Introduction to Radio Interferometry + Workshop Overview

Urvashi Rau , NRAO

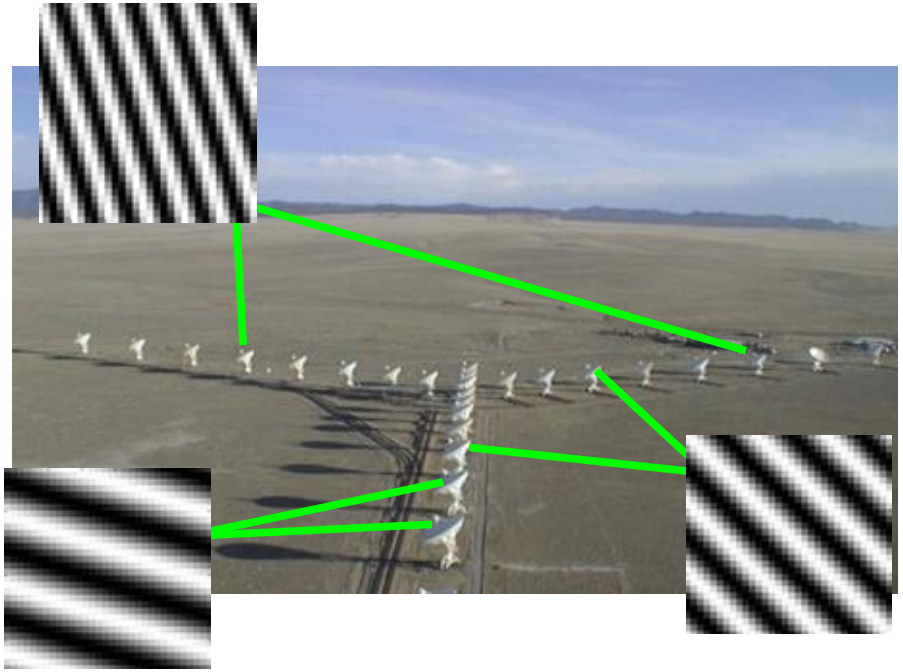
21st NRAO Synthesis Imaging Workshop

27 May 2026

Principles of Radio Interferometric Imaging

An interferometer is an indirect imaging device

We sample the spatial Fourier transform of the sky brightness



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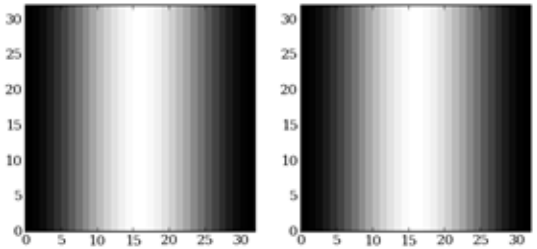
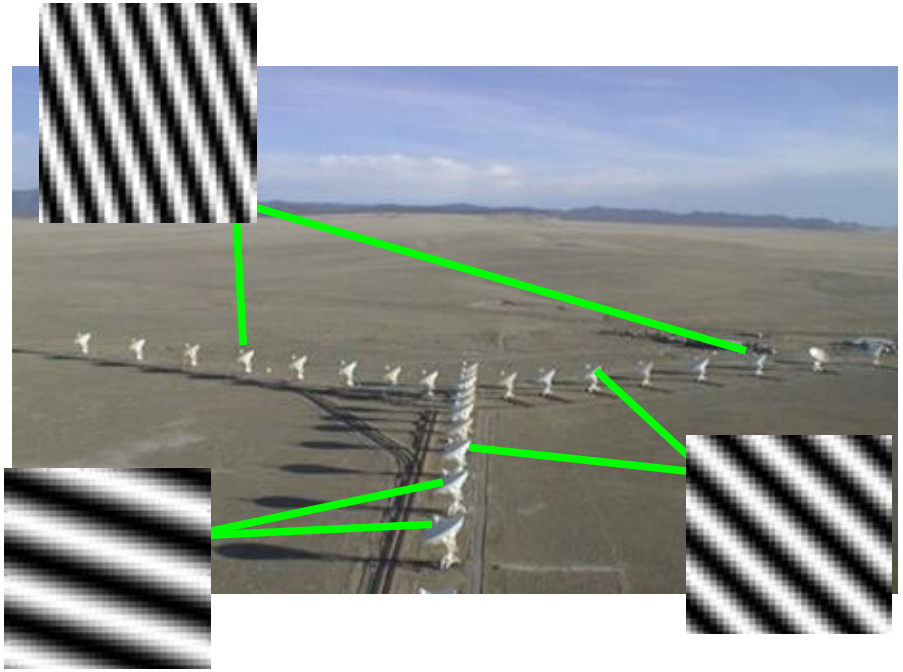
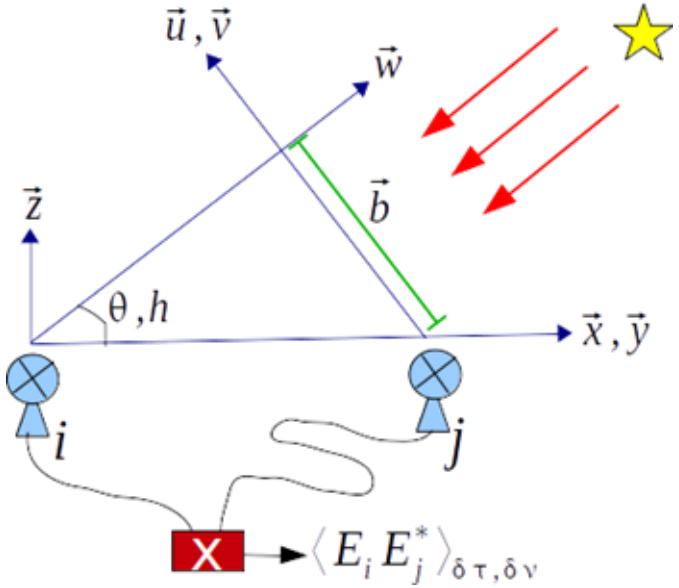
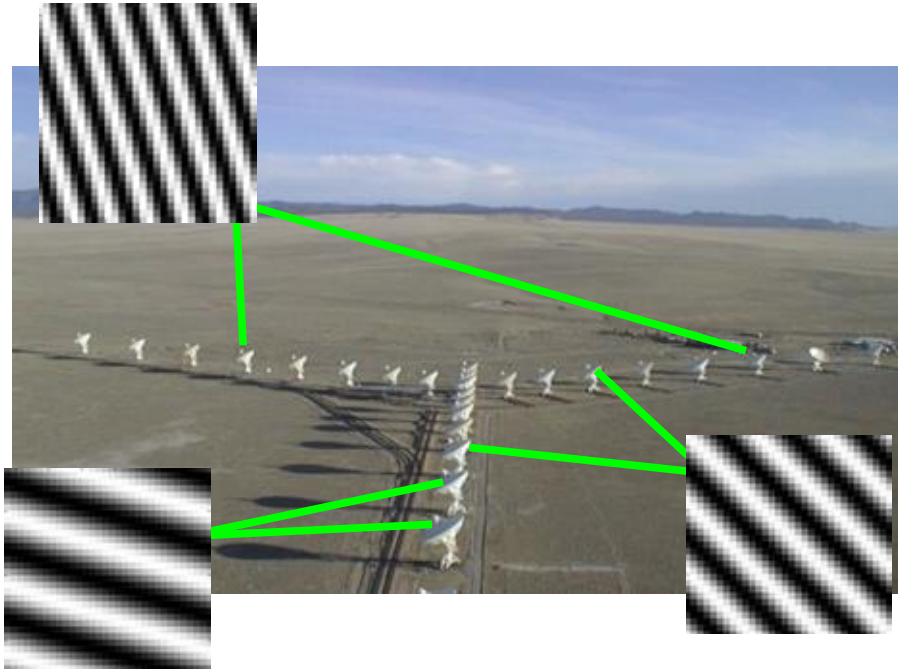




Principles of Radio Interferometric Imaging





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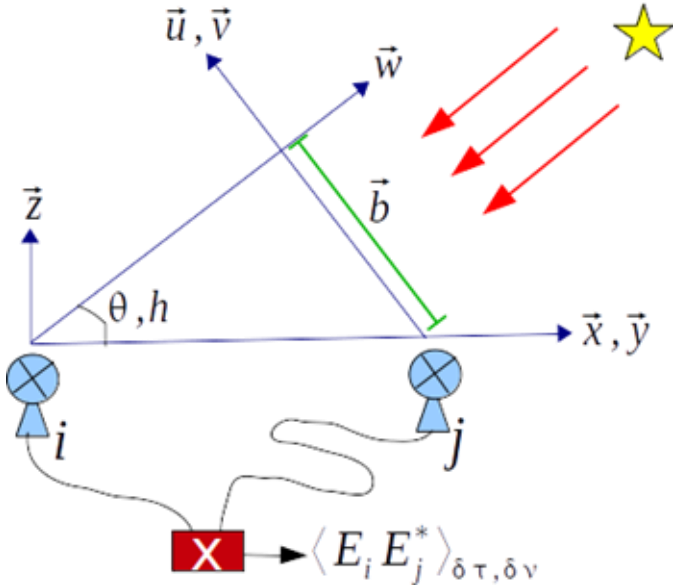
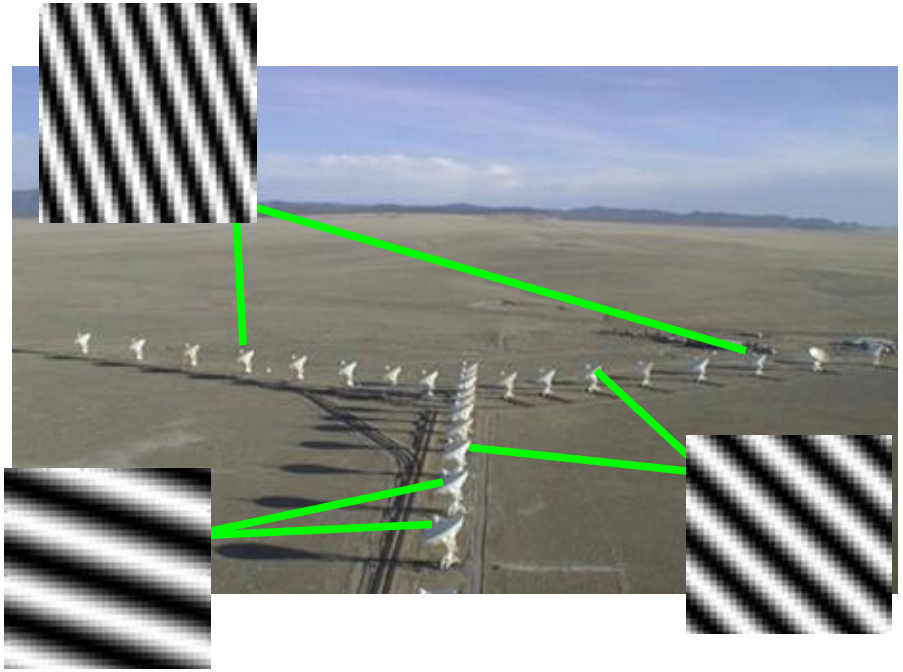
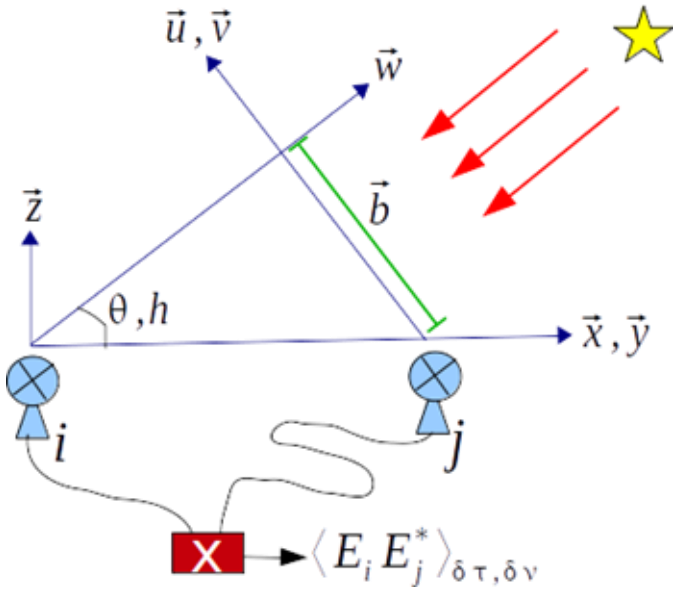
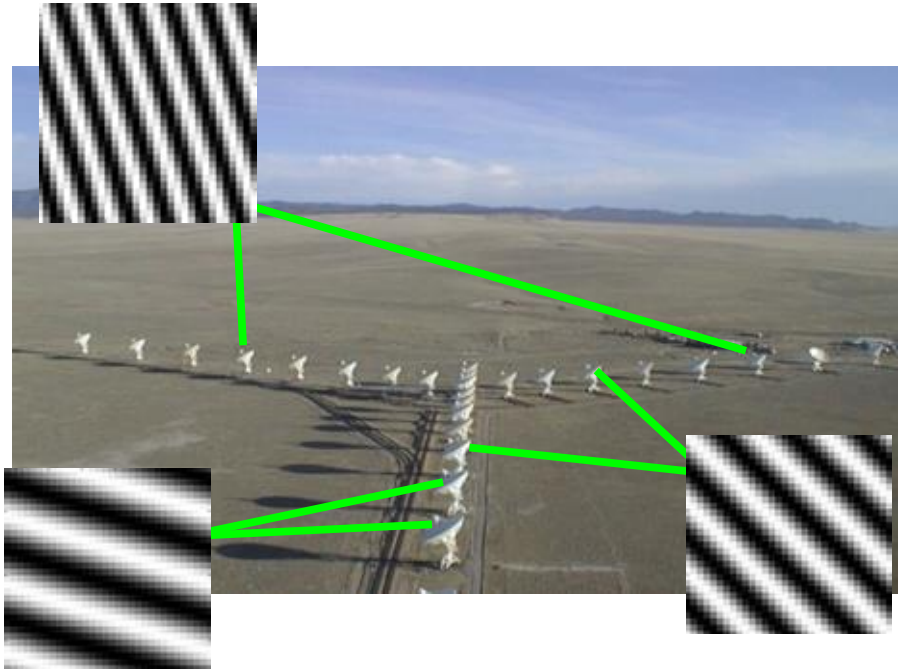




Each $\langle E_i E_j^* \rangle_{\delta\tau,\delta\nu}$: Amplitude, Phase, Wavelength, Orientation

Principles of Radio Interferometric Imaging



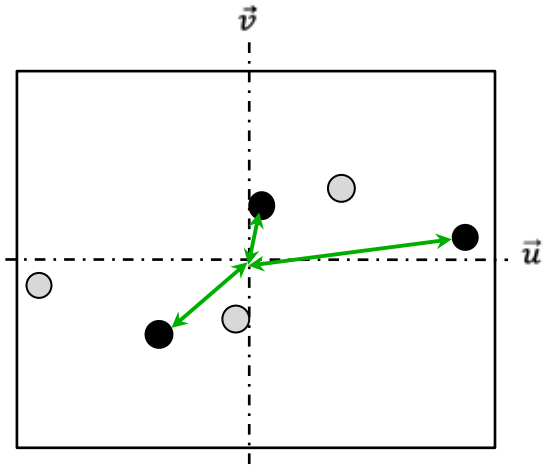


Measure $\langle E_i E_j^* \rangle_{\delta\tau,\delta\nu}$ for N(N-1)/2 antenna pairs, and over time and frequency

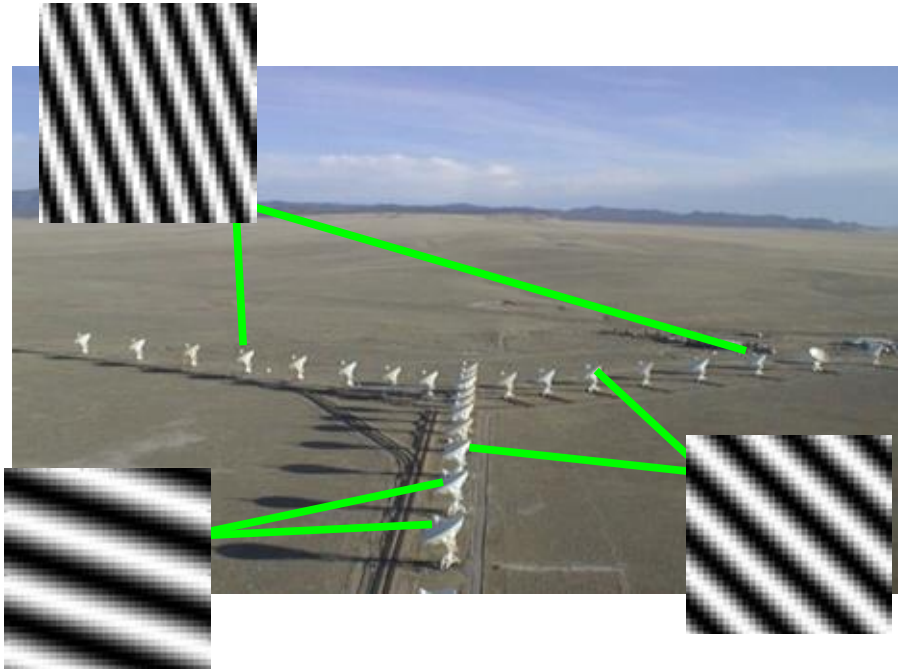
Principles of Radio Interferometric Imaging

Accumulate all $\langle E_i E_j^* \rangle_{\delta\tau,\delta\nu}$

on a spatial frequency grid



UV-space



Perform an inverse Fourier transform to make an Image

Aperture Synthesis

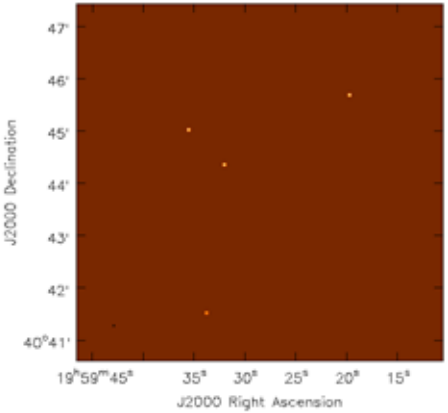
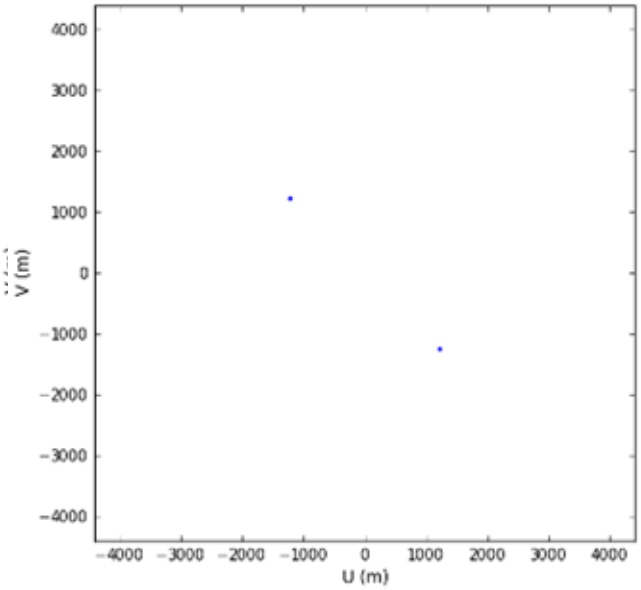


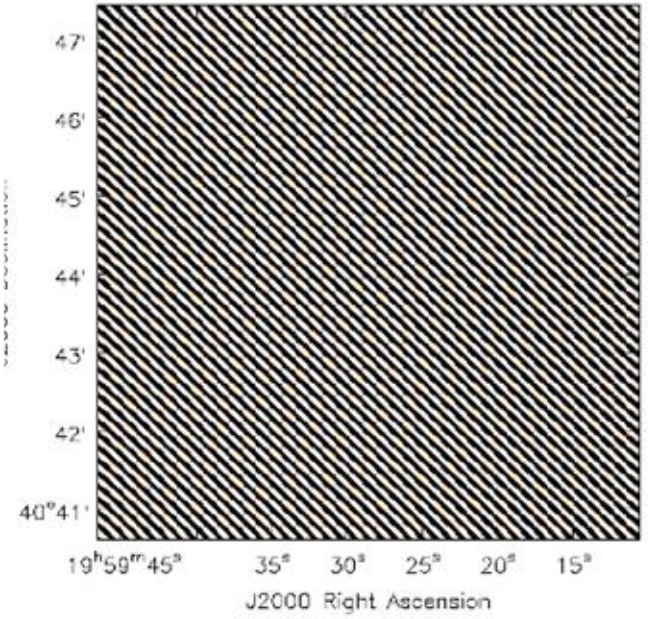
Image formed with

2 antennas

$S(u,v)$



$I^{obs}(l,m)$



Aperture Synthesis

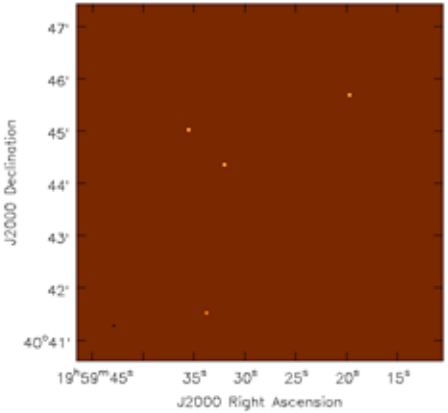
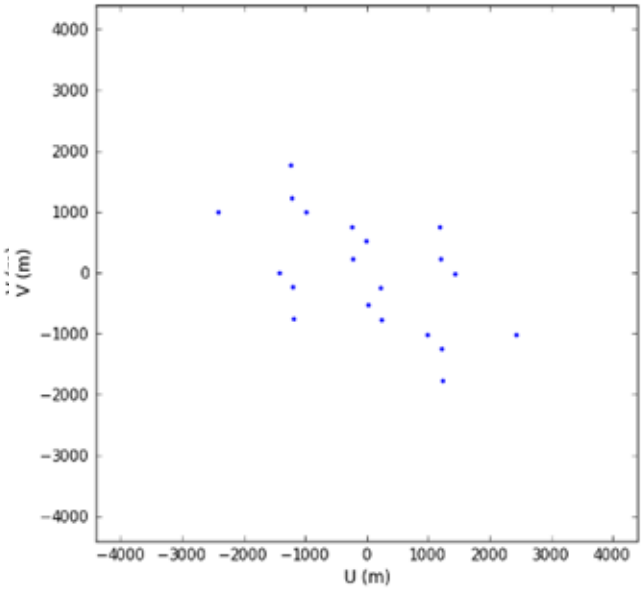


Image formed with

5 antennas

$S(u,v)$



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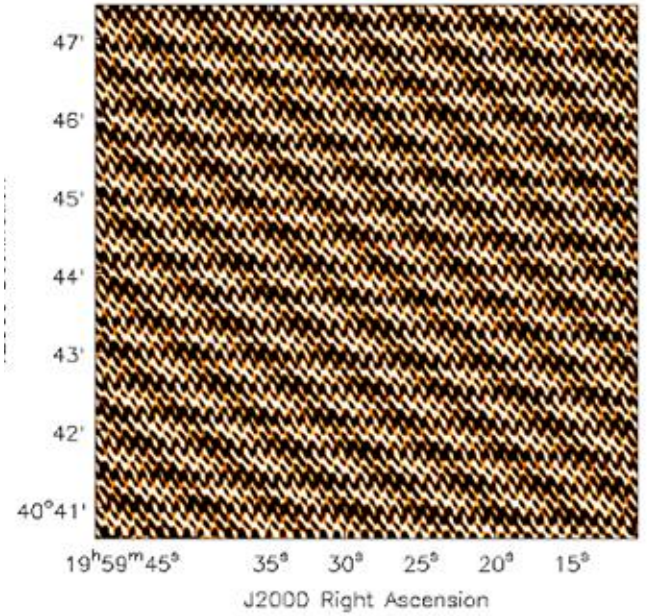

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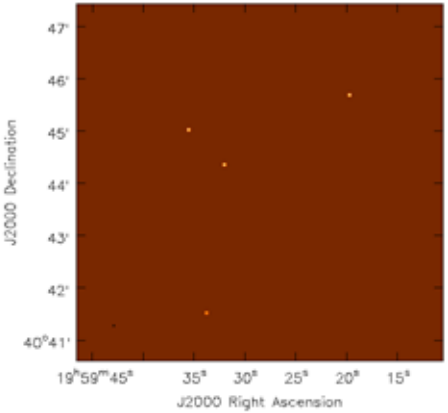
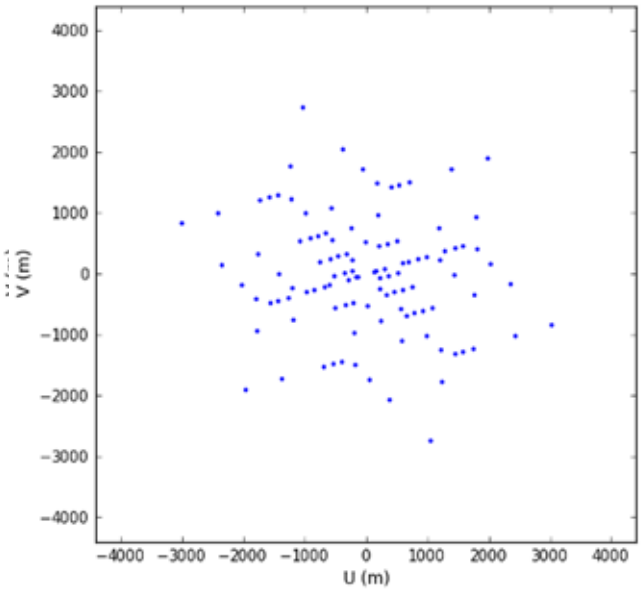


Image formed with

11 antennas

$S(u,v)$



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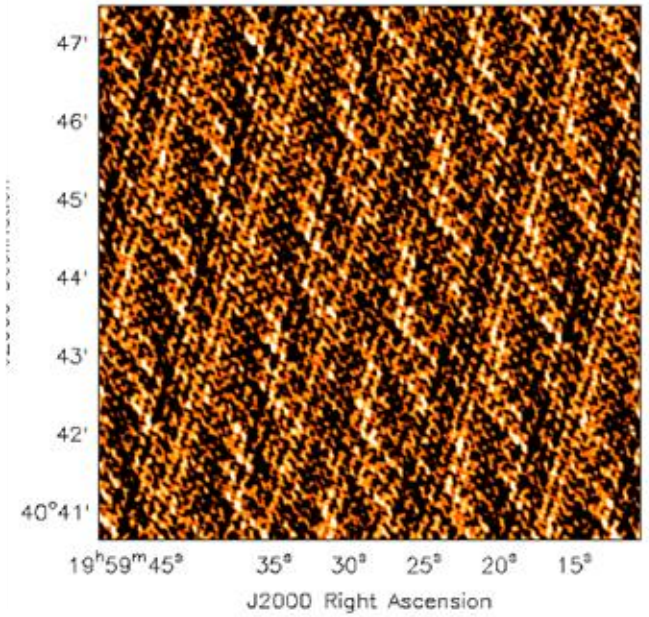

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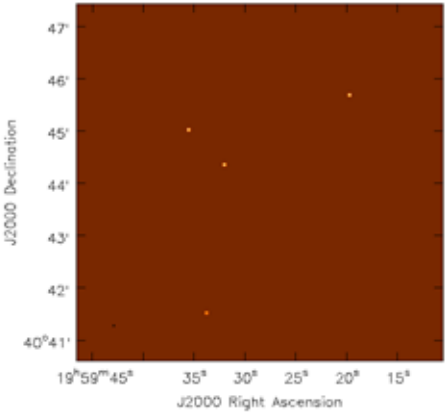
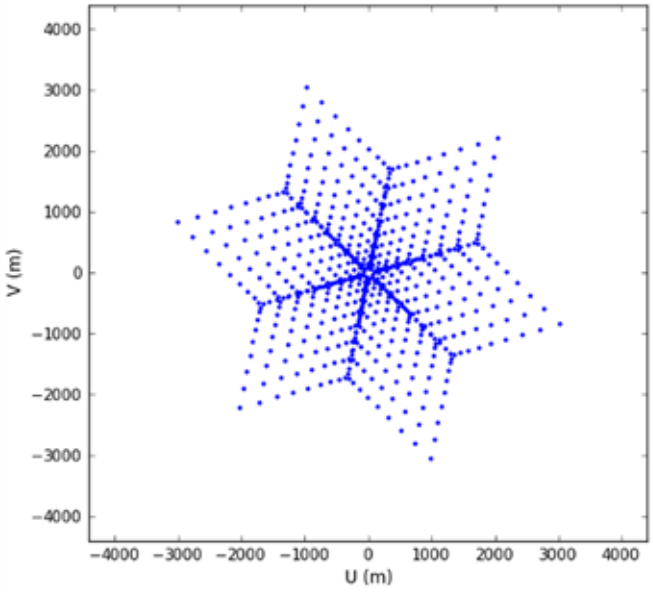


Image formed with

27 antennas

$S(u,v)$



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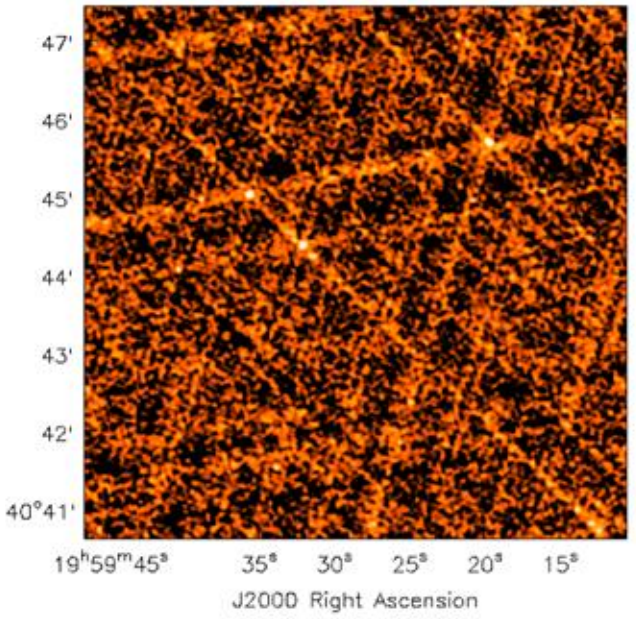

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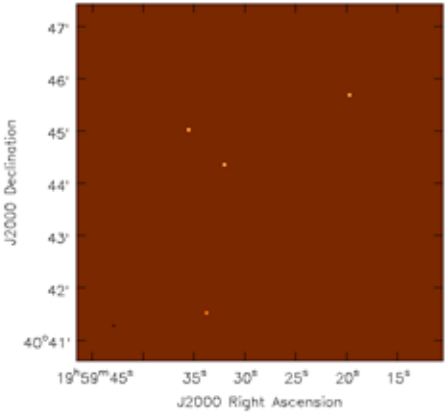
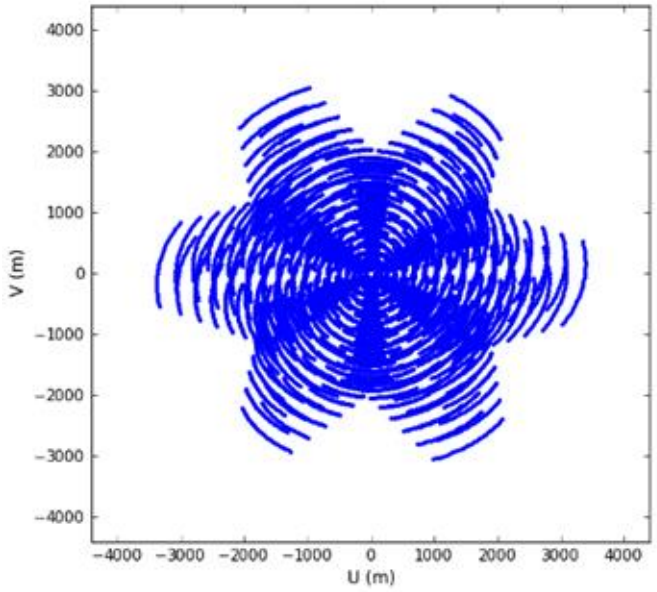


Image formed with

27 antennas

2 hours

$S(u,v)$



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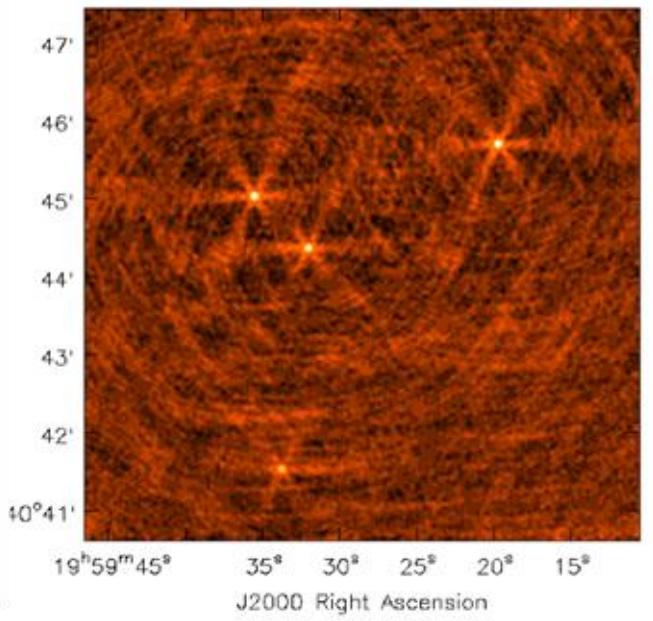

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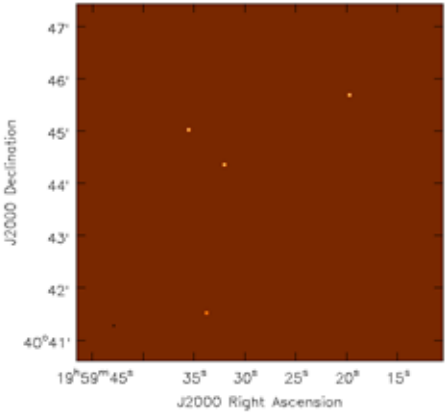
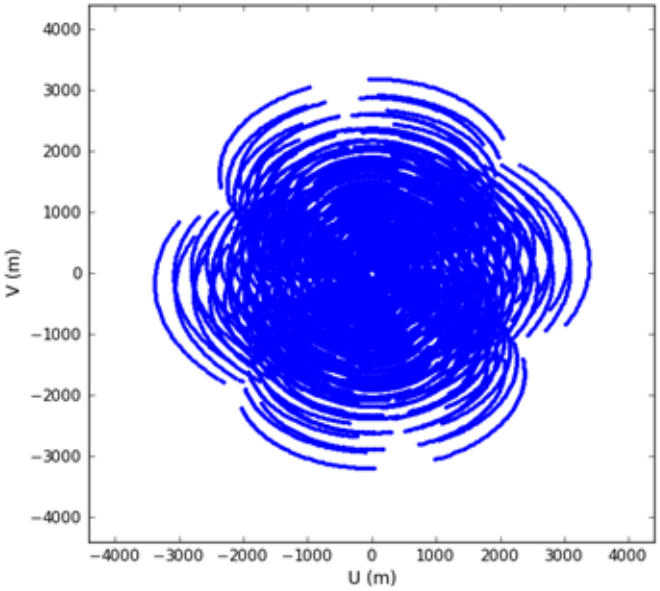


Image formed with

27 antennas

4 hours

$S(u,v)$



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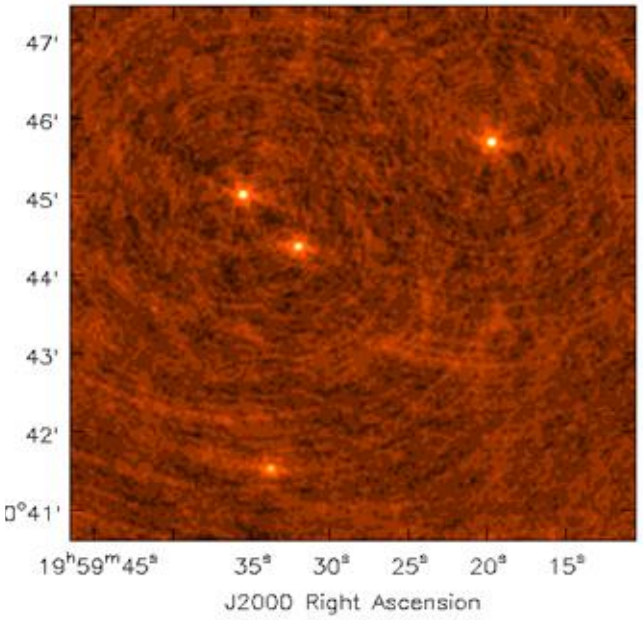

Principles of Radio Interferometric Imaging

Wed May 27

Fundamentals of Radio Interferometry

Part I —> Concepts : Measuring fringes + response to sky emission structures

Part II —> Using real sensors (bandwidth, time averaging, electronics)

Part III —> Geometry and coordinate systems, UV-coverage,
Examples of measured data

Array Design —> Radio telescopes of the world (slides)

Measurement Equation

$$\langle E_i E_j^* \rangle \propto V_{ij}^{obs}(\nu, t) \approx S_{ij}(\nu, t) \iint I(l, m) e^{2\pi i(ul+vm)} dl\, dm$$

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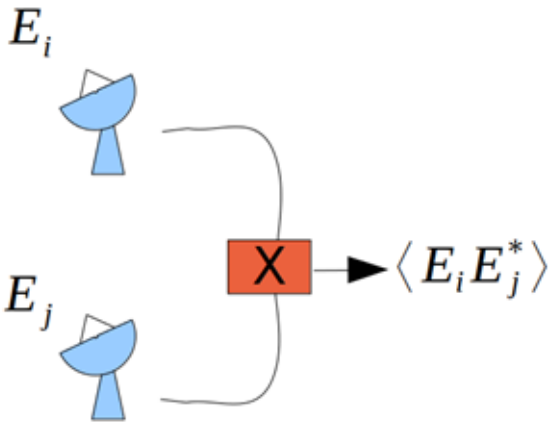

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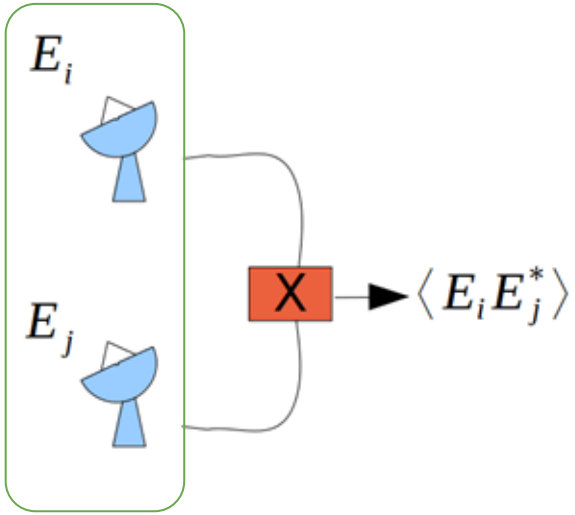

Fri May 29
Antennas and Receivers

- Temperature & Sensitivity
- Power pattern (primary beam)
- Receivers and Electronics
- Linear and Circular Feeds

$\vec{\vec{J}}_i$ = Jones matrix

Tue Jun 2
Polarization in Radio Interferometry

- Stokes Parameters IQUV
- Instrumental and propagation effects

Measurement Equation

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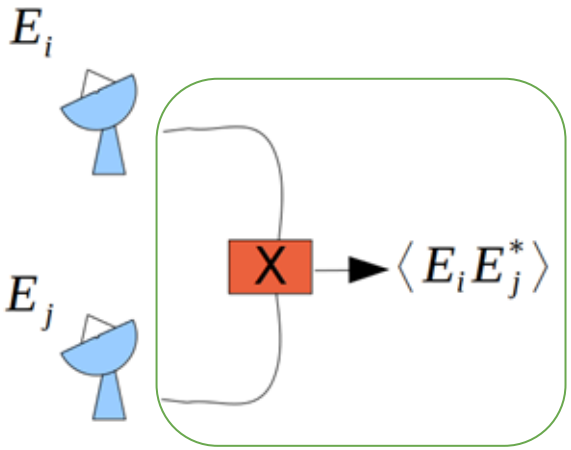


Fri May 29
Cross Correlators and Digital Signal Proc.

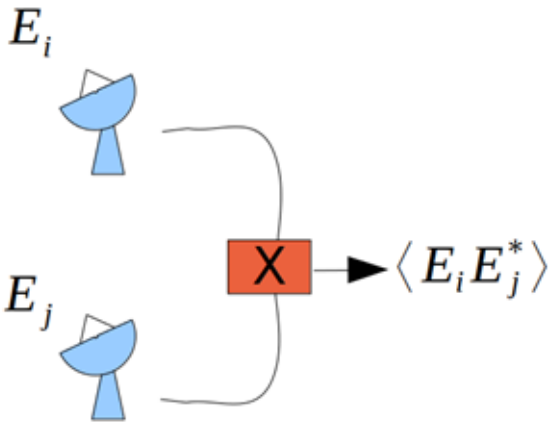
- Digitize voltage streams from each antenna
- Calculate cross-correlations (FX vs XF)

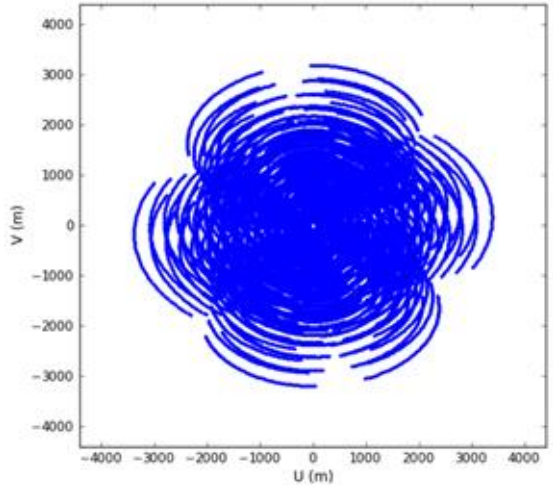
- Correlation pairs
  - R/L ⇒ RR, RL, LR, LL
  - H/V ⇒ HH, HV, VH, VV (or X/Y)

$\vec{J}_i \otimes \vec{J}_j = \vec{M}_{ij}$ = Mueller matrix

Measurement Equation

$$\langle E_i E_j^* \rangle \propto V_{ij}^{obs}(\nu, t) \approx S_{ij}(\nu, t) \iint I(l, m) e^{2\pi i(ul+vm)} dl\, dm$$





Imaging

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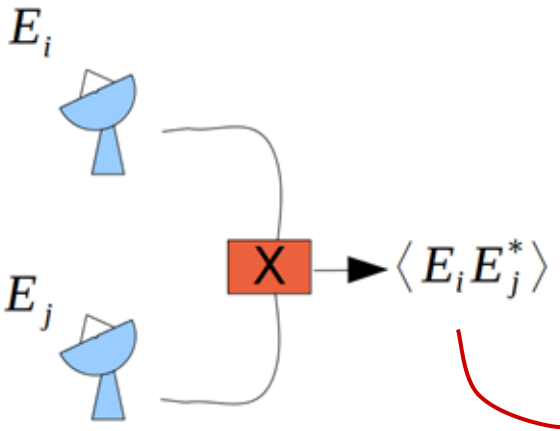

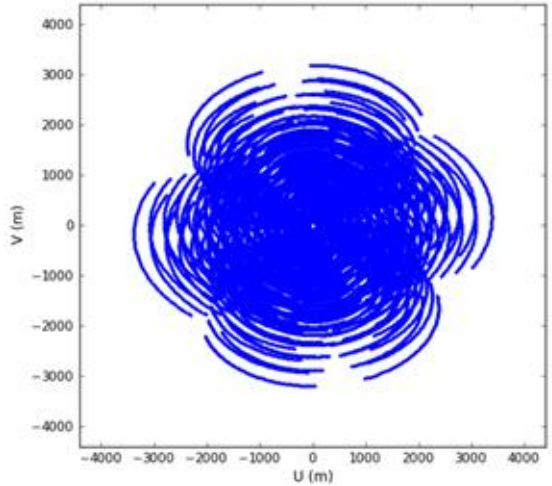

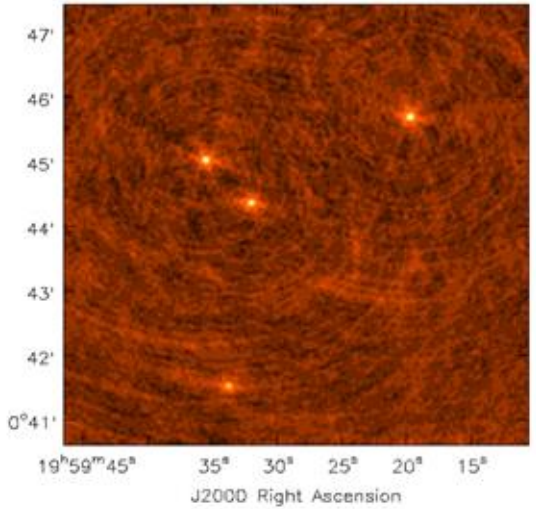

Thu May 28 – Imaging & Deconvolution

Imaging & Deconvolution

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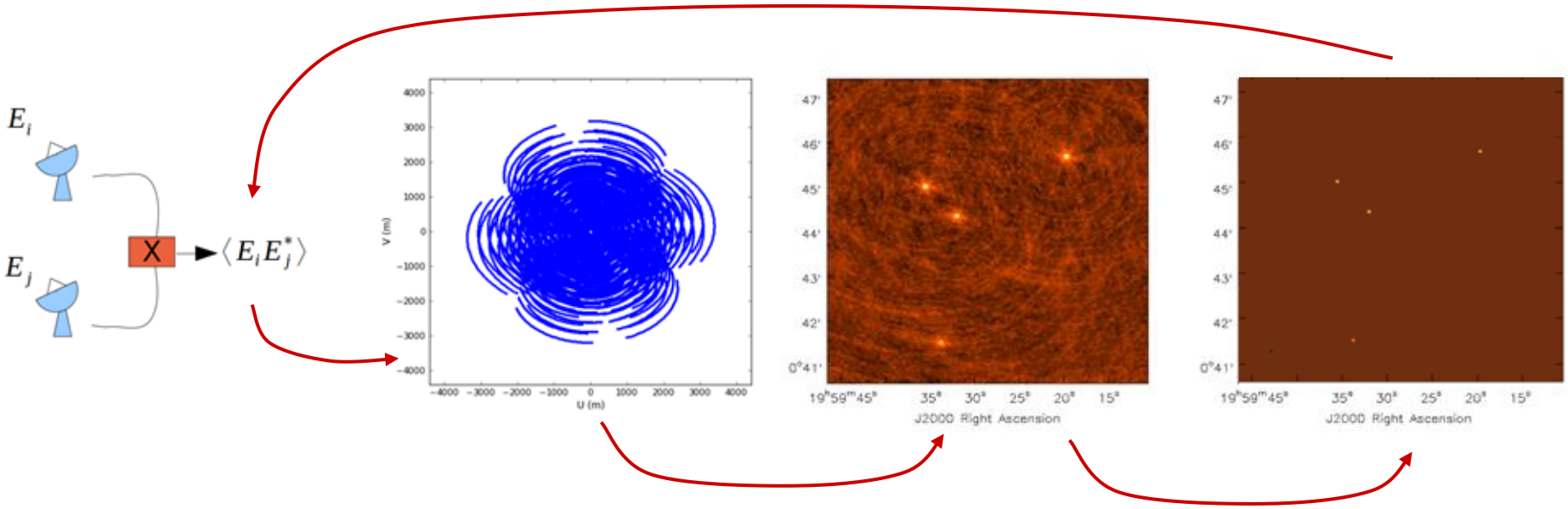

Measurement Equation

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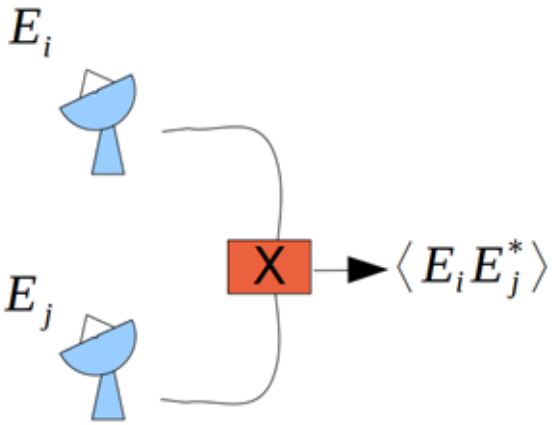
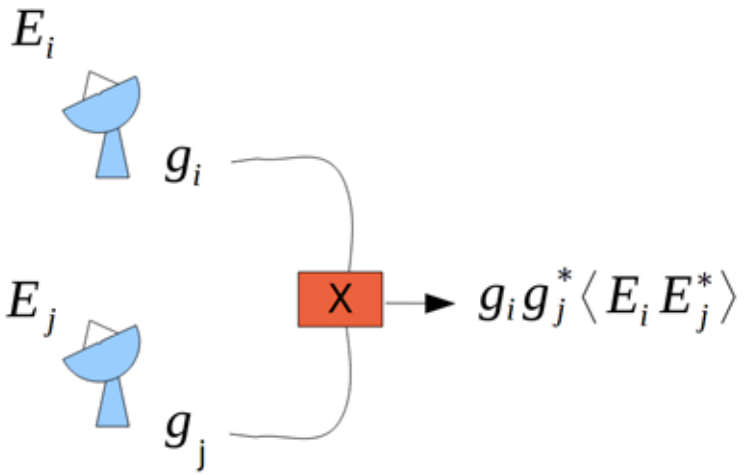


Measurement Equation

$$V_{ij}^{obs}(\nu,t) \approx M_{ij}(\nu,t) S_{ij}(\nu,t) \iint I(l,m) e^{2\pi i(ul+vm)} dl\, dm + n_{ij}$$



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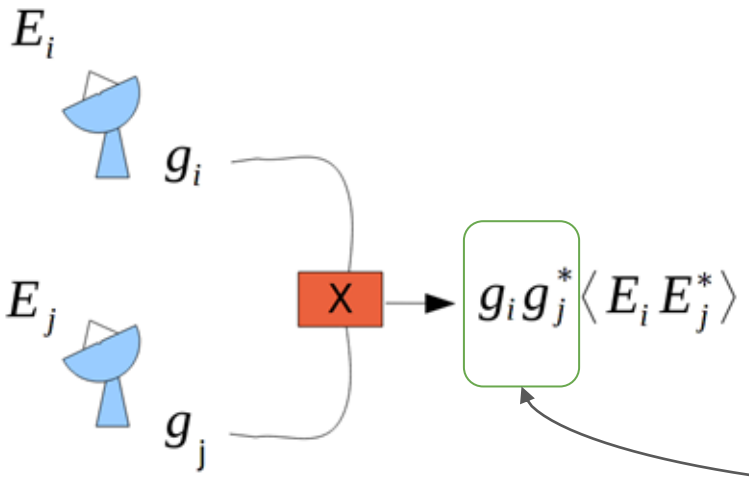


Instrumental + Propagation Effects

Jones matrix per antenna

$$\vec{\vec{J}}_i = \vec{\vec{K}}_i \vec{\vec{B}}_i \vec{\vec{G}}_i \vec{\vec{D}}_i \vec{\vec{E}}_i \vec{\vec{X}}_i \vec{\vec{P}}_i \vec{\vec{T}}_i \vec{\vec{F}}_i$$

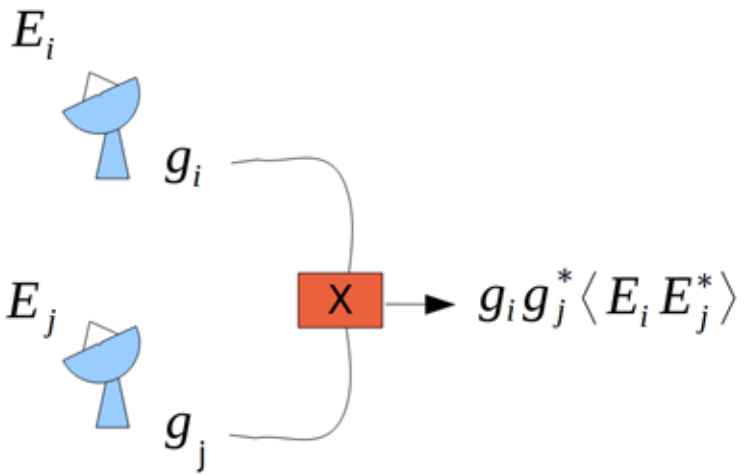
Mueller matrix per baseline

$$\vec{M}_{ij} = \vec{J}_i \otimes \vec{J}_j$$

Calibration

$$V_{ij}^{obs}(\nu,t) \approx \boxed{M_{ij}(\nu,t)} S_{ij}(\nu,t) \iint I(l,m) e^{2\pi i(ul+vm)} dl\, dm + n_{ij}$$

Before imaging, we must undo
Instrumental + Propagation Effects $g_i g_j^*$



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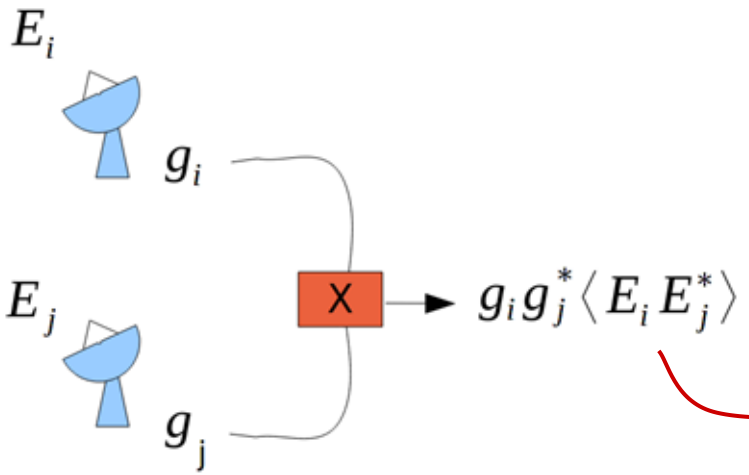


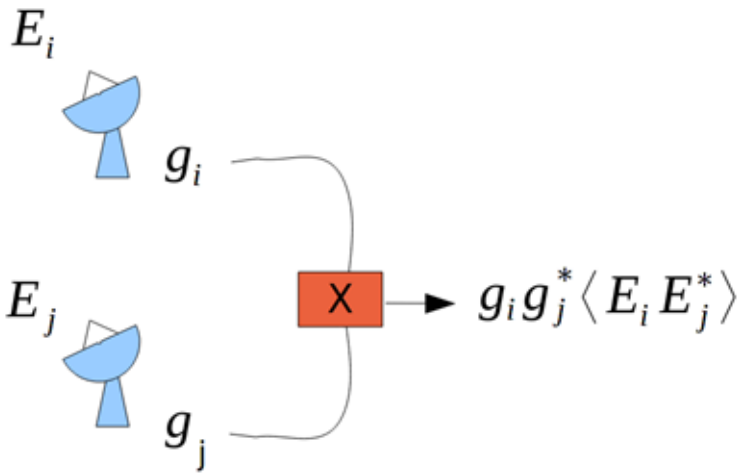
Before imaging, we must undo
Instrumental + Propagation Effects $g_i g_j^*$

Observe a known source (calibrator)
and solve for a gain model g_i^m

$$\langle E_i E_j^* \rangle = \frac{g_i g_j^* \langle E_i E_j^* \rangle}{g_i^m g_j^{m*}}$$

Measurement Equation

$$V_{ij}^{obs}(\nu,t) \approx M_{ij}(\nu,t)\, S_{ij}(\nu,t) \iint I(l,m)\, e^{2\pi i(ul+vm)}\, dl\, dm + n_{ij}$$



Measurement Equation

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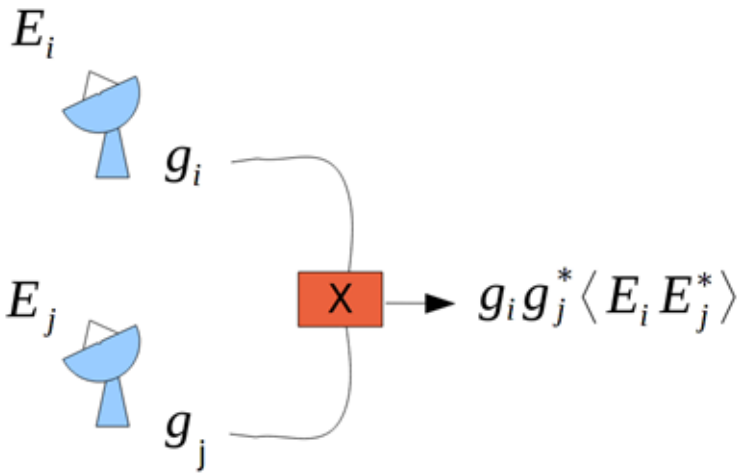

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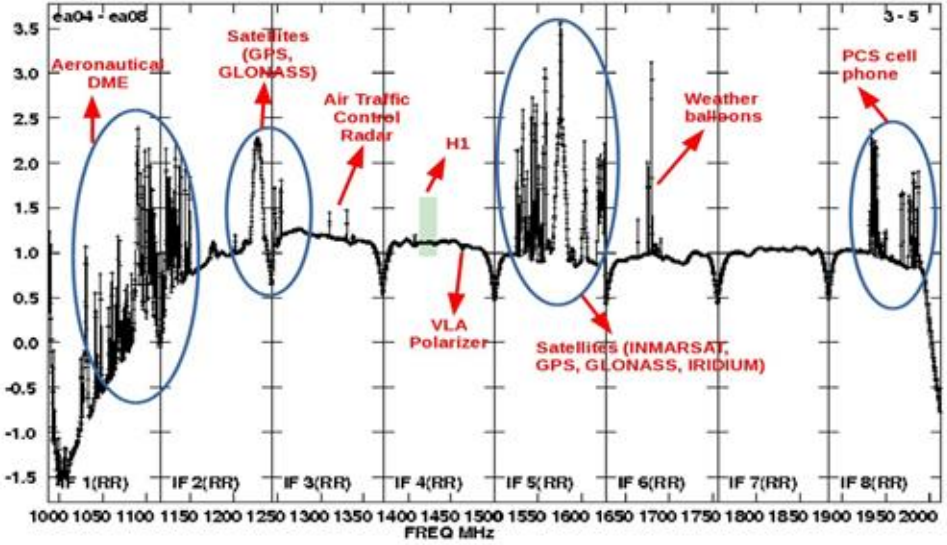
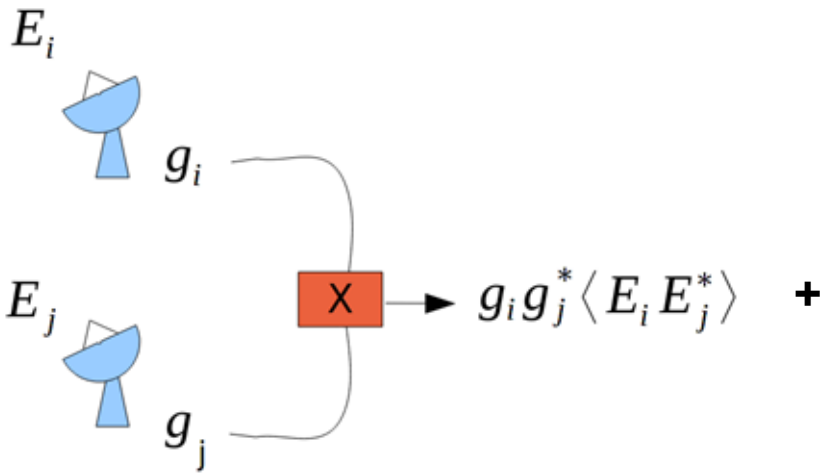


Fri May 29 — Radio Frequency Interference

Flagging

$$V_{ij}^{obs}(\nu,t) \approx M_{ij}(\nu,t)\,S_{ij}(\nu,t)\iint I(l,m)\,e^{2\pi i(ul+vm)}\,dl\,dm + n_{ij} + N_{ij}^{RFI}$$



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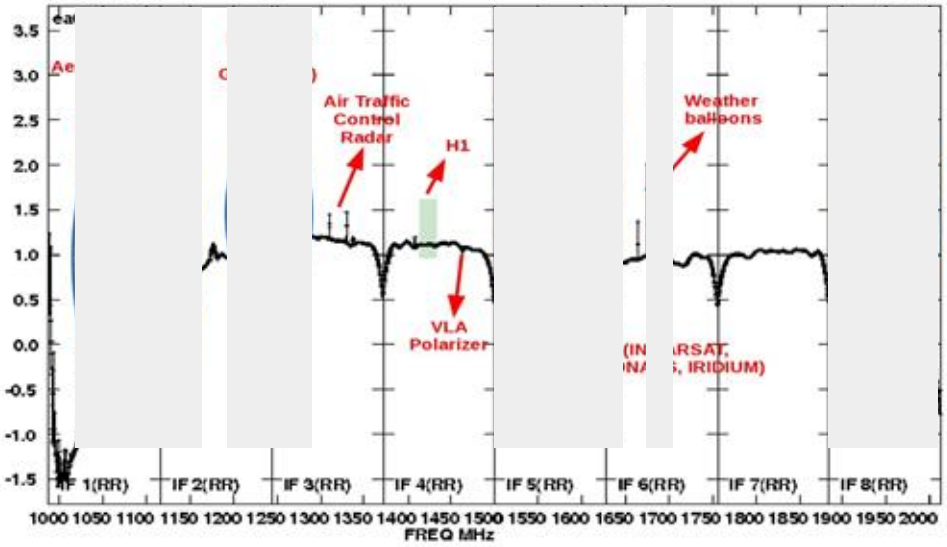
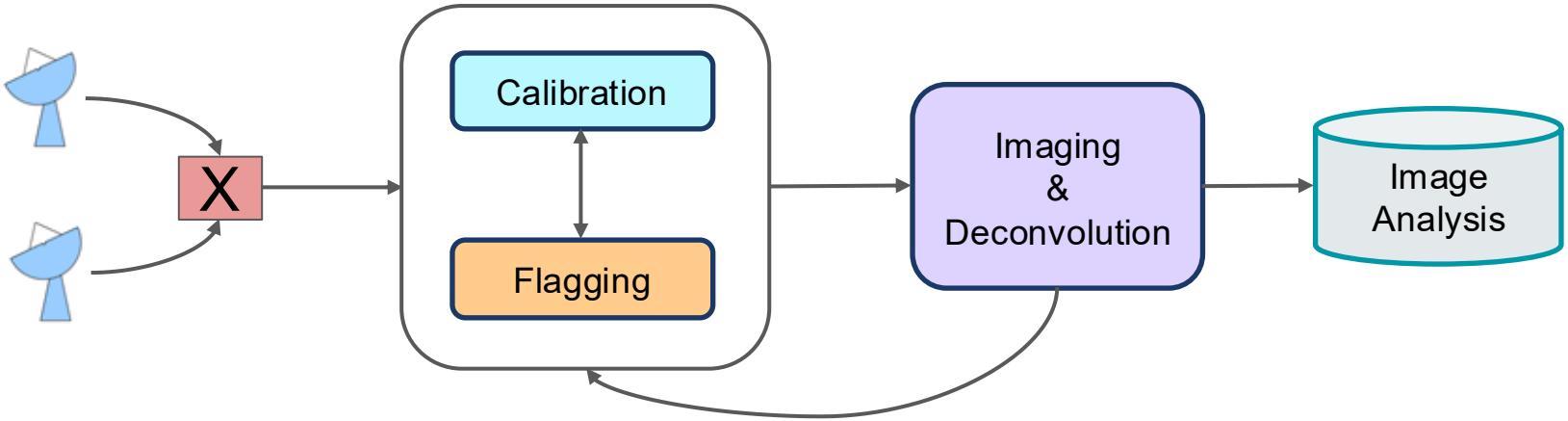


Fri May 29 — Radio Frequency Interference

Data Processing Techniques

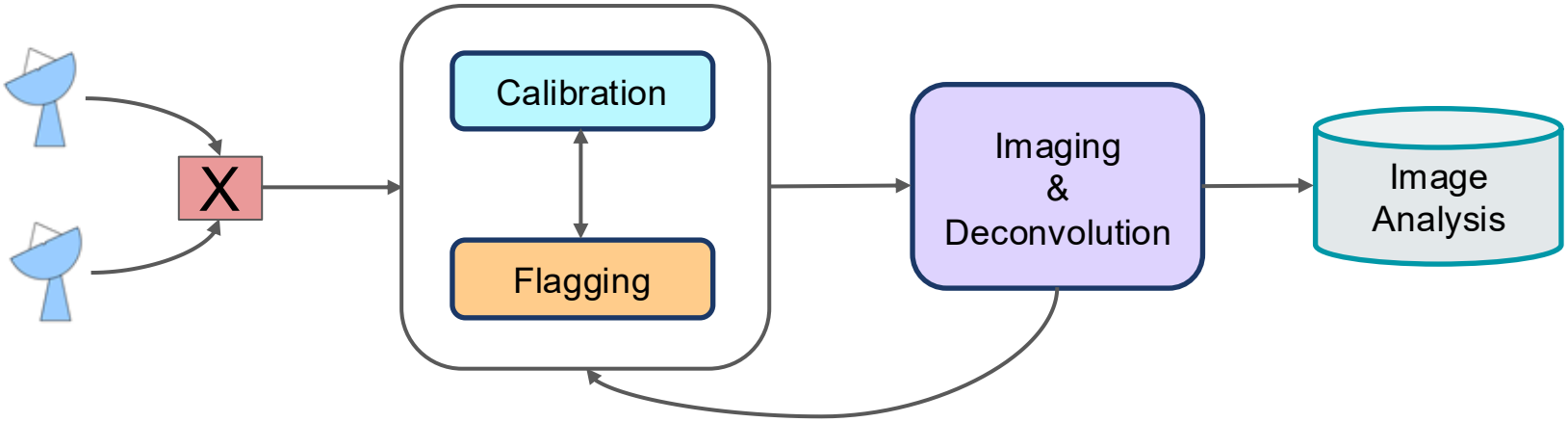
$$V_{ij}^{obs}(\nu,t) \approx M_{ij}(\nu,t)\,S_{ij}(\nu,t)\iint I(l,m)\,e^{2\pi i(ul+vm)}\,dl\,dm + n_{ij} + N_{ij}^{RFI}$$



Data Analysis is *an iterative process* of solving different parts of the Measurement Eqns

Data Processing Techniques

$$V_{ij}^{obs}(\nu,t) \approx M_{ij}(\nu,t)\,S_{ij}(\nu,t)\iint I(l,m)\,e^{2\pi i(ul+vm)}\,dl\,dm + n_{ij} + N_{ij}^{RFI}$$



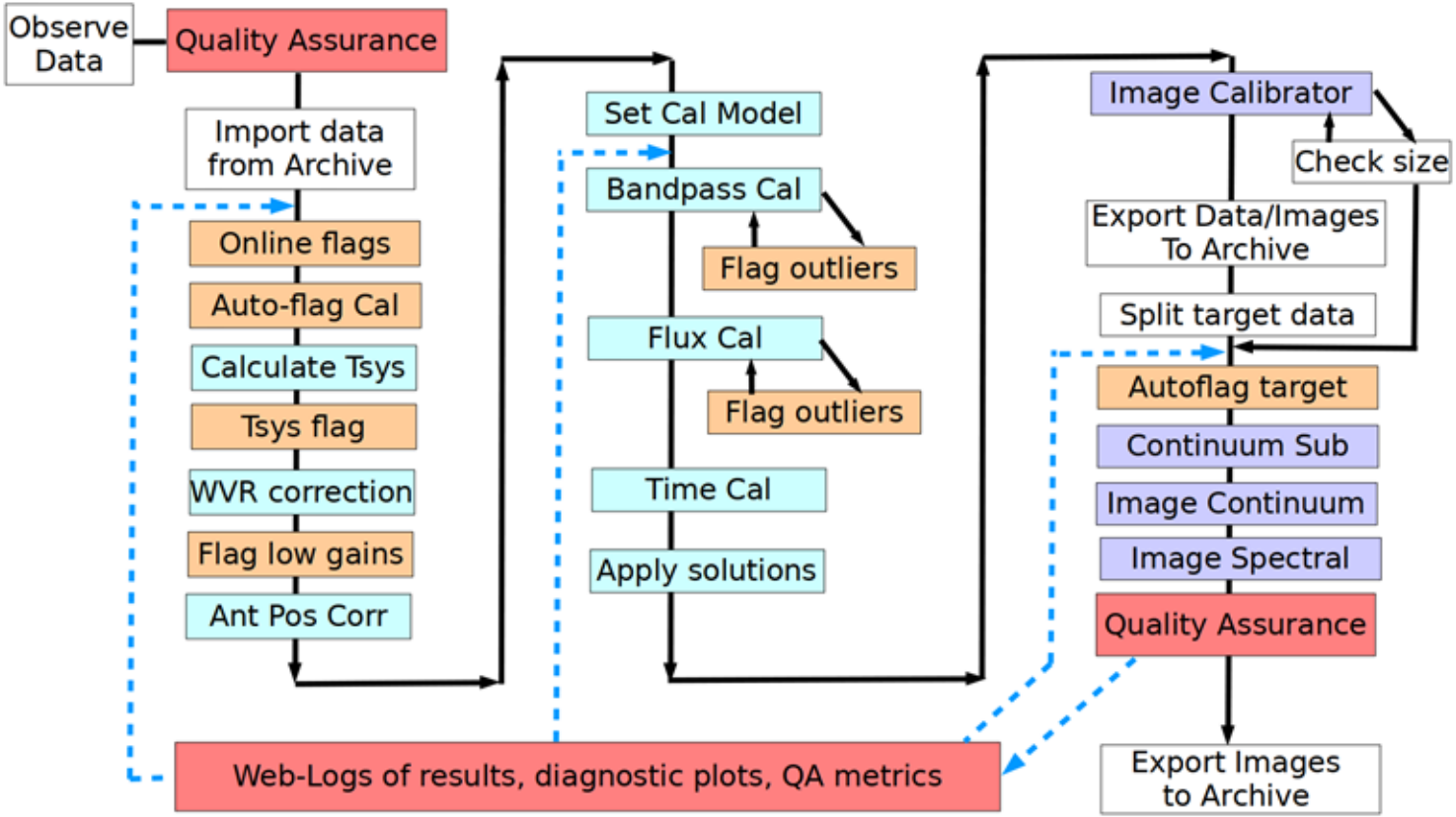
Thu May 28 + Mon June 1

Manual Data Reduction (Tutorials)

Thu May 28 – Self-Calibration

Tue Jun 2 – Image Analysis
Error Recognition

Data Processing Pipelines



A simplified depiction of the ALMA Pipeline

Current pipeline heuristics : Hunter et al 2023

Wed Jun 3

Science Ready Data Products

\+ **Tutorials**

Measurement Equation ++

Measurement Equation ++

$$V_{ij}^{obs}(\nu,t) \approx M_{ij}(\nu,t)\,S_{ij}(\nu,t)\iint I(l,m)\,e^{2\pi i(ul+vm)}\,dl\,dm + n_{ij} + N_{ij}^{RFI}$$

Measurement Equation ++

$$V_{ij}^{obs}(\nu,t) \approx M_{ij}(\nu,t) S_{ij}(\nu,t) \iint I(l,m) e^{2\pi i(ul+vm)} dl\, dm + n_{ij} + N_{ij}^{RFI}$$

Direction-independent effects

g_i

Measurement Equation ++

$$V_{ij}^{obs}(\nu,t) = M_{ij}(\nu,t)\, S_{ij}(\nu,t) \iiint M_{ij}^{dd}(l,m)\, I(l,m)\, e^{2\pi i(ul+vm+w(n-1))}\, dl\, dm\, dn \;+\; n_{ij} \;+\; N_{ij}^{RFI}$$

Direction-independent effects

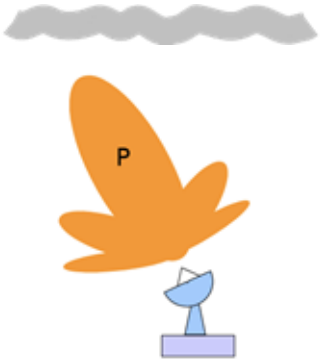
g_i

Direction-dependent effects

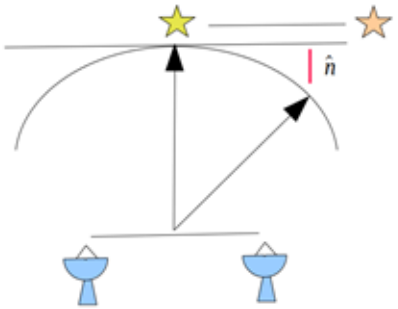
Measurement Equation ++

$$V_{ij}^{obs}(\nu,t) = M_{ij}(\nu,t)\, S_{ij}(\nu,t) \iiint M_{ij}^{dd}(l,m)\, I(l,m)\, e^{2\pi i(ul+vm+w(n-1))}\, dl\, dm\, dn \;+\; n_{ij} \;+\; N_{ij}^{RFI}$$

Direction-dependent effects



Instrumental and Propagation Effects



Geometric Effects

Measurement Equation ++

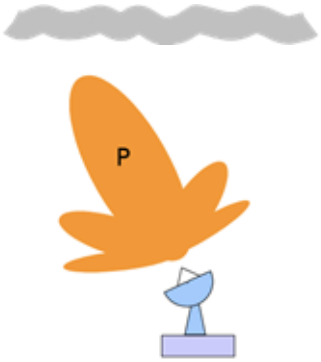
$$V_{ij}^{obs}(\nu,t) = M_{ij}(\nu,t)\, S_{ij}(\nu,t) \iiint M_{ij}^{dd}(l,m)\, I(l,m)\, e^{2\pi i(ul+vm+w(n-1))}\, dl\, dm\, dn \;+\; n_{ij} \;+\; N_{ij}^{RFI}$$

Direction-dependent effects

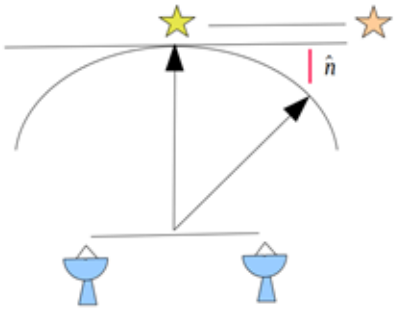
Fri May 29

Wide-field Imaging

- Primary Beams and full-beam imaging
- Mosaic Imaging
- W-term and non-coplanar arrays



Instrumental and Propagation Effects



Geometric Effects

Measurement Equation ++

$$V_{ij}^{obs}(\nu,t) = M_{ij}(\nu,t)\,S_{ij}(\nu,t)\iiint M_{ij}^{dd}(l,m,\nu,t)\,I(l,m,\nu,t)\,e^{2\pi i(ul+vm+w(n-1))}\,dl\,dm\,dn + n_{ij} + N_{ij}^{RFI}$$

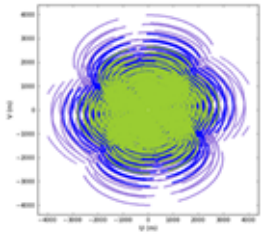
Frequency Dependent Effects

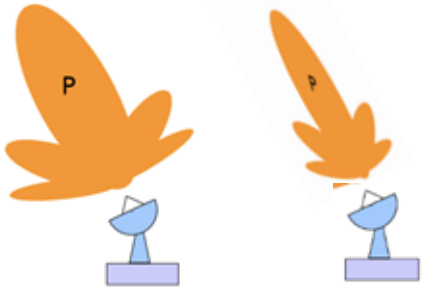
Measurement Equation ++

$$V_{ij}^{obs}(\nu,t) = M_{ij}(\nu,t)\,S_{ij}(\nu,t) \iiint M_{ij}^{dd}(l,m,\nu,t)\,I(l,m,\nu,t)\,e^{2\pi i(ul+vm+w(n-1))}\,dl\,dm\,dn + n_{ij} + N_{ij}^{RFI}$$

Frequency Dependent Effects

Instrument :
Response scales with frequency





Measurement Equation ++

$$V_{ij}^{obs}(\nu,t) = M_{ij}(\nu,t)\,S_{ij}(\nu,t) \iiint M_{ij}^{dd}(l,m,\nu,t)\,I(l,m,\nu,t)\,e^{2\pi i(ul+vm+w(n-1))}\,dl\,dm\,dn + n_{ij} + N_{ij}^{RFI}$$

Frequency Dependent Effects

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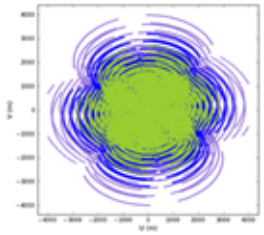
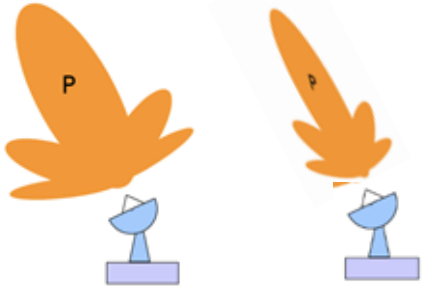
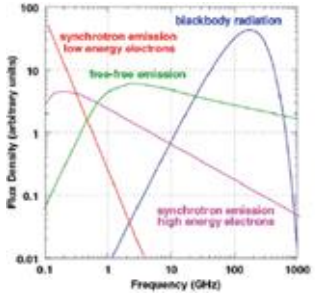
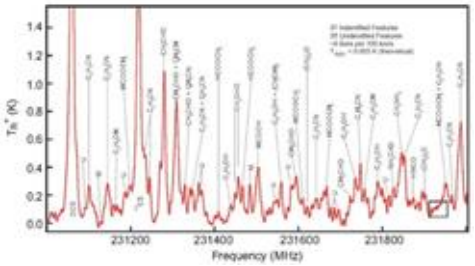
Response scales with frequency





Sky :
Brightness distribution is frequency-dependent

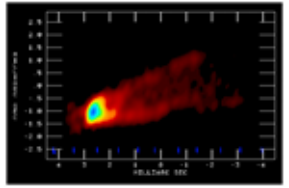




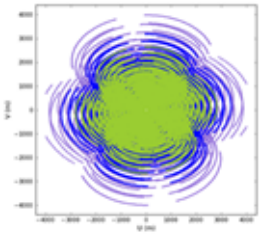
Measurement Equation ++

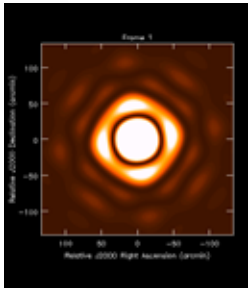
$$V_{ij}^{obs}(\nu,t) = M_{ij}(\nu,t)\,S_{ij}(\nu,t) \iiint M_{ij}^{dd}(l,m,\nu,t)\,I(l,m,\nu,t)\,e^{2\pi i(ul+vm+w(n-1))}\,dl\,dm\,dn + n_{ij} + N_{ij}^{RFI}$$

Frequency Dependent Effects & Time Dependence

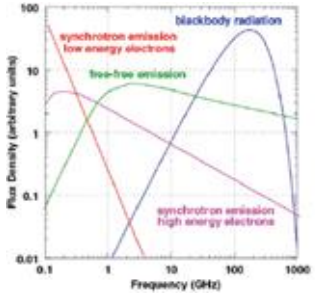


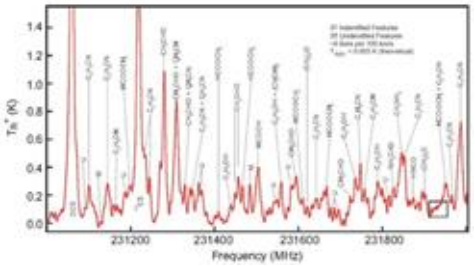
Instrument :
Response scales with frequency





Sky :
Brightness distribution is frequency-dependent





Measurement Equation ++

$$V_{ij}^{obs}(\nu,t) = M_{ij}(\nu,t)\,S_{ij}(\nu,t)\iiint M_{ij}^{dd}(l,m,\nu,t)\,I(l,m,\nu,t)\,e^{2\pi i(ul+vm+w(n-1))}\,dl\,dm\,dn + n_{ij} + N_{ij}^{RFI}$$

Frequency Dependent Effects

Fri May 29

WideBand Imaging

- Multi-frequency synthesis
- Wideband sky model
- Wideband Primary Beams

Fri May 29

Spectral Line Imaging

- Doppler shifts and Velocities
- Working with large cubes
- Bandpass calibration and line self-calibration

More Use-Cases

More ways to extend the concepts covered so far….

Thu May 28 — Very Long Baseline Interferometry

Extreme angular resolution, No real-time correlation, Fringe fitting during data analysis,etc…

Tue Jun 2 — Low Frequency Radio Interferometry

Aperture arrays, station beams (primary beam), ionospheric effects, etc…

Tue Jun 2 — High Frequency Radio Interferometry

Atmospheric effects, Water vapor, Pointing accuracy, etc..

[**Interferometry of Solar System Objects** - see slides from 16th SIW workshop

Extra delay/phase corrections to 'follow' a source moving against the celestial sphere]

Tue June 2 : Optical Interferometry (4 lectures) - Magdalena Ridge Observatory

Compare and contrast radio vs optical interferometry - theory and instrumentation

Data Reduction Tutorials

	ALMA	VLA	VLBA
Thursday May 28	Calibrate ALMA data and inspect data quality (CASA)	End-to-end continuum Processing / Imaging (CASA)	Spectral lines and Astrometry (AIPS)
Monday June 1	Imaging ALMA data and visualizing image cubes (CASA / CARTA)	End-to-end high-freq spectral line processing (CASA)	Phase referencing calibration (CASA)
Wednesday June 3	ALMA Pipeline products, restoring calibrated data, evaluate processing quality (CASA)	VLA Spectral Line and Continuum pipelines - use and evaluation (CASA)	Phase referencing calibration (CASA)

Mon Jun 1 : Receiver hardware demo

Wed Jun 3 : Demo of optical interferometry data processing

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