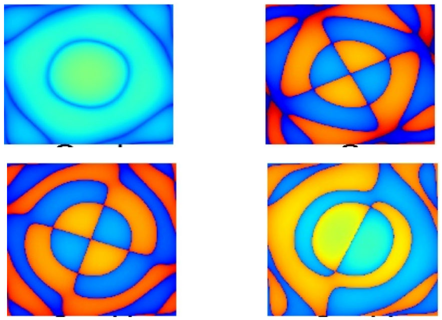
[Jagannathan, Bhatnagar, Rau & Taylor, AJ, 2017]

Measured full-Stokes PB maps



Measurements of the first row (or column) of the Full-Stokes Mueller Matrix

- Maps are an average over antennas(!) and frequency

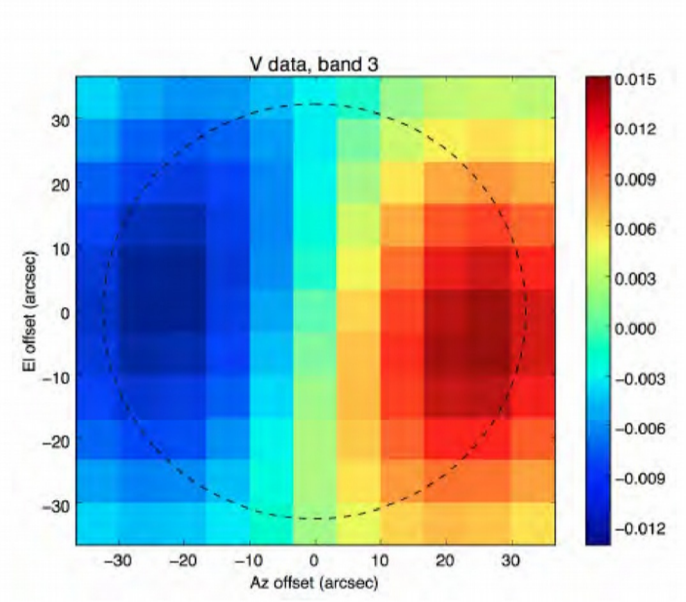


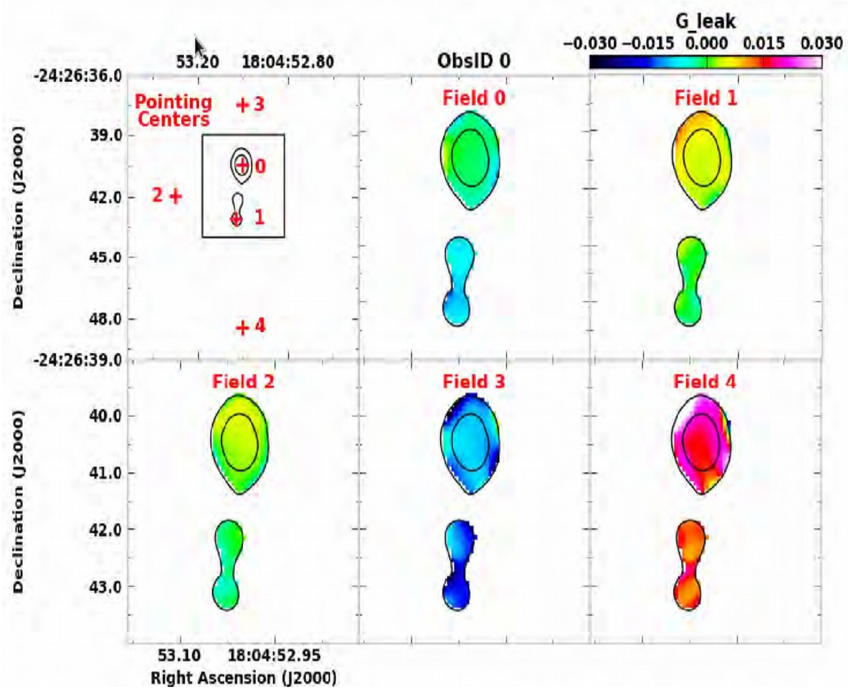
- Expected from antenna optics
- Also measured for EVLA antennas

[S. Kameno & ALMA Pol. Team; 2015]

On-sky tests: Measured Stokes-V

- Measurement of Stokes-V for a CN(1-0) maser line emission
  - The measurements of the Stokes-V *qualitatively* match the *average* Stokes-V beam (Hull, 2015)
  - Does not match quantitatively (more leakage than shown by PB alone)
  - Does not reproduce the residual Stokes-V for *different times or with small offsets* (position in the beam) after taking into account the PB

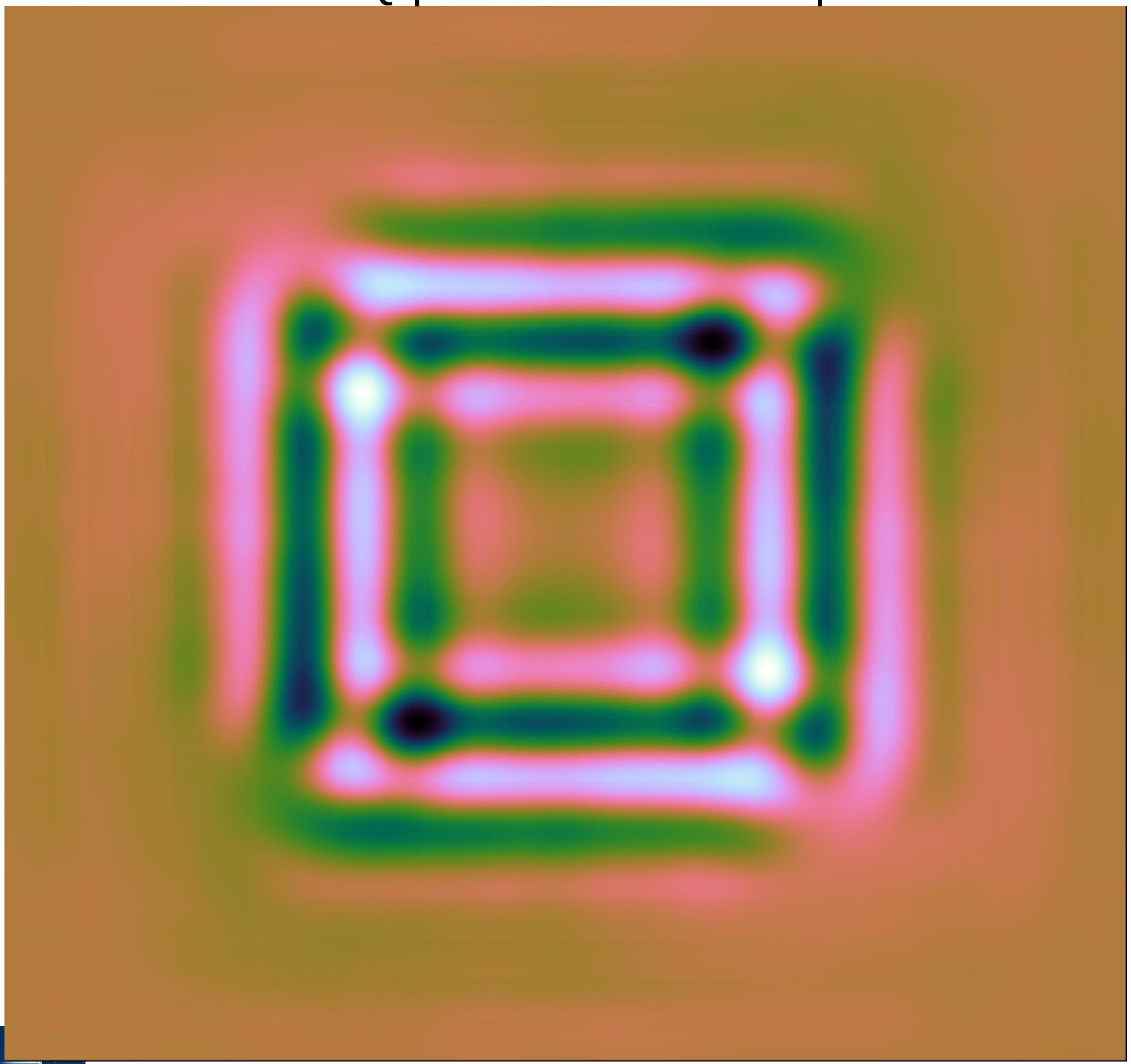




[Brogna, Hunter & Moellenbrock; 2015]

Full-pol. Imaging: Mosaic Sensitivity Pattern

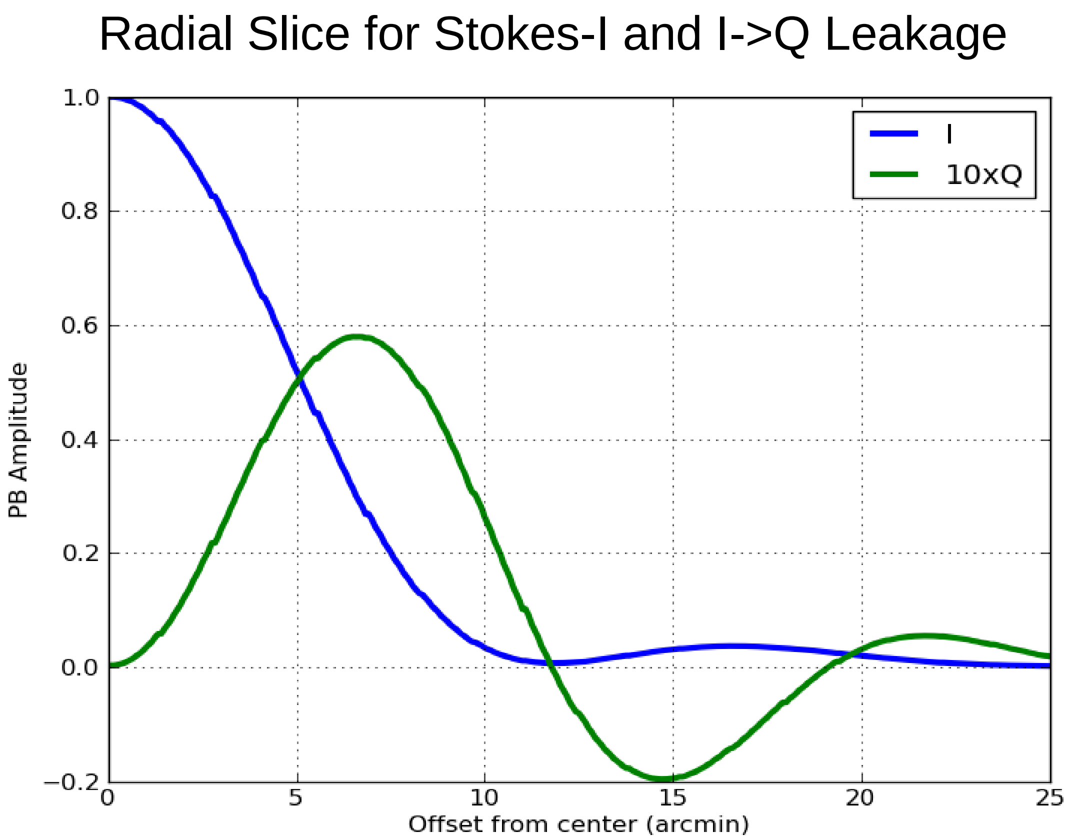
In-beam Stokes-Q pattern for a 11x11 point mosaic

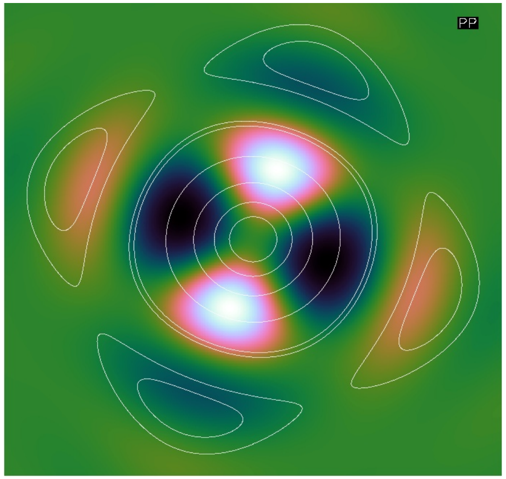


- Pol. Leakage requriement for ALMA too loose to allow precision polarimetry ("...<3% within inner 1/3 PB").
- In-beam DD leakage pattern spreads across the mosaicked region
- Effects ignored here:
  - Heterogeneous case
  - Rotation due to PA change
- The resulting pattern is combination of overlapping Clover-leaf pattern of each pointing

Full-pol. Imaging: In-beam Leakages

- Leakage (Off-diagonal elements of the Mueller matrix)
    - Vary with direction (position in the beam), Parallactic Angle (time) and frequency





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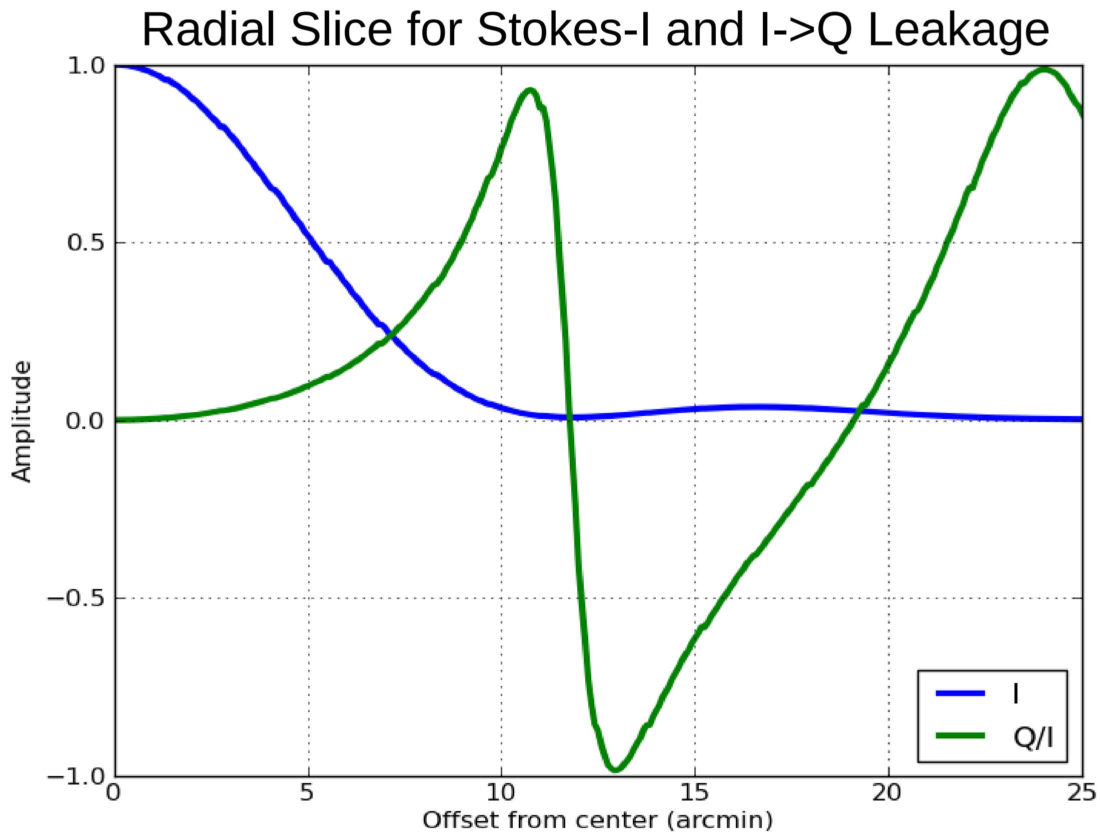
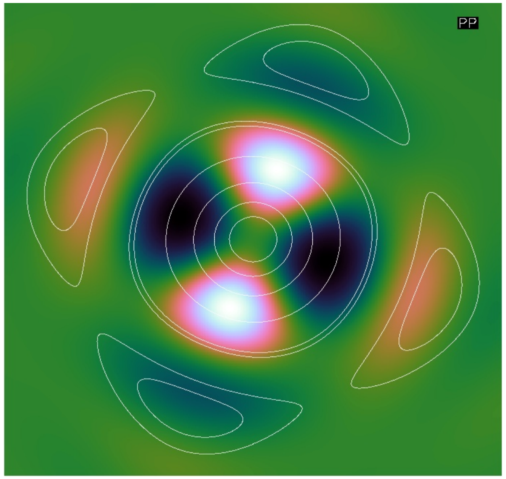
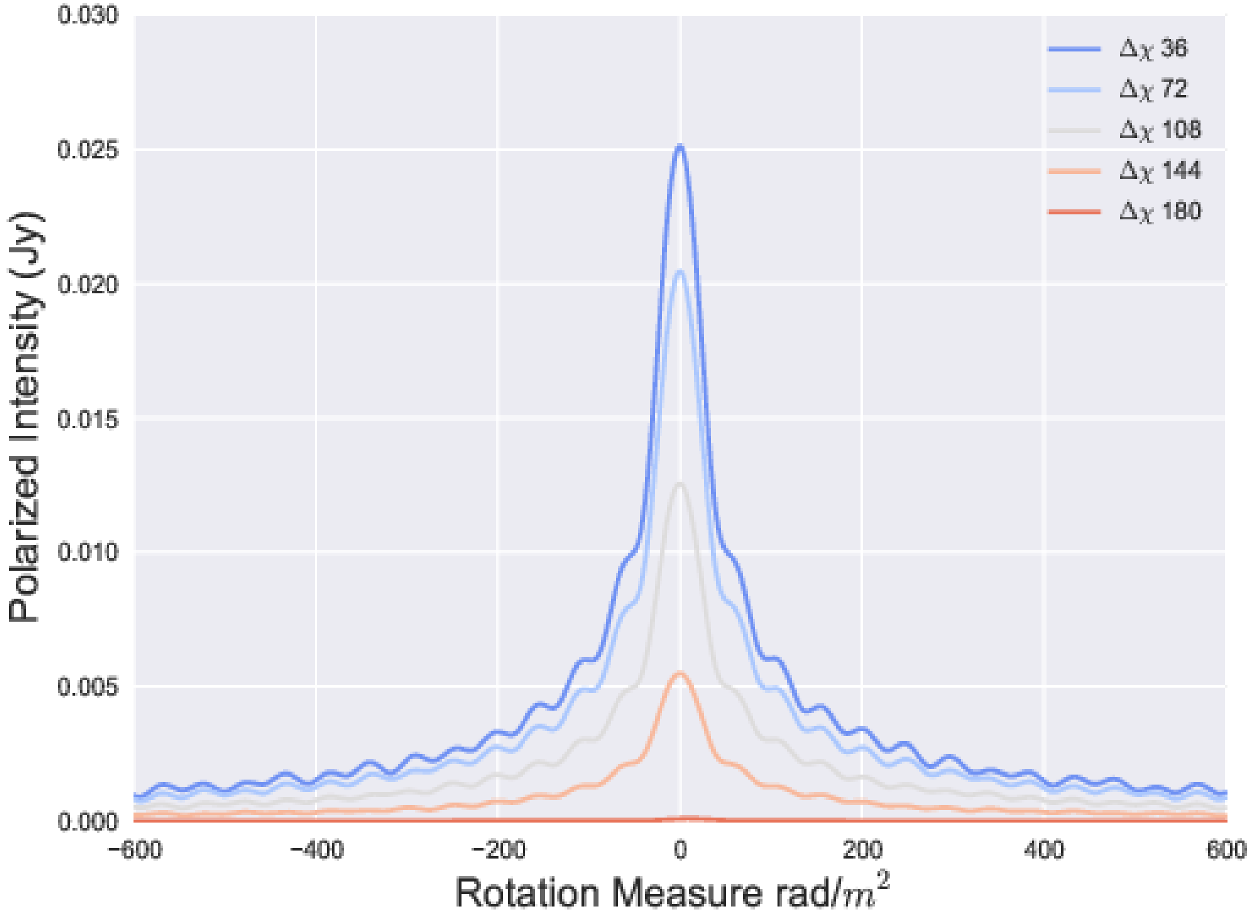




[Jagannathan, Bhatnagar, Rau & Taylor]

Full-pol. Imaging: In-beam Leakages

- Effect of PA averaging: Instrumental RM

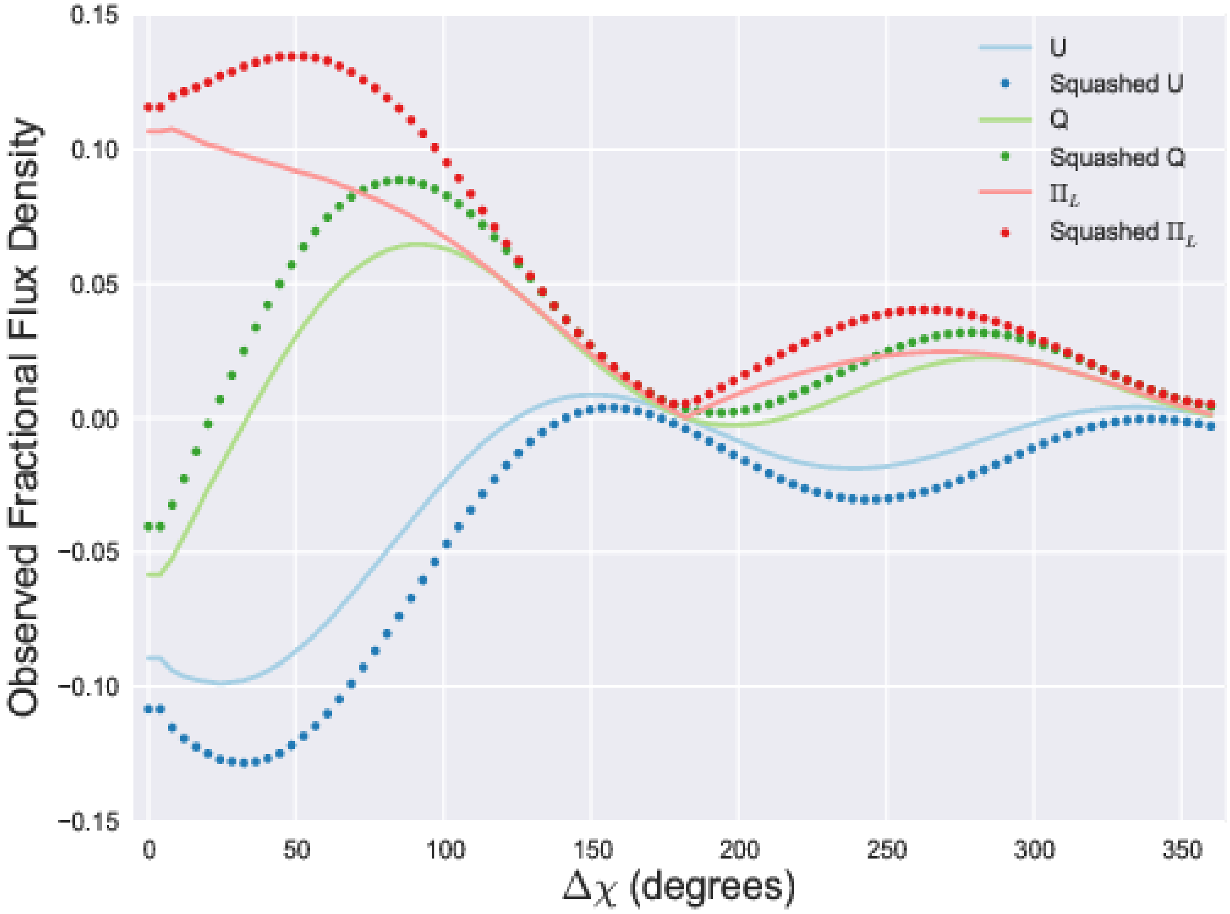


[PhD Thesis, Jagannanthan, 2017]

[Jagannathan, Bhatnagar, Rau & Taylo AJ, 2017]

Full-pol. Imaging: In-beam Leakages

- Effect of PA averaging: Residual instrumental leakage



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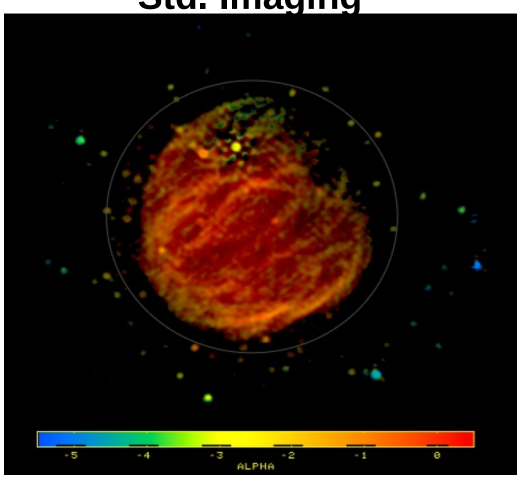
A-Projection algorithm

- Correct for the PB effects (DD effects in general) during imaging
- Essentially, apply a (pseudo) inverse of the Mueller matrix during imaging

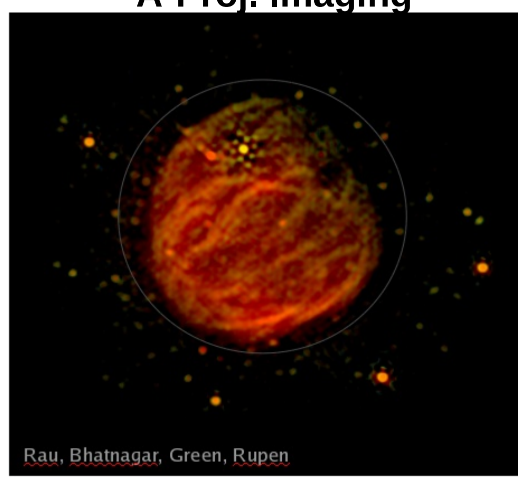
$$I^{Obs} = \left[M^M\right]^{-1} \cdot \left[M\right] \cdot \left[I^o\right]$$

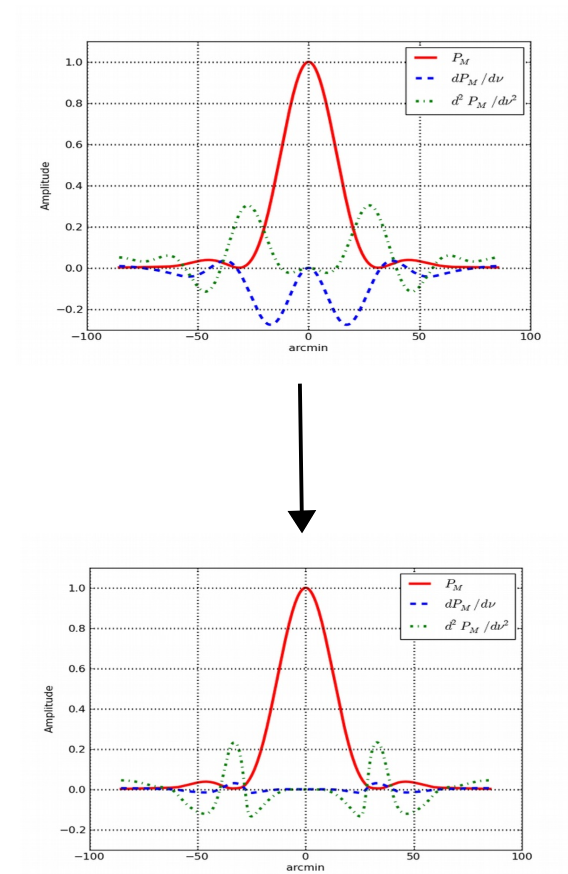
Actual algorithms applies corrections in the visibility domain using antenna aperture illumination patterns (voltages).

Std. Imaging



A-Proj. Imaging





Needs good model for the PB (***M^M***)

Full-Mueller A-Projection algorithm

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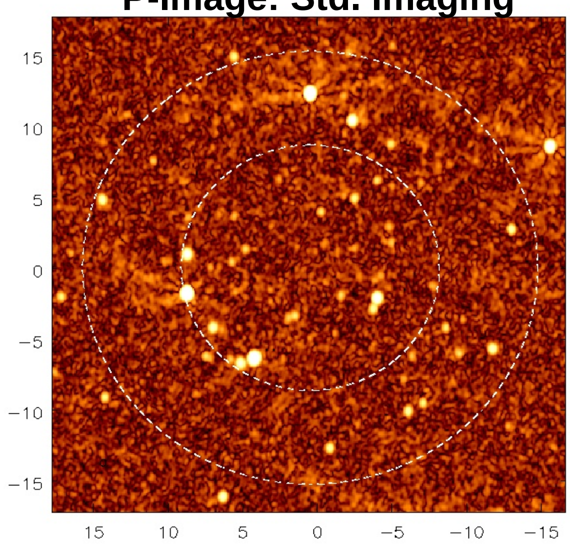
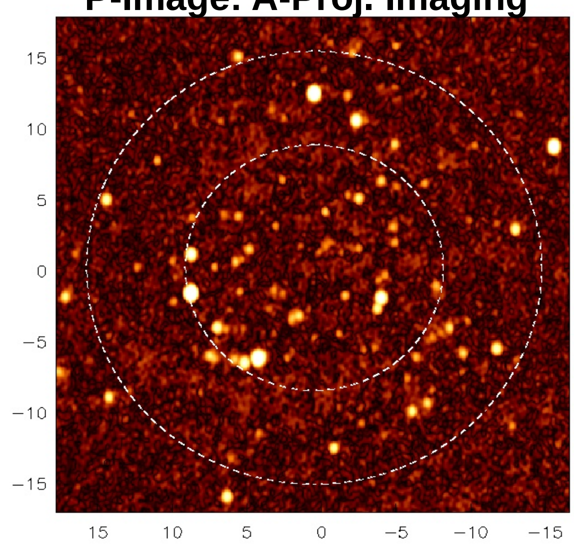
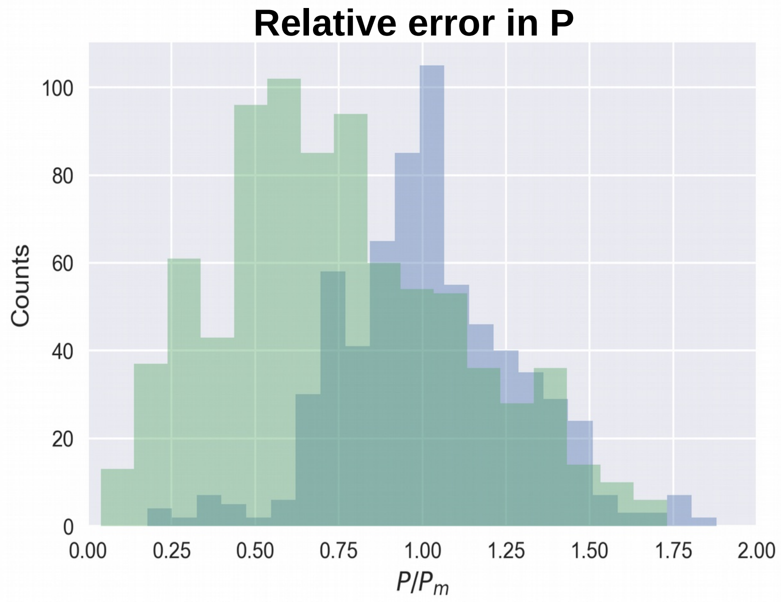






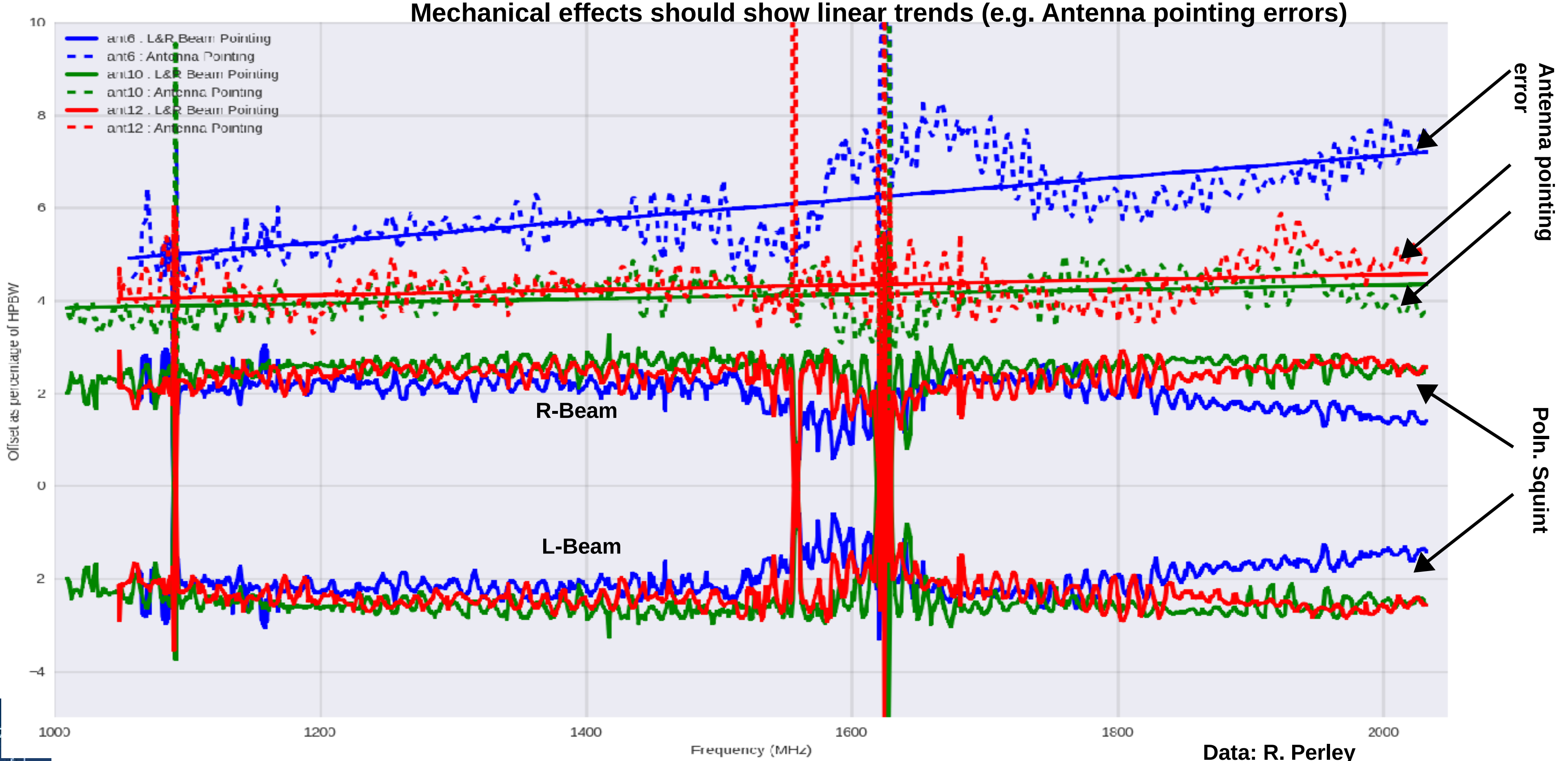
Needs good model for the PB (M^M)

[PhD Thesis, Jagannanthan, 2017]

PB Effects: EVLA antenna holographic measurements

- Parametric model of antenna Aperture Illumination
  - Difference between Ant6 and Ant10 in a “homogeneous array”

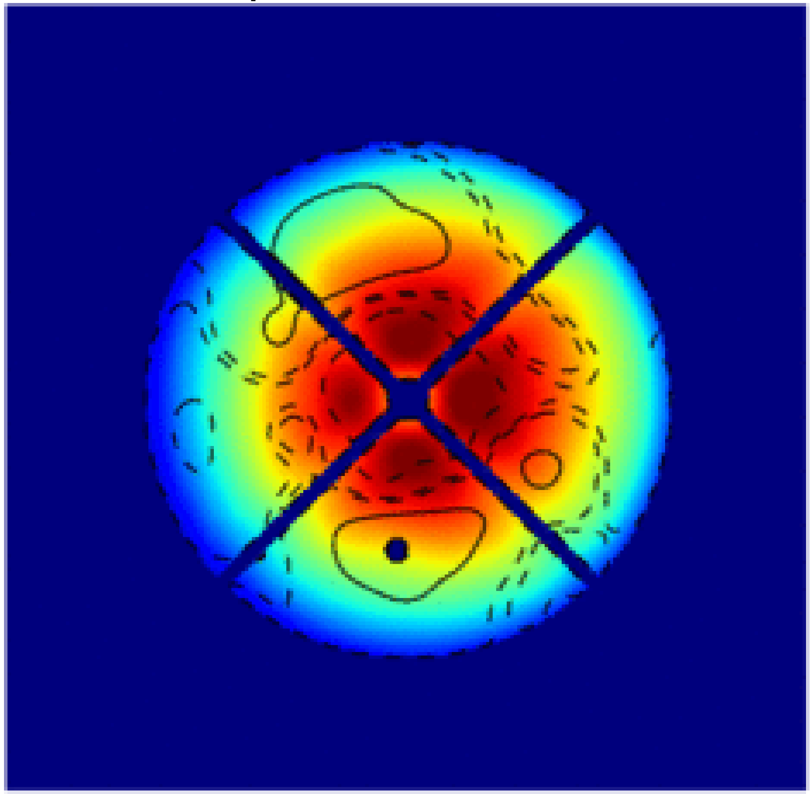
In the graph below: Optical effects should be independent of frequency (e.g. Poln. Squint)
Mechanical effects should show linear trends (e.g. Antenna pointing errors)



Data: R. Perley
Analysis: P.Jagannathan, S.Bhatnagar

PB Effects: ALMA antenna holography

- Antenna-to-antenna variations in aperture illumination (older holography data)



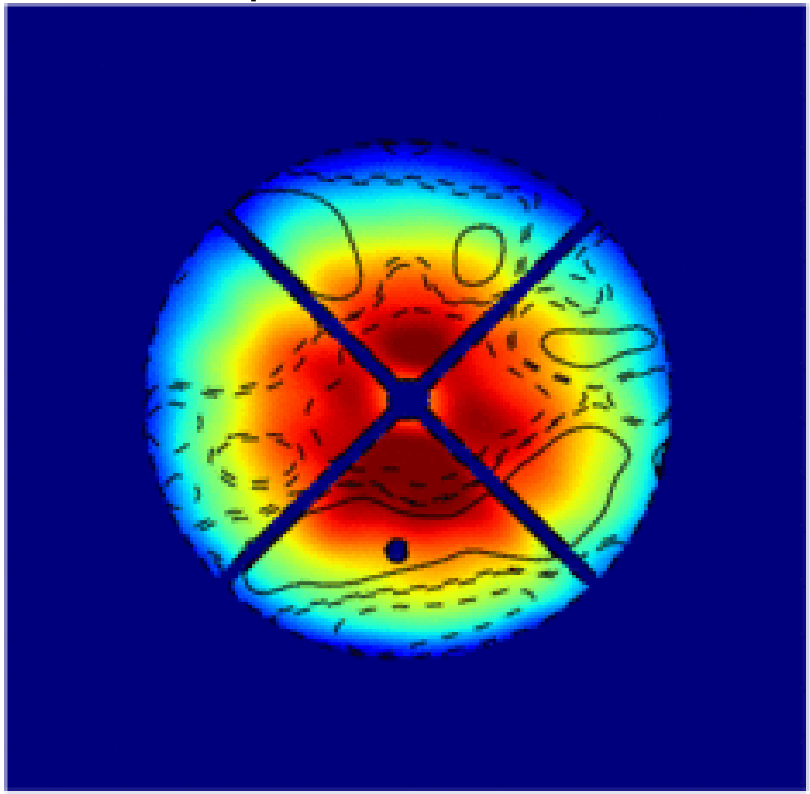
- Strongest effects
  - Antenna size,Pointing errors
  - Quadrapods
  - Antenna-to-antenna variations

**[Kundert et al.
IEEE Trans. A&P, V. 65, No.1, 2016]**

Full-pol. Imaging: PB Effects

- Antenna-to-antenna variations in aperture illumination (older holography data)

Aperture Illumination



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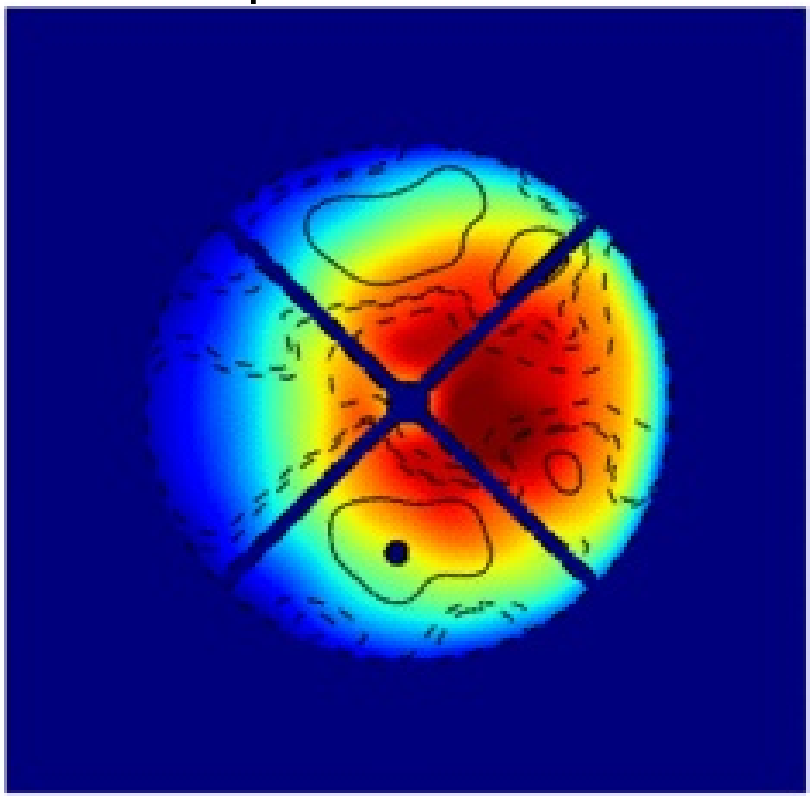

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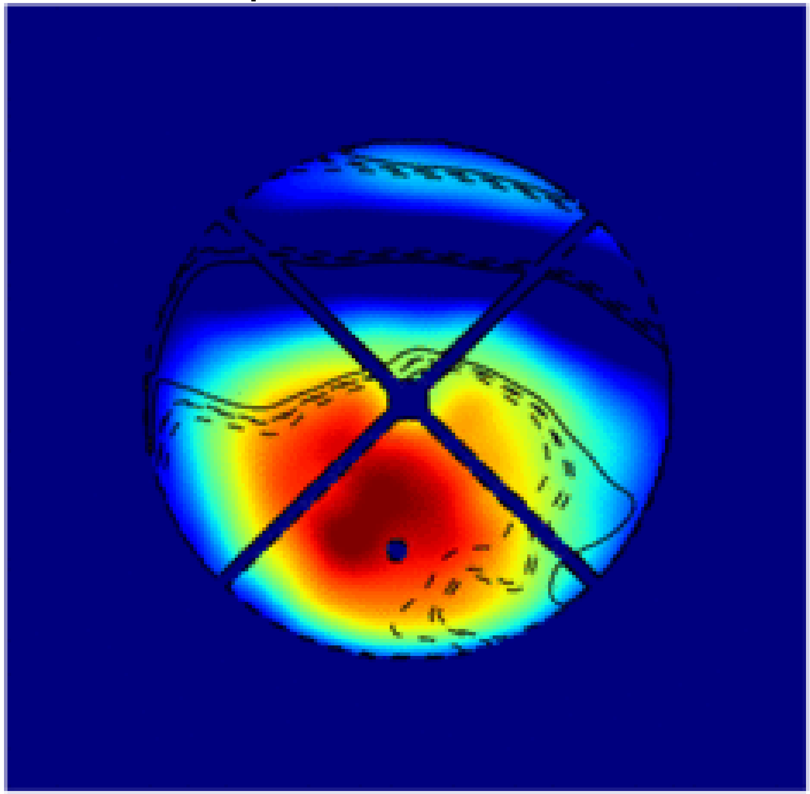

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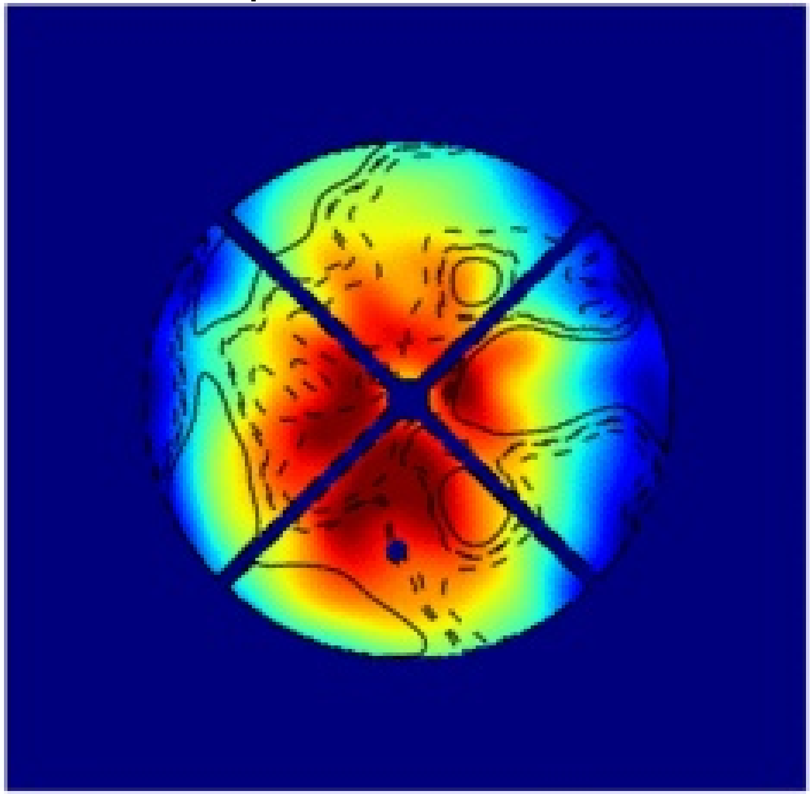

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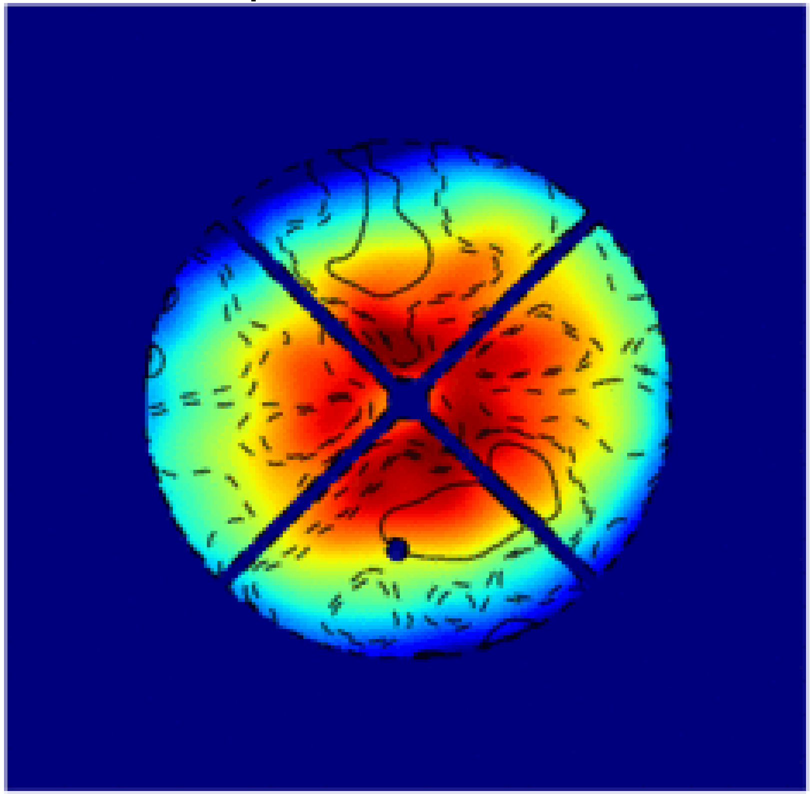

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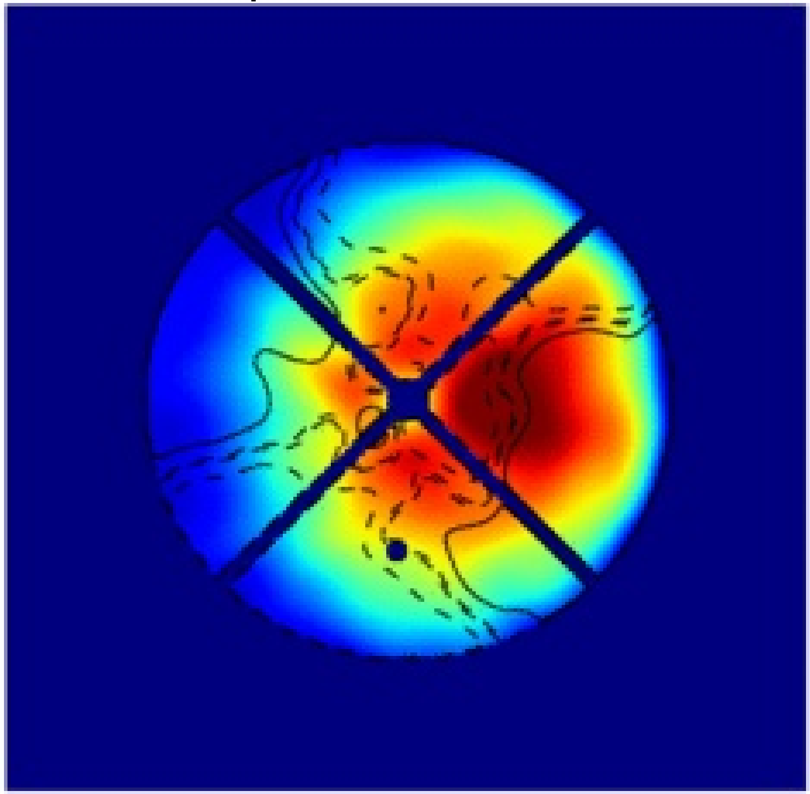

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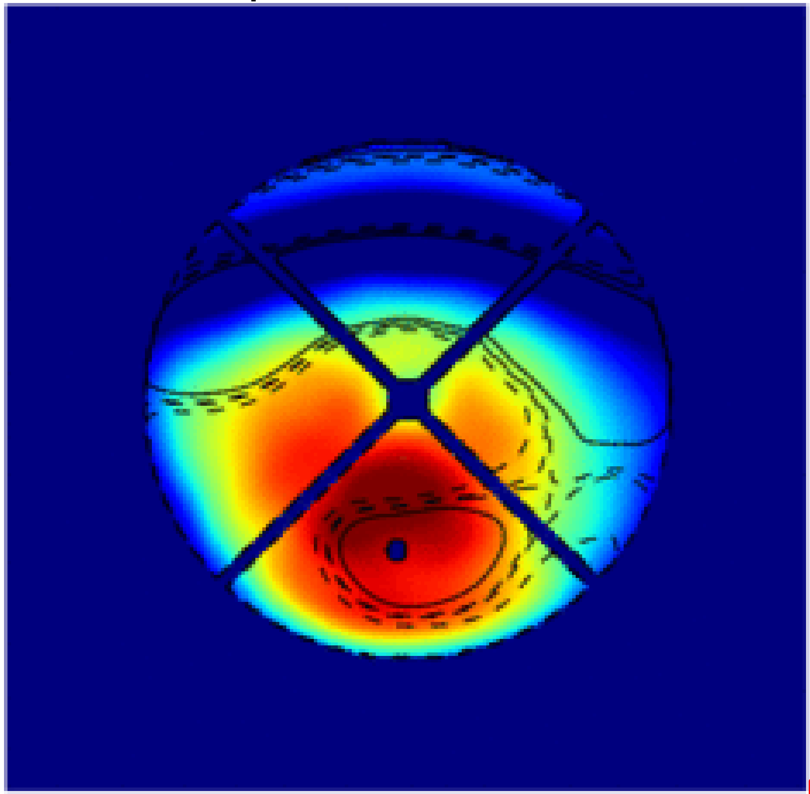

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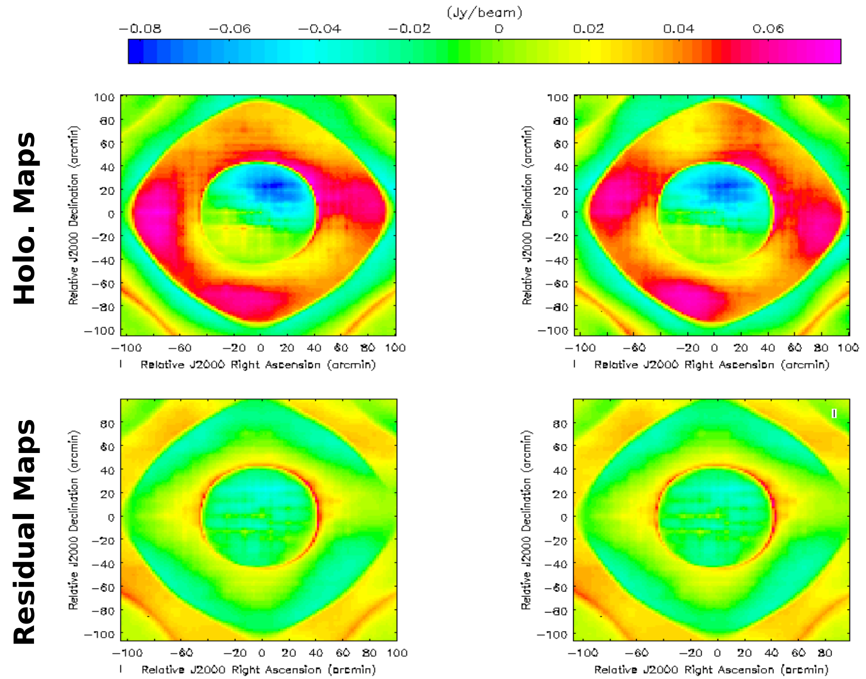
Feed alignment and displacementa affect various elements of the Mueller Matrix differently

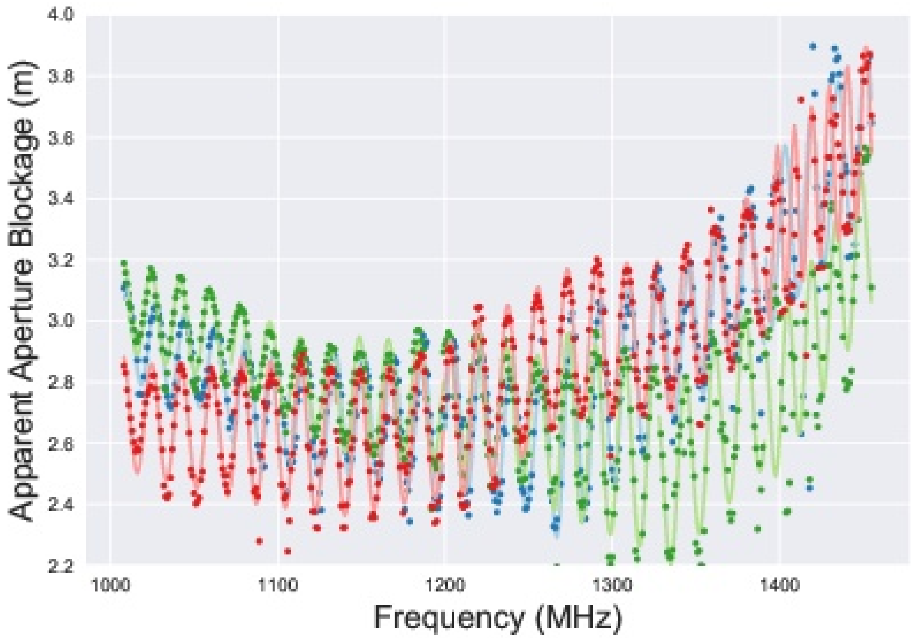
- Cost equations
  - Cheaper to fix the hardware?
  - Cheaper to handle in post processing?

ALMA Study Project: Goals

- Goals

  1. Build a full-Mueller model for the antenna PB(s)
     - Use the holography maps to solve for antenna structural parameters (A-Solver)





  2. Incorporate the ray-trace models (heterogeneous array) in (WB) A-Projection for ALMA

Jagannathan, Bhatnagar & Brisken, 2016, AJ, 2017 [arXiv:1711.00875]

ALMA Study Project: Full-Mueller Mosaic Imaging with ALMA

- Plan for work
  - Understand the existing holography data
    - Zeeman effect (Stokes-V) measurements suggestive of residual PB effects
  - Possibly acquire new data using the artificial sources at the high site to get higher SNR PB maps.

- Status
  - Work started on Nov. 1, 2017
  - Hired Brian Kirk
    - Former Senior-DA at CV, experienced in ALMA data processing and pipeline operations
  - Re-processing data using standard (debugged) tools
    - DD Jones matrix (far field voltage patterns) per antenna as a function of frequency