The Next Generation of Radio Interferometers

Principles, Challenges, and Plans for the RSST Square Kilometer Array Concept

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What I will talk about…

Part I

- Principles of Radio Interferometry
- Techniques of Interferometric Imaging
- Challenges Ahead

Part II

- The Square Kilometer Array / RSST
- The path forward here in NM

Part I: Principles of Radio Interferometry and Image Processing

Interferometric Imaging

- Principles of Interferometry
  - Interferometry 101
- Techniques of Interferometric Imaging
  - Imaging algebra
  - Maximum Likelihood (Optimal) Maps
  - Dirty Maps
  - Deconvolution
  - Model Spaces and Multiscale Methods
  - Self-calibration
- Challenges Ahead

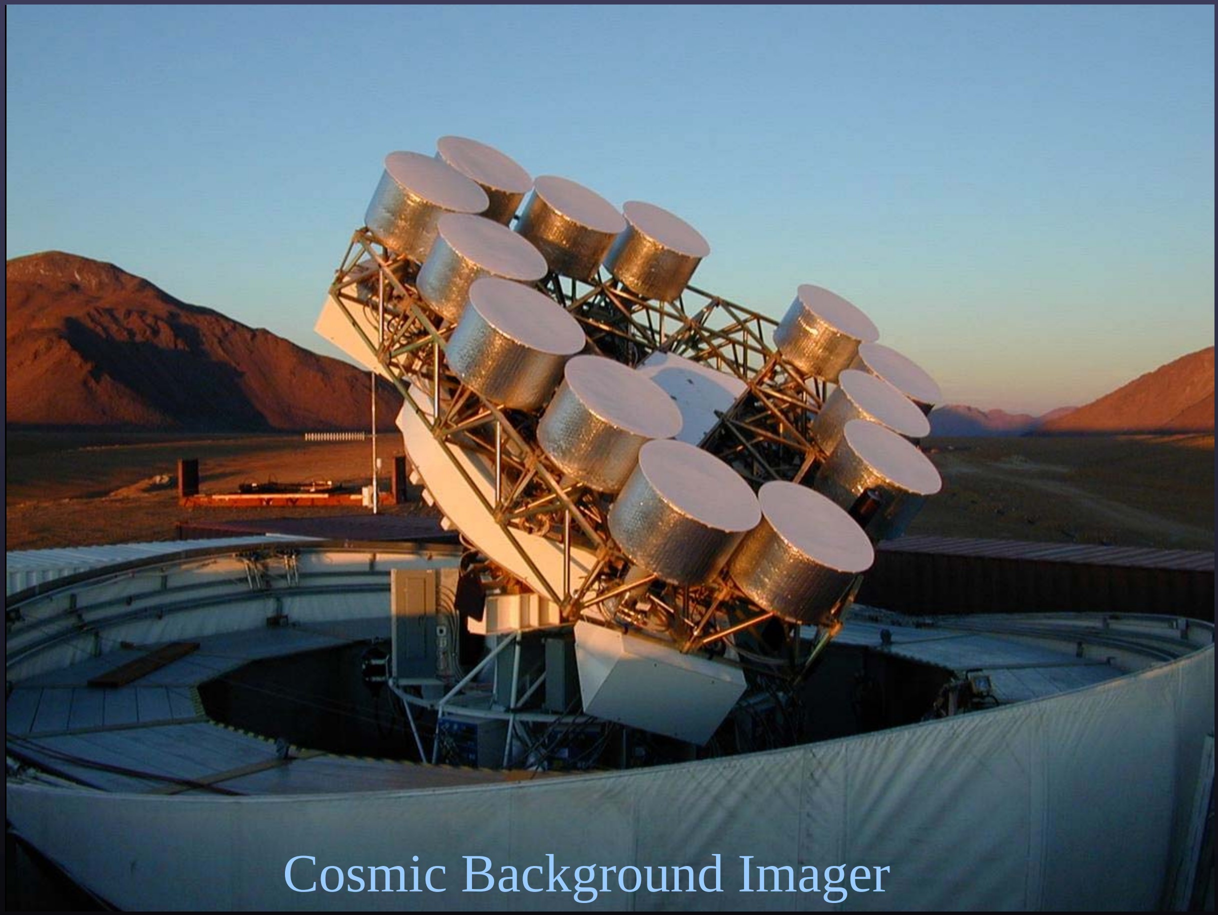
Radio Interferometry

Traditional Inteferometer – The VLA

- The Very Large Array (VLA)
  - 27 elements, 25m antennas, 74 MHz – 50 GHz (in bands)
  - independent elements ➔ Earth rotation synthesis

CMB Interferometer – The CBI

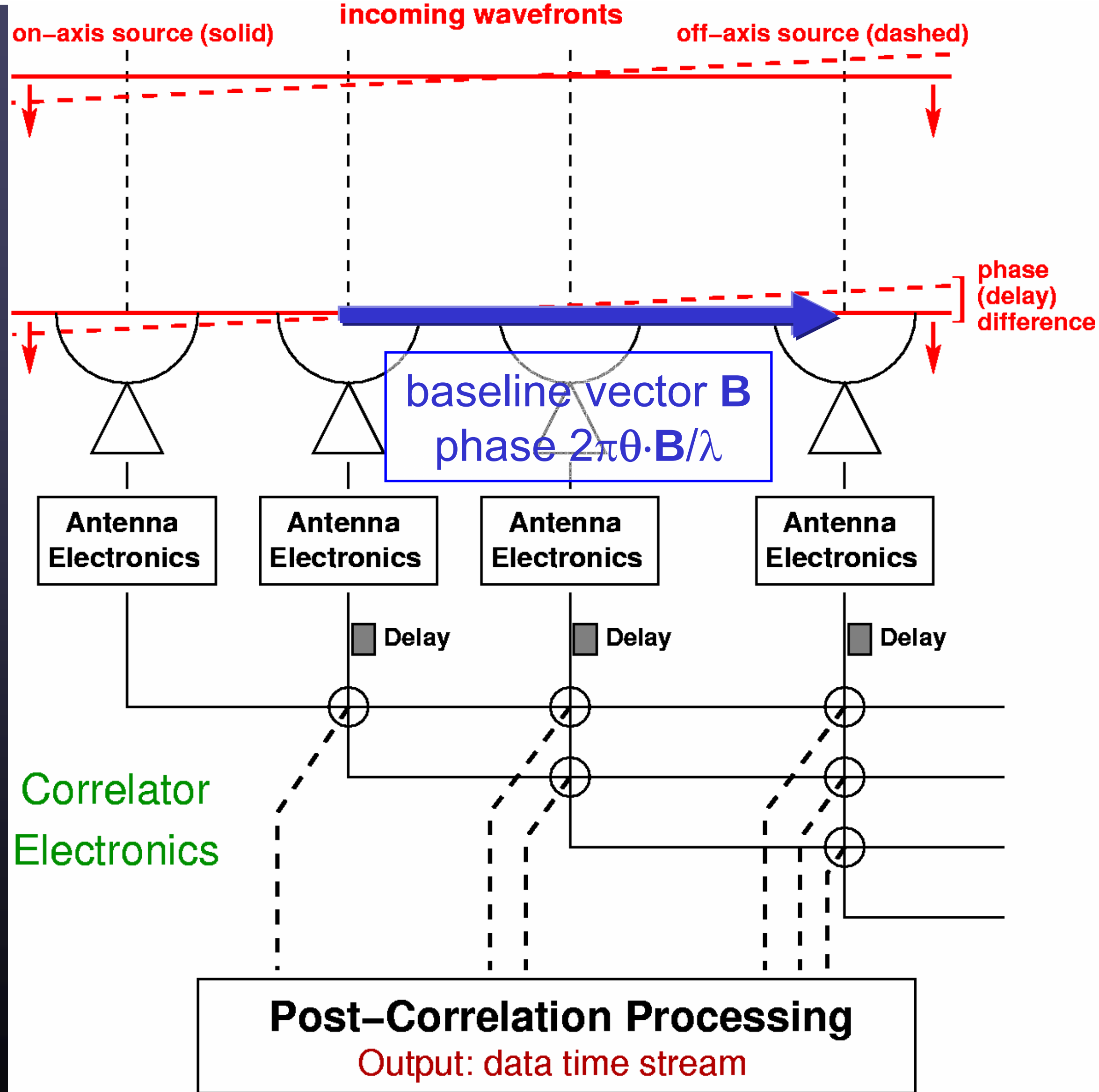
- The Cosmic Background Imager (CBI)
  - 13 elements, 90 cm antennas, 26-36 GHz (10 channels)
  - fixed to platform, telescope rotation synthesis!



Cosmic Background Imager

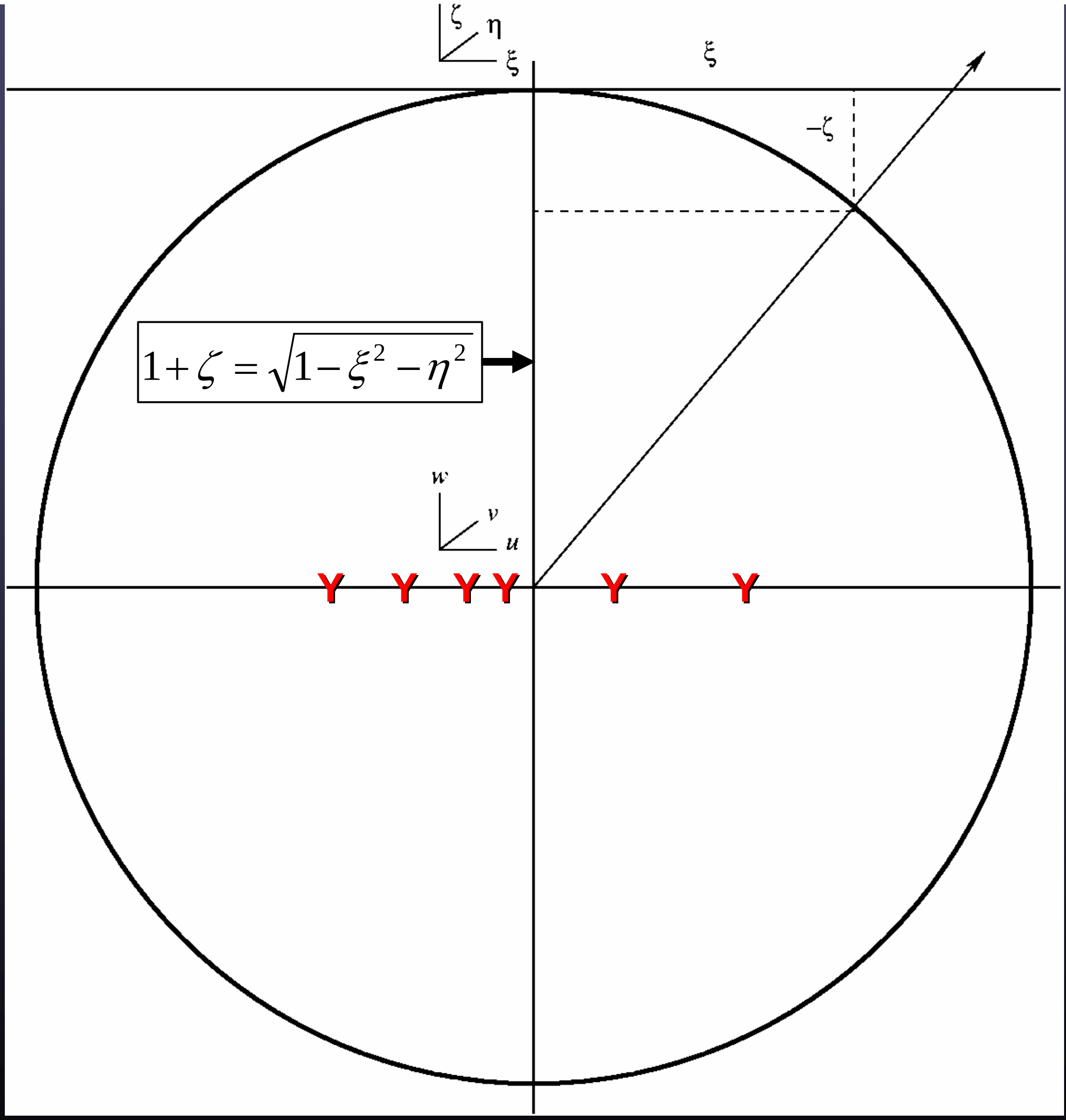
Radio Interferometer – schematic

- Spatial coherence of radiation
  - wave-front correlations
  - structure of source
- Correlate pairs of antennas
  - "visibility" = correlated fraction of total signal, calibrated as flux density
  - correlate real (cosine) and imaginary (90° shift=sine): amplitude and phase
- Function of baseline **B**
  - measures spatial frequencies $\boldsymbol{u} = \boldsymbol{B} / \lambda$
  - longer baselines = higher resolution
  - similar to double-slit interference and diffraction



Standard sky geometry

- sky:
  - unit sphere
  - tangent plane
  - direction cosines
  - $\boldsymbol{\xi} = (\xi,\eta,\zeta)$
- interferometer:
  - $\mathbf{u} = \mathbf{B} / \lambda$
  - $\mathbf{u} = (u,v,w)$
- project plane-wave onto baseline vector
  - phase $2\pi\ \boldsymbol{\xi}\cdot\mathbf{u}$



Wavefront correlations

- Sum wavefronts over (incoherent) source distribution

$$V(u,v,w) = \iint \frac{d\xi\, d\eta}{1+\zeta} I(\xi,\eta)\, e^{i2\pi \boldsymbol{\xi}\cdot\mathbf{u}}$$

Visibility in *uv*-plane

Intensity field on sky

$$\boldsymbol{\xi} = (\xi,\eta,\zeta) \qquad \mathbf{u} = (u,v,w)$$

$$1+\zeta = \sqrt{1-\xi^2-\eta^2}$$

- for small fields-of-view can ignore w term, treat as 2D Fourier transform pair (Van Cittert-Zernicke theorem)

$$V(u,v) = \int dx\,dy\, I(x,y)\, e^{i2\pi(ux+vy)}$$

Basic Interferometry

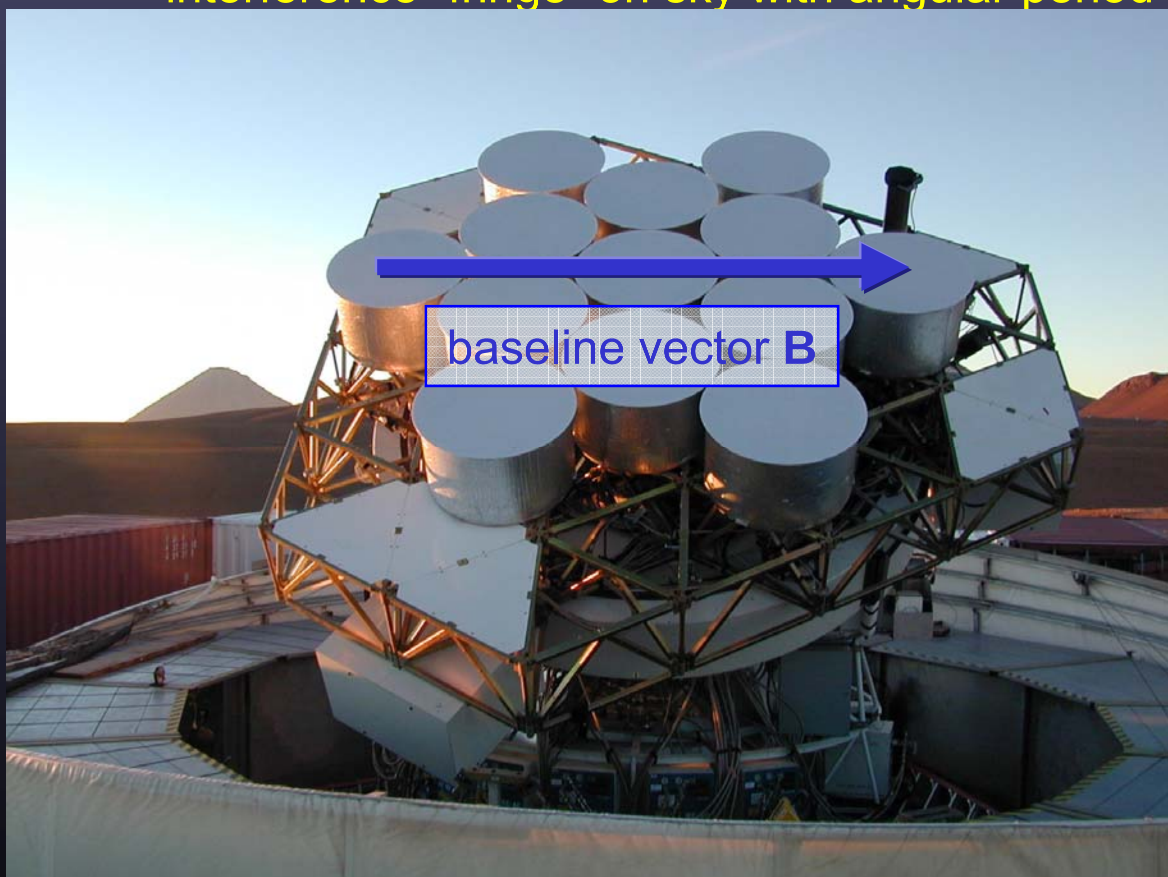
- An interferometer naturally measures the transform of the sky intensity in *uv*-space convolved with aperture
  - cross-correlation of aperture voltage patterns in uv-plane
  - its transform **A** on sky is the <u>primary beam</u> with FWHM ~ λ/D
  - uv-plane convolution restricts field of view

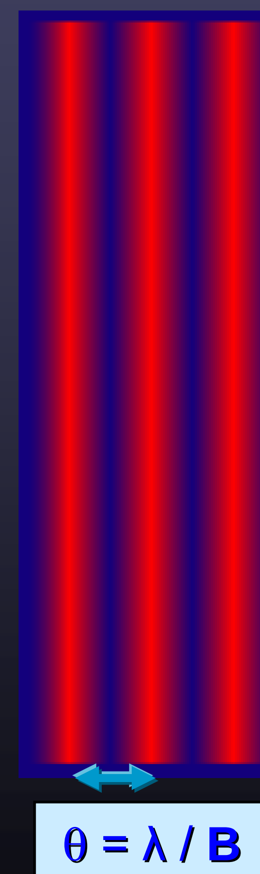
$$V(\mathbf{u}) = \int d^2\mathbf{x}\, A(\mathbf{x}-\mathbf{x}_p)\, I(\mathbf{x})\, e^{-2\pi i\,\mathbf{u}\cdot(\mathbf{x}-\mathbf{x}_p)} + \mathrm{e}$$
$$= \int d^2\mathbf{v}\, \tilde{A}(\mathbf{u}-\mathbf{v})\, \tilde{I}(\mathbf{v})\, e^{2\pi i\,\mathbf{v}\cdot\mathbf{x}_p} + \mathrm{e}$$

- For small (sub-radian) scales the spherical sky can be approximated by the Cartesian tangent plane
  - spherical harmonics can be approximated as a Fourier transform for The conjugate variables are customarily (*u,v*) in radio interferometry, with $|\mathbf{u}| = \ell / 2\pi$ for spherical harmonic multipole ℓ >>1

Interferometer Baselines

- Baseline vector ***B*** in "aperture plane"
  - coherent signal applied to interferometer would produce plane-wave interference "fringe" on sky with angular period λ/B

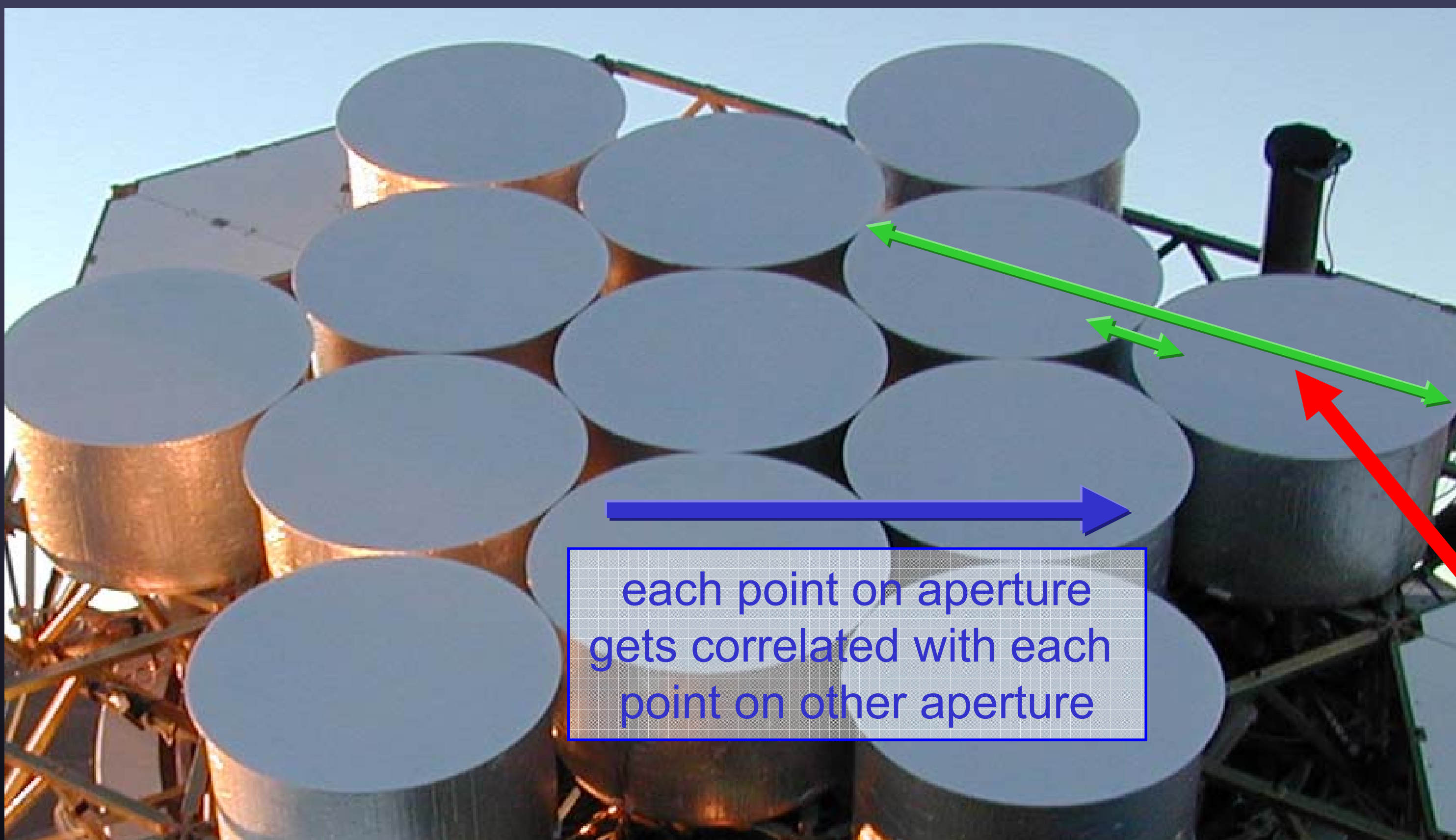




<u>interferometer naturally decomposes sky into plane waves!</u>

The Aperture Plane

- Correlate wavefronts in plane of apertures (Fourier transform of sky)
  - dish optics sum aperture plane at focus
  - visibility is cross-correlation of wavefronts of the 2 apertures



visibility contains range of baselines from closest to furthest parts of apertures

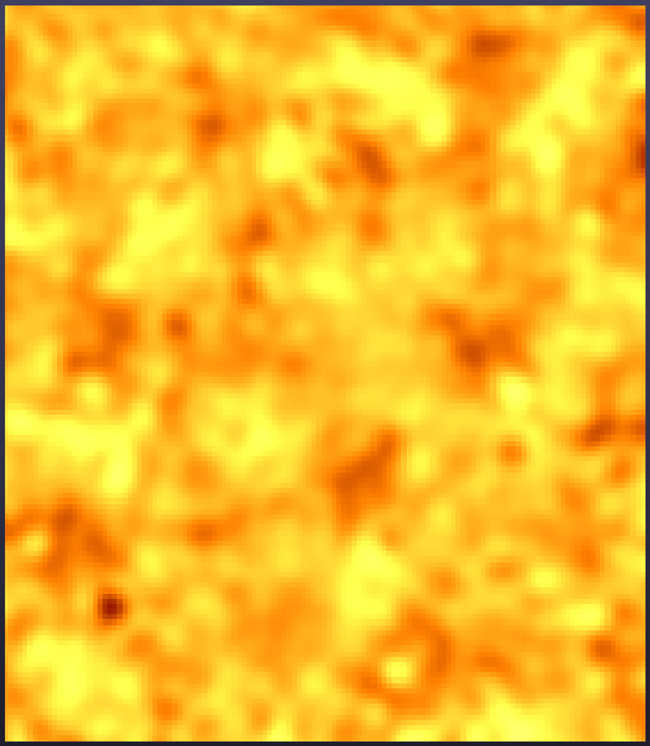
autocorrelations measure uv spacings inside D/λ

interferometer cannot measure "zero-spacing" w/o autocorrelations

From sky to uv-plane

The uv-plane is the Fourier Transform of the tangent plane to the sky

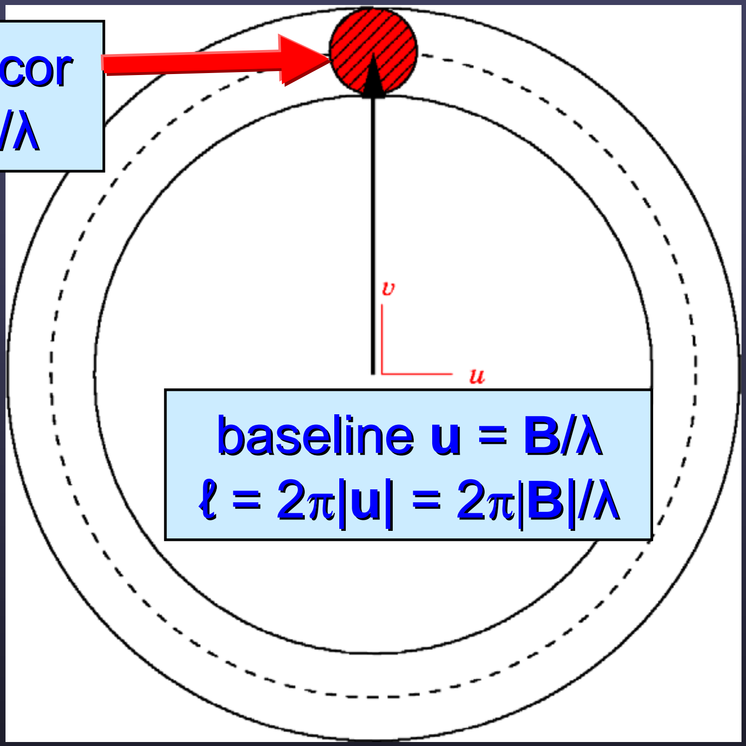
2.5^{o}



aperture xcor
width 2D/λ

F^{-1}

F



Sky Plane **x** = (x,y)

Fourier Plane **u** = (u,v)

$$V(\mathbf{u}) = \int d^2\mathbf{v}\, \tilde{A}(\mathbf{u}-\mathbf{v})\, \tilde{I}(\mathbf{v})\, e^{2\pi i\, \mathbf{v}\cdot\mathbf{x}_p} + \mathrm{n}$$

Polarization – Stokes parameters

- CBI or VLA receivers can observe RCP or LCP
  - cross-correlate RR, RL, LR, or LL from antenna pair
- Correlation products (RR,LL,RL,LR) to Stokes (I,Q,U,V) :

$$\begin{pmatrix} \langle e_R e_R^* \rangle \\ \langle e_R e_L^* \rangle \\ \langle e_L e_R^* \rangle \\ \langle e_L e_L^* \rangle \end{pmatrix} = \begin{pmatrix} I+V \\ (Q+iU)e^{-i2\theta} \\ (Q-iU)e^{i2\theta} \\ I-V \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 1 \\ 0 & e^{-i2\theta} & ie^{-i2\theta} & 0 \\ 0 & e^{i2\theta} & -ie^{-i2\theta} & 0 \\ 1 & 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

- note – similar relation for XY feeds

Polarization Interferometry : Q & U

- Parallel-hand & Cross-hand correlations
  - for visibility *k* (antenna pair *ij* , time, pointing *x*, and channel ν) :

$$V_k^{RR}(\mathbf{u}_k) = \int d^2\mathbf{v}\, \tilde{A}_k^{RR}(\mathbf{u}_k - \mathbf{v})\, \tilde{I}_\nu(\mathbf{v})\, e^{2\pi i\, \mathbf{v}\cdot\mathbf{x}_k} + \mathrm{e}_k^{RR}$$

$$V_k^{RL}(\mathbf{u}_k) = \int d^2\mathbf{v}\, \tilde{A}_k^{RL}(\mathbf{u}_k - \mathbf{v})\, \tilde{P}_\nu(\mathbf{v})\, e^{-i2\psi_k}\, e^{2\pi i\, \mathbf{v}\cdot\mathbf{x}_k} + \mathrm{e}_k^{RL}$$

  - where kernel A is the aperture cross-correlation function, and

$$\tilde{P}(\mathbf{v}) = \tilde{Q}(\mathbf{v}) + i\tilde{U}(\mathbf{v}) = \left|\tilde{P}(\mathbf{v})\right| e^{i2\phi(\mathbf{v})}$$

  - and ψ the baseline parallactic angle (w.r.t. deck angle 0°)

$$\psi_k = \tan^{-1}\left(v_k / u_k\right) - \psi_{ij0}$$

Interferometric Image Processing

From sky to Fourier domain

- The Fourier Transform
  - the sky in the image domain $\mathbf{x}_i = (x_i, y_i)$

    $\mathrm{s} \quad : \quad \mathrm{s}_i = \mathrm{s}(\mathbf{x}_i)$
  - the Fourier domain ("uv-plane") $\mathbf{u}_l = (u_l, v_l)$

    $\underline{s} \quad : \quad \underline{s}_l = \underline{s}(\mathbf{u}_l)$
  - the Fourier kernel

    $\mathrm{s} = \mathbf{F}\, \underline{s} \quad \Leftrightarrow \quad \underline{s} = \mathbf{F}^{-1}\, \mathrm{s}$

$$F_{il} = e^{2\pi i \mathbf{u}_l \cdot \mathbf{x}_i} \Leftrightarrow F_{li}^{-1} = e^{-2\pi i \mathbf{u}_l \cdot \mathbf{x}_i}$$

Visibilities

- Visibility in the uv-plane $\underline{v}_k = \underline{v}(\mathbf{u}_k)$

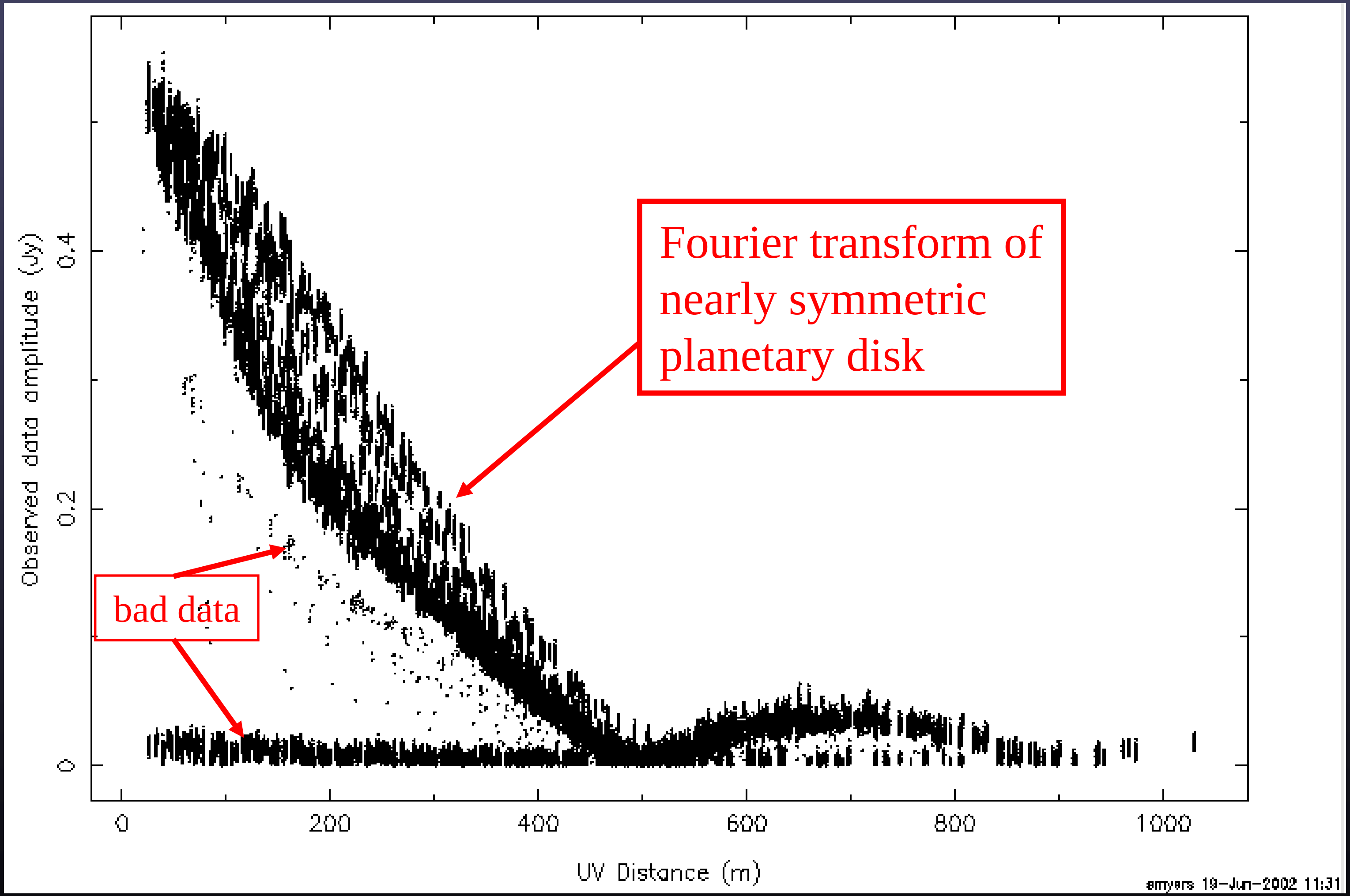
$$\underline{v} = \underline{\boldsymbol{A}}\,\underline{s} + \underline{n}$$

  - aperture (cross-correlation) function $\underline{\boldsymbol{A}}$
  - instrumental noise $\underline{n}$
- The Aperture Function
  - the cross-correlation of the voltage pattern of the two apertures forming the baseline

$$\underline{\mathbf{A}}_{kl} = \widetilde{A}(\mathbf{u}_k - \mathbf{u}_l)\, e^{-2\pi i \mathbf{u}_l \cdot \mathbf{x}_k}$$

Example: VLA observes Jupiter

- A 6cm VLA observation of Jupiter:



Reconstruction of the Sky

- Visibilities and the Sky

$$\underline{v} = \underline{\mathbf{A}}\, \mathbf{F}^{-1}\, s + \underline{n}$$

  - however: ***A*** is not invertible
  - instrumental noise *n* is a random variable
- The issues:
  - unknown random noise *n*
  - convolution due to size of ***A*** in uv domain
  - incomplete sampling of uv-plane by visibilities
- One approach – statistical inference:
  - Maximum Likelihood Estimation

Maximum Likelihood Reconstruction

- The noise and its covariance

$$\underline{n} = \underline{v} - \underline{\mathbf{A}}\ \underline{s} \quad : \quad \underline{\mathbf{N}} = \langle \underline{n}\ \underline{n}^{\mathrm{T}} \rangle$$

  - if noise is uncorrelated (Gaussian) then $\underline{\mathbf{N}}$ is diagonal

$$\underline{N}_{kk'} = \sigma_k^2\ \delta_{kk'}$$

- The likelihood function

$$\mathcal{L}(\underline{\mathbf{s}} \mid \underline{\mathbf{v}}) = \det\left(2\pi\underline{\mathbf{N}}\right)^{-1/2} \exp\left[-\tfrac{1}{2}(\underline{\mathbf{v}} - \underline{\mathbf{A}}\underline{\mathbf{s}})^T \underline{\mathbf{N}}^{-1}(\underline{\mathbf{v}} - \underline{\mathbf{A}}\underline{\mathbf{s}})\right]$$

  - find map $\underline{m}$ that maximizes L

$$dL/d\underline{s}\ |_{\underline{s}=\underline{m}} = 0$$

  - Maximum Likelihood Estimate (MLE) :

$$m_{\mathrm{MLE}} = (\ \underline{\mathbf{A}}^{\mathrm{T}}\ \underline{\mathbf{N}}^{-1}\ \underline{\mathbf{A}})^{-1}\ \underline{\mathbf{A}}^{\mathrm{T}}\ \underline{\mathbf{N}}^{-1}\ \underline{v}$$

The Optimal Map

- The MLE map

$$m_{MLE} = (\underline{\boldsymbol{A}}^{T}\, \underline{\boldsymbol{N}}^{-1}\, \underline{\boldsymbol{A}})^{-1}\, \underline{\boldsymbol{A}}^{T}\, \underline{\boldsymbol{N}}^{-1}\, \underline{v}$$

  - refactor in terms of gridding and deconvolving

$$\underline{m} = \underline{\boldsymbol{R}}^{-1}\, \underline{d} \qquad \underline{d} = \underline{\boldsymbol{H}}\, \underline{v} = \underline{\boldsymbol{R}}\, \underline{s} + \underline{n}_{d}$$

  - with kernels

$$\underline{\boldsymbol{R}} = \underline{\boldsymbol{H}}\, \underline{\boldsymbol{A}} \qquad \underline{\boldsymbol{H}}_{MLE} = \underline{\boldsymbol{A}}^{T} \underline{\boldsymbol{N}}^{-1} \qquad \underline{\boldsymbol{R}}_{MLE} = \underline{\boldsymbol{A}}^{T} \underline{\boldsymbol{N}}^{-1} \underline{\boldsymbol{A}}$$

  - noises

$$\underline{n}_{d} = \underline{\boldsymbol{H}}\, \underline{n} \qquad \underline{\boldsymbol{N}}_{d} = < \underline{n}_{d}\, \underline{n}_{d}^{T} > = \underline{H}\, \underline{\boldsymbol{N}}\, \underline{H}^{T}$$

- The problem:
  - $\underline{\boldsymbol{R}}$ is singular (or at best ill-conditioned) for fully sampled $\underline{s}$

The Dirty Map

- Grid onto sampled uv-plane

$$\underline{d} = \underline{\boldsymbol{H}}\,\underline{\boldsymbol{v}} = \underline{\boldsymbol{H}}\,\underline{s} + \underline{n}_d$$

  - $\underline{\boldsymbol{H}}$ should be close to $\underline{\boldsymbol{H}}_{MLE}$, e.g.

$$\underline{\boldsymbol{H}} = \underline{\boldsymbol{B}}^T\,\underline{N}^{-1} \quad : \quad \underline{\boldsymbol{B}} \sim \underline{\boldsymbol{A}}$$

  - $\underline{\boldsymbol{B}}^T$ should sample onto suitable grid in uv-plane

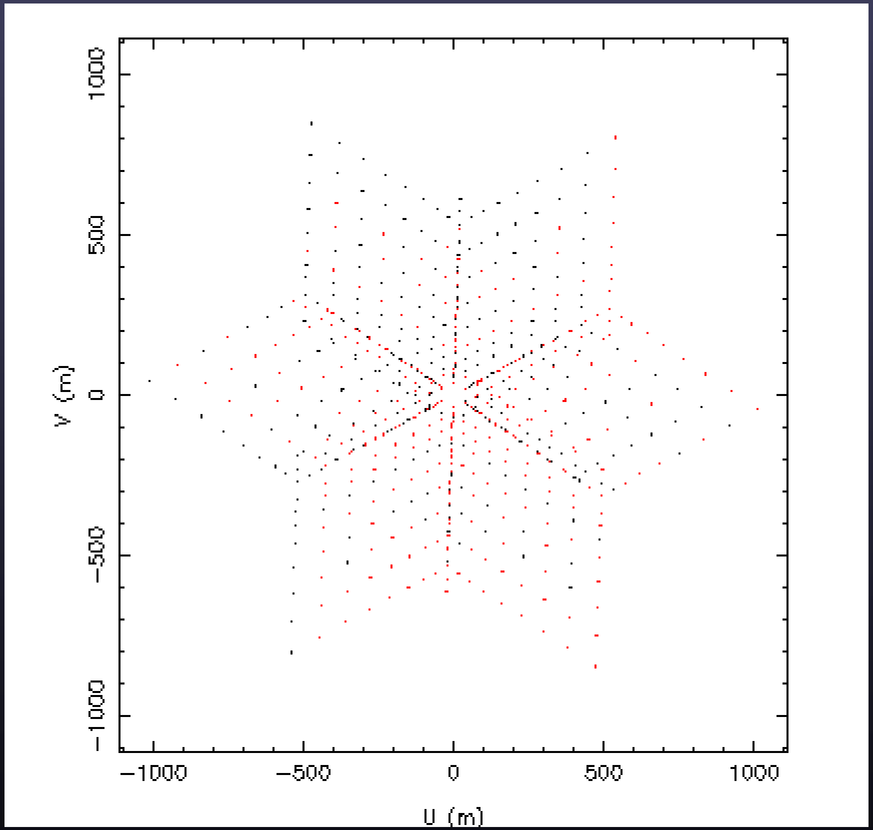
- Invert onto sky ➔ “dirty image”

$$\mathrm{d} = \mathbf{F}\,\underline{d} = \mathbf{R}\,\mathrm{s} + \mathrm{n}_d \qquad \mathbf{R} = \mathbf{F}\,\underline{\boldsymbol{R}}\,\mathbf{F}^{-1}$$

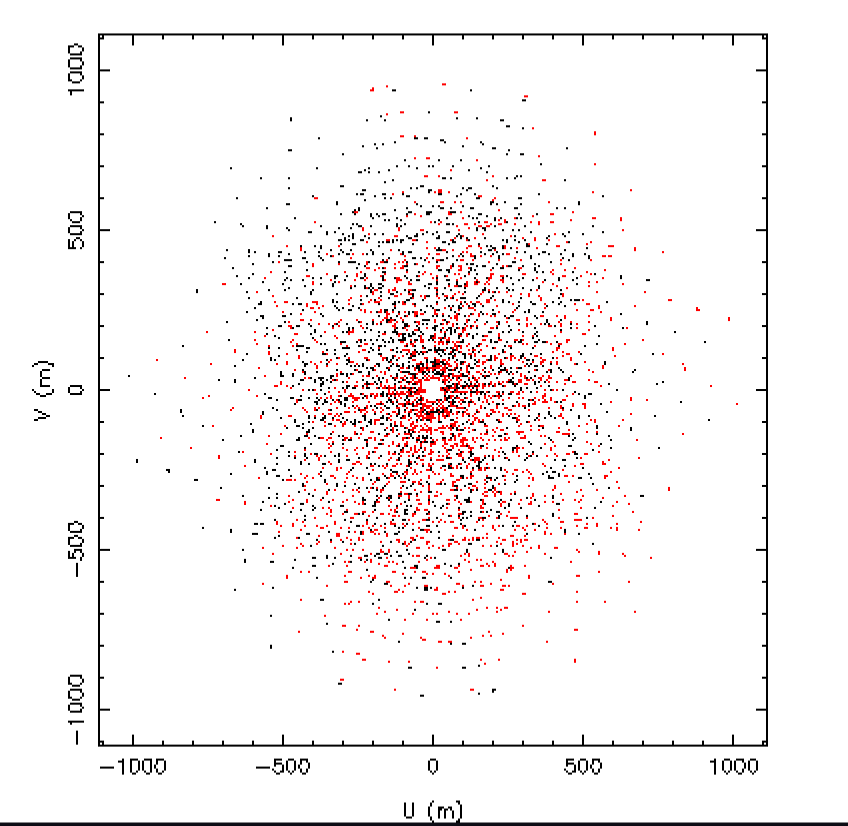
  - image is “dirty” as it contains artifacts
    - convolution by “point spread function” (columns of **R**)
    - multiplication by response function (diagonal of **R**)
    - noise

VLA uv coverage

- The VLA is an example of a sparsely filled array
  - there are many unmeasured Fourier modes in uv-plane
  - image reconstruction from incomplete uv-coverage ambiguous



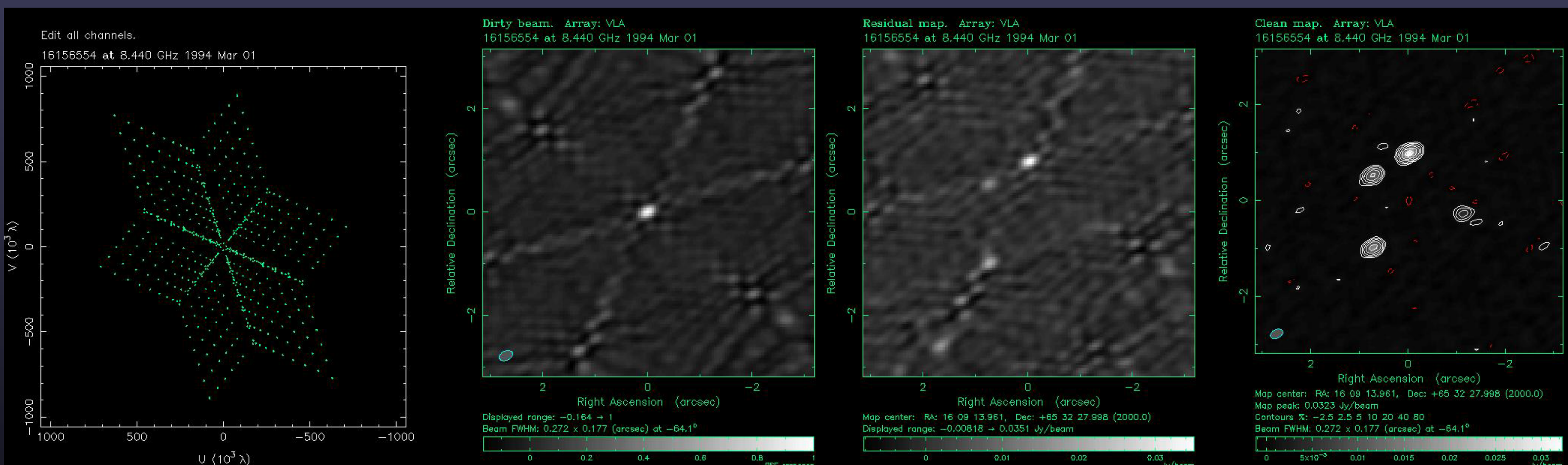
snapshot coverage



8 scans over 10 hours

VLA point-spread function (PSF)

- The VLA is an example of a sparsely filled array
  - uv-plane gaps are treated as zeroes, cause “sidelobes” in PSF
  - many solutions for sky that fit data, “dirty image” is principal solution
  - must use “deconvolution” techniques to “clean” image



snapshot uv-coverage | PSF “dirty beam” | “dirty” image | “clean” image

<u>Example: VLA 30s snapshot discovery data for gravitational lens CLASS B1608+656</u>

(Myers et al. 1995, ApJL, 447, L5-L8)

Image, uv, and Data Spaces

- image plane ⇔ uv-plane ⇔ visibilities
  - operators **F** , ***H*** , ***A*** handle these transformations
  - not all operators have inverses (*H* and ***A*** do not)
- example: model image m
  - first transform sky model to uv-plane

$$\underline{m} = \mathbf{F}^{-1}\, m$$

  - then project onto the visibilities (data space)

$$\underline{v}_m = \underline{\mathbf{A}}\, \underline{m} = A\, \mathbf{F}^{-1}\, m$$

  - form residual

$$\underline{\delta v}_m = \underline{v} - \underline{v}_m = \underline{\mathbf{A}}\, (\, \underline{s} - \underline{m}\,) + \underline{n}$$

  - finding "best model" will involve minimizing this residual

Classic Deconvolution

- CLEAN algorithm
  - iterate on dirty residual images removing point models
  - initial residual data, and model: $\delta \underline{v}_0 = \underline{v}$ $\quad m_0 = 0$
  - form dirty image: $d_0 = \mathbf{F}\, \underline{\boldsymbol{H}}\, \delta \underline{v}_0$
  - locate peak and residual and put fraction *f* into model

$$\delta m_1 = f\, M\, d_0 \qquad \text{mask } M: \text{ 1 at max, else 0}$$

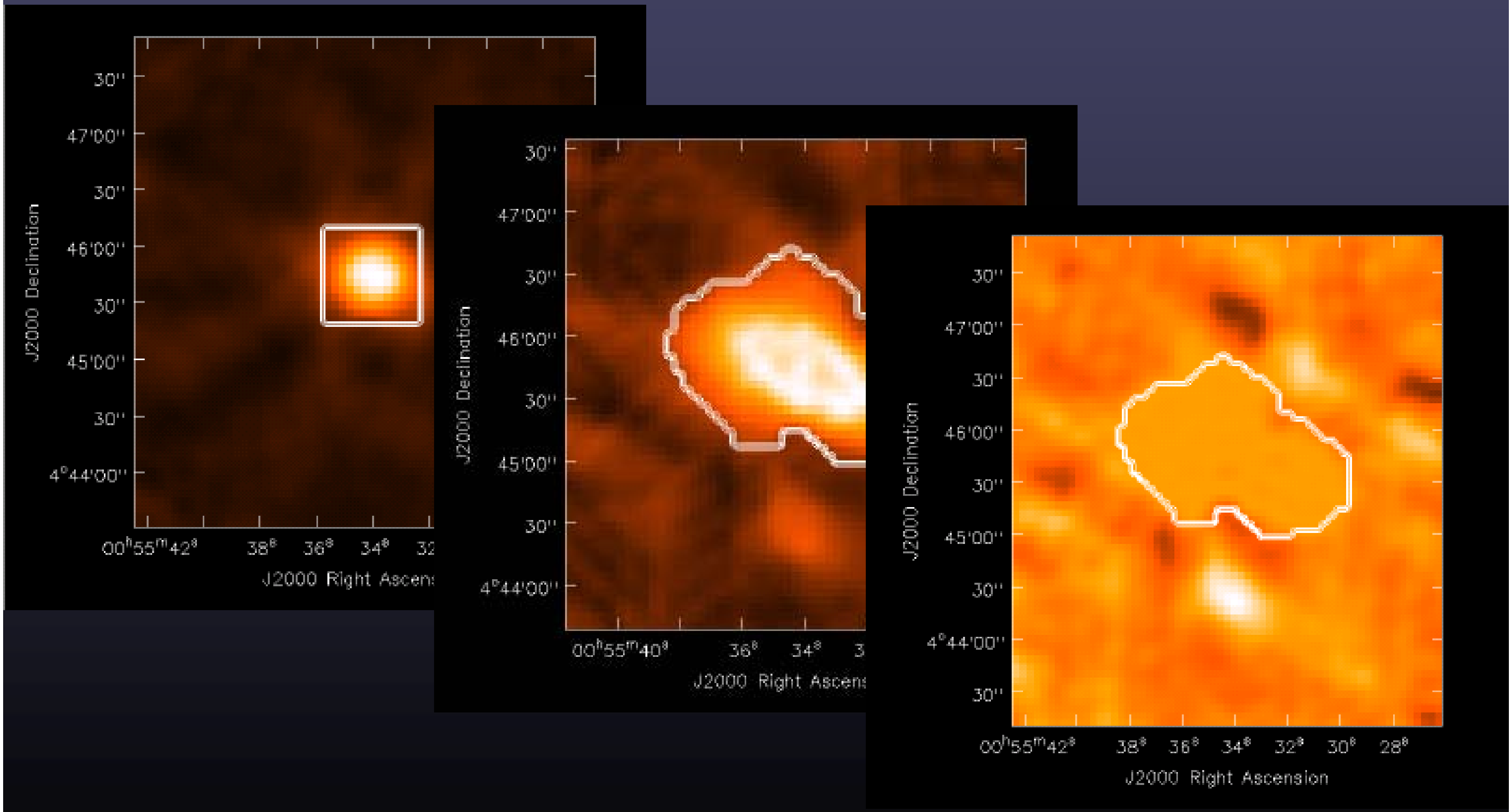
  - increment model: $m_1 = m_0 + \delta m_1$
  - form cumulative visibilities and residual

$$\underline{v}_1 = \underline{\boldsymbol{A}}\, \underline{m}_1 = \underline{\boldsymbol{A}}\, \mathbf{F}^{-1} m_1 \qquad \delta \underline{v}_1 = \underline{v} - \underline{v}_1$$

  - form new dirty residual image: $d_1 = \mathbf{F}\, \underline{\boldsymbol{H}}\, \delta \underline{v}_1$
  - and repeat until final residual image d_f is noise-like

CLEAN Example

- Jupiter 6cm – interactive cleaning in CASA



MEM and CLEAN

- CLEAN
  - algorithm: find peak in residual image; add fraction to model; form new residual data & residual image; iterate
  - performance: good on compact emission, difficult for extended
- Maximum Entropy Method (MEM)
  - algorithm: for pixel values p : maximize entropy $-\Sigma$ p ln p ; minimize $\chi^2(p)$
  - performance: complicated, suppresses spiky emission, but fast
- CLEAN and MEM use point (pixel) basis
  - complete basis – unique representation of image

Sparse Approximation Imaging

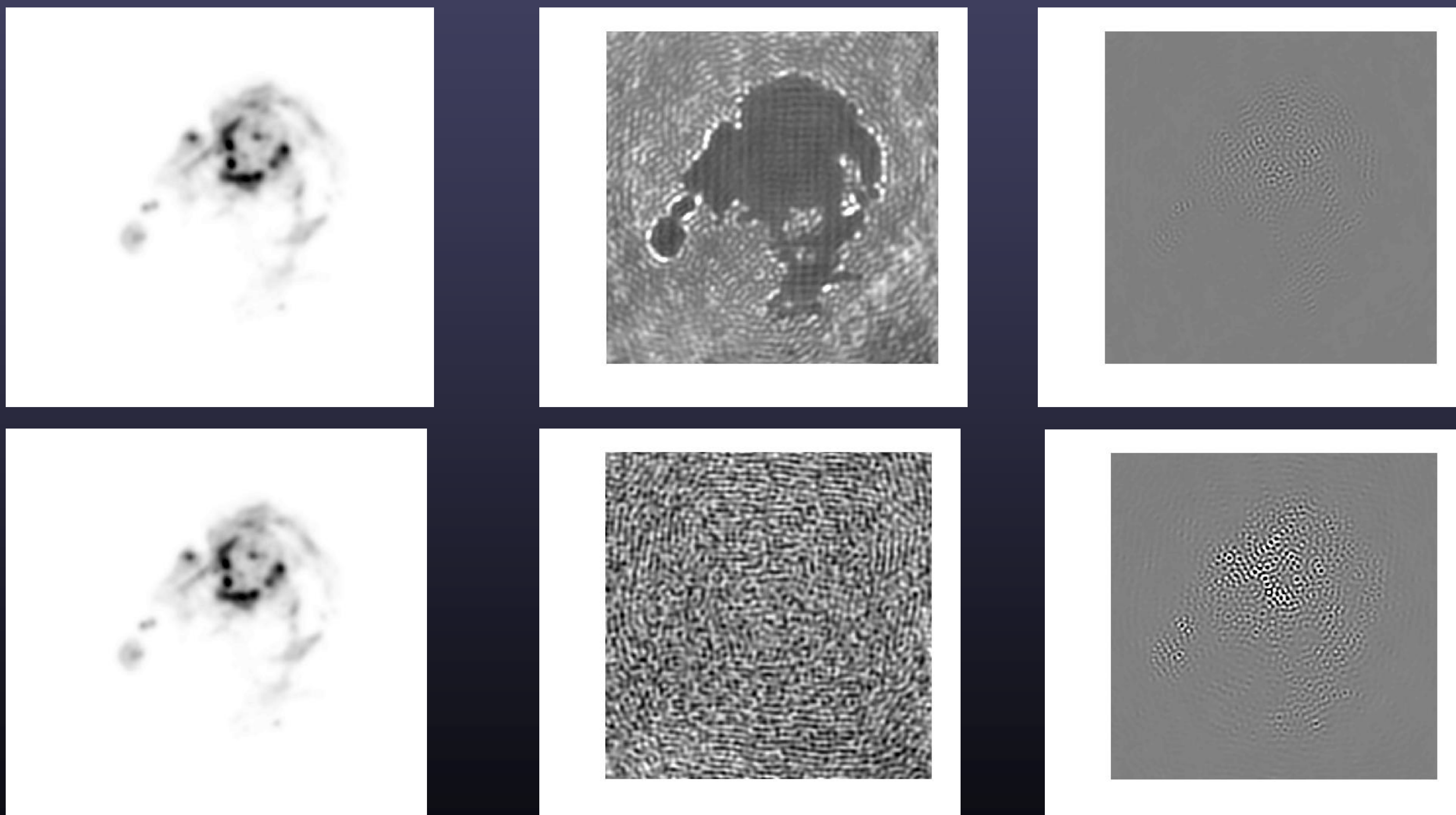
- Problem: find a model to represent the sky as efficiently as possible, subject to the data constraints and within the noise uncertainty, possibly also subject to prior constraints.
  - some problems (like ours) cannot be efficiently reconstructed using orthonormal bases (like pixels or Fourier modes)
  - extensive literature on this!
  - use non-orthogonal bases: multiscale (e.g. Gaussians)
  - choose *dictionary* of model elements (*atoms*)
  - efficiency: find a representation that uses the fewest number of atoms

Example: MEM versus CLEAN

Restored *Residual* *Error*

Maximum Entropy

MS Clean



The Future of Multiscale Methods

- Algorithms
  - mostly iterative, starting from a blank model
  - "greedy" methods make locally optimal choices at each step
- MS-CLEAN is a greedy algorithm in this class!
  - dictionary of points and Gaussians on different scales
  - is essentially a "Matching Pursuit" (MP) algorithm (e.g. Tropp 2004)
- Key Research Area for next decade
  - new arrays are designed for high dynamic range & fidelity
  - will need efficient, robust, and accurate multiscale methods
  - we are interested in collaboration with groups at LANL!

Challenges to the State of the Art

Challenges in Image Processing

- high data rates and large data volumes
- high dynamic range, high fidelity
- the multiscale problem
- direction-dependent calibration effects
- the ionosphere and atmosphere

- the EVLA and LWA will start to see these issues…

What is the EVLA?

- The Expanded Very Large Array
- retrofit VLA with state-of-the-art electronics
  – high-bandwidth fiber optic transmission
  – digitize signals at antennas
  – new wide-band digital correlator (up to 8GHz)
  – new receivers for full coverage from 1-50 GHz

The EVLA will provide

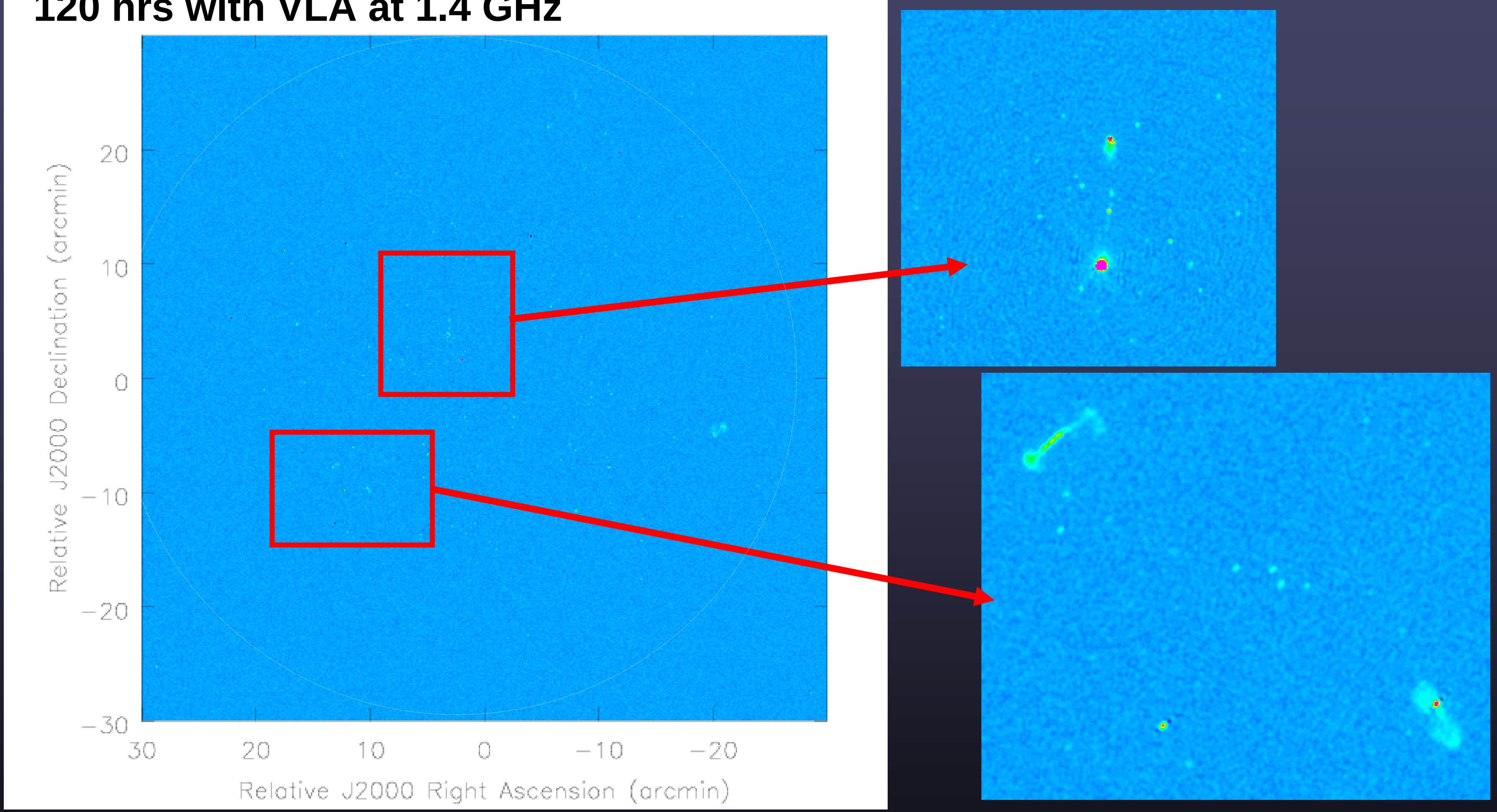
- High Data rates
  - 2008 spec 25 MB/s max (cf. VLA 0.1 MB/s)
  - sustained rate spec ramps up with time
  - WIDAR can produce much higher rates!
- Large Data Volumes
  - TeraByte datasets (25 MB/s = 2 TB/day)
  - thousands to millions of channels (16k – 4M)
  - will eventually need high-performance computing

How Much When?

- Near Term (2008)
  - 10 ant @ 1.5 GHz, commissioning, handle data
- Ramp Up (2009-2010)
  - implement and use current best algorithms
- Routine Use (2010-2012)
  - handle high-sensitivity wide-band continuum
- Full Operation (2012+)
  - improve efficiency to handle maximum data rates

Deep VLA image at 1.4GHz: 3μJy

120 hrs with VLA at 1.4 GHz

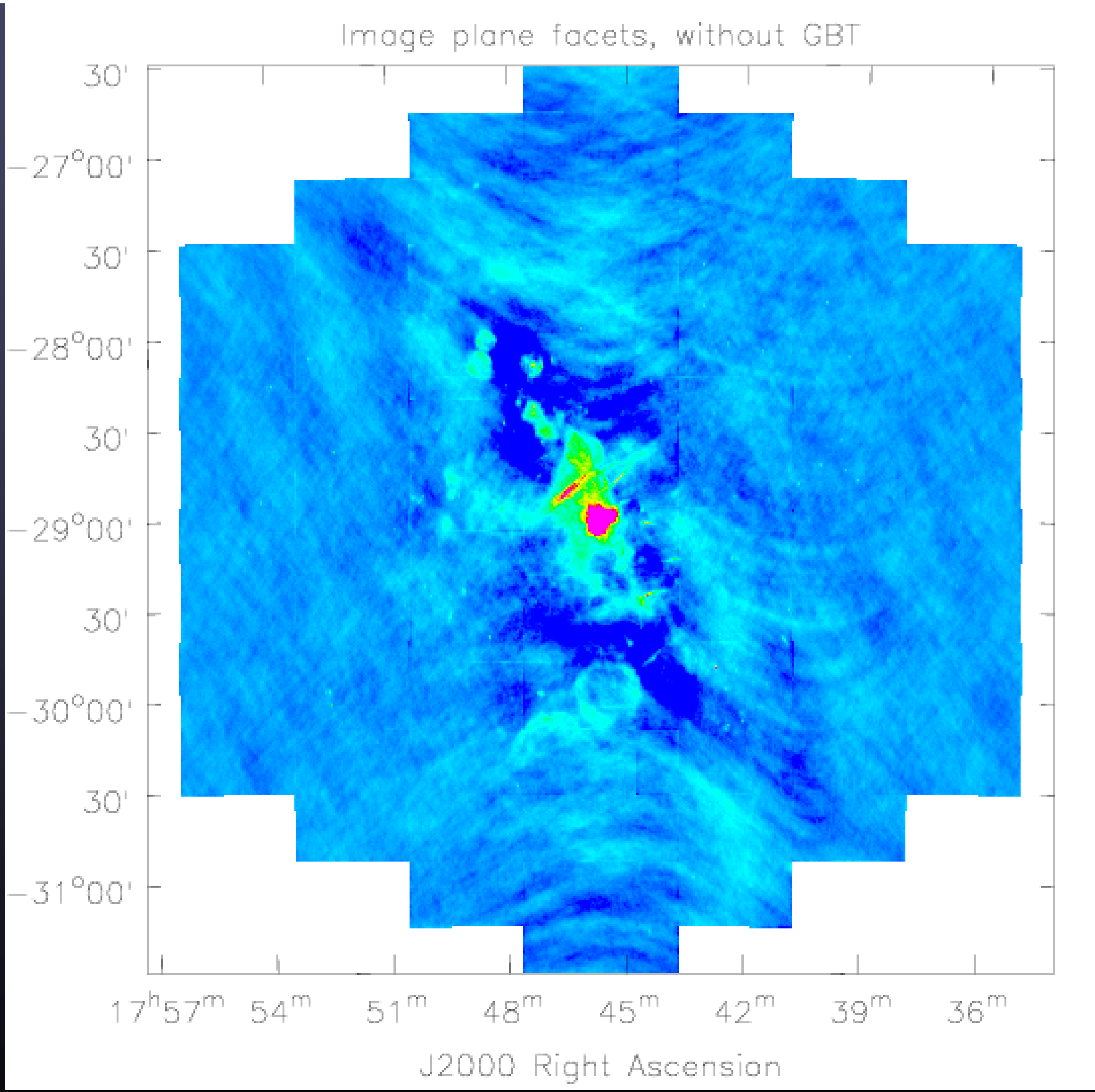


EVLA will go 3-10 times deeper, SKA will go 10 times deeper in a few hours

We are already limited by calibration effects (e.g. pointing errors)

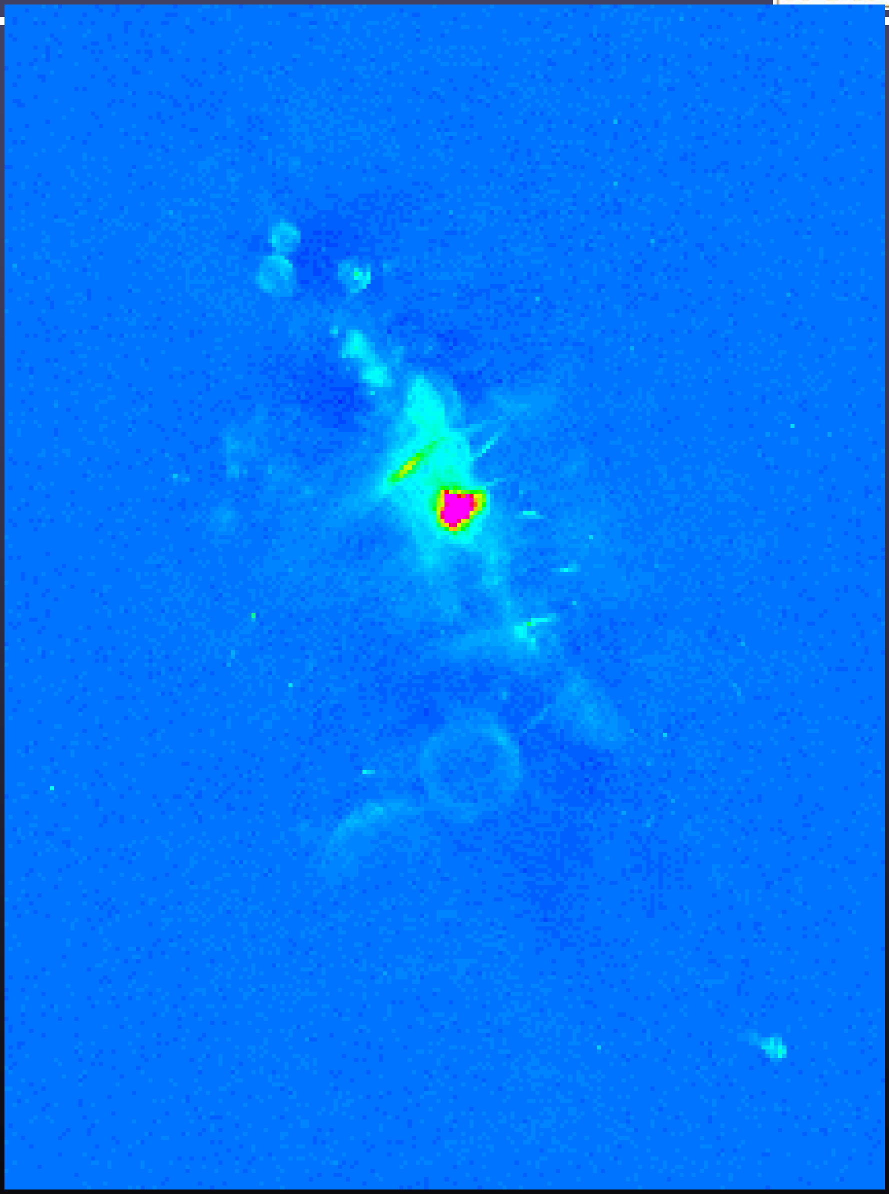
Galactic plane at 90cm

- Nord *et al.* observations
- AIPS IMAGR program using faceted transforms (Cornwell and Perley 1992)
- Poor deconvolution of extended emission
- Facet boundaries obvious



State of the Art: Wide-field image

- VLA B,C,D configs
- λ90cm
- imaged using w-projection to counter non-coplanar baselines effect
- deconvolved using Multi-scale CLEAN
- still residual errors and artifacts



Calibration and Imaging

- Some effects corrupt the visibilities
  - most are on a per-antenna basis, other per-baseline
  - antenna based effects can be “self-calibrated” out
- The Measurement Equation (ME)

$$V_{ij}^{obs} = \overset{\leftrightarrow}{J}_i \vec{s}_i \otimes \overset{\leftrightarrow}{J}_j^* \vec{s}_j^* = \left(\overset{\leftrightarrow}{J}_i \otimes \overset{\leftrightarrow}{J}_j^* \right) \left(\vec{s}_i \otimes \vec{s}_j^* \right)^{ideal}$$

  - the Jones matrices ***J*** contain the corruptions to *V*

$$\vec{V}_{ij}^{obs} = \overset{\leftrightarrow}{B}_{ij} \overset{\leftrightarrow}{G}_{ij} \overset{\leftrightarrow}{D}_{ij} \overset{\leftrightarrow}{E}_{ij} \overset{\leftrightarrow}{P}_{ij} \overset{\leftrightarrow}{T}_{ij} \overset{\leftrightarrow}{F}_{ij} \vec{V}_{ij}^{ideal}$$

  - there are different corruption terms to the ***J***
    - gain ***G***, pol leakage ***D***, ionosphere ***F***, parallactic angle ***P***

Jones Matrices

- The Jones matrices for the antennas are multiplied:

$$\overleftrightarrow{J}_i \otimes \overleftrightarrow{J}_j = \overleftrightarrow{B}_i \overleftrightarrow{G}_i \overleftrightarrow{D}_i \overleftrightarrow{E}_i \overleftrightarrow{P}_i \overleftrightarrow{T}_i \overleftrightarrow{F}_i \otimes \overleftrightarrow{B}_j^* \overleftrightarrow{G}_j^* \overleftrightarrow{D}_j^* \overleftrightarrow{E}_j^* \overleftrightarrow{P}_j^* \overleftrightarrow{T}_j^* \overleftrightarrow{F}_j^*$$
$$= \left(\overleftrightarrow{B}_i \otimes \overleftrightarrow{B}_j^*\right)\left(\overleftrightarrow{G}_i \otimes \overleftrightarrow{G}_j^*\right)\left(\overleftrightarrow{D}_i \otimes \overleftrightarrow{D}_j^*\right)\left(\overleftrightarrow{E}_i \otimes \overleftrightarrow{E}_j^*\right)\left(\overleftrightarrow{P}_i \otimes \overleftrightarrow{P}_j^*\right)\left(\overleftrightarrow{T}_i \otimes \overleftrightarrow{T}_j^*\right)\left(\overleftrightarrow{F}_i \otimes \overleftrightarrow{F}_j^*\right)$$
$$= \overleftrightarrow{B}_{ij} \overleftrightarrow{G}_{ij} \overleftrightarrow{D}_{ij} \overleftrightarrow{E}_{ij} \overleftrightarrow{P}_{ij} \overleftrightarrow{T}_{ij} \overleftrightarrow{F}_{ij}$$

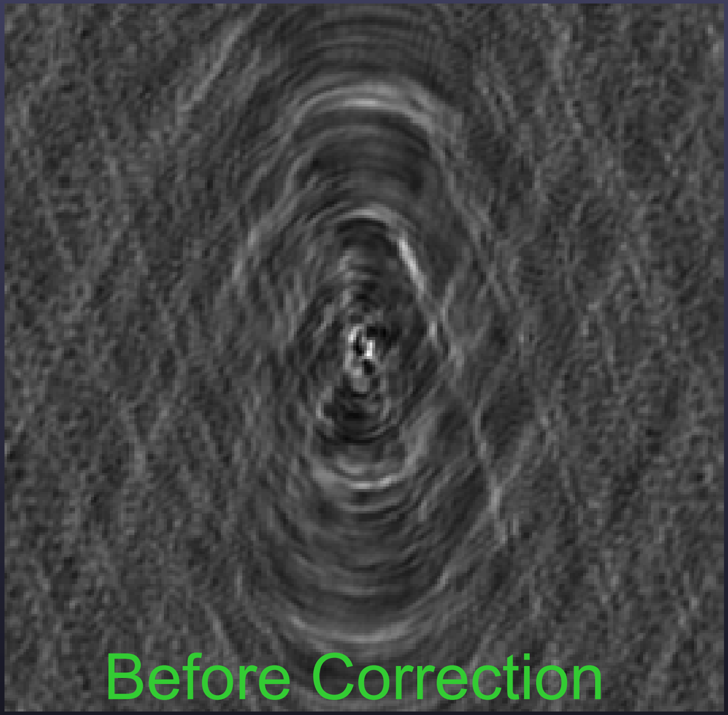
- The total *Measurement Equation* has the form:

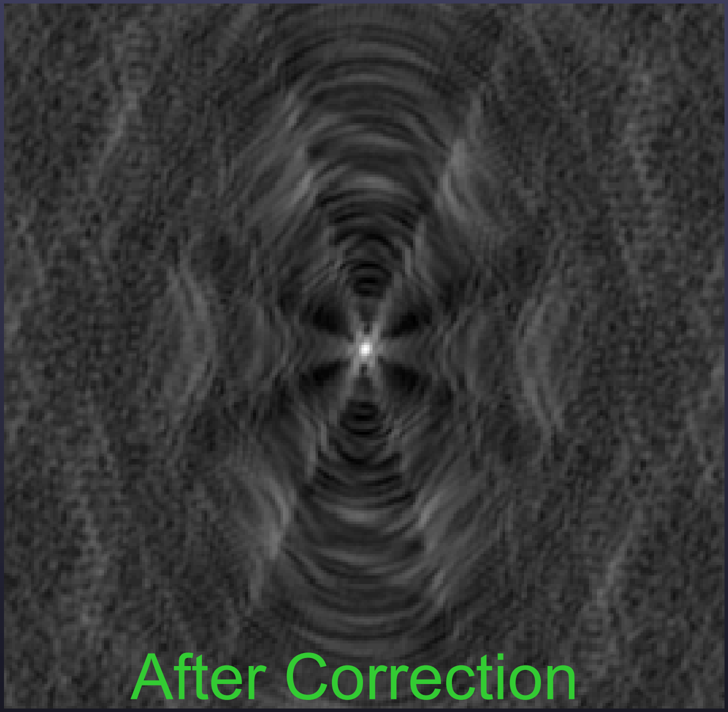
$$\vec{V}_{ij} = \overleftrightarrow{M}_{ij} \int \overleftrightarrow{B}_{ij} \overleftrightarrow{G}_{ij} \overleftrightarrow{D}_{ij} \overleftrightarrow{E}_{ij}(x,y) \overleftrightarrow{P}_{ij} \overleftrightarrow{T}_{ij} \overleftrightarrow{F}_{ij}\; S\vec{I}_\nu(x,y)\, e^{-i2\pi(u_{ij}x+v_{ij}y)} dx\, dy + \vec{A}_{ij}$$

  - *S* maps the Stokes vector *I* to the polarization basis of the instrument
  - M_{ij} and A_{ij} are multiplicative and additive baseline-based errors
  - In general, all J_{ij} may be direction-dependent, so inside the integral….
- Direction-dependent terms must be dealt with in imaging
  - in particular, the polarization primary beam ***E***

Calibration in Image Plane

- Calibration errors show up as artifacts in image plane:

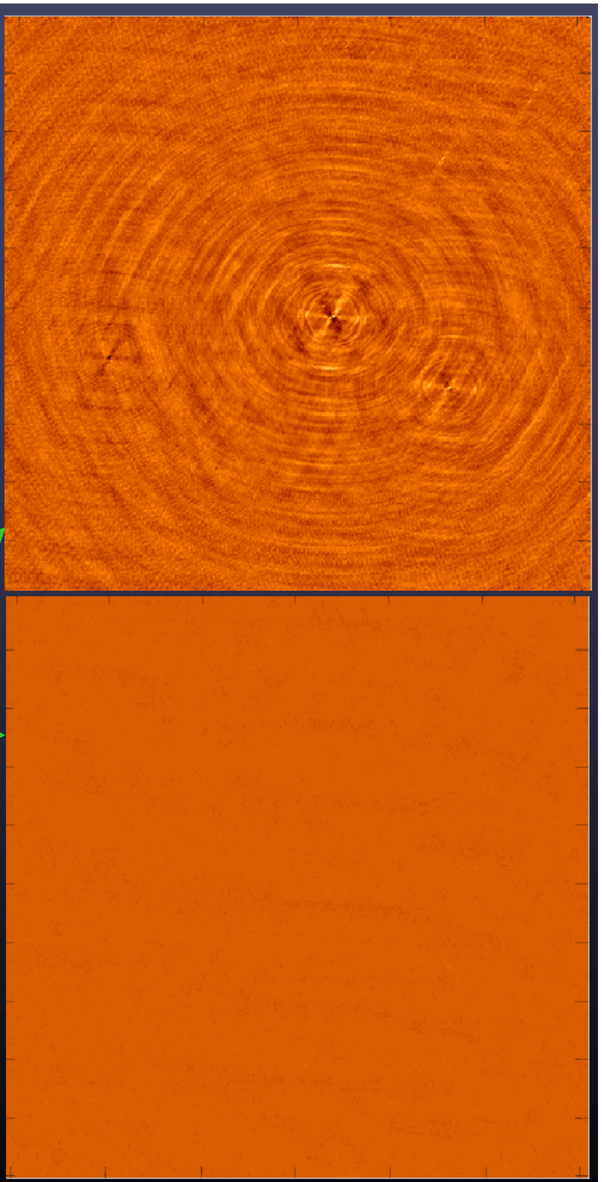




  – given an approximate model for the image we can solve for the errors ➔ “self-calibration”

Pointing Corrections

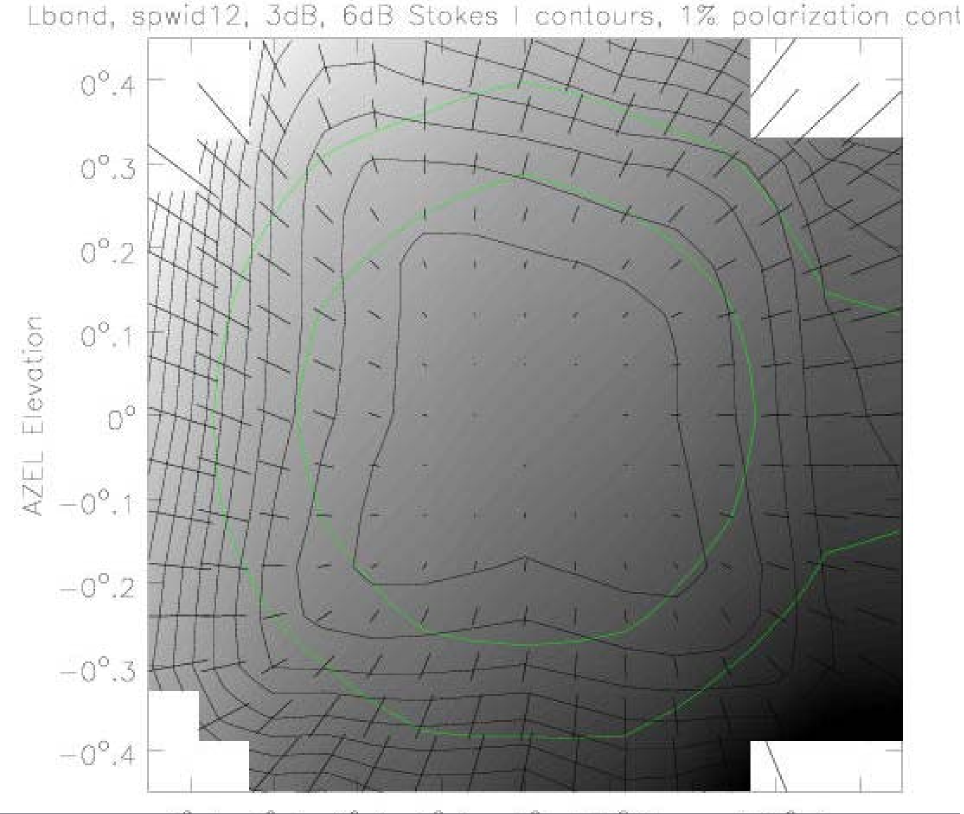
- Example of direction-dependent errors:
  - VLA antennas have ~10’’ pointing residual
  - affects high-dynamic range imaging
  - also “squint” between R and L beams
- Work by Sanjay Bhatnagar (NRAO)
- Simulation of 1.4GHz EVLA observations
- Residual images
  - Before correction: Peak 250μJy, RMS 15μJy
  - After correction: Peak 5μJy, RMS 1μJy



- Can incorporate into standard self-cal
- Computational cost ok for now
- See EVLA Memos 100 & 84
  - Implementing in CASA, testing underway

Primary Beam: full field polarization

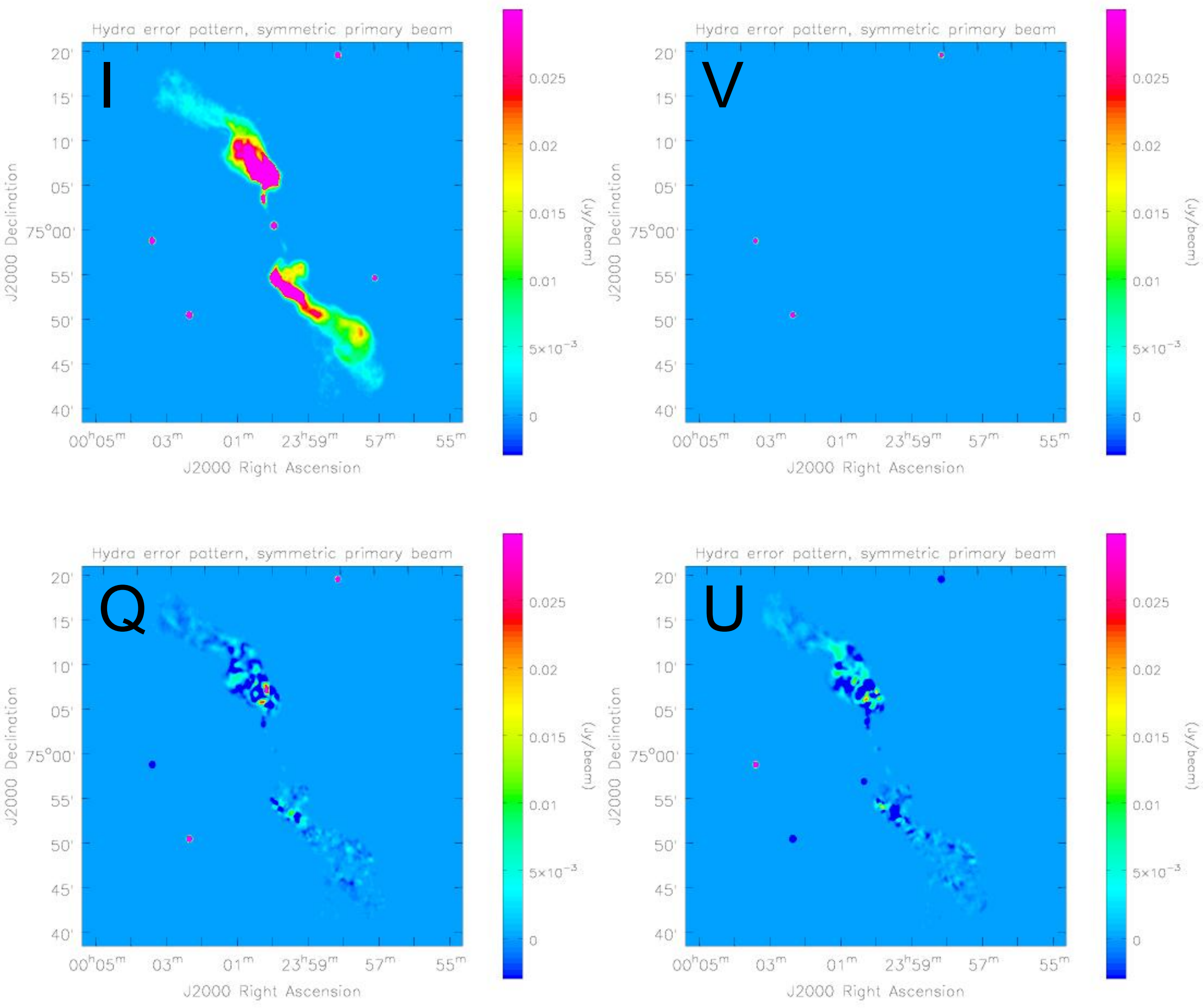
- VLA primary beams
  - Beam squint due to off-axis system
  - Instrumental polarization off-axis
  - Az-El telescopes
- Instrumental polarization patterns rotate on sky with parallactic angle
  - Limits polarization imaging
  - Limits Stokes I dynamic range (via second order terms)
  - must implement during imaging



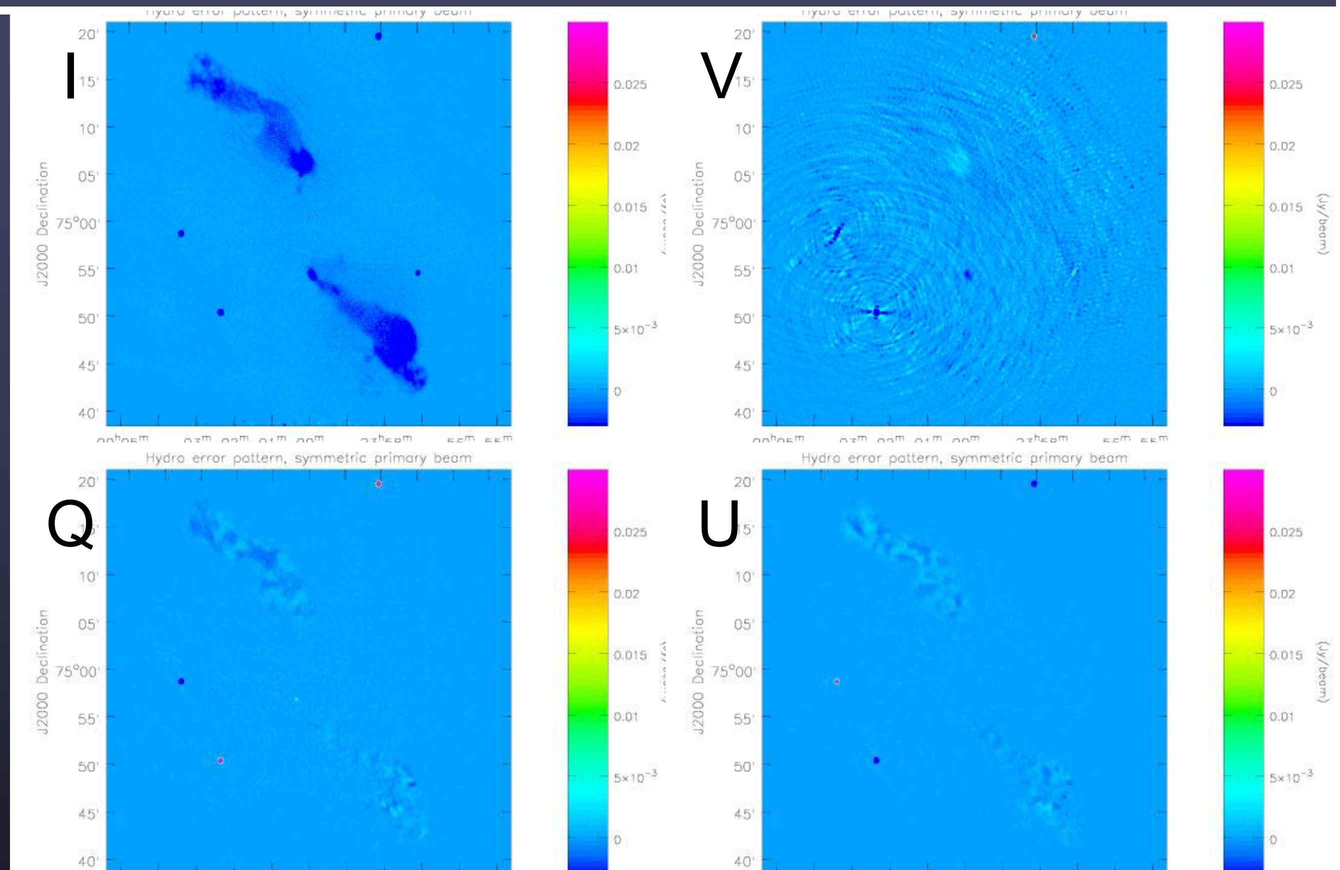
Green contours: Stokes I 3dB, 6dB, black contours: fractional polarization 1% and up, vectors: polarization position angle, raster: Stokes V

Simulations on a complex model

- VLA simulation of ~ 1 Jy point sources + large source with complex polarization (“Hydra A”)
- Long integration with full range of parallactic angles
- equivalent to weak 1.4GHz source observed with EVLA
- Antenna primary beam model by W. Brisken
- See EVLA memo 62



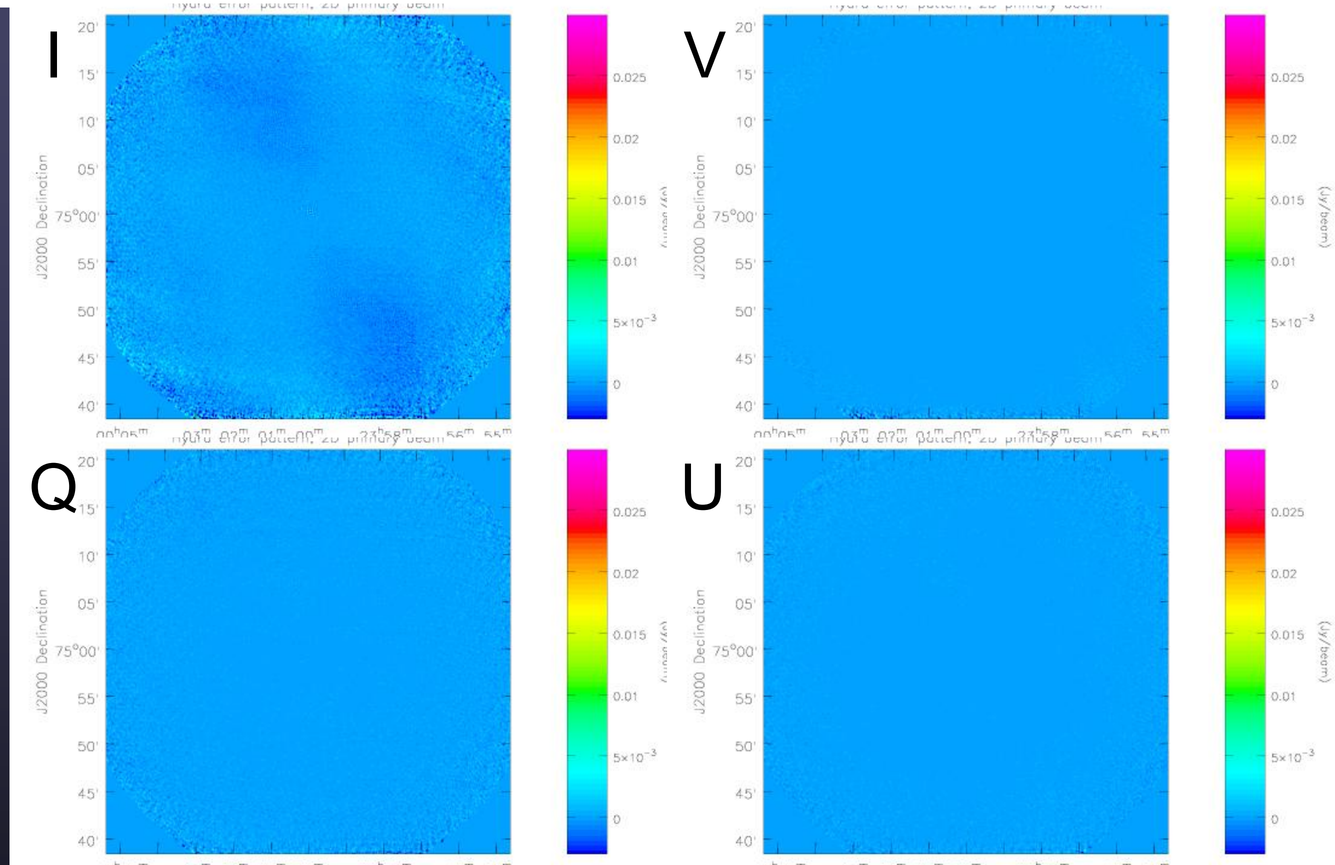
1-D Symmetric Beam



Dynamic Range ~200 using symmetric beam model

- dynamic range limited by errors from incorrect approximate primary beam

2-D Polarized Beam

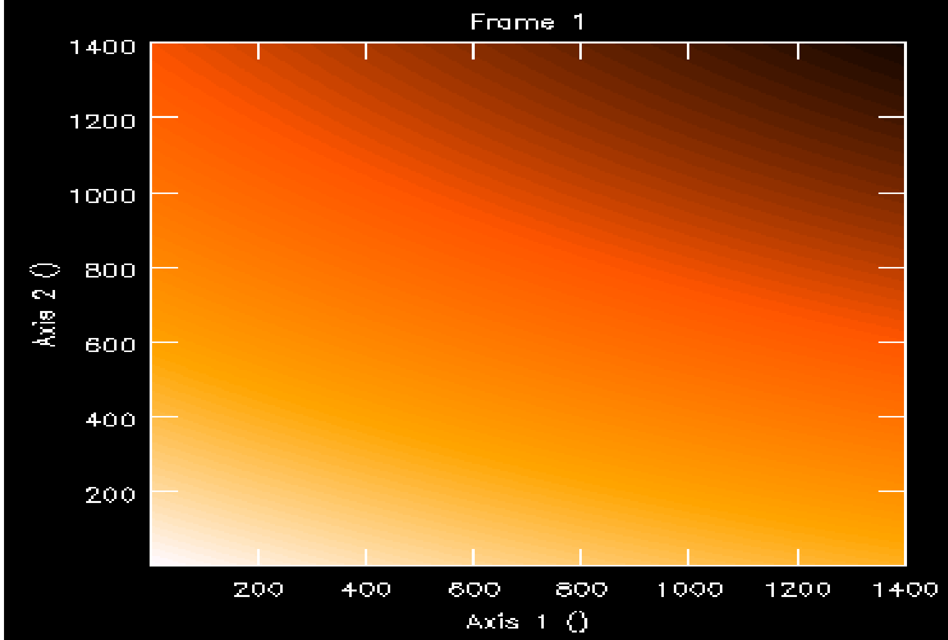


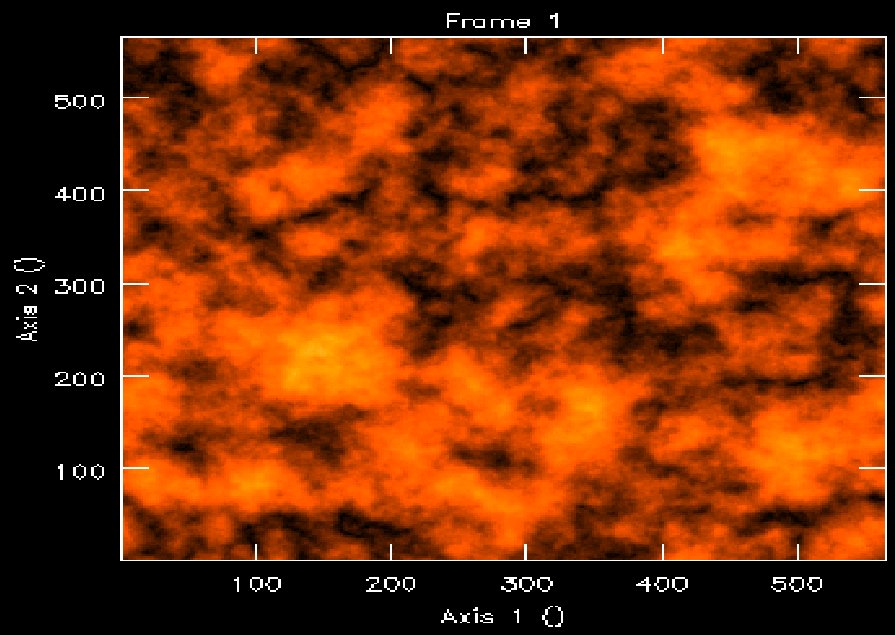
Dynamic Range $\sim10^4$ using 2-D beam model

- need to use accurate polarized beam to reach high fidelity and dynamic range

Simulated Phase Screen

- ionospheric simulation by A. Datta (NMT)





Present:

- Single (time-variable) Gradient (dominant) & Curvature – good enough above 1 GHz?

Future:

- Typical turbulent screen
- Needed for A-config below 1GHz

High Performance Computing Needs

- High-fidelity imaging comes at high cost
  - 8^h VLA-A/Lband ~10h for 20 GB (1% EVLA)
- Parallel I/O
  - Parallelize gridding by data partitioning
- Parallel Algorithms and Codes
  - focus on parallelizing key bottlenecks
  - both multi-cores and clusters (MPI + OpenMP?)
- Pipeline Processing and Data Mining
  - data sets too large for interactive analysis
- Excellent area for LANL collaboration

Part II: The Future of Radio Interferometry and the Square Kilometer Array (SKA)

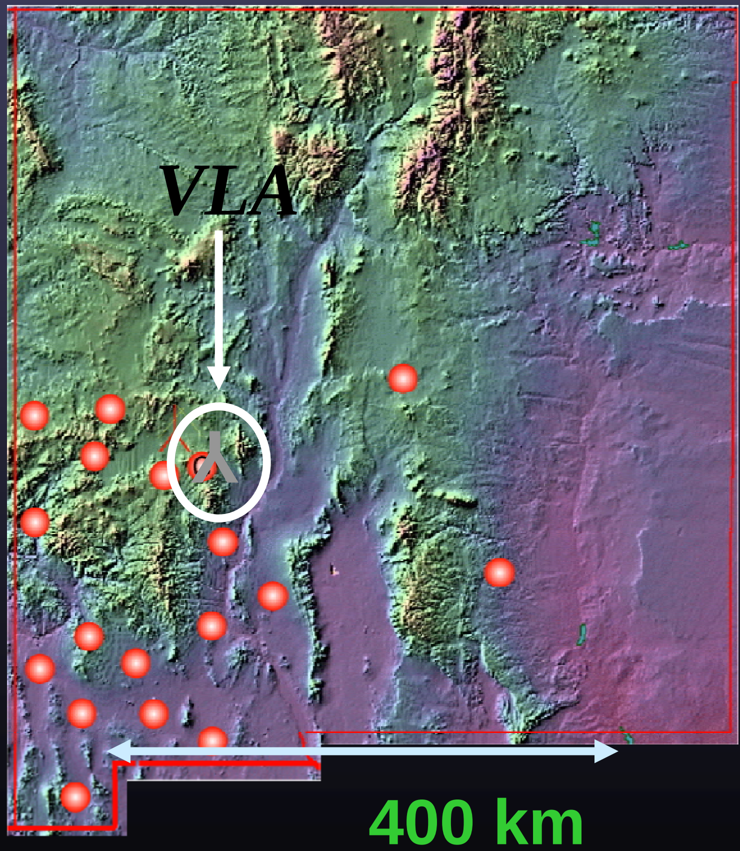
The Square Kilometer Array

- The SKA is an international "project" to construct one or more next-generation radio arrays with large collecting area
- SKA-low : 10 MHz – 500 MHz
  - epoch of reionoization, ionosphere, relic radio emission
  - pathfinders: LWA, LOFAR, MWA, PAPER, GMRT
- SKA-mid : 300 MHz – 3 GHz
  - 21cm neutral hydrogen line (HI), pulsars, AGN
  - pathfinders: ASKAP, MeerKAT
- SKA-high : 1 GHz – 50 GHz
  - recombination lines, molecular lines, thermal emission

The Long Wavelength Array (LWA)

- Just got construction funding from ONR
- LWDA "demonstrator array" operating at VLA site:

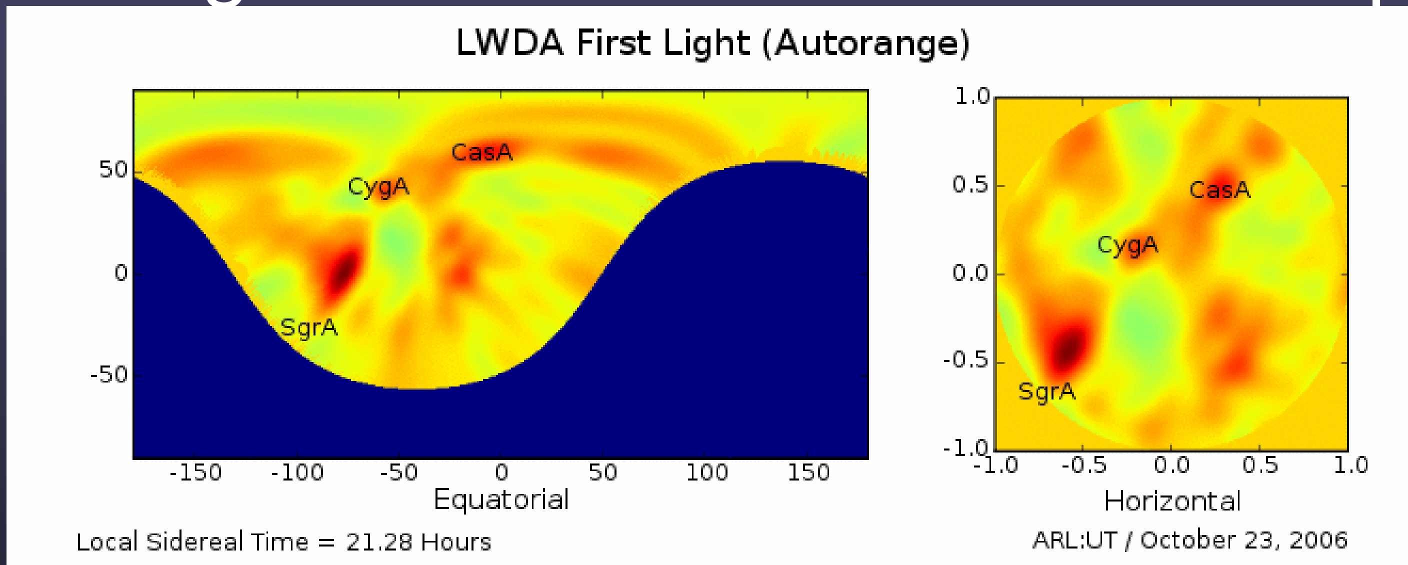
52 stations of 128 dipoles

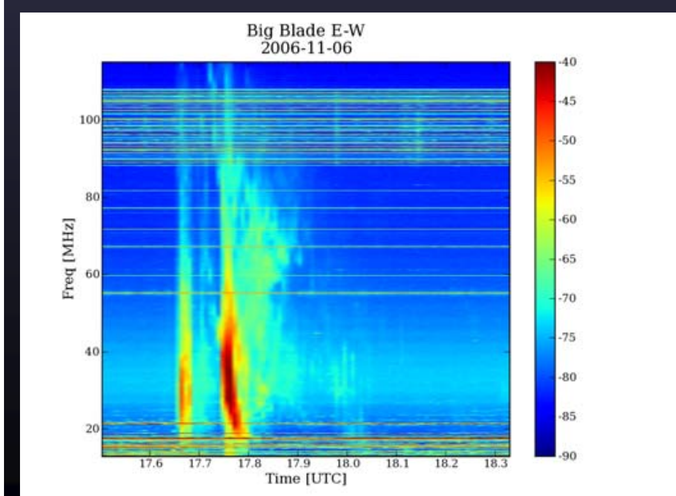


The University of New Mexico
Los Alamos NATIONAL LABORATORY
ARL The University of Texas at Austin

LWDA progress

- First Light 2006-10-23: 24 hours 16 dipoles





LWA website – *http://lwa.unm.edu*

Type III solar bursts (2006-11-06) with "Big Blade" LWDA prototype

What is the RSST?

The Radio Synoptic Survey Telescope

- The RSST concept is for a “SKA-mid” facility
  - it is proposed here as the “SKA-mid” from a US science perspective
- Primary Science Goals
  - Cosmological HI
  - Deep continuum imaging of active galaxies and objects
  - Transient detection and monitoring
- Also
  - other redshifted lines (e.g. OH mega-masers)
  - pulsars, SETI, etc.

The RSST is …

- Radio?
  - core frequency range 0.4-1.4 GHz ($z<2.5$) “HSST”
    - some science cases may want 0.3-3 GHz (must justify $$)
- A Square Kilometer Array
  - square kilometer of something (not white papers)
  - high gain/low noise $A/T_{sys} \approx 2\times10^4$ m^2 K^{-1}
    - don’t throw away all that collecting area!
  - wide field-of-view, target 1 square degree
    - $A\Omega/T \approx 2\times10^4$ m^2 K^{-1} deg^2 ~ $n_a n_b/T$ “megapix”
- A Survey Telescope
  - cover large areas of sky 10^4 deg^2 = ¼ sky
    - survey speed $(A\Omega/T)(A/T)\Delta\nu = n_a n_b A/T^2 \Delta\nu$

The Synoptic Part

- Revisit the sky regularly
  - if you want to cover 10^4 deg^2 with $1deg^2$ FOV
  - can do so in 1 day with $2\text{-}8^s$ per point
  - different parts of survey can have different depths (and thus cadences)
- What cadence? Depends on the science
  - many short visits or fewer longer ones?
  - looking for individual "bursts" or "pulses"?
  - looking for groups or trains of pulses?
  - classical variability curves (e.g. microlensing)?
  - also remember, many compact radio sources are variable (both intrinsic and scintillation)

RSST Key Science Surveys

- Key Projects (example)
  - Cosmological HI Large Deep Survey (CHILDS)
    - billion galaxies to z~1.5 (and beyond)
    - HI redshift survey for cosmology
    - galaxy evolution
  - Deep Continuum Survey (DeCoS)
    - radio photometric and polarimetric survey (static sky)
    - commensal with CHILDS, extracted from spectral data
  - Transient Monitoring Program (TraMP)
    - bursts, variability, pulsars, etc.
    - commensal with other RSST surveys – freeloading!
- These are part of one big survey (Big Sur)

Is the RSST a …

- National Facility?
  – well, its an international facility, but a National resource for US astronomers
- targeted experiment?
  – the primary science goals & key projects are big surveys
- general observer facility?
  – probably not primarily, but perhaps 10-25% of time could be made available for proposers (and for TOO)
- an exclusive club?
  – No! RSST must involve and support a large part of the US astronomy community

RSST Science

Science Precursors

- The case for precursor science
  - do not just “stop everything” to build new stuff
  - need science output throughout decade
- Use “current” facilities
  - Arecibo, EVLA, GBT, VLBA, ATA
    - e.g. ALFALFA HI survey, large EVLA surveys
  - also mm/sub-mm : ALMA, CARMA, CSO, etc.
  - also other wavebands : O/IR, Xray, Gamma Ray, etc.
- Use in new (and complementary) ways
  - pilot surveys and special targets
  - also science with SKA demonstrators (ASKAP, meerKAT)

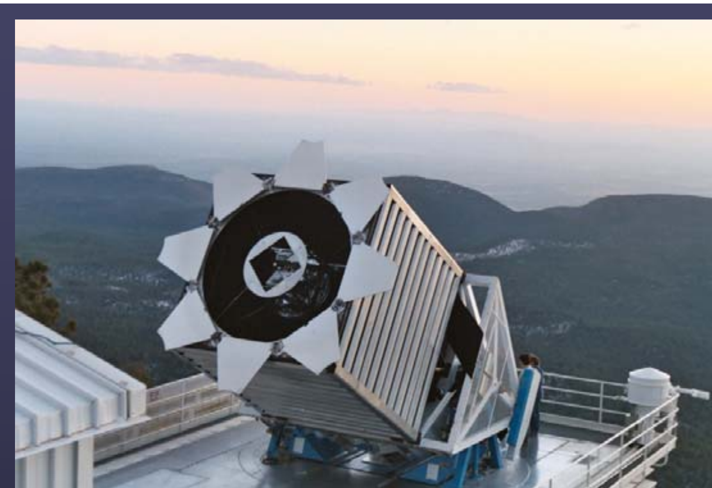
RSST Science Example: HI Cosmology

- “billion galaxy” HI survey
  - redshifts for gas-rich galaxies out to z=1.5 (and beyond)
  - Baryon Acoustic Oscillations (BAO)
  - cosmography of Universe d(z) , V(z) ⇔ H(z)
  - growth of structure and Cosmic Web
  - HI is critical window on galaxy formation and evolution
- complementarity with “Dark Energy” surveys
  - e.g. JDEM, LSST,DES, SDSS, DES, LSST, PanSTARRS
  - mutual interest with the DOE community (JDEM)
  - engage O/IR extragalactic and cosmology communities
  - NASA missions (JDEM, Planck, JWST, GLAST, etc.)

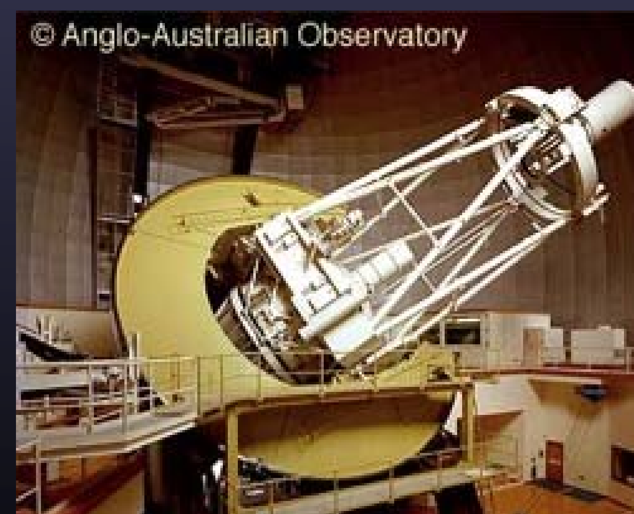
Current State of the Art in BAO

Four published results

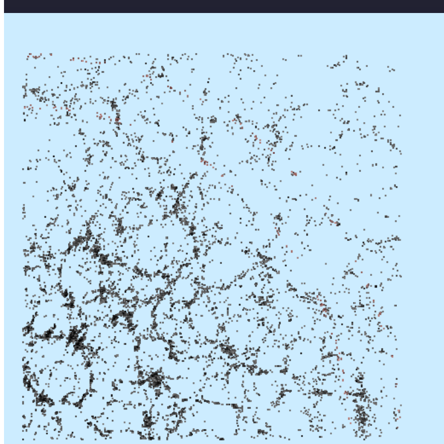
1. Eisenstein et al 2005 (spectro-z) 3%
   - 3D map from SDSS
   - 46,000 galaxies in 0.72 $(h^{-1}Gpc)^3$
2. Cole et al 2005 (spectro-z) 5%
   - 3D map from 2dFGRS at AAO
   - 221,000 galaxies in 0.2 $(h^{-1}Gpc)^3$
3. Padmanabhan et al 2007 (photo-z) 5%
   - Set of 2D maps from SDSS
   - 600,000 galaxies in 1.5 $(h^{-1}Gpc)^3$
4. Blake et al 2007
   - (Same data as above)



SDSS 2.5-m telescope, Apache Point, NM



AAO 4-m telescope at Siding Spring, Australia



HI surveys are woefully behind in numbers of detections

Thanks to Pat McDonald (CITA)

RSST Science: A Broad Community

- More on the DOE & LANL connection
  - RSST “SKA” is a Phase IV project in the DETF report
  - addresses “Connecting Quarks to the Cosmos” questions
  - active astrophysics and cosmology groups at LANL
    - involved in SDSS, LWA, high-energy astrophysics
  - “Astro-Informatics” aspects
    - data mining and high-performance computing a lab mission
- Obvious connections to LST & DE projects
  - many of the same galaxies as LSST,PanSTARRS,DES
    - RSST can provide HI redshifts
    - complementary to galaxies seen in O/IR (e.g. HETDEX)
  - complete view of the Universe
    - “whole Universe telescope” sees gas and stars and dark matter

RSST Science Example: Continuum

- Extremely deep (10 nJy) continuum survey
  - “billion” extragalactic radio sources
  - AGN
  - star-forming galaxies
  - SNR and HII regions in galaxies
- Census of “rare” phenomena
  - Gravitational Lenses (e.g. CLASS)
- Polarimetry
  - Rotation Measure (RM) survey
  - galactic and extragalactic magnetic fields

RSST Science Example: Transients

- Bursty phenomena
  - giant pulsar pulses out to Virgo
  - brown dwarf flares
- Variability
  - compact radio sources (IDV, scintillation, etc.)
  - GRB afterglows
- Exotica
  - UHE particles in lunar regolith
  - SETI
- Pulsars
  - provide spigot Pulsar Machine attachment

RSST Roadmap

What really needs to happen

- Need to write a proposal for Decadal Review
  - assemble small "blue team" to write the case
  - need punchy science case
  - solidify numbers (simulations?)
  - remaining technical development? choices?
  - need "Phase A" level costing
  - put in front of "red team" next year
  - present to Decadal Review
- This is time critical – if the community wants to participate in a "RSST" project, then must get this into the Decadal Review

The New Mexico connection…

- There is a core community in NM for RSST
  - groups at all NM institutions!
  - interest in HI, AGN, pulsars, transients
  - technology base in computing, informatics, hardware
  - surveys at all wave bands from 10MHz to 10^{20}eV!
- Forum for further NM action: NMC-IAS
  - New Mexico Consortium Institute for Advanced Study
    - LANL, UNM, NMSU, NMT (NRAO)
  - Astrophysics & Cosmology Center (ACCent)
    - RSST could be the subject of a Focus Group
- NM can play a significant role in RSST!
  - can get in now on the ground floor…

Challenges for the RSST Proposal

- Building the Science Case
  - e.g. comology with the RSST in 2020+
- Accurate Costing
  - both hardware and software
  - can we get a square kilometer? what are tradeoffs?
- Data Management component
  - what will it take to handle 1000's of antennas?
  - new algorithms, architectures, real-time processing…
- Research & Development plans
  - Technology Pathfinders
  - Science Precursors

Next Steps

- US-SKA group is leading DR drafting
- Teams being assembled for specific cases
  - HI and Cosmology group (Myers & Henning)
  - Data Mangement group
- Meetings and Workshops
  - "Early Science with SKA" AAS special session
    - AAS Austin, TX meeting Jan 2008
  - Proposed NMCIAS "Great Surveys" workshop July'08?
    - Bring together groups like SKA, SDSS, PanSTARRS, LSST, …
    - Deal with science and technology issues (data management)
  - NRAO/NAIC workshop on HI Legacy surveys in 2008?
    - Science precursors with EVLA, Arecibo, ATA, others

Conclusion: Connections to LANL

- Informatics & Sensing
  - interferometric imaging = synthetic apertures (eg. radar)
  - 3D ionospheric modeling = 3D radiative transfer
  - connecting local and global ionospheric models
  - detection of transients: cosmic ray showers, Solar and Jovian bursts, the dynamic ionosphere
  - image reconstruction techniques
  - statistical methods, maximum entropy, information theory
  - high performance computing and data mining
- Beyond the Standard Model
  - next generation radio array: the Radio Synoptic Survey Telescope
    - the RSST is a "SKA" concept for imaging the universe in HI (0.4-1.4GHz)
    - LANL/DOE could play a major role from ground up (in white-paper stage)
  - Cosmic Explosions, Cosmic Magnetic Fields and UHE Cosmic Rays

For more information…

- RSST Proto-White Paper (draft)
  - on the Arecibo Frontiers conference website:
    http://www.naic.edu/~astro/frontiers/RSST-Whitepaper-20070910.txt
- SKA Info
  - http://www.skatelescope.org
  - particularly see the "Science Book"
    - "The Dynamic Radio Sky" by Cordes, Lazio & McLaughlin
    - "Galaxy Evolution, Cosmology, and Dark Energy with the SKA" by Rawlings et al.
    - others…