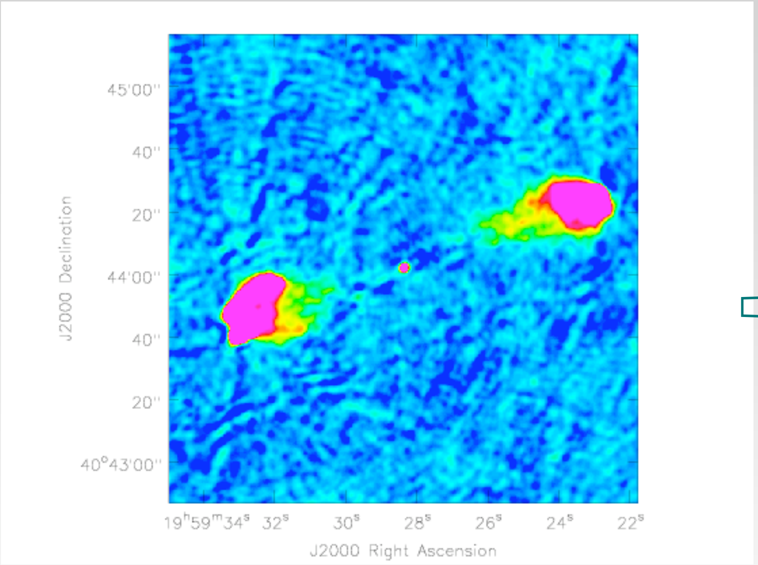
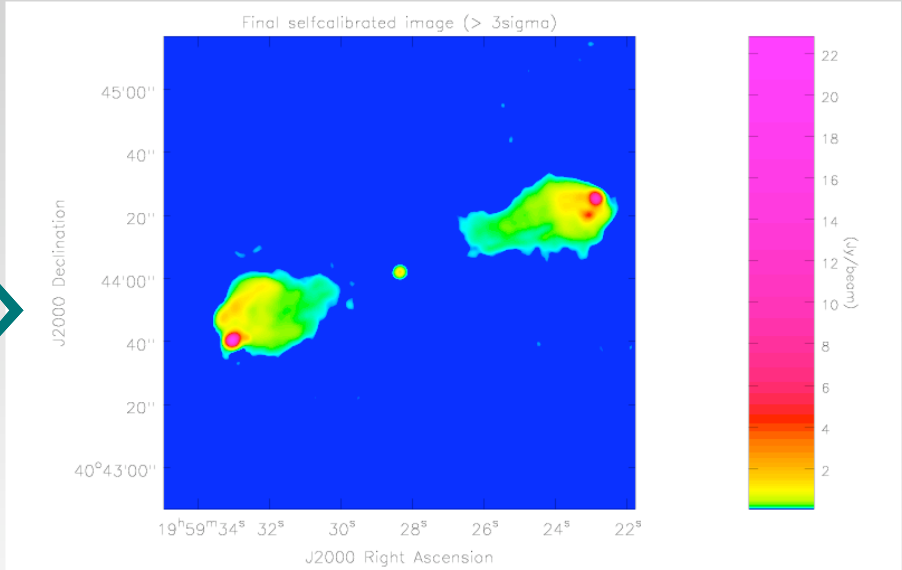
High Dynamic Range Imaging





Juan M. Uson (NRAO) 06/16/08

Luz

Ando pendiente de los juegos
de la luz
de como el vidrio empañado
se ilumina de repente
contrastando con la noche

de Alejandra Pinto

Light

I am taken by light's play,
how suddenly a fogged glass lights up
in contrast with the night

by Alejandra Pinto

Imaging with high dynamic range

- Dynamic range is the ratio of the observed signal to the noise.
- Fidelity is the ratio of the true sky signal to the noise
- These are limited by errors
  - Random
  - Systematic
  - Absence of measurements
  - Malfunction

EVLA observations will be limited often by systematic errors

Imaging concepts

Radio interferometers are linear devices

Imaging: Estimation of true sky brightness from the observed visibilities

Imaging is a non-linear process

① Imaging: Fourier inversion of the visibilities

Weighting modifies the point-spread function
and the noise characteristics (SNR)

② Deconvolution: Correcting for “missed” visibilities

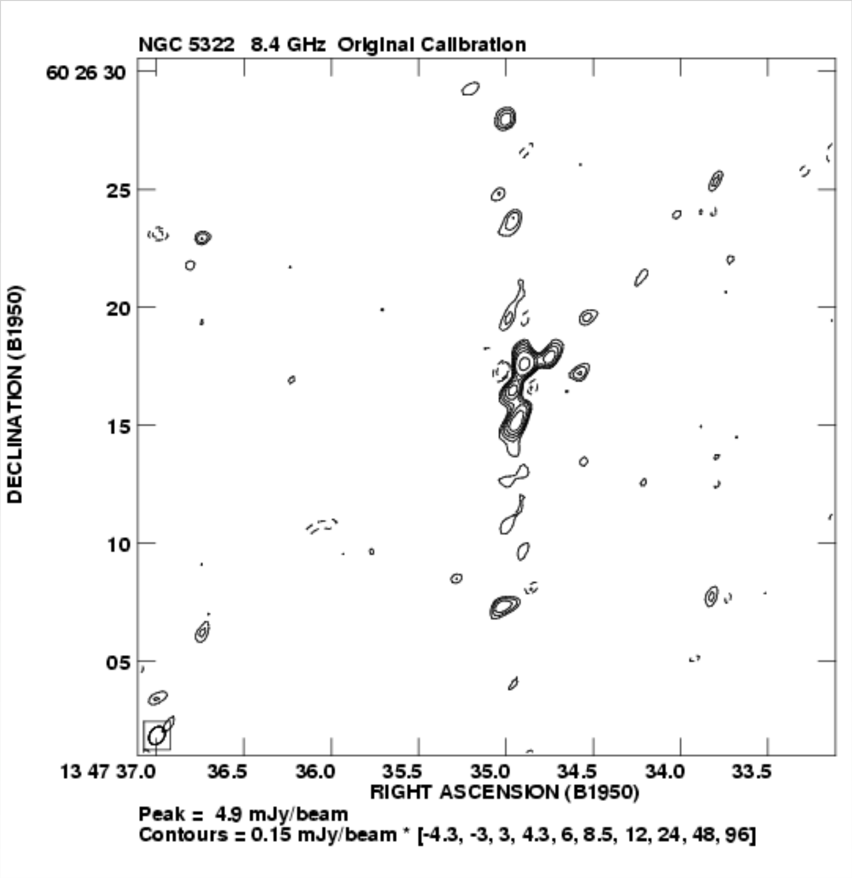
A number of methods lead to somewhat different results

③ Self-calibration: Correcting the visibilities to sharpen the image

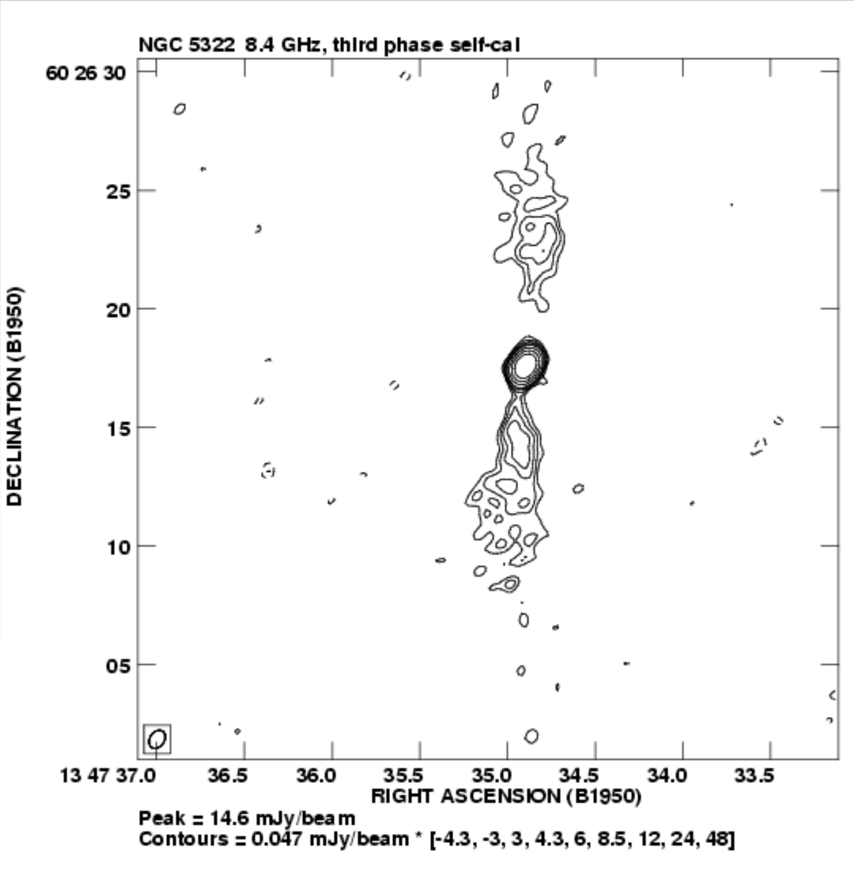
Improve on calibration (SNR permitting)

Example: Self-calibration of a VLA snapshot

Initial image



Final image



Formal Description (simple version)

- For small fields of view, the visibility function is the 2-D Fourier transform of the sky brightness:

$$V(u,v) = \int I(l,m) \cdot e^{j.2\pi.(ul+vm)} dl.dm$$

- We sample the Fourier plane at a discrete number of points:

$$S(u,v) = \sum_k w_k \cdot \delta(u-u_k) \cdot \delta(v-v_k)$$

- So the inverse transform is:

$$I^D(x,y) = F^{-1}[S(u,v) \cdot V(u,v)]$$

- Applying the Fourier convolution theorem:

$$I^D(x,y) = B(x,y) \otimes I(x,y)$$

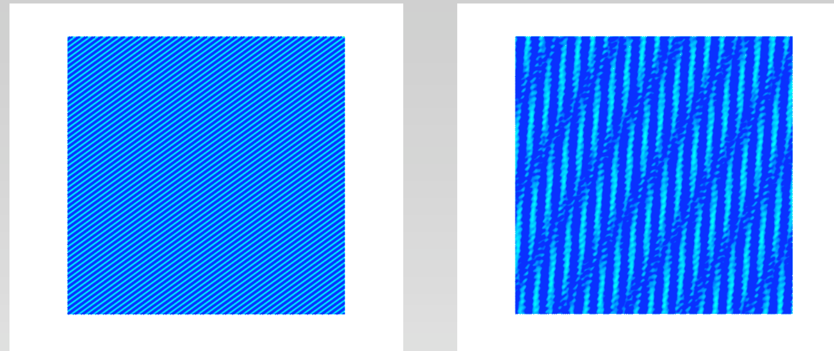
- where B is the point spread function:

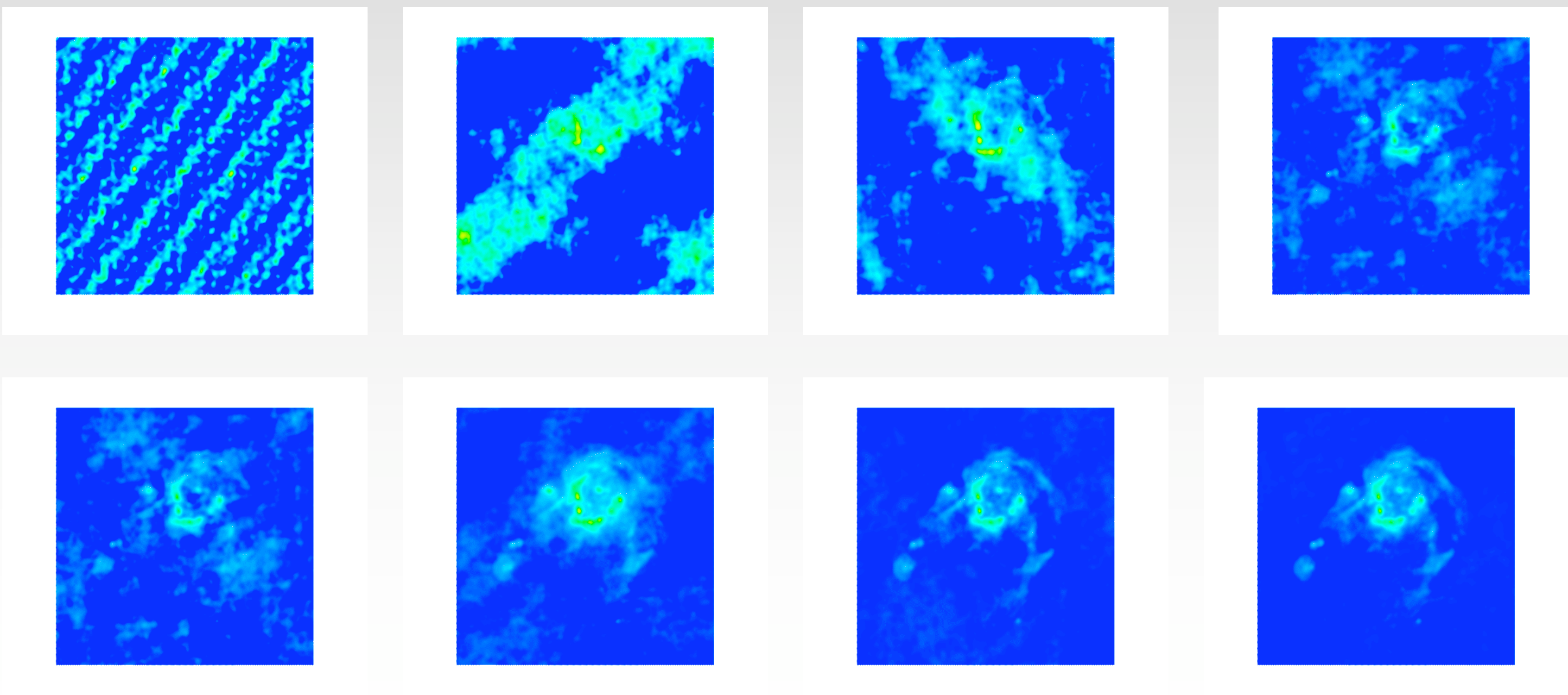
$$B(x,y) = F^{-1}[S(u,v)]$$

Images: Sum of interference patterns

Double the number of interferometers from frame to frame:

- 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024





Errors due to one bad interferometer

- Consider a point source at the phase center, 1 Jy
- Errors in one baseline:

$$V(u) = (1+\varepsilon)\delta(u-u_0)e^{-i\phi}$$

- lead to errors in the image:

$$I(l) = 2\sum_{k=1}^{N(N-1)/2} \cos(2\pi u_k l) + 2\phi\sin(2\pi u_0 l) + 2\varepsilon\cos(2\pi u_0 l)$$

- and dynamic range is limited to: $D \sim \frac{Peak}{Noise} \sim \frac{N(N-1)}{\sqrt{2(\varepsilon^2+\phi^2)}}$
- or ~2500 for $\phi \sim 6^o$ and $\varepsilon \sim 0.1$
- the errors might or not average over baselines, time, …

Errors due to missing data

- Deconvolution interpolates unmeasured visibility values

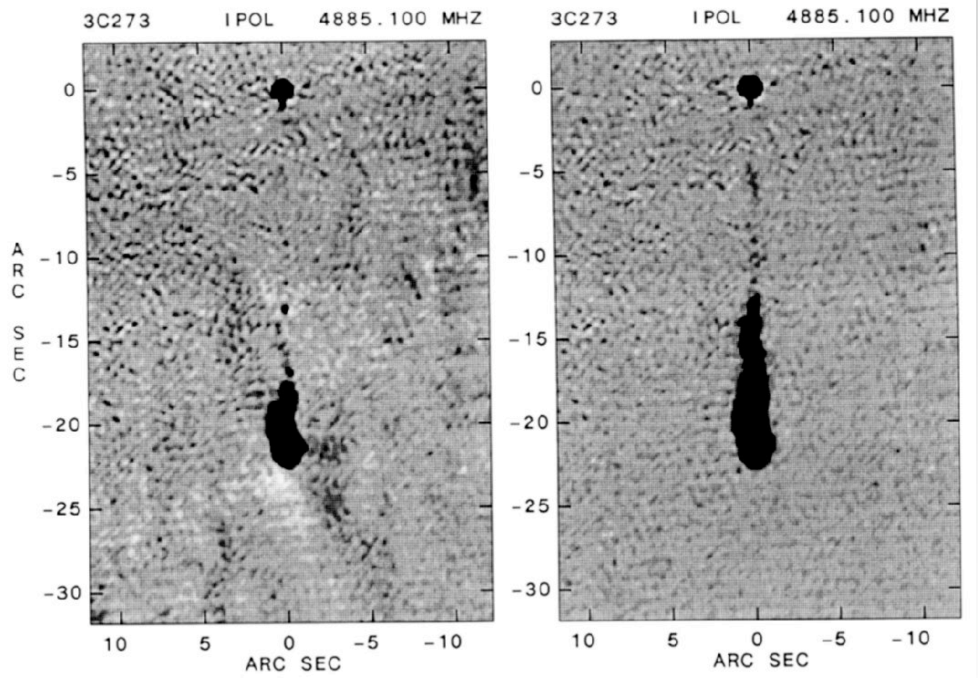
  The missing spacings can be important if V(u,v) changes significantly

  Errors result in ripples, bowls, missing or altered structures, …

  Example:

  3C273 at ~5 GHz

  A vs. A+B array



  Pixelization can induce errors even on isolated point sources!

Real Arrays

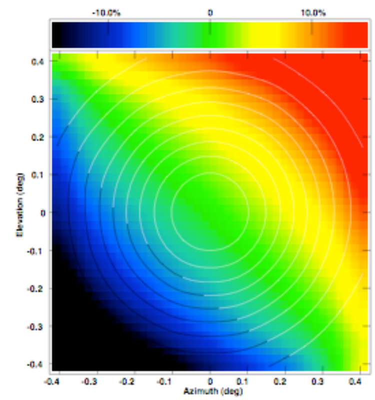


Figure 1: The VLA primary antenna pattern as measured during the NVSS survey [3] at 1.4 GHz. The instrumental Stokes V is shown in color with a scale bar at the top and contours are plotted every 10 percent in power.

- Each beam is offset from the nominal pointing center by:
  - $\Theta_S = \pm\, 237.56$ (arcsecond/meter) $\cdot\ \lambda$
- (a beam squint of 1.70′ for $\nu = 1.4$ GHz).
- This leads to a fractional value of: Squint / FWHM = 0.0549 ± 0.0005
- Also polarization coupling; these errors vary with elevation, Temp., time

Real Arrays: Measurement Equation

- Actual observations measure:

$$V_{ij}^{Obs} = M_{ij} \int M_{ij}^{Sky}(s) I(s) e^{2\pi i s \bullet b_{ij}} ds$$

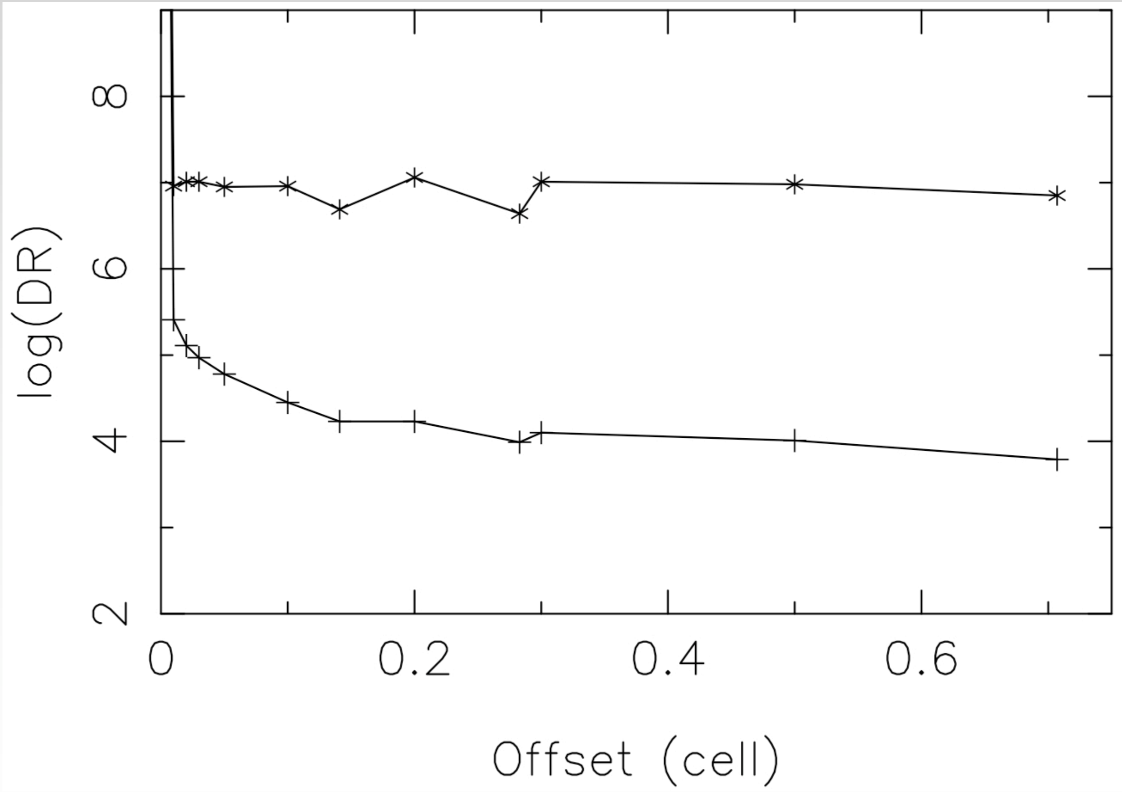
- where V_{ij}^{Obs} is the full-polarization visibility vector,
- $M_{ij}(s)$ and $M_{ij}^{Sky}(s)$ are matrices describing directionally-
- independent and directionally-dependent gains, *I* describes the full-polarization sky emission, *s* is the position vector and b_{ij} denotes the baseline.

High-accuracy imaging

- Initialize: Set of images (facets, planes if using w-projection)
  - Re-center facets, add new facets
- Deconvolve, update model image
- Compute residual visibilities accurately - corrections go here!
- Compute residual images
- Back to deconvolution step, or
- Self-calibration
- Back to beginning unless residuals are noise-like
- Smooth the deconvolved image, add residual image

Example: 3C84 (λ~21cm, B array)

- Even off-centering by 0.01 pixel limits dynamic range.



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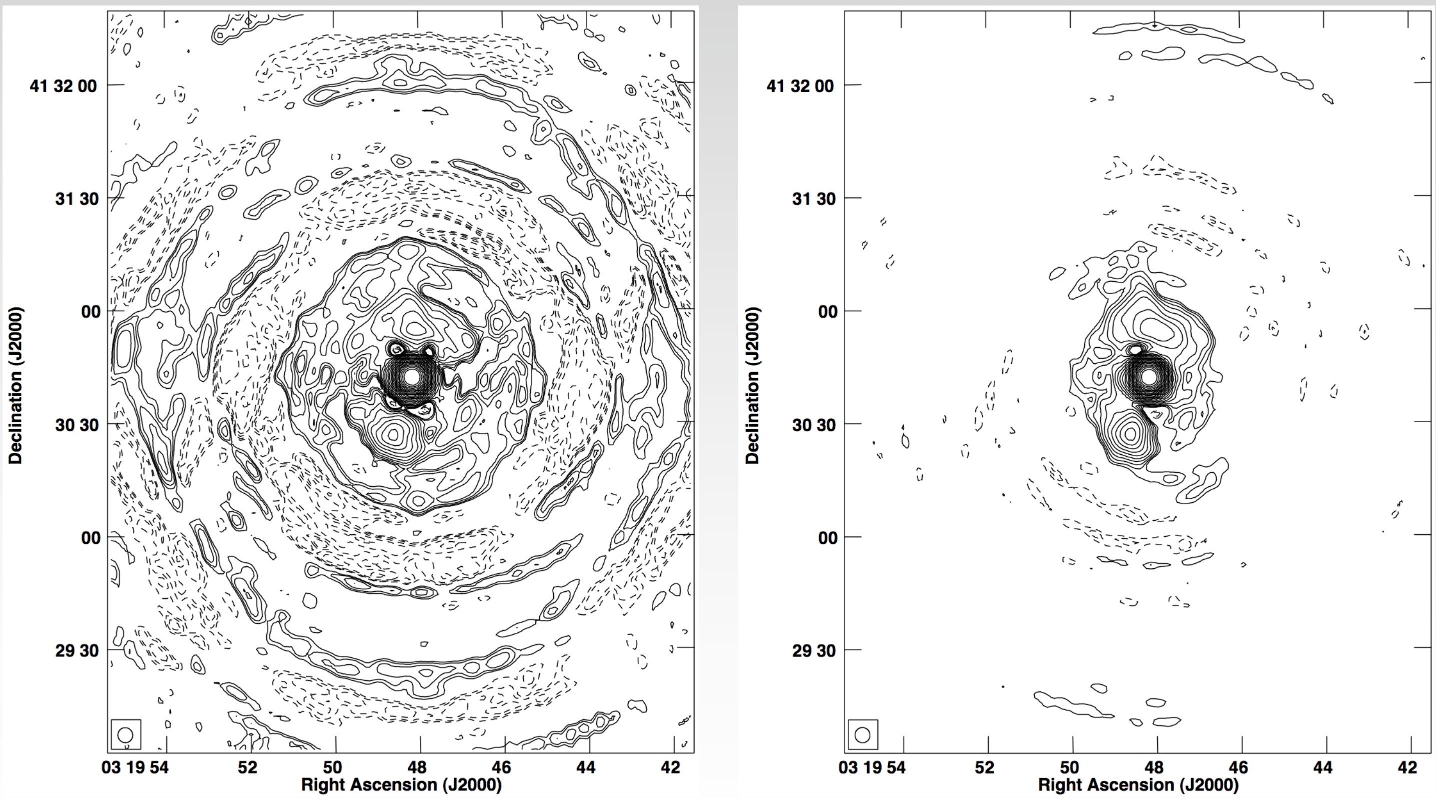

Example: 3C84 (λ~21cm, B array)

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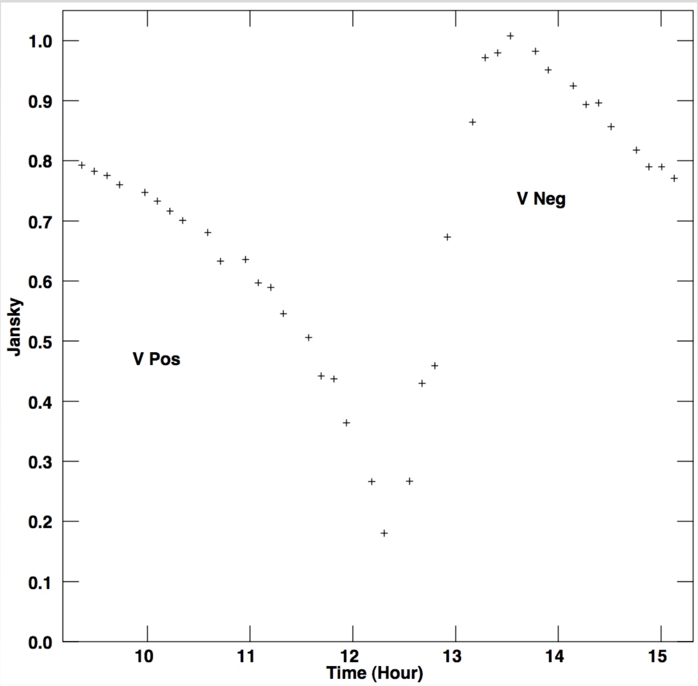

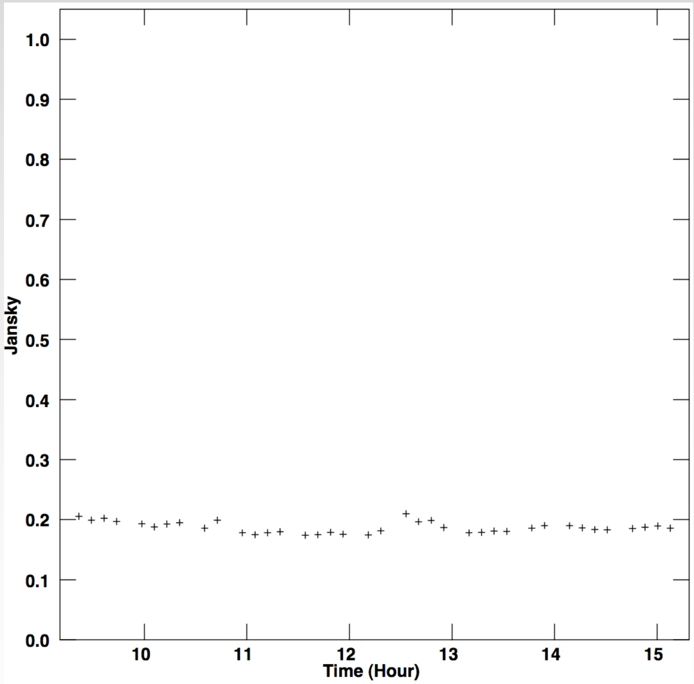

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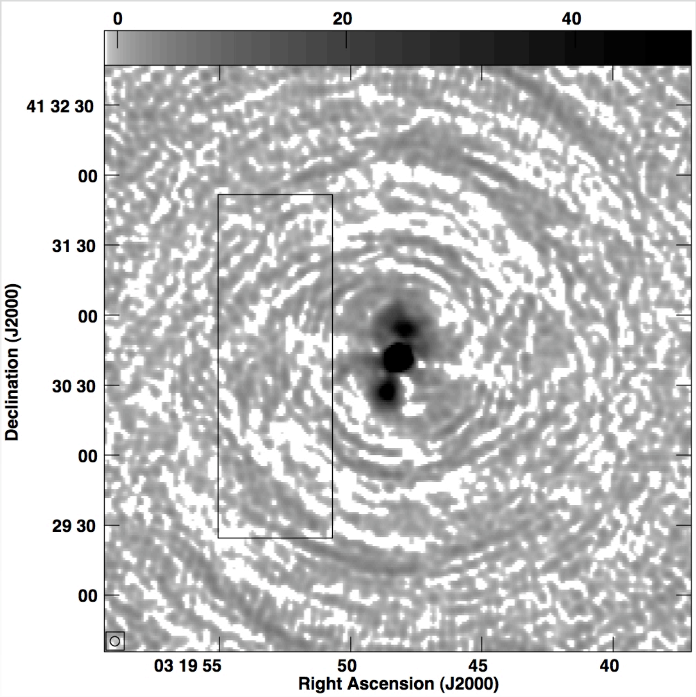

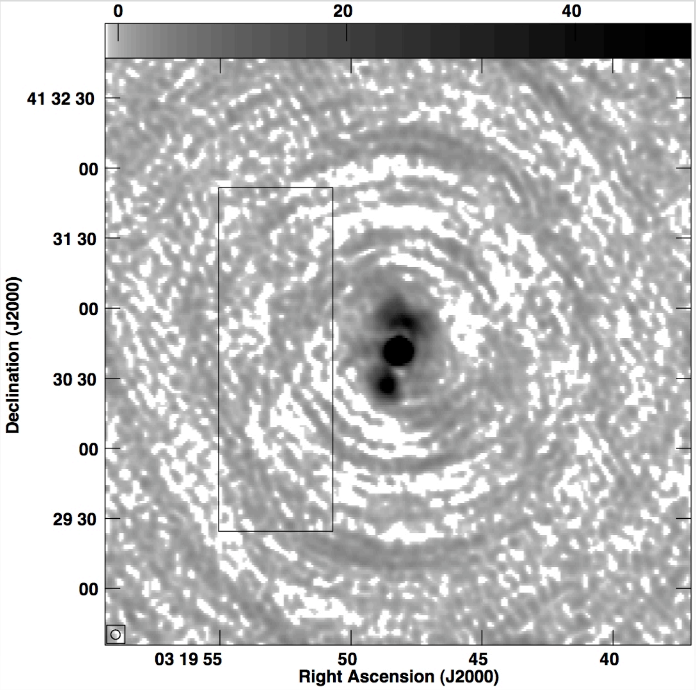

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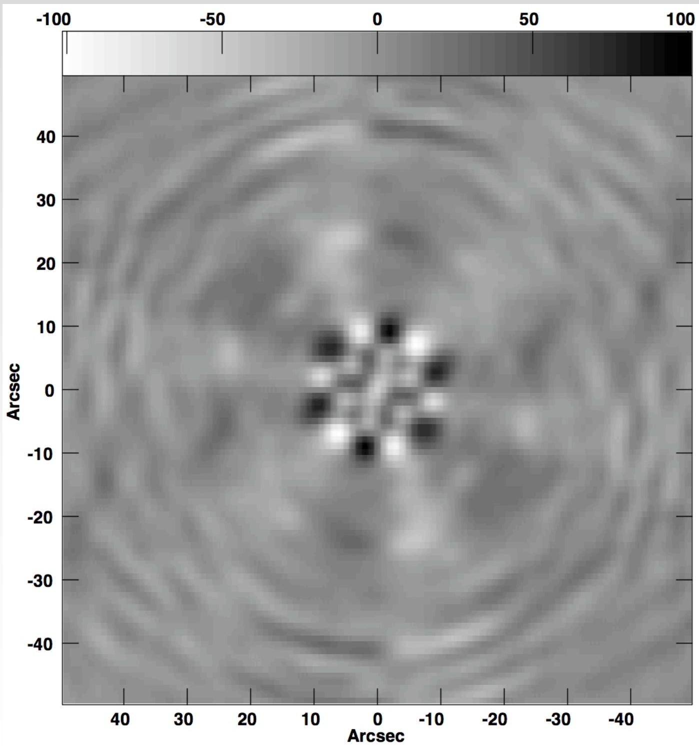
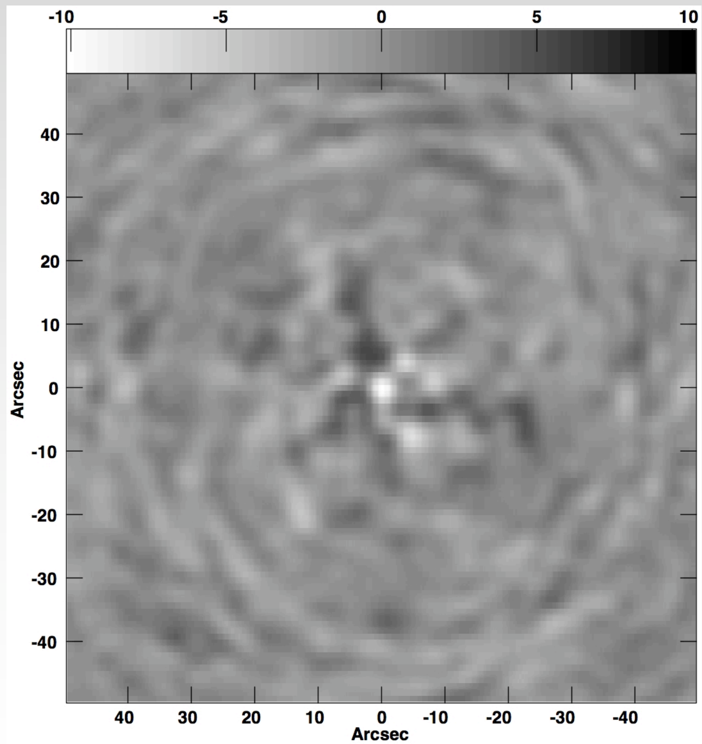




Example: 3C84 (λ~21cm, B array)

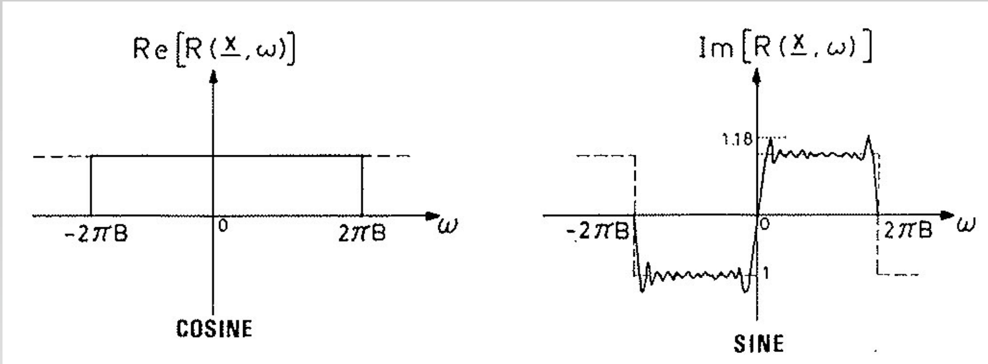
- Even off-centering by 0.01 pixel limits dynamic range.
- Observations at half-power are limited by the squint
- After full-correction, dynamic range is limited by coverage
- Dynamic range can be increased by dropping baselines
  - But Fidelity is surely lowered!

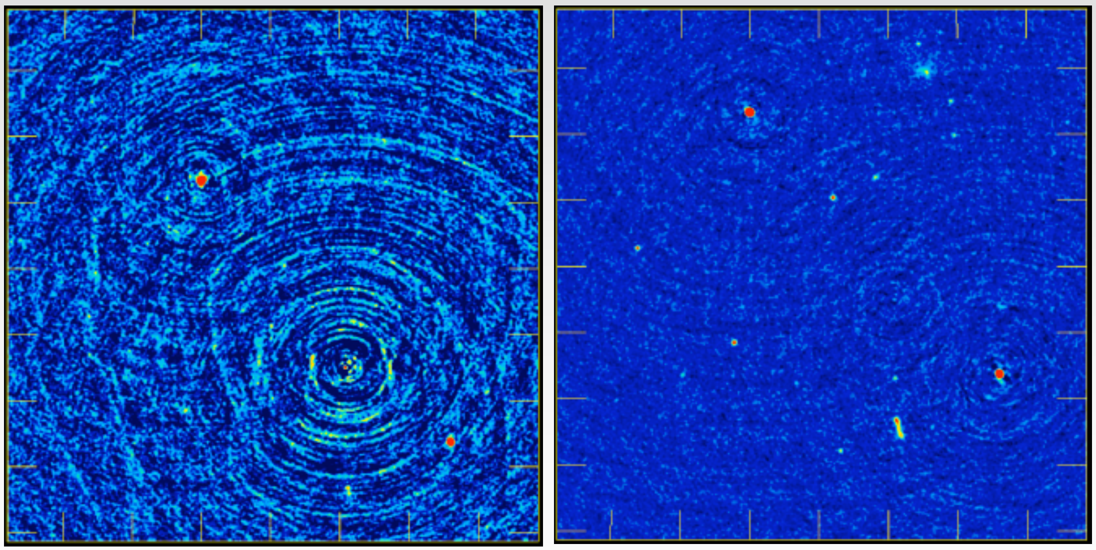
Example: IC 2233 & Mk 86

- IC 2233 is an isolated superthin galaxy (D ~ 10.5 +/- 1 Mpc)
- Mk 86 is a blue compact dwarf galaxy (D ~ 7 +/- 1 Mpc)
- They were believed to be an interacting pair

- Key experimental points:
  - The Field contains 2 “4C” sources so high dynamic range was necessary
  - The VLA suffers from Beam-Squint which leaves behind spurious signals
  - Small errors in the continuum emission can mask spectral line emission
    (errors cause ripples, chromatic aberration leads to spurious spectral features)
  - There are ghost sources at the band edges (rms higher in edge channels)

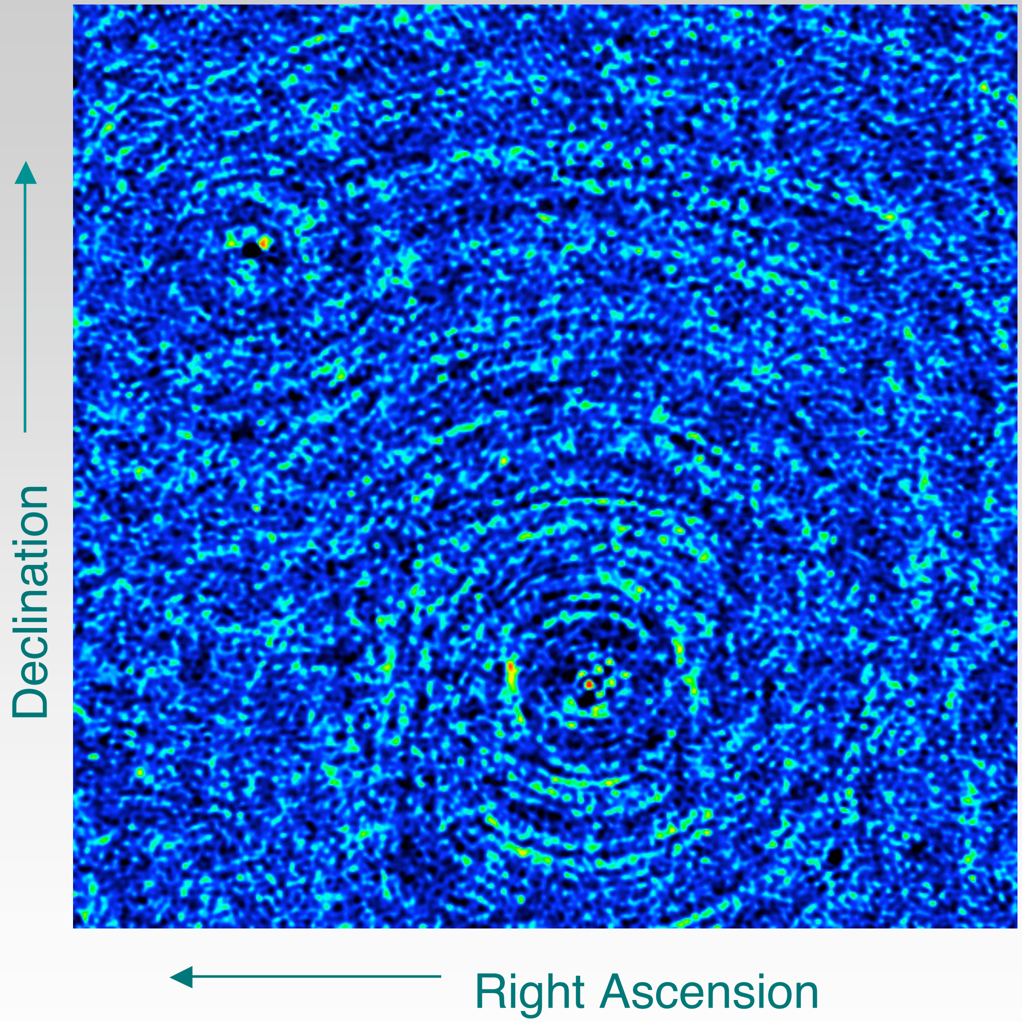
Ghosts: Spectral ripples





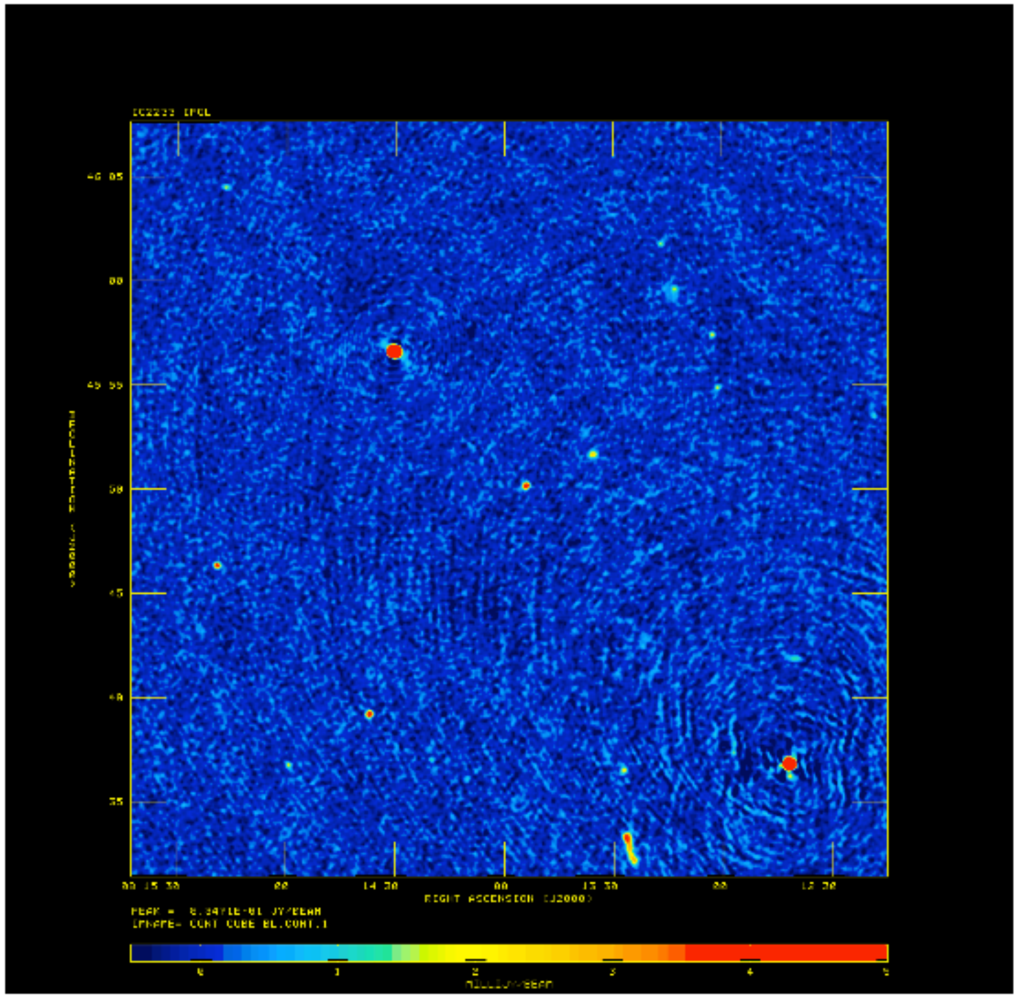
- Cannot be corrected easily as amplitude depends on the phase of the *uncalibrated* visibility. It cancels at the phase center.

The final spectral cube

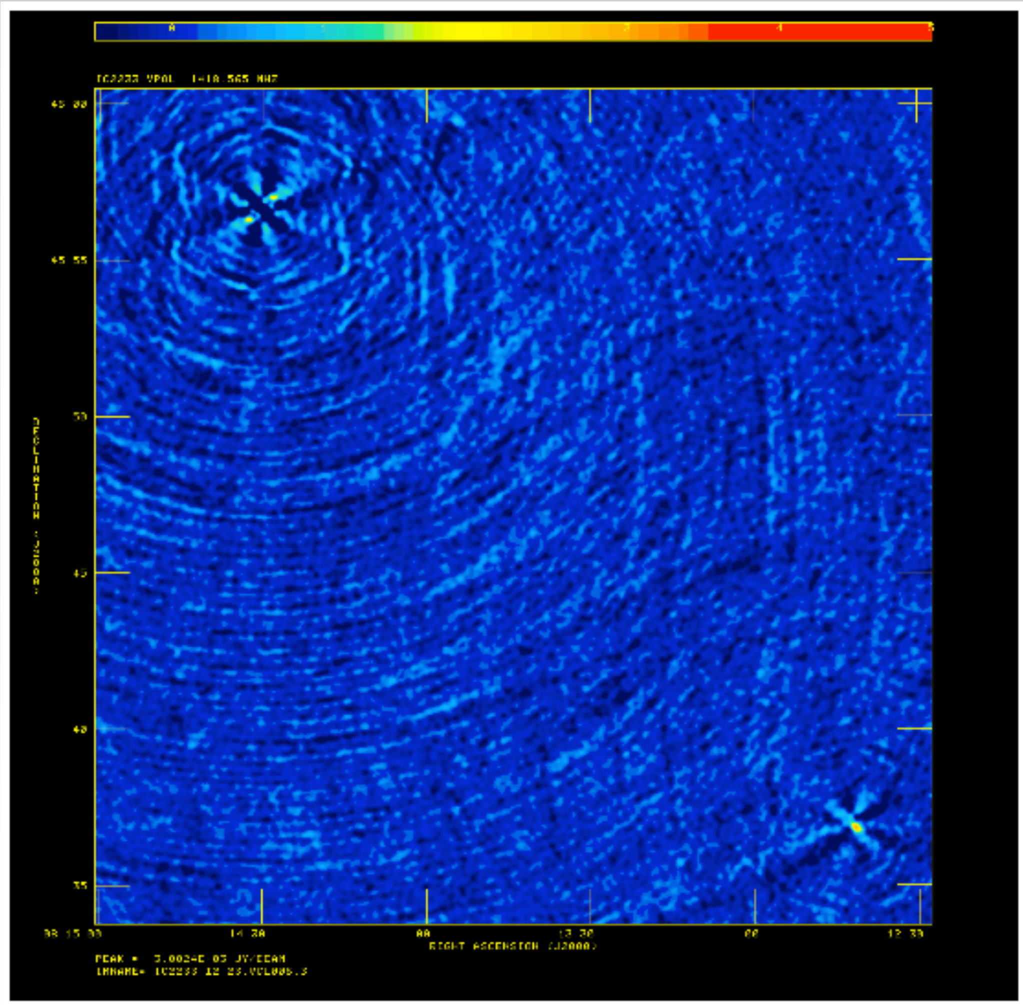


"Movie" showing a consecutive series of channel images of IC 2233 & Mk 86 (notice the ghost images in the first and last few channels).

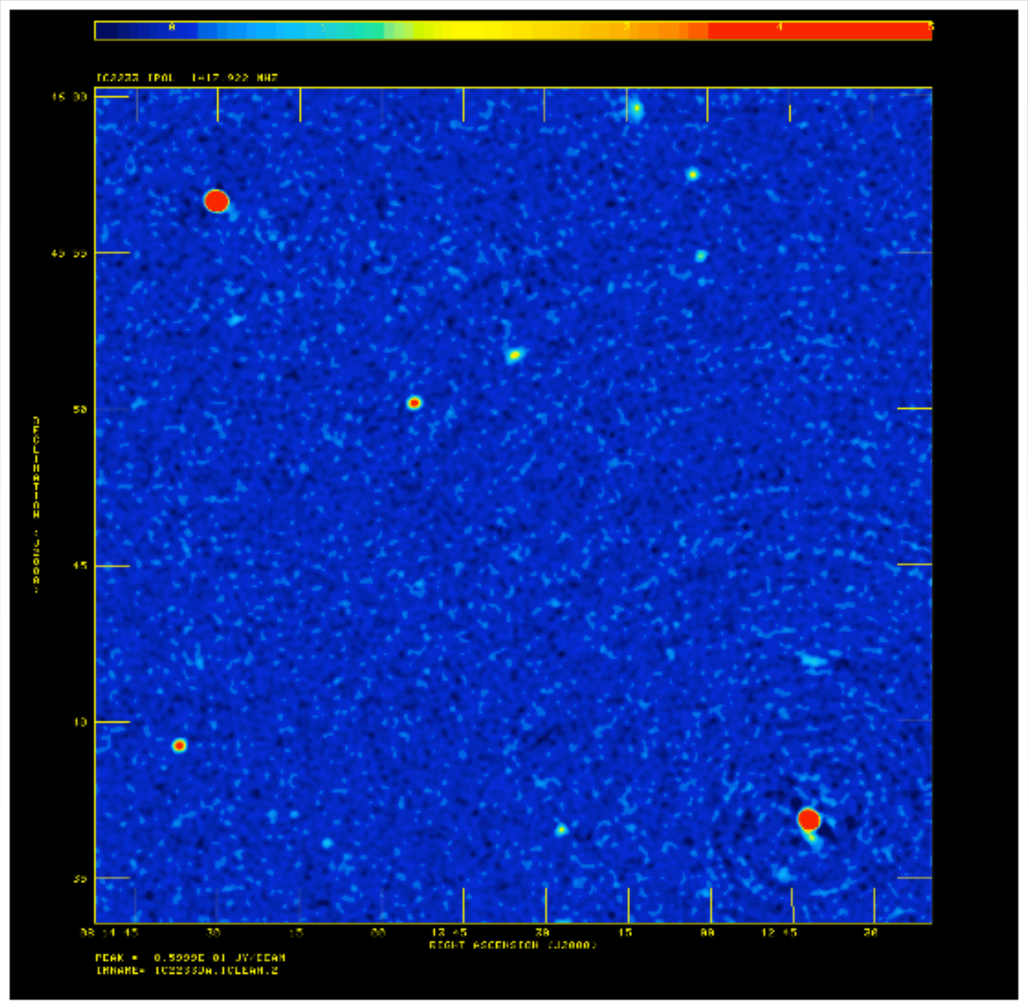
IC 2233 & Mk 86: Standard continuum



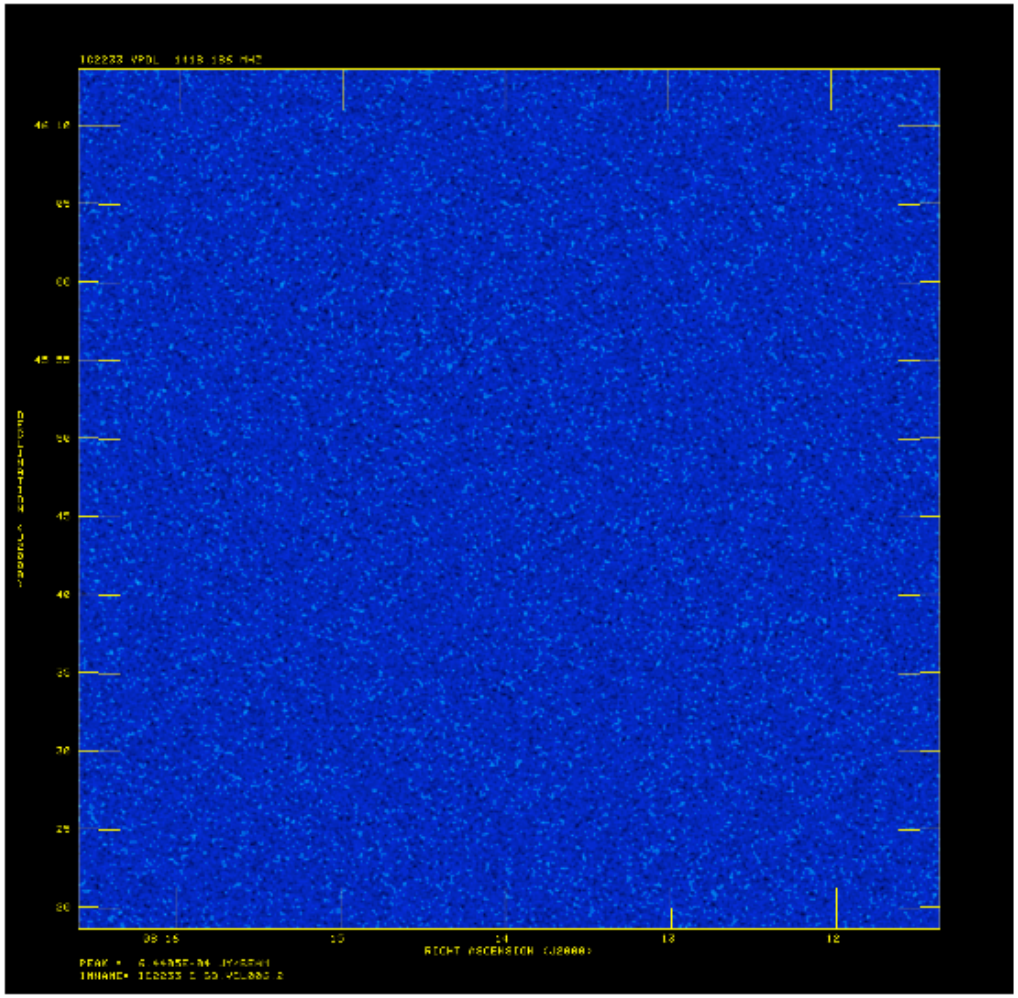
IC 2233 & Mk 86: Stokes V



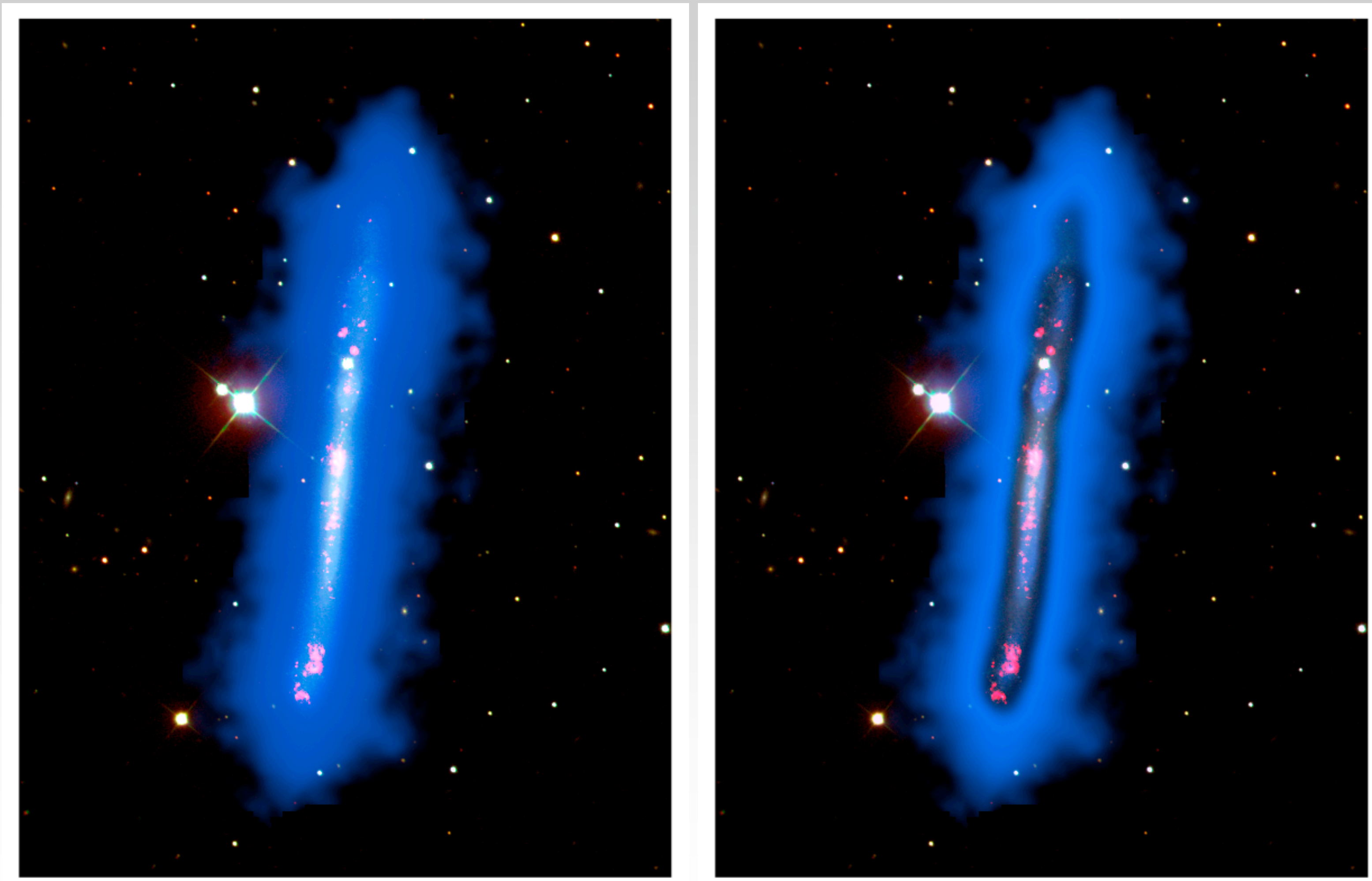
IC 2233 & Mk 86: Squint corrected



IC 2233 & Mk 86: Stokes V, Squint corrected



IC 2233 shows corrugations in HI !



(L. D. Matthews & JMU, AJ 135, 291, 2008)

Other effects: Pointing corrections?

- It would seem possible (in principle)
  - Demonstrated on simulations (point sources, perfect calibration)
- But, the correction is not orthogonal to Amplitude selfcal
  - Likely always dominated by one source (as in IC2233)
  - Need correction of other effects too (extended emission)

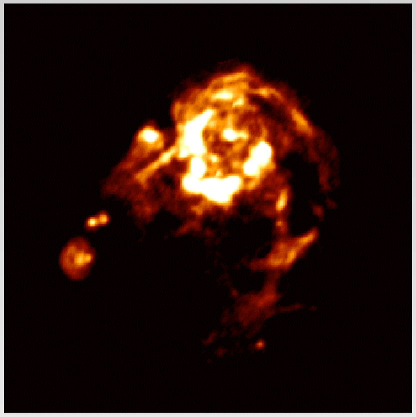
- It would seem best to point the VLA better!
  - Better understanding of antennas and pointing equation
  - Might need reference pointing for high dynamic range (always?)

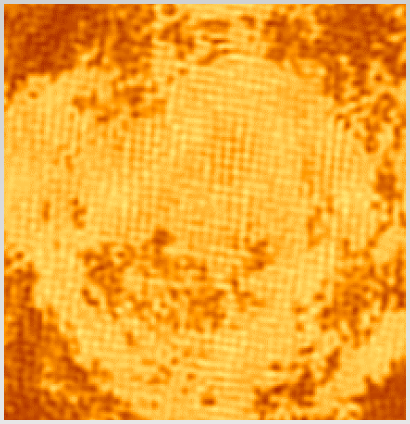
Other effects: Extended Emission

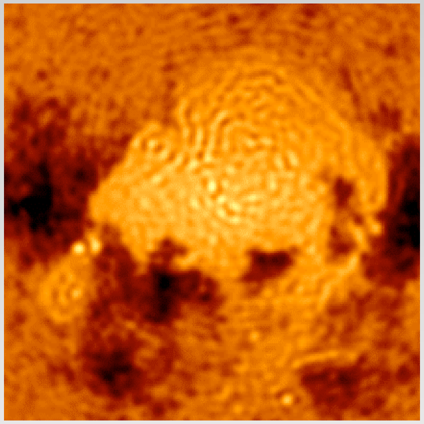
- It will be necessary to represent extended emission correctly
- A number of scale-sensitive algorithms are being developed
  - Multi-scale, multi-resolution clean (a-priori scales)
  - Adaptive Scale Pixel decomposition (no a-priori scales assumed)

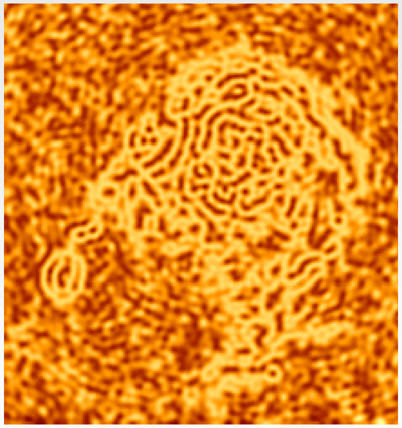
- It will be necessary to include spectral indices
  - Position dependent
- Should be hands-off
  - Scales, spectral indices should be derived from the visibilities

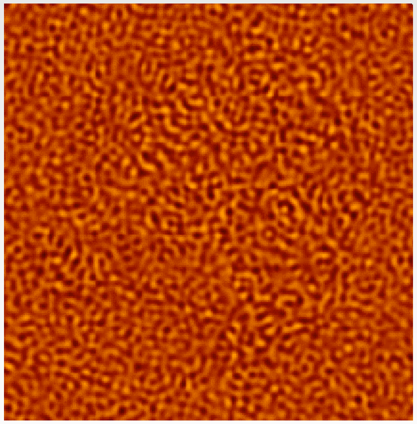
Imaging of extended emission





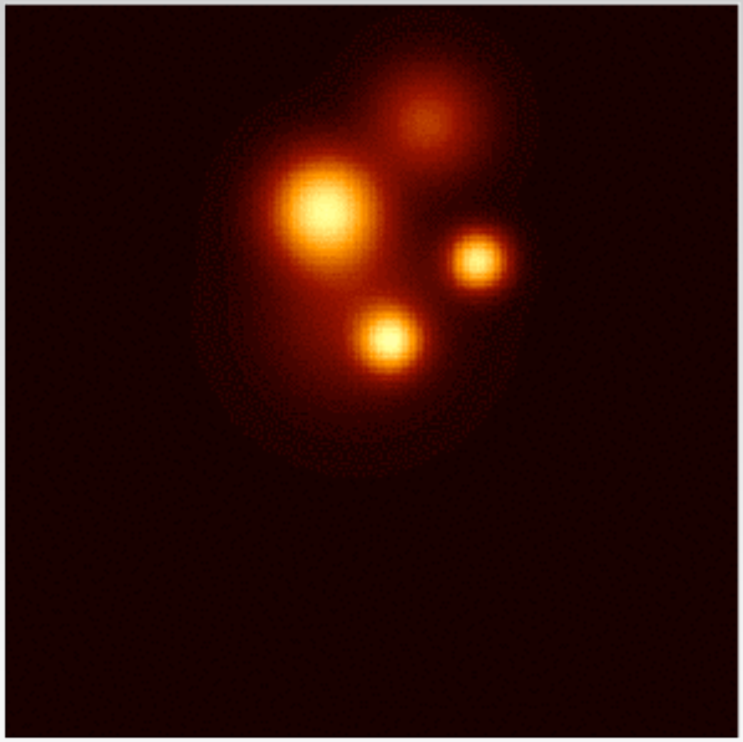






- Simulated “data.”
- Images similar
- (Clean, MEM,
- MS-clean, ASP).
- But the residuals are very different!

ASP deconvolution: Example

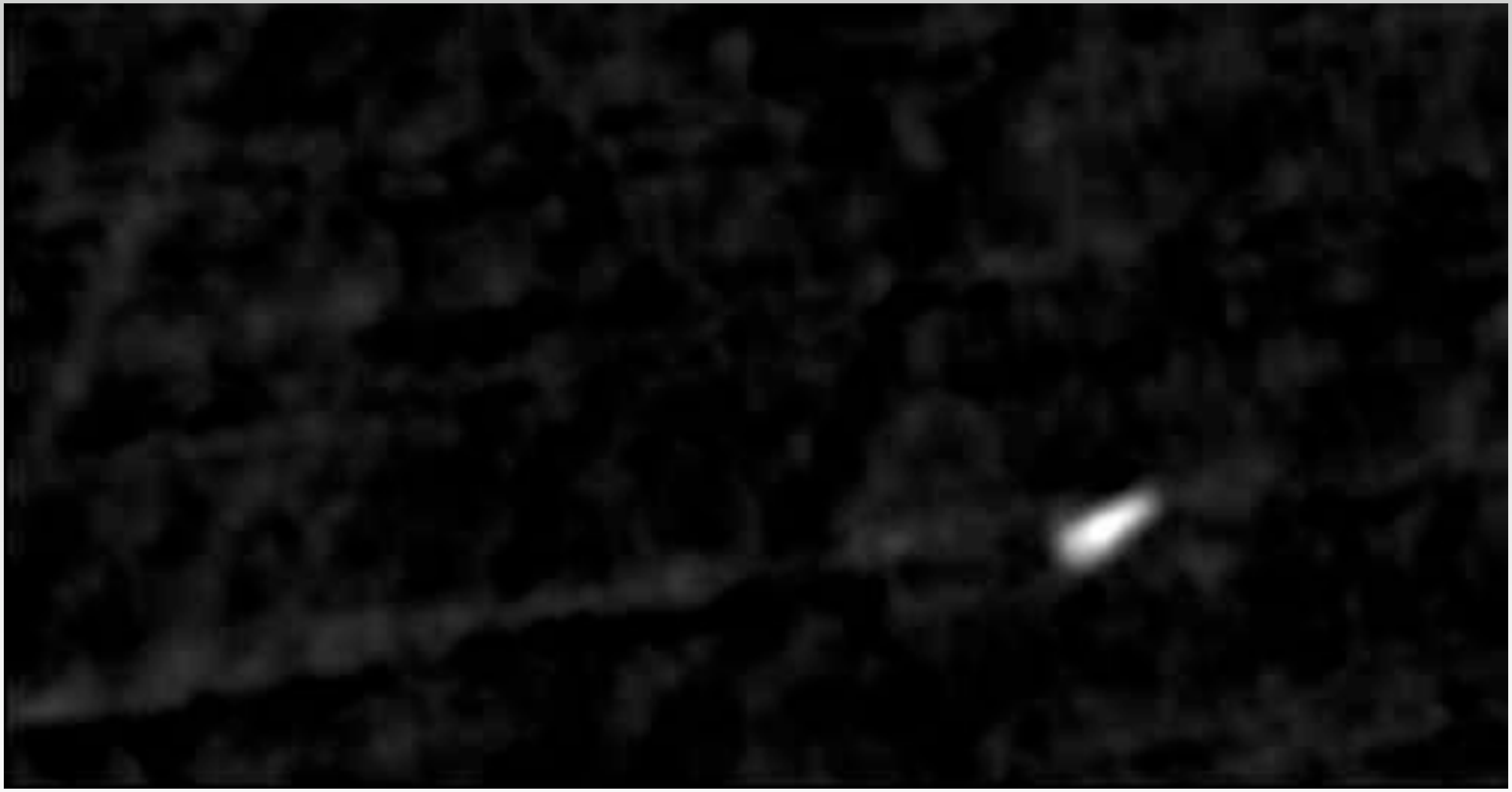


- Animation courtesy of Sanjay Bhatnagar.

Other effects: Non-isoplanaticity

- Wide-fields need direction-dependent corrections.
- Often handled with “peeling” algorithms:
  - Introduce (too) many degrees of freedom
  - Nonlinear effects generate ghosts
  - Only correct the vicinity of strong sources

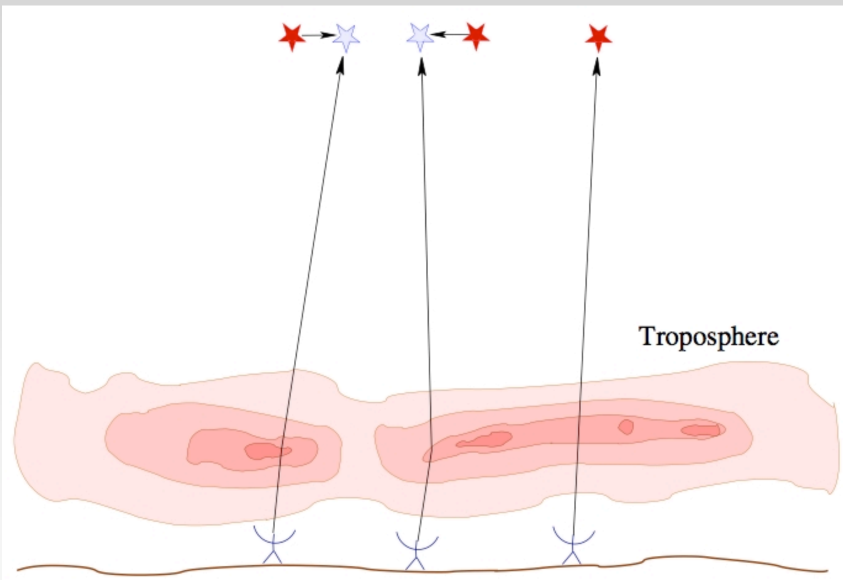
Virgo A, 75 MHz (VLA A configuration)

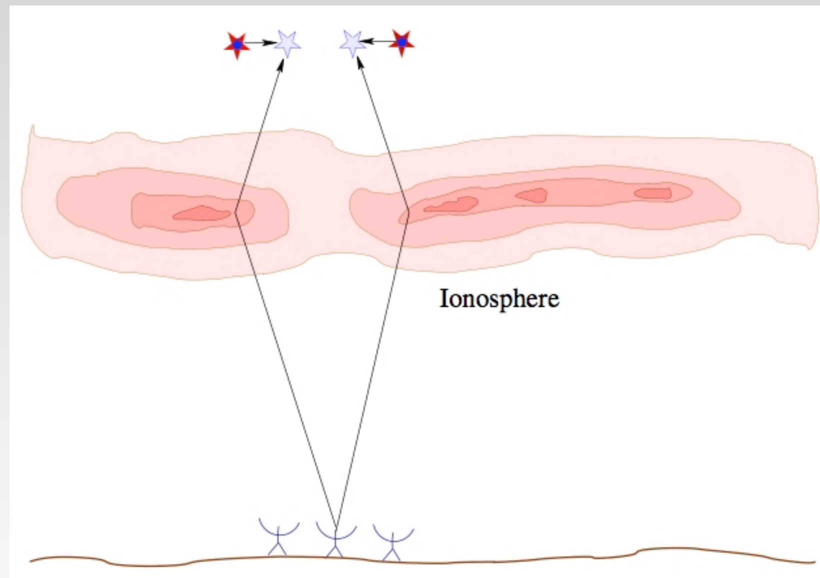


FOV ~ 30′ x 15′, 1 minute snapshots

data from Rick Perley, movie courtesy of Bill Cotton

Troposphere vs. ionosphere





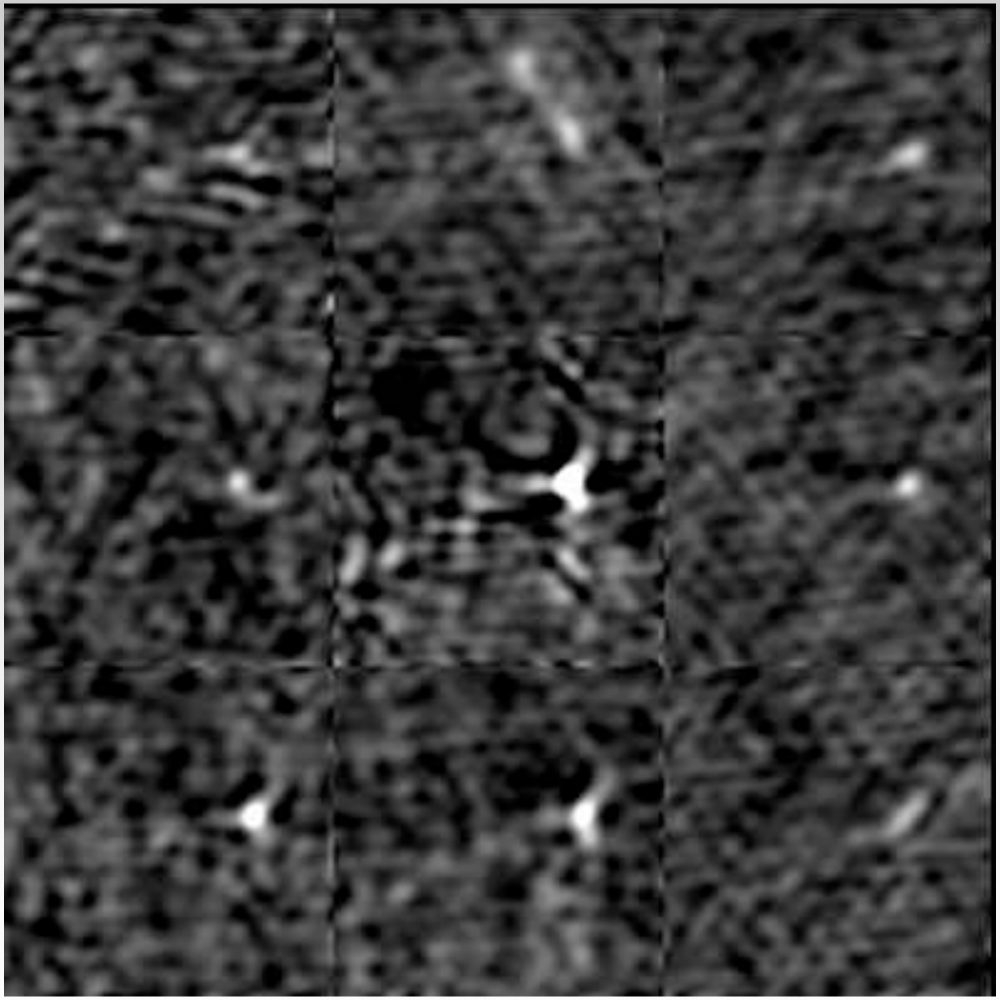
~DI errors

corrected with selfcalibration

~DD errors

attempted correction with phase-screen models

Images distorted by ionosphere

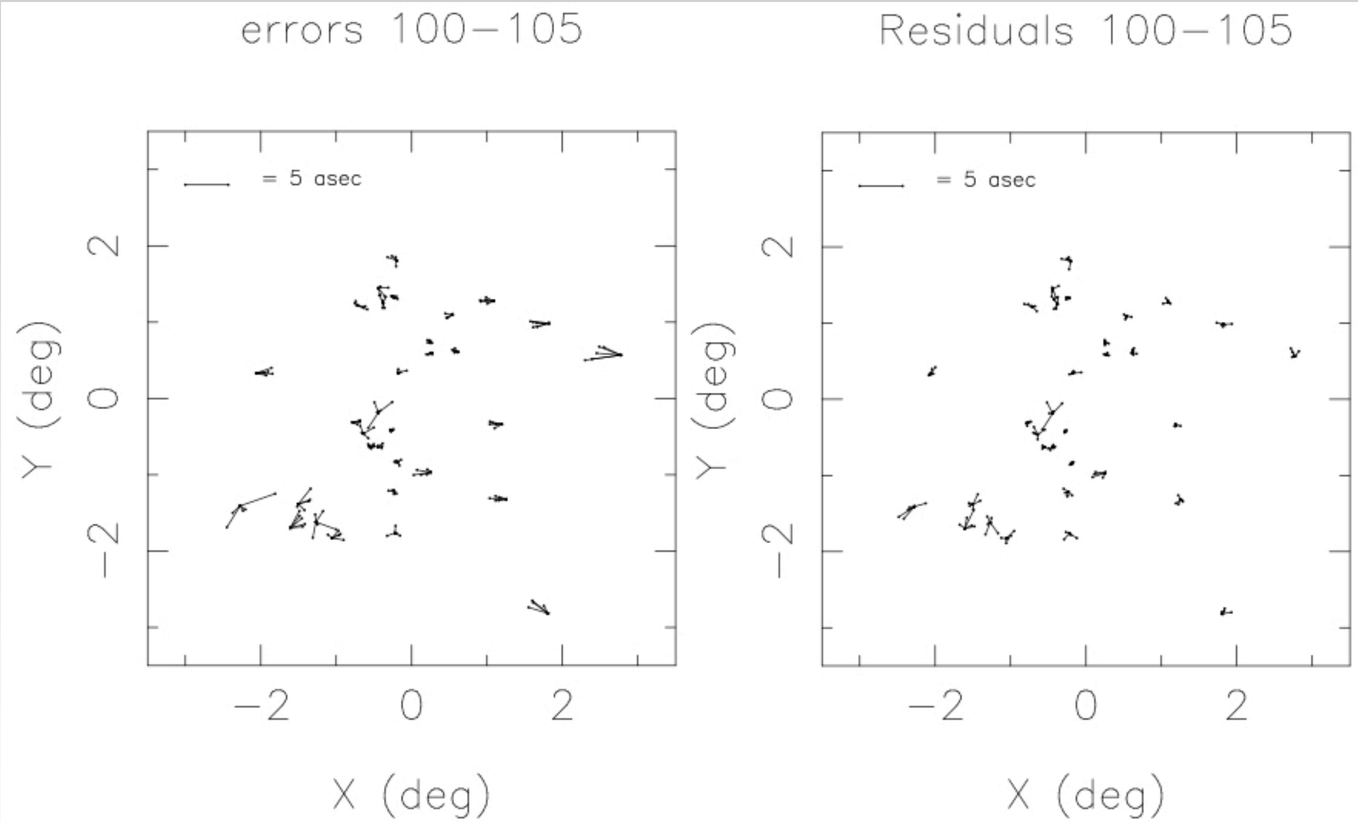


- Some changes appear correlated, some do not …

Non-isoplanaticity corrections

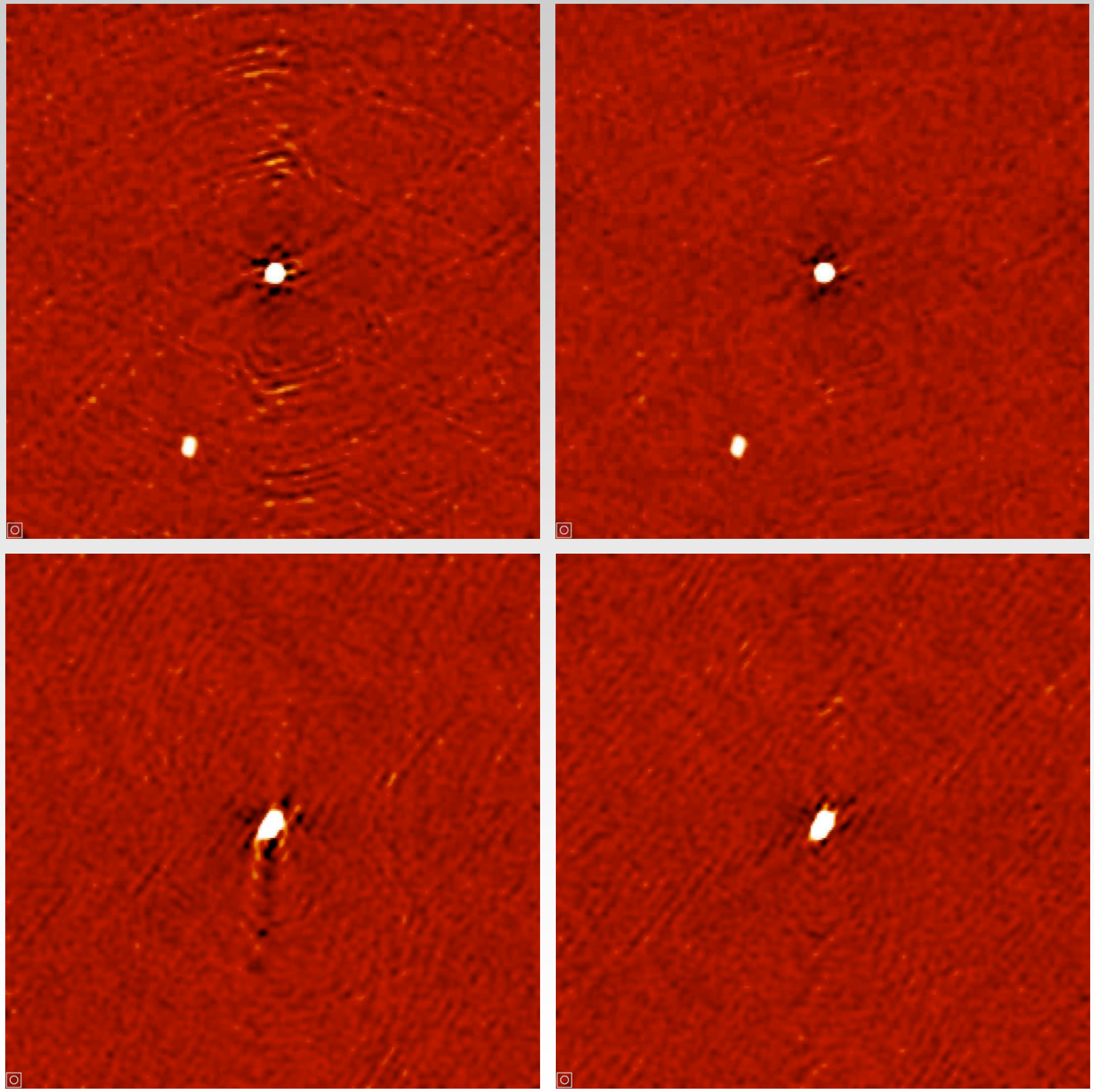
- Model ionosphere as a wedge over each antenna
  - Fit 2nd order Zernicke polynomials to strong-source positions
- Evaluate residual “seeing,” impose cutoff
  - Apply corrections to whole field.
- Center strong sources on separate “facets”
  - Apply corrections to whole field.
- Dynamic range still limited (artifacts on strong sources)
  - Local selfcalibration on strong sources (peeling)
  - Non-linear procedure → can generate ghosts

Ionospheric corrections: Distortions

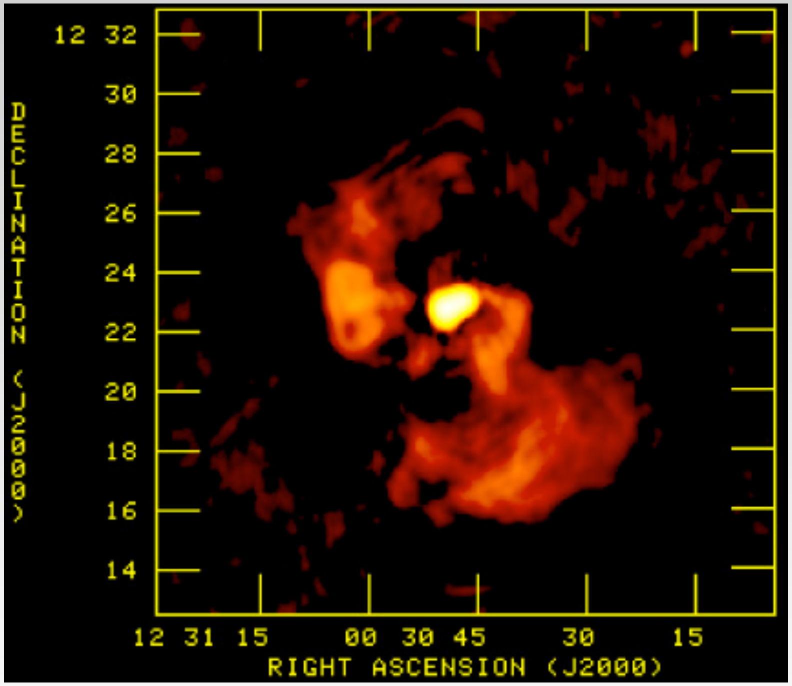


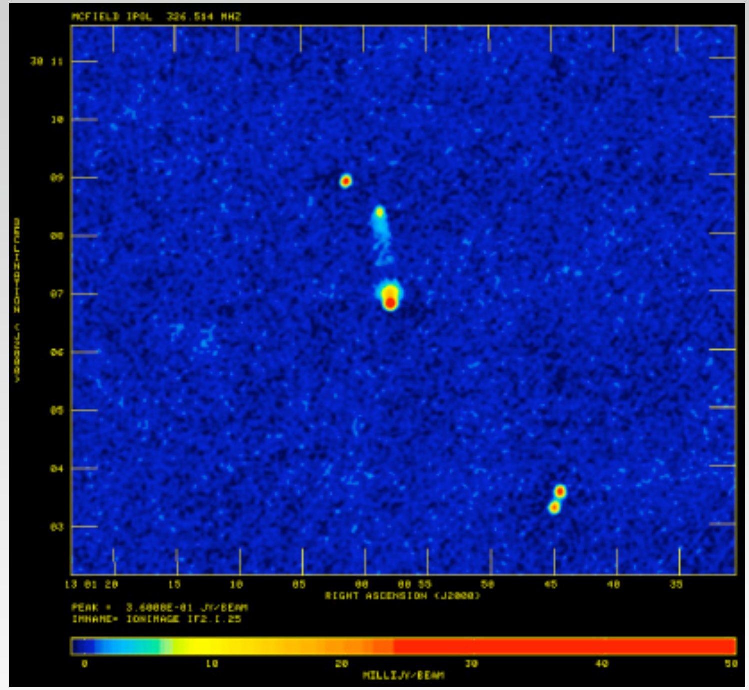
- Observations at 322 MHz with VLA A-configuration

Ionospheric corrections: Images



Ionospheric corrections: Images





- Virgo A, 74 MHz, 25”

“Empty field,” 322 MHz, 6”

Acknowledgements and references

I have benefited from many conversations with Bill Cotton, Tim Cornwell, Sanjay Bhatnagar and Ed Fomalont.

References:

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Uson, J. M. & Cotton, W. D. Astron & Astrophys. (2008, in press)

The Edge Facing Us

We know the stars are reliable.
The moon is not forever
but, too, we know it returns.

by Simon J. Ortiz

A Demonstration

- Real-time demonstration of Stokes I+V imaging that includes finding and re-centering strong sources, auto-windowing, squint correction and phase and amplitude self-calibration.
- Run using the Obit platform developed by Bill Cotton.