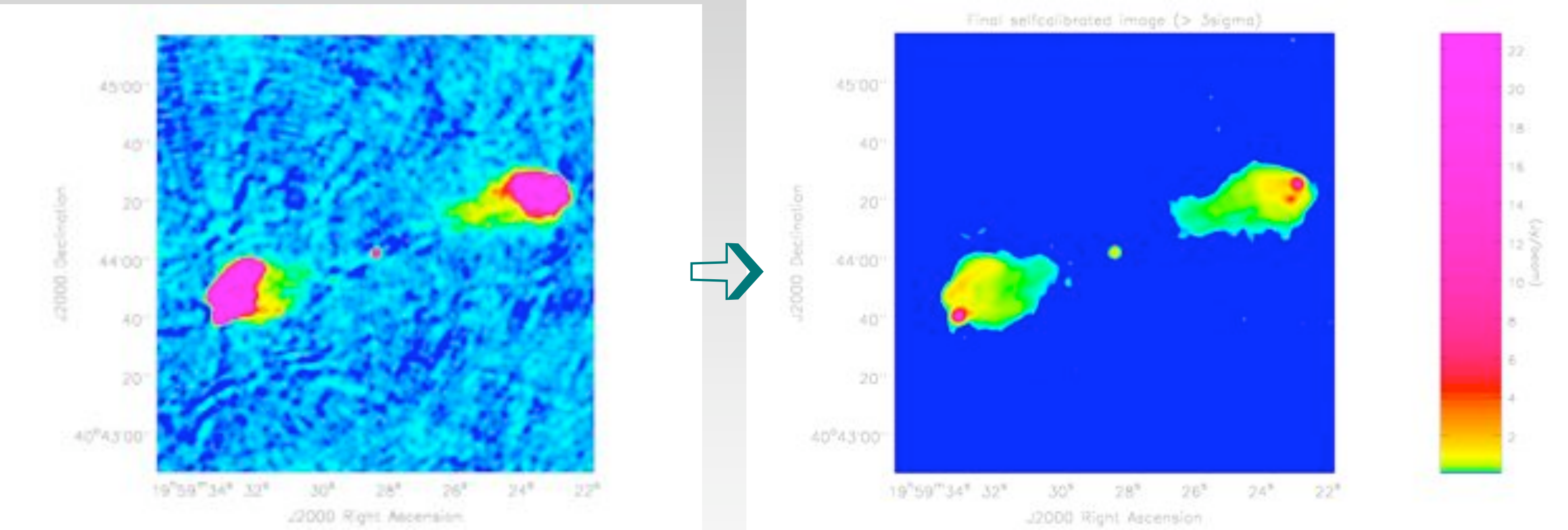
High Dynamic Range Imaging:

"Squint, Pointing, Peeling and all that Jazz"



Juan M. Uson (NRAO/Observatoire de Paris) 02.10.09

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

Lumière

Je suis pris par les jeux de la lumière

comment un verre embué

s’allume subitement contrastant avec la nuit

par 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
  - Source variability

EVLA, ALMA, SKA observations will be limited often by systematic errors

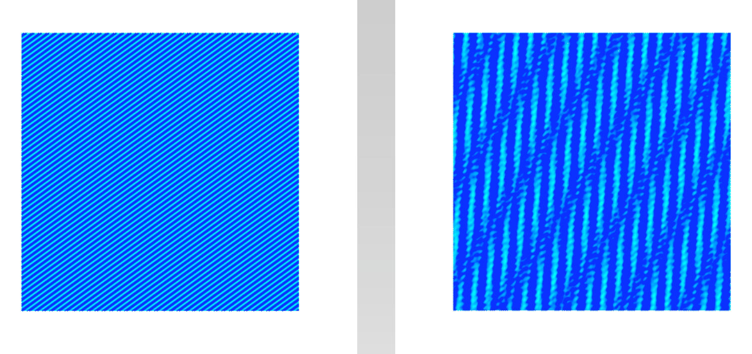
A Radio Telescope: NRAO's VLA

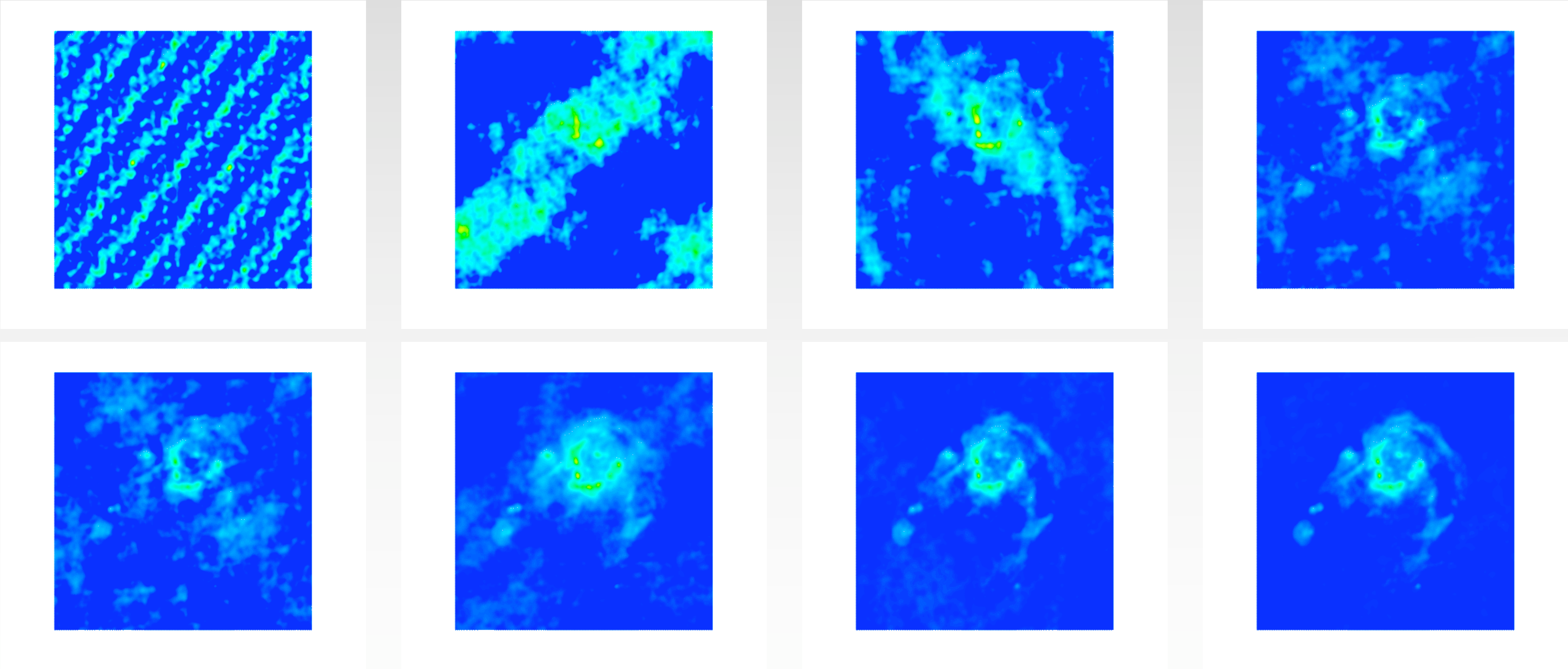
- We make images of the radio sky from measurements of the electric field measured by our antennas.
- The voltages detected at each antenna are multiplied in a "correlator" which provides us with a discretely-sampled Fourier Transform of the Sky and inserting delays prior to multiplication yields the Fourier Transform as a function of frequency, which yields spectral image "cubes."
- This is analogous to observing through a lens covered with a mask with a bunch of holes (there are ripples, the image quality depends on the number and location of the holes, and so on…).

Images: Sum of interference patterns

Double the number of interferometers from frame to frame:

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

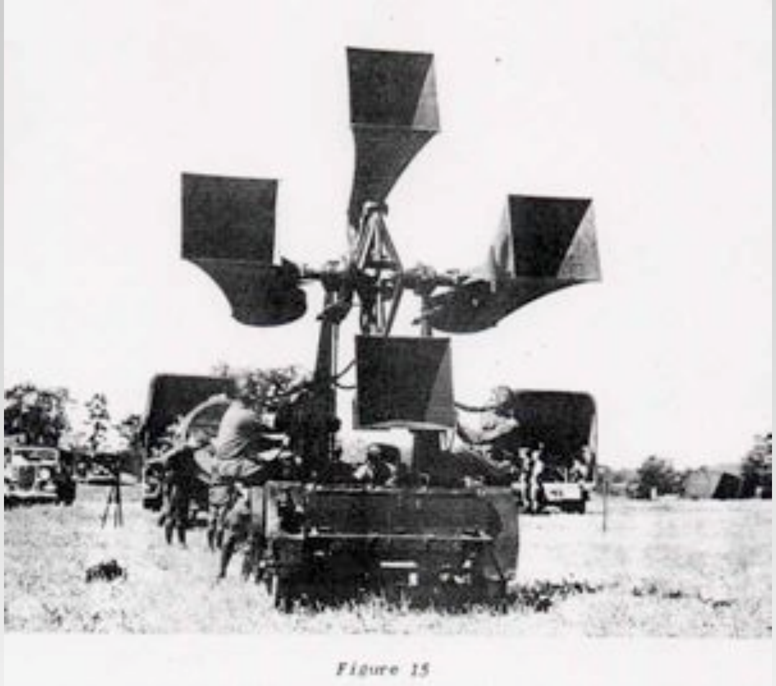




- Slide courtesy of Tim Cornwell

Imaging concepts

Phase “locates” the flux



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

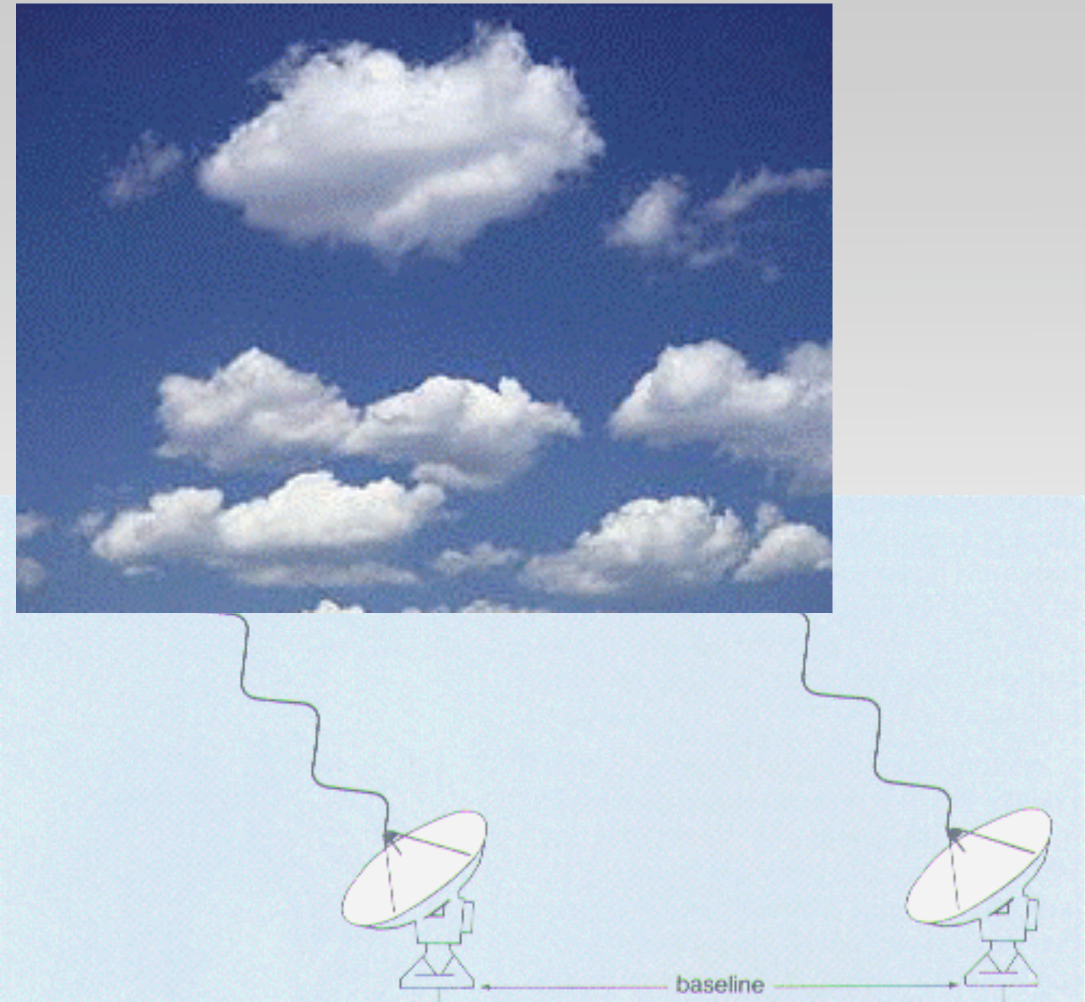
③ Self-calibration: Correcting the visibilities to sharpen the image

Improve on calibration (SNR permitting)

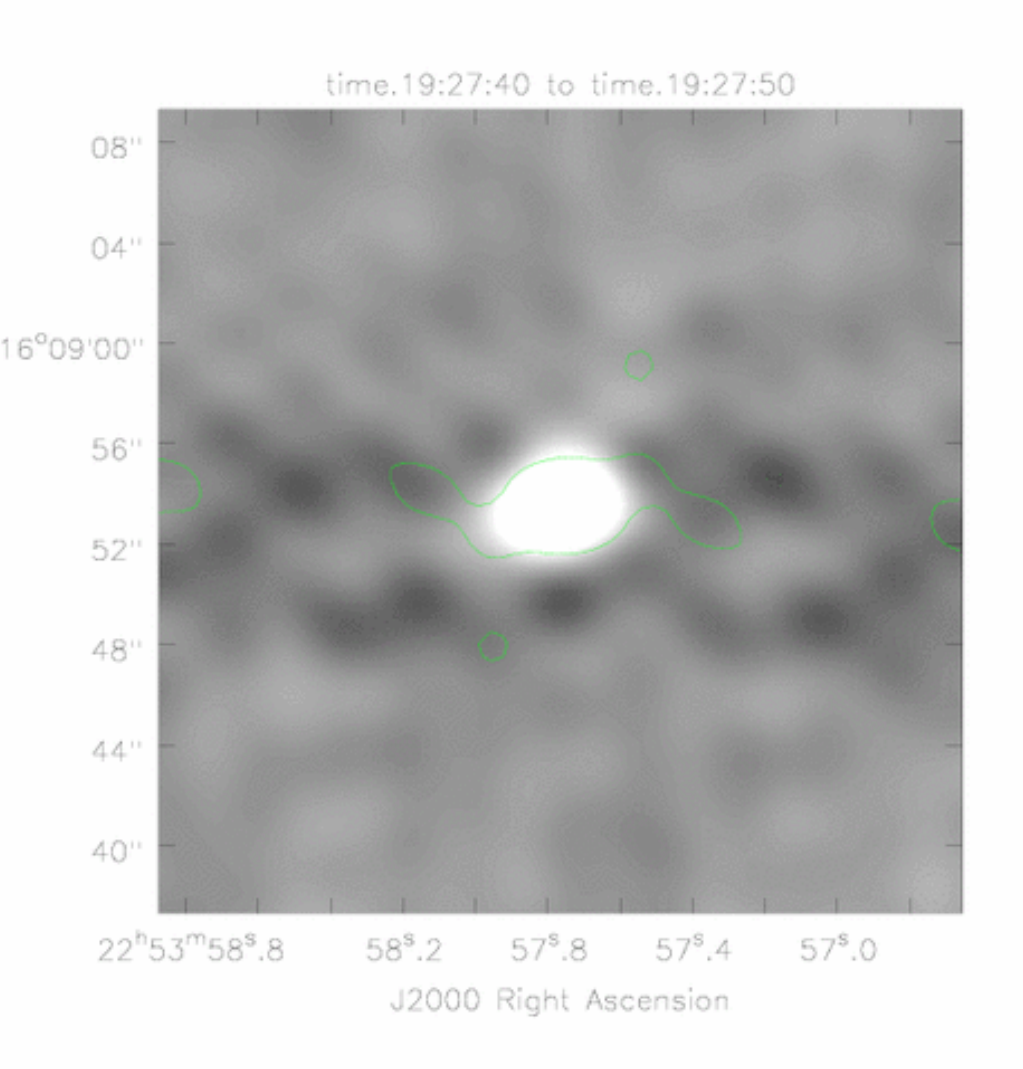
What happens in the Troposphere/Ionosphere?

- Clouds contain water vapor (ions)
- Index of refraction differs from “dry” air
- Variety of moving spatial structures

- DI and DD errors!



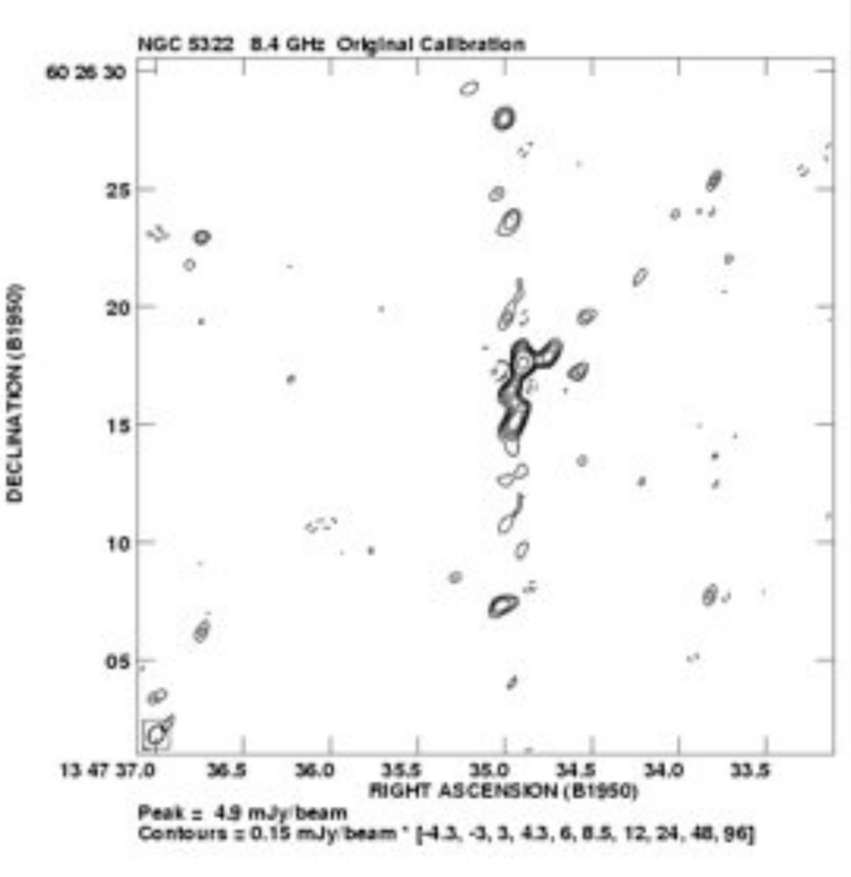
Movie of point source at 22GHz



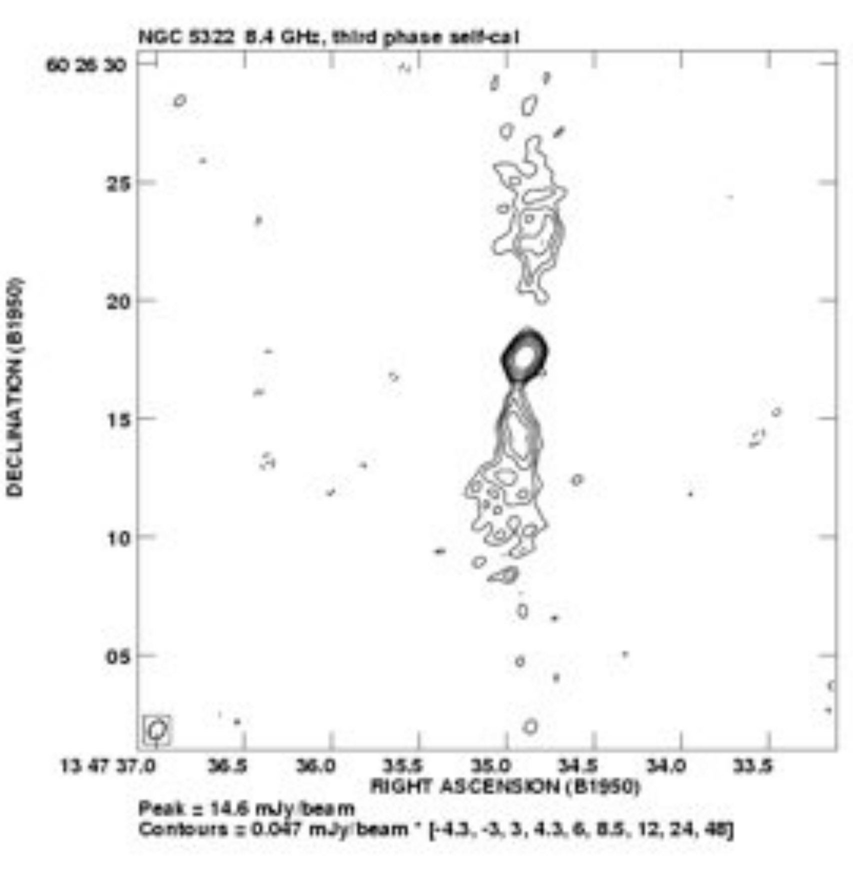
Animation courtesy of Tim Cornwell

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:

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

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

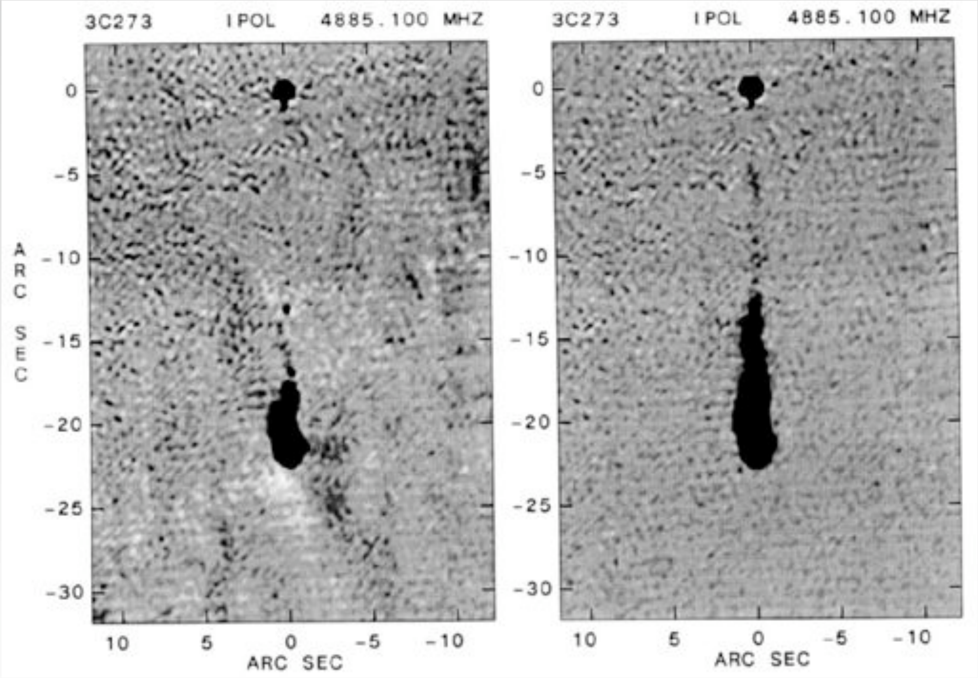
  The missing spacings can be important if V(u,v) changes significantly

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

Example:

3C273 at ~5 GHz

A vs. A+B array

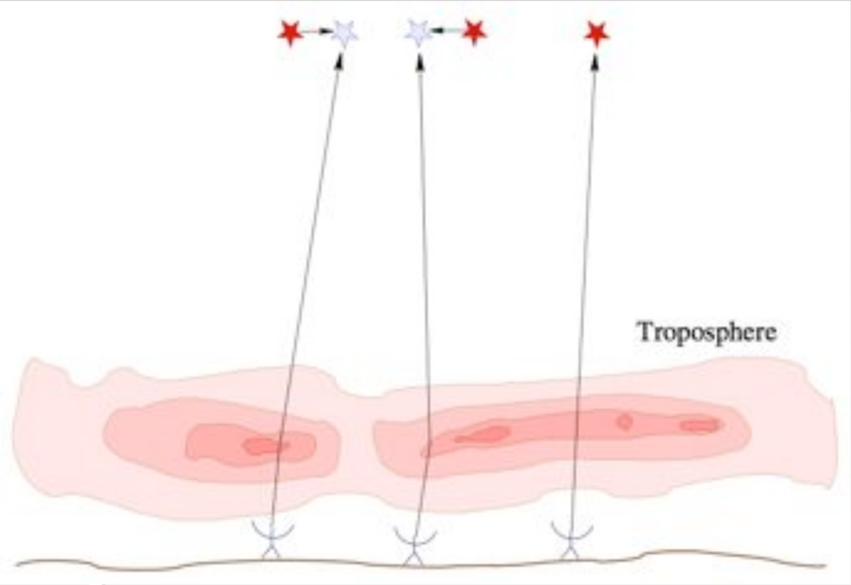


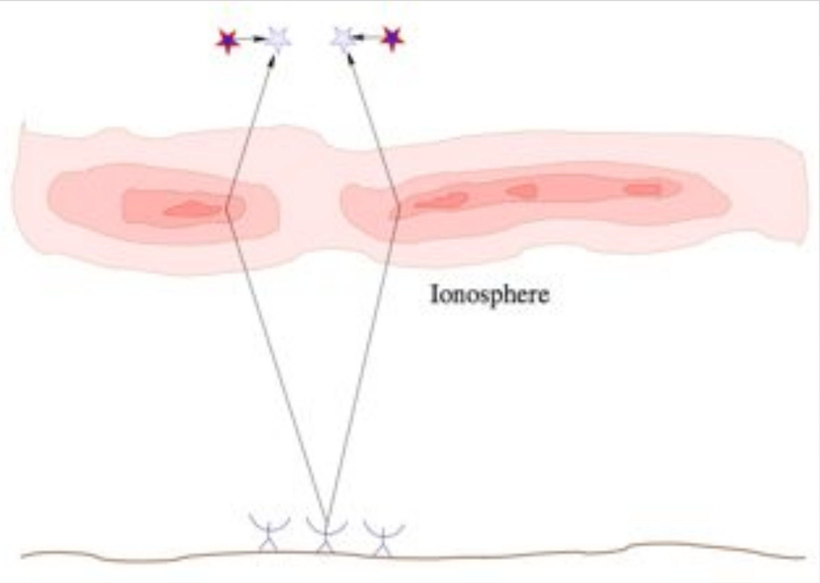
Pixelization can induce errors even on isolated point sources!

Other effects: Non-isoplanaticity

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

Troposphere vs. ionosphere





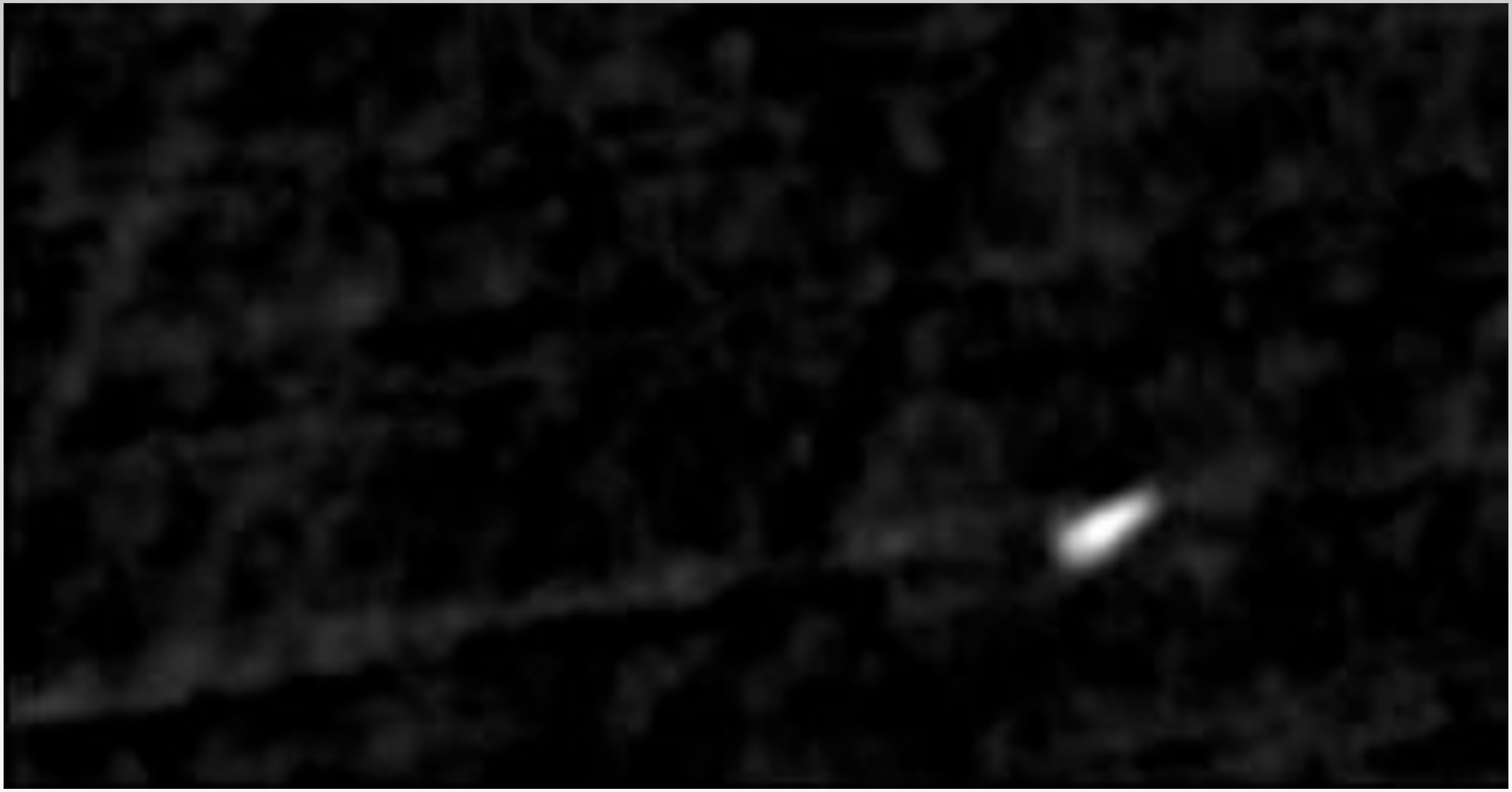
~DI errors

corrected with self-calibration

~DD errors

attempted correction with
phase-screen models

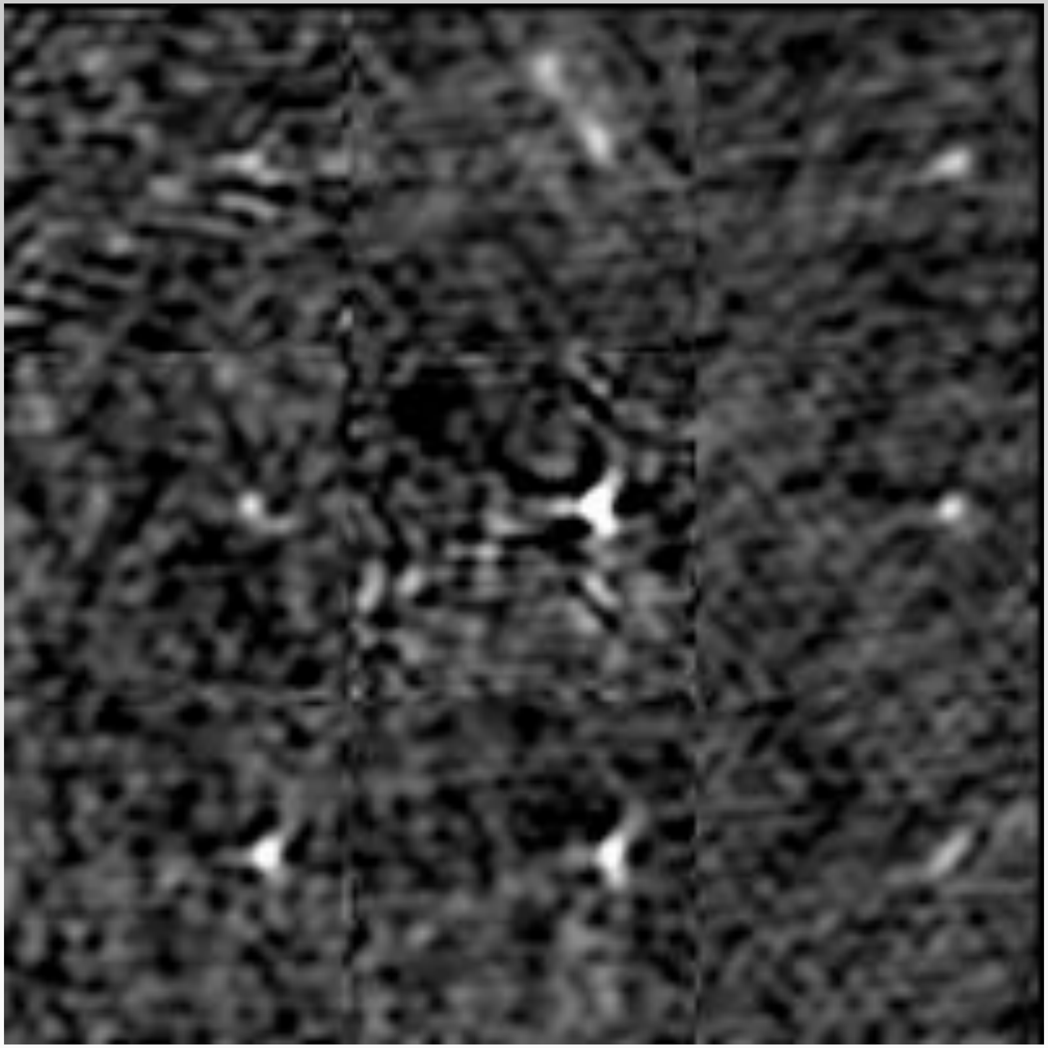
Virgo A, 75 MHz (VLA A configuration)



FOV ~ 30′ x 15′, 1 minute snapshots.

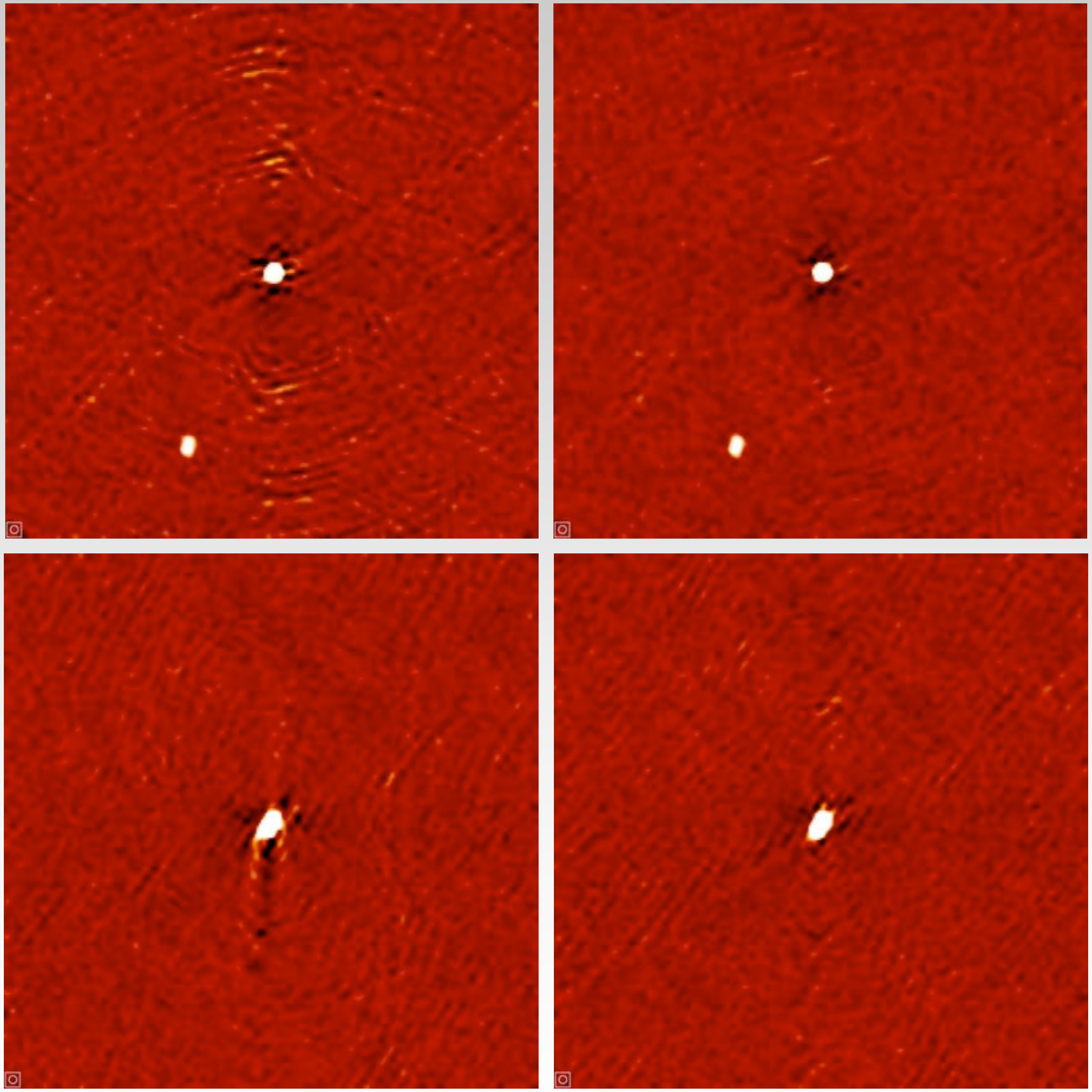
Data from Rick Perley, movie courtesy of Bill Cotton.

Images distorted by ionosphere



- Some changes appear correlated, some do not …
- Data from Namir Kassim, animation courtesy of Bill Cotton.

Ionospheric corrections: Images



Real Arrays

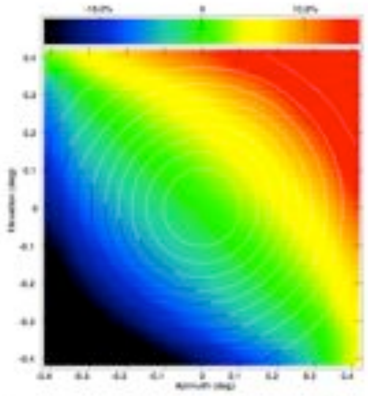


Figure 1: The VLA primary antenna pattern as measured during the NVSS survey [3] at 1.4 GHz. The instrumental Stokes V is shown in color with a scale bar at the top and contours are plotted every 10 percent in power.

- Each beam is offset from the nominal pointing center by:
  - Θ_S = ±237.56 (arcsecond/meter) · λ
- (a beam squint of 1.70′ for ν = 1.4 GHz).
- This leads to a fractional value of: Squint / FWHM = 0.0549 ± 0.0005
- Also polarization coupling; these errors vary with elevation, temperature, time

Real Arrays: Measurement Equation

- Actual observations measure:

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

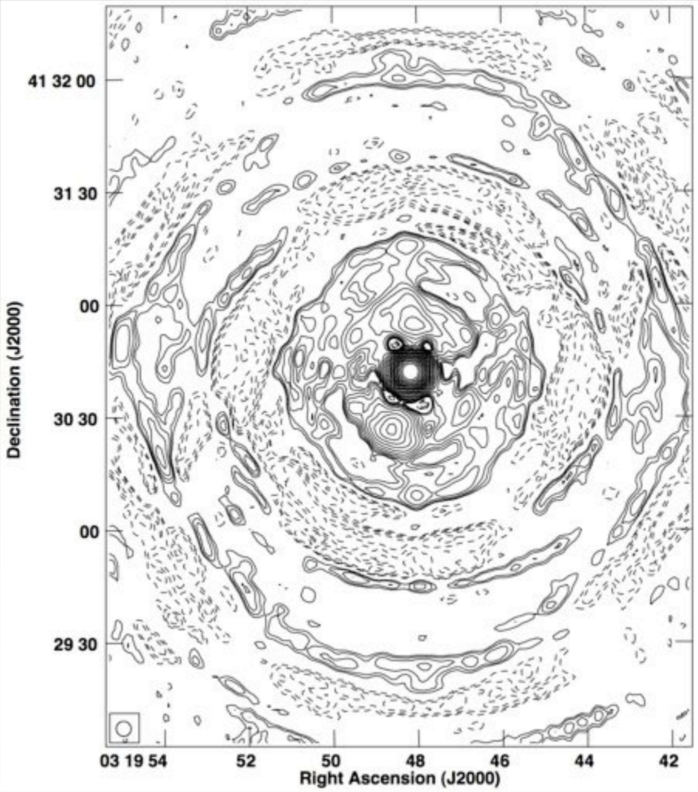
- where V_{ij}^{Obs} is the full-polarization visibility vector,
- $M_{ij}(s)$ and $M_{ij}^{Sky}(s)$ are matrices describing directionally-
- independent and directionally-dependent gains, *I* describes the full-polarization sky emission, *s* is the position vector and b_{ij} denotes the baseline.

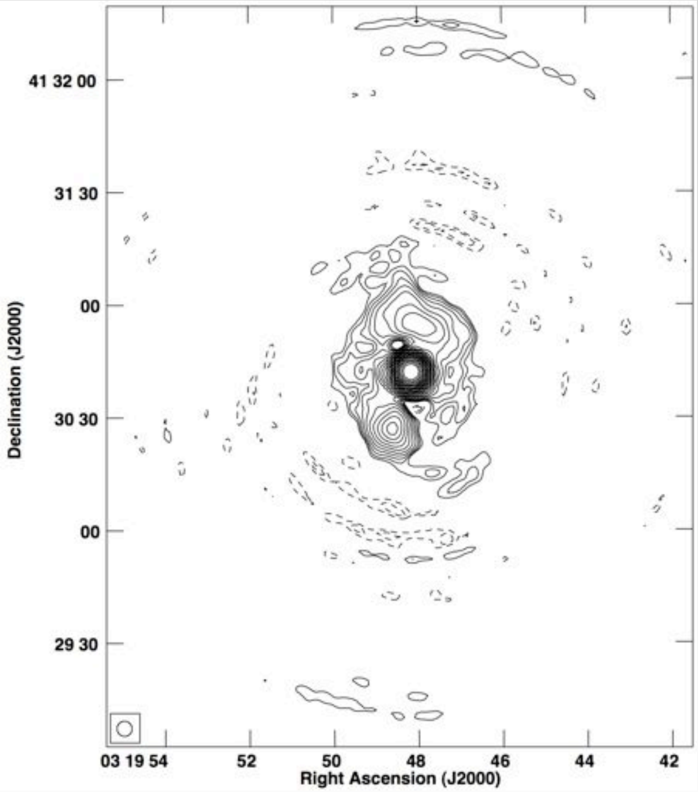
High-accuracy imaging

- 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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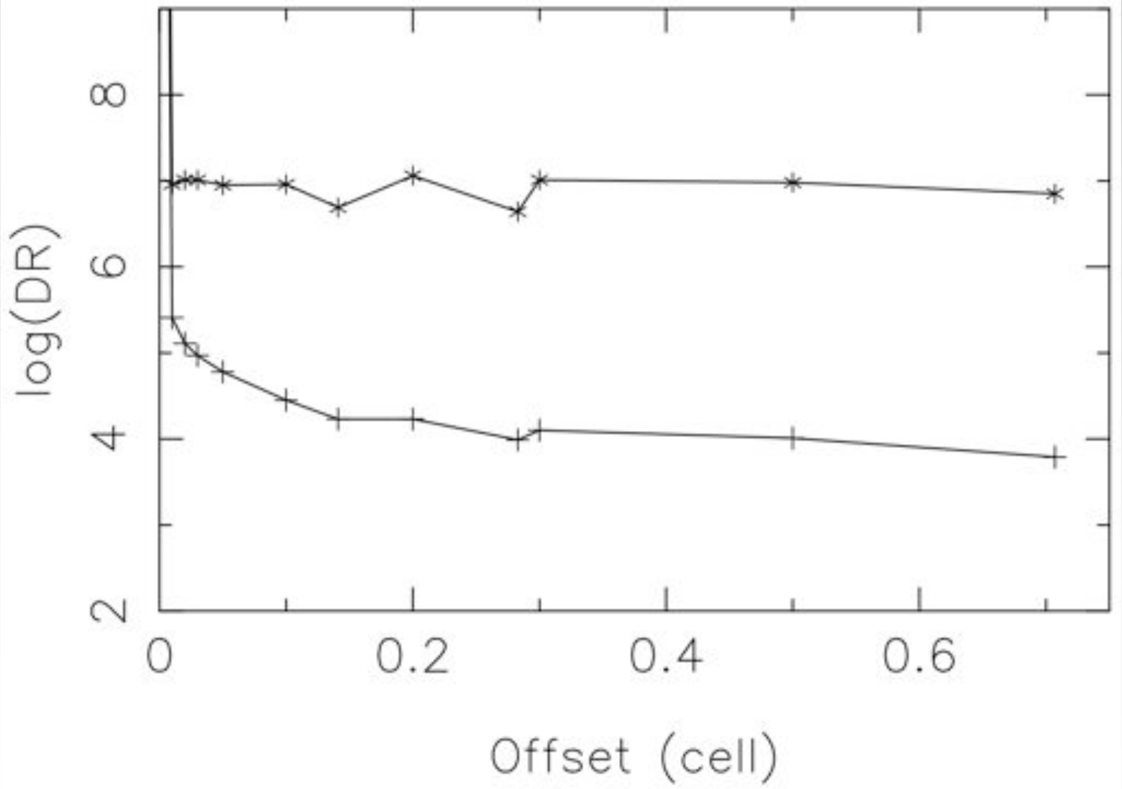


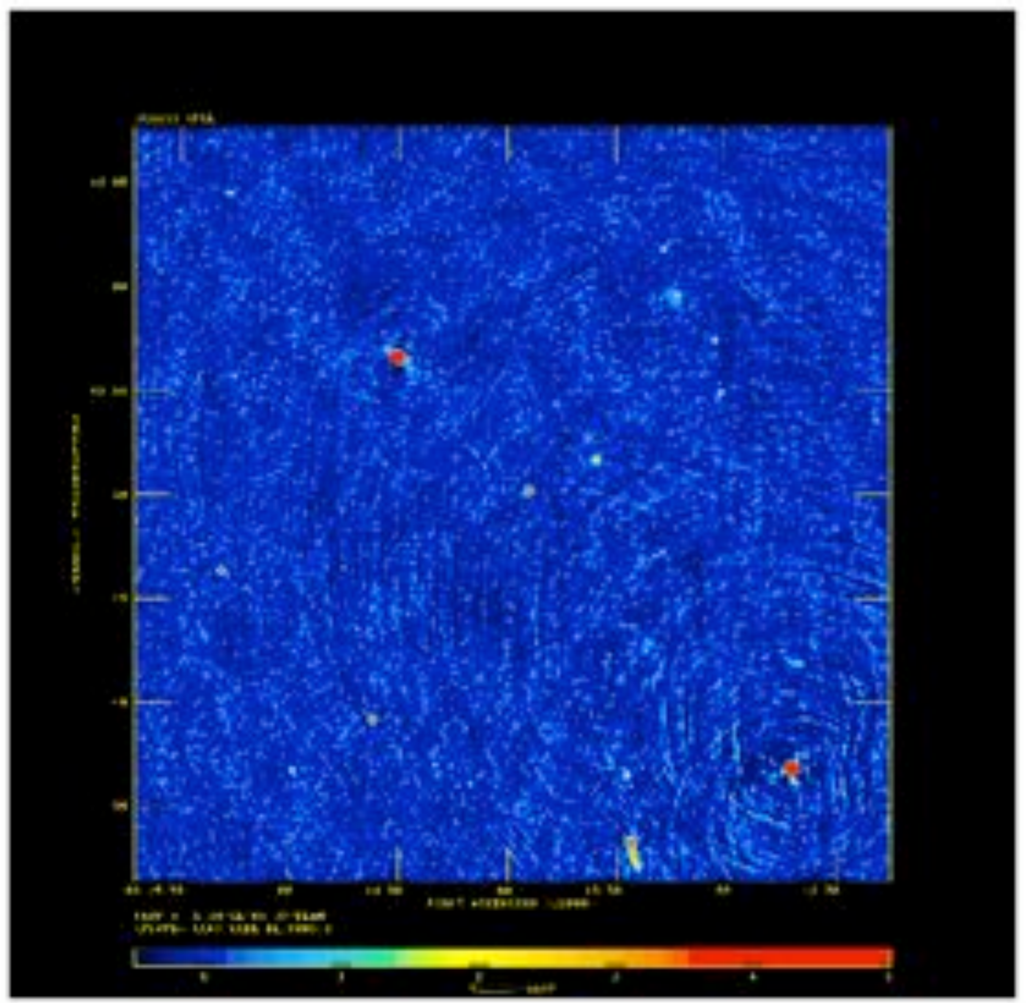
Observing with Beam Squint: IC 2233 & Mk 86

- IC 2233 is an isolated superthin galaxy (D ~ 10.5 +/- 1 Mpc)
- Mk 86 is a blue compact dwarf, spiral galaxy (D ~ 7 +/- 1 Mpc)

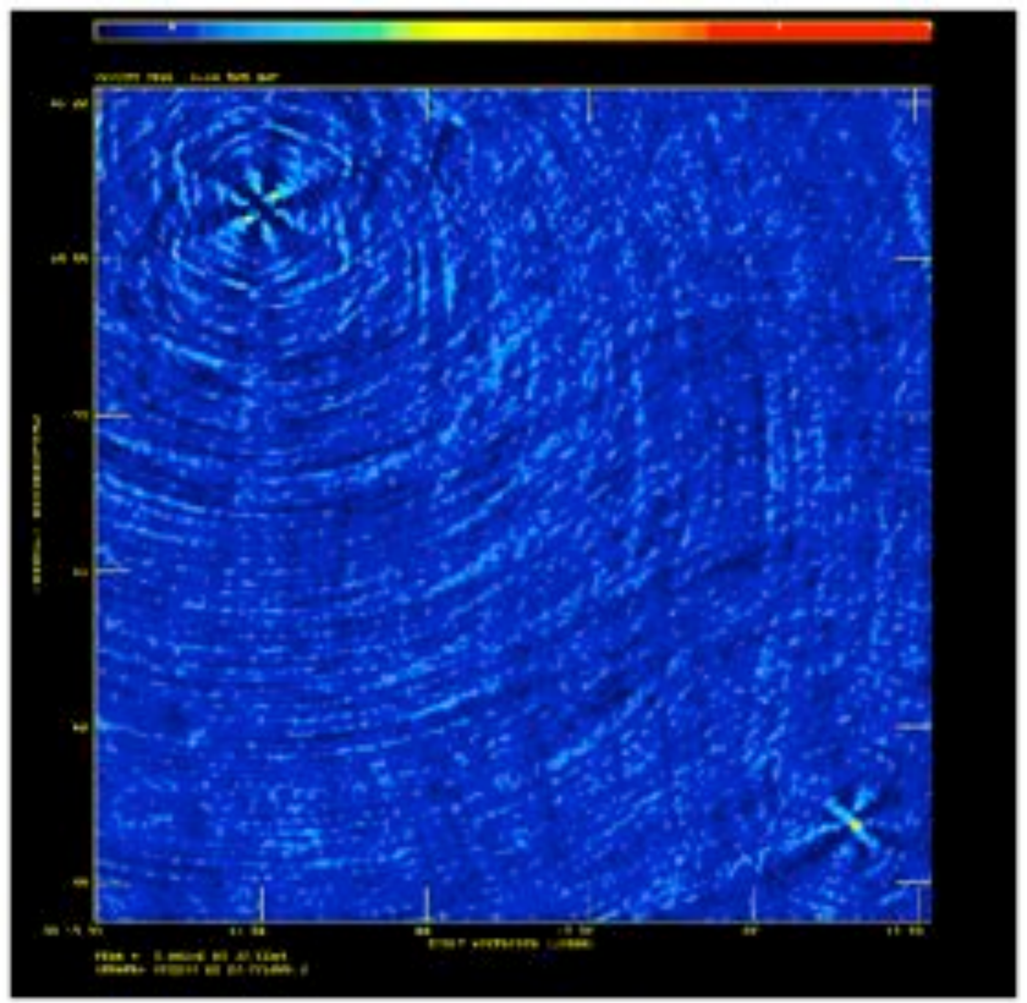
- Key experimental points:
  - The Field contains 2 "4C" sources so high dynamic range was necessary
  - The VLA suffers from Beam-Squint which leaves behind spurious signals
  - Small errors in the continuum emission can mask spectral line emission

    (errors cause ripples, chromatic aberration leads to spurious spectral features)
  - There are ghost sources at the band edges (rms higher in edge channels)

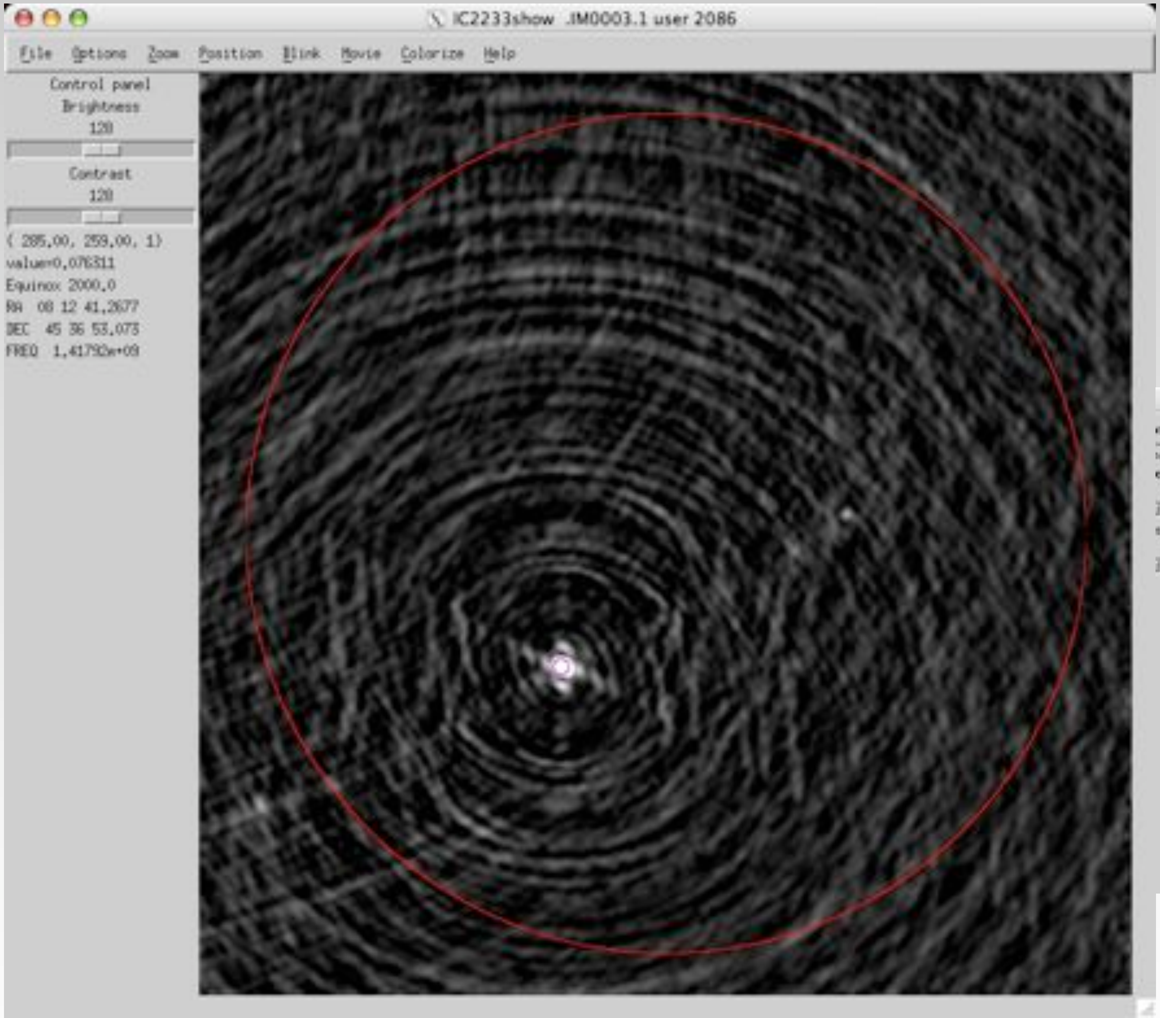
IC 2233 & Mk 86: Standard continuum



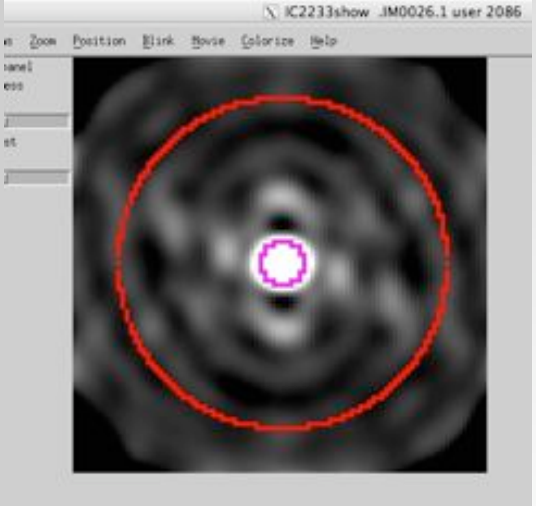
IC 2233 & Mk 86: Stokes V



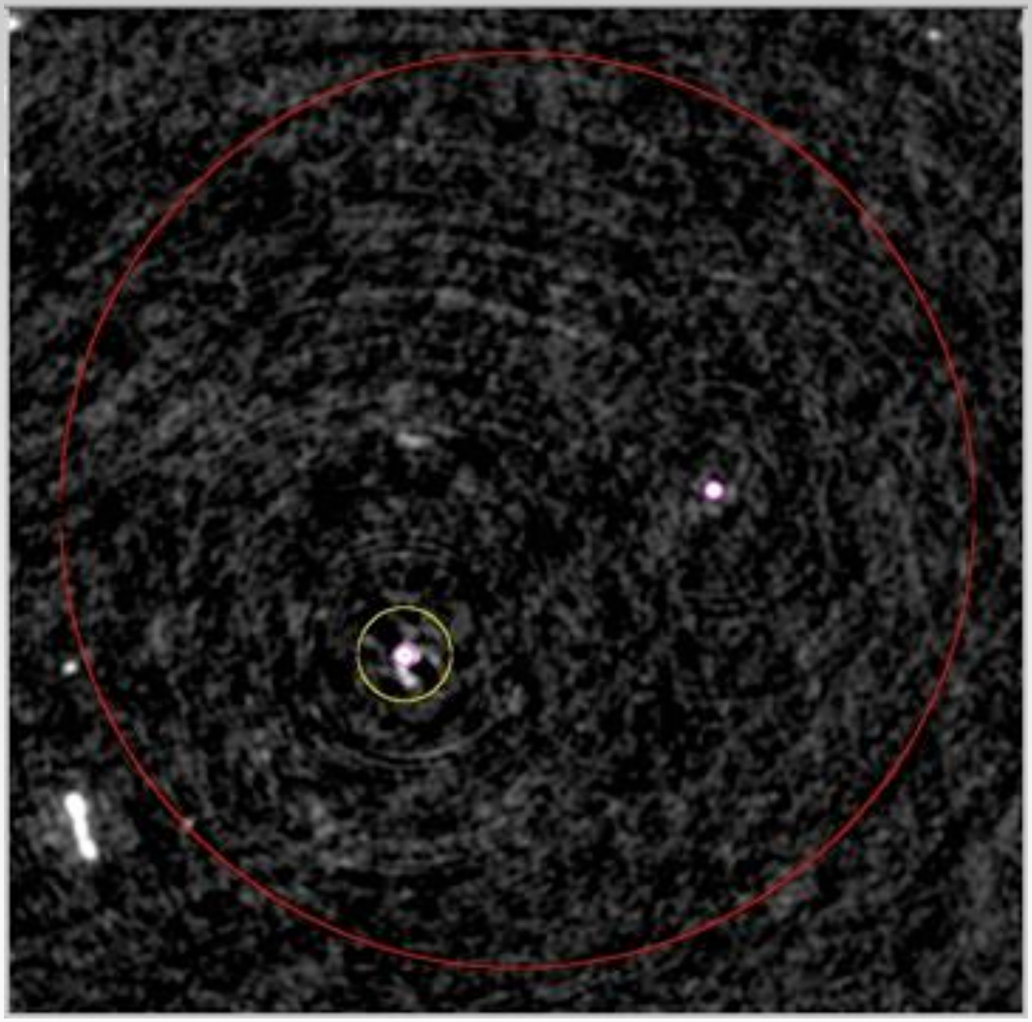
IC 2233 & Mk 86: intermediate steps



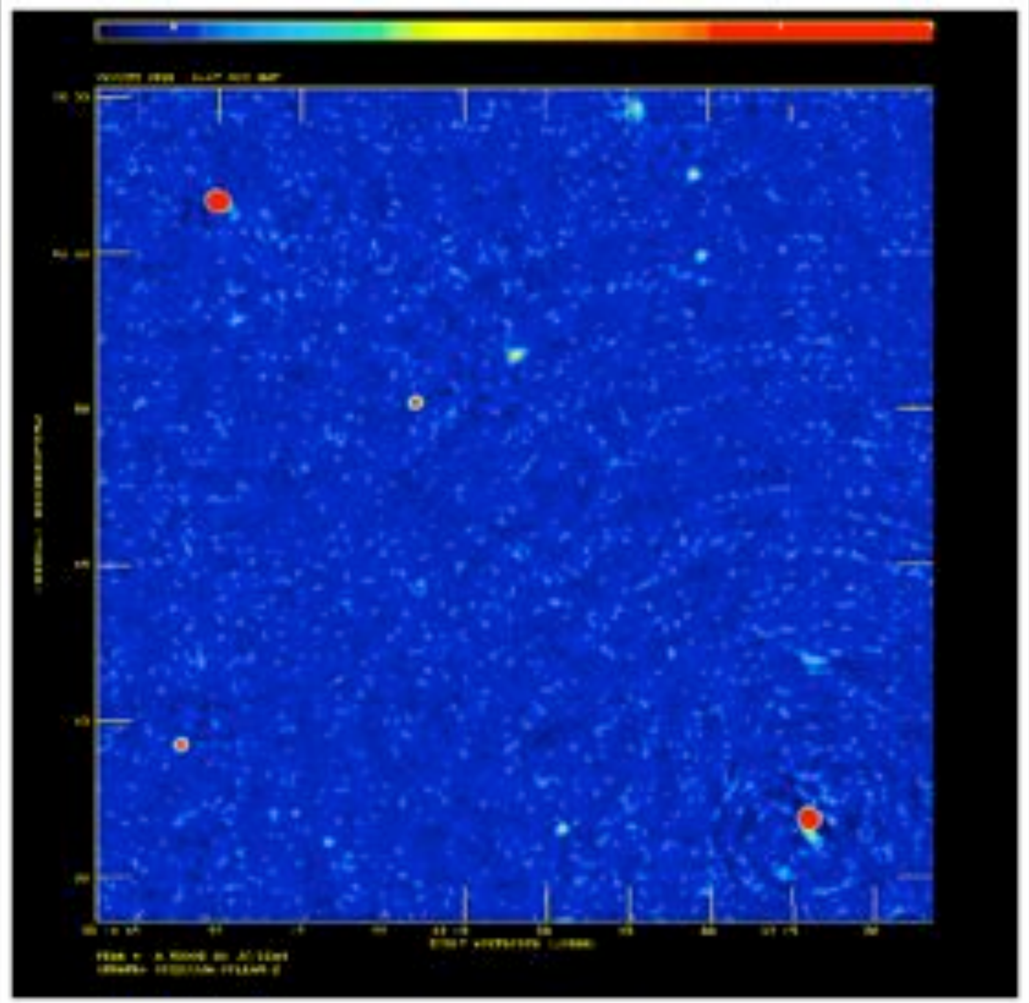
Control panel
Brightness
128
Contrast
128
(285,00, 259,00, 1)
value=0,076311
Equinox 2000,0
RA 08 12 41,2677
DEC 45 36 53,073
FREQ 1,41792e+09



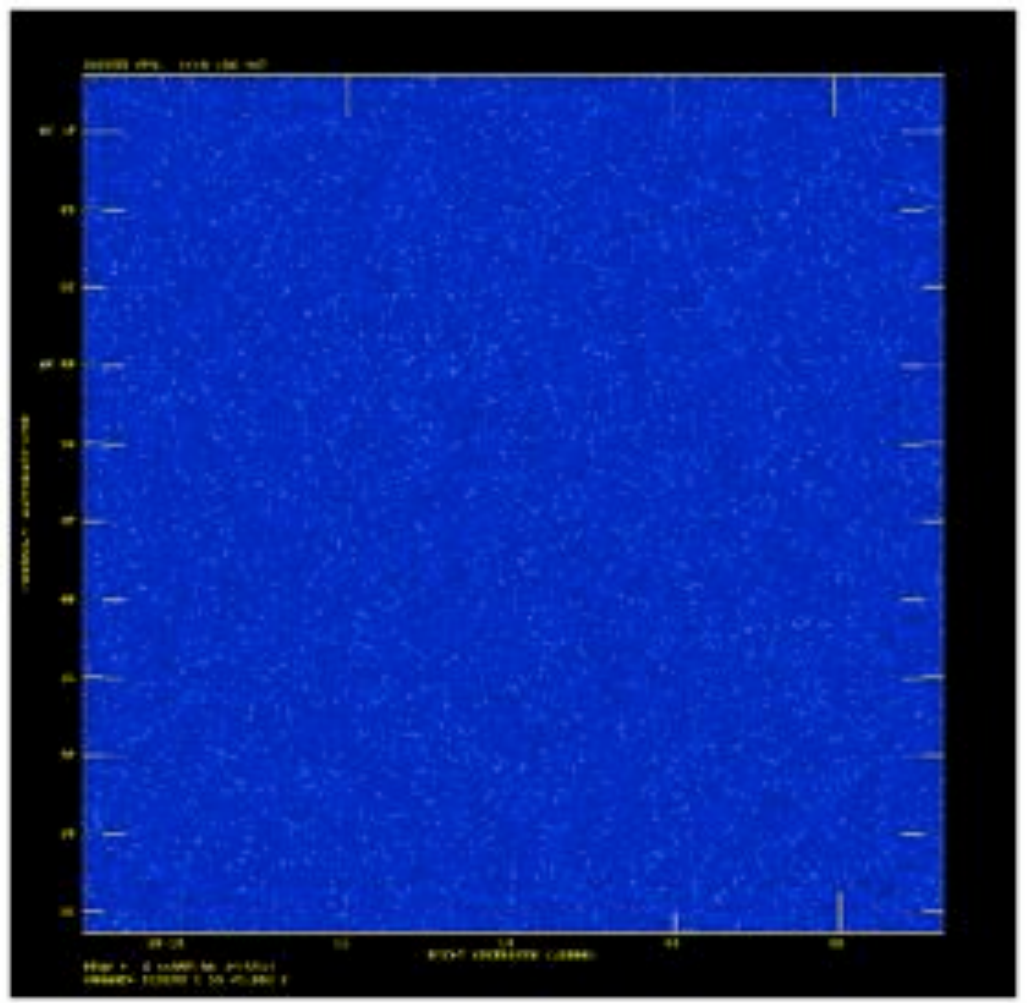
IC 2233 & Mk 86: intermediate steps



IC 2233 & Mk 86: Stokes I, Squint corrected



IC 2233 & Mk 86: Stokes V, Squint corrected



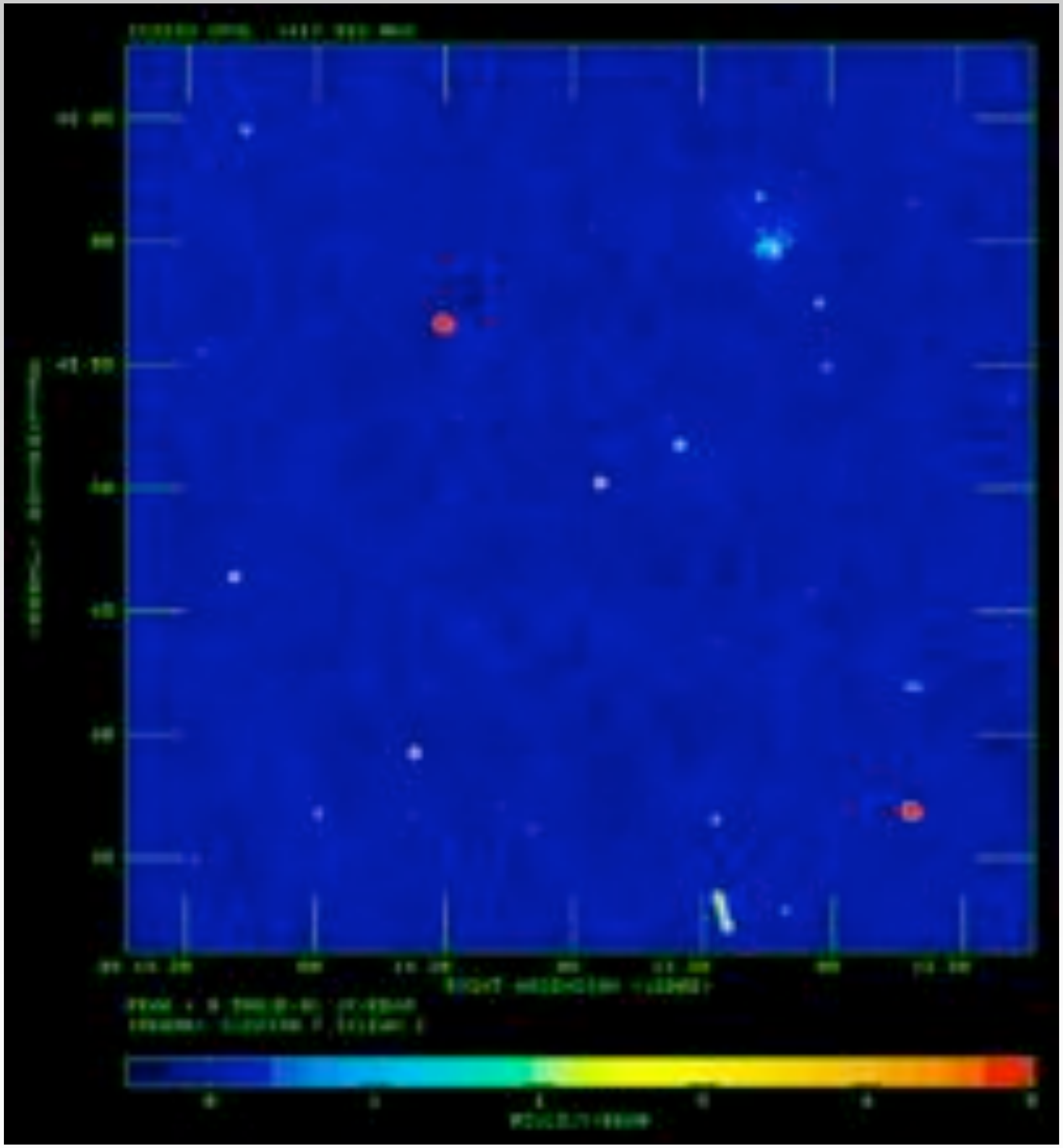
Other effects: Non ideal primary beams

- Hard to measure the primary beam with high precision
  - Antennas deform with changes in elevation, temperature,…
- Needed for high dynamic range imaging
  - Errors are likely dominated by a few sources (as in IC2233)
- Better (stiffer) antennas will help
  - Expensive
- It is possible to correct a few sources with “peeling” algorithms

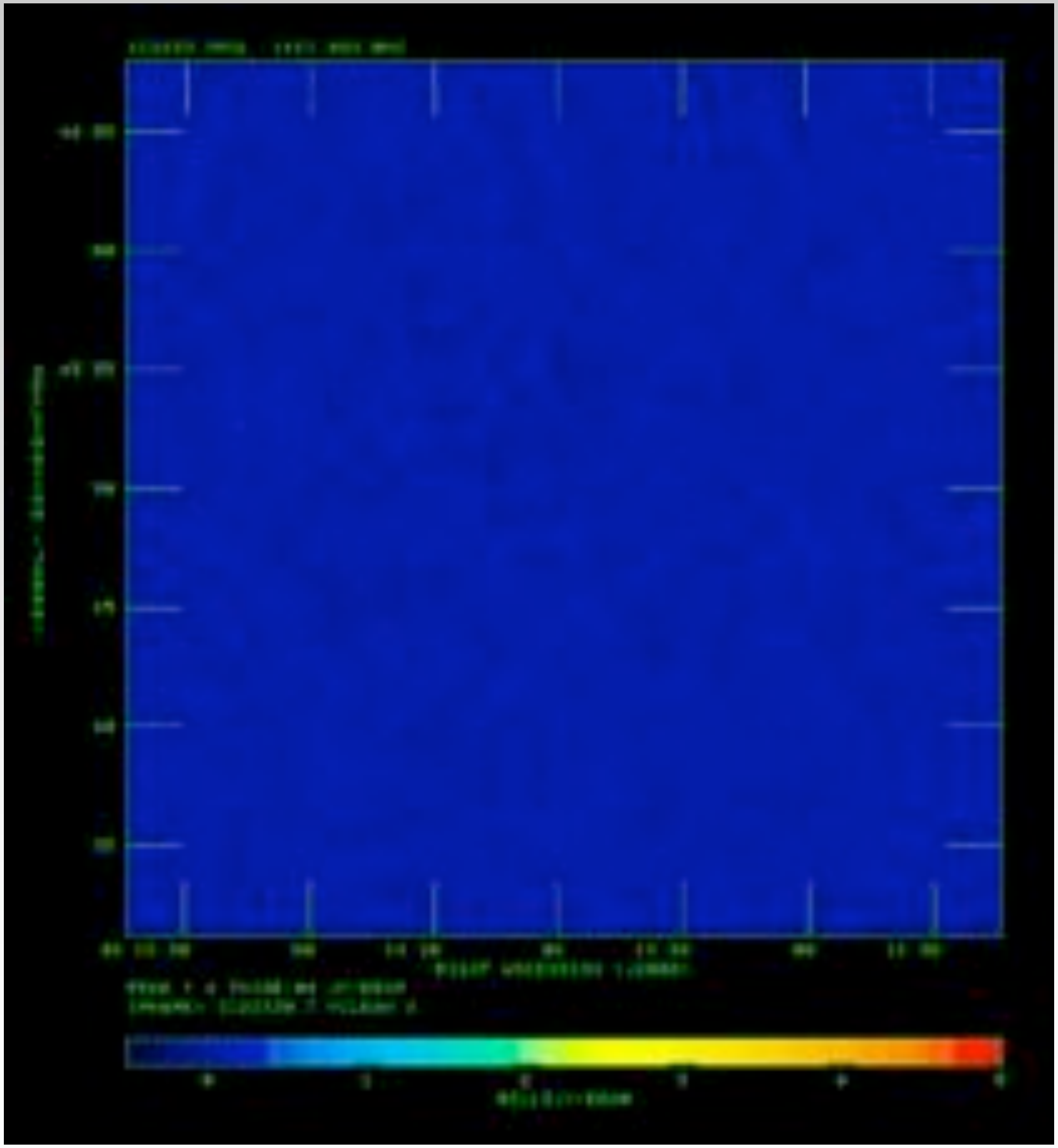
Non ideal primary beams: Peeling

- Limited Peeling can help
  - Important to avoid ghosts: Must subtract non-peeling sources first
  - Undo (self)-calibration, subtract peeled source from original visibilites
- Operate on several sources in succession
- It is possible to iterate on the lot
  - Easier on strong sources but beware of the noise bias…
  - Appears to work on suitably long timescales
  - Hard to do on intermediate-strength sources
  - Hard to do on short timescales
- Limited by SNR, works only on sufficiently strong sources
  - Expensive

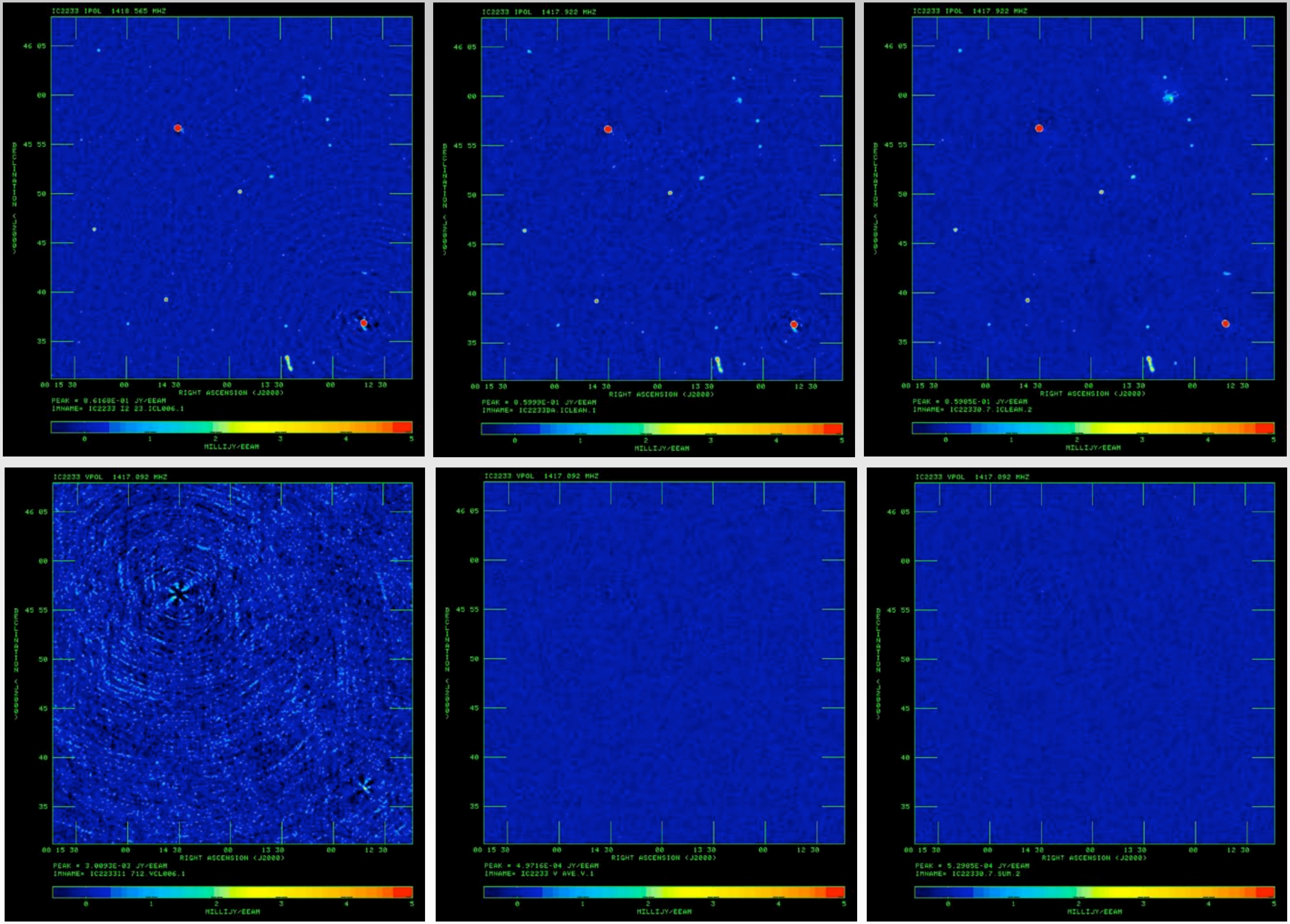
IC 2233 & Mk 86: I, Squint corrected + peeled



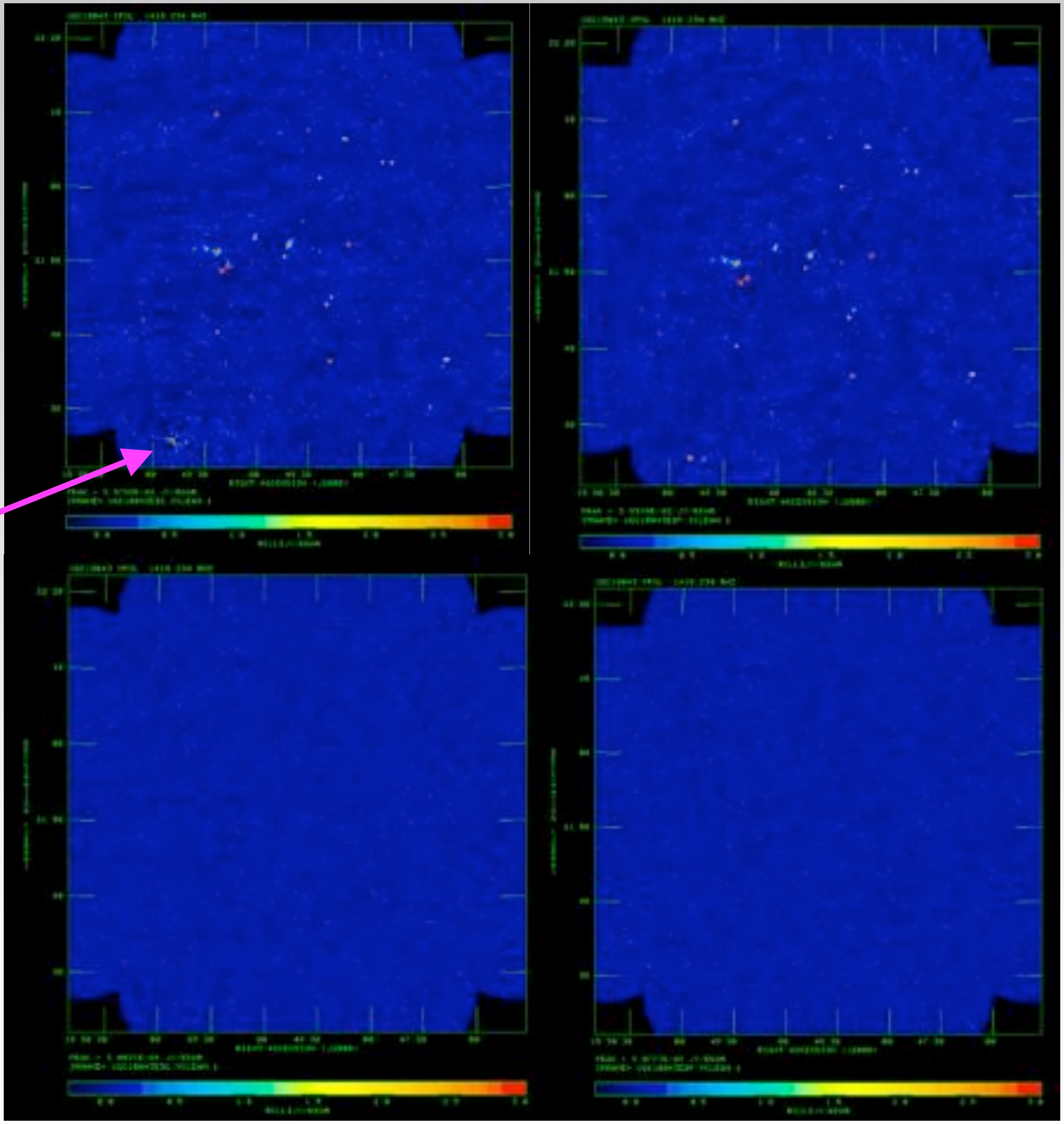
IC 2233 & Mk 86: V, Squint corrected + peeled



IC 2233 & Mk 86: A comparison



UGC 10043: A harder case?



3C 324
at ~1.5%
of P. Beam

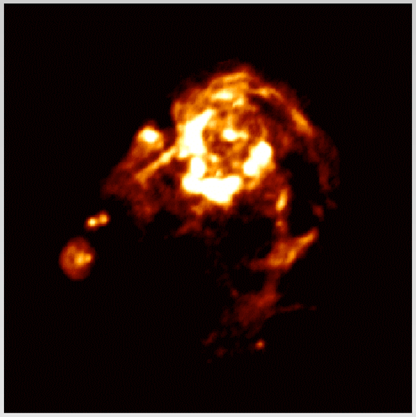
- Uncorrected sidelobes induce spurious spectral signatures

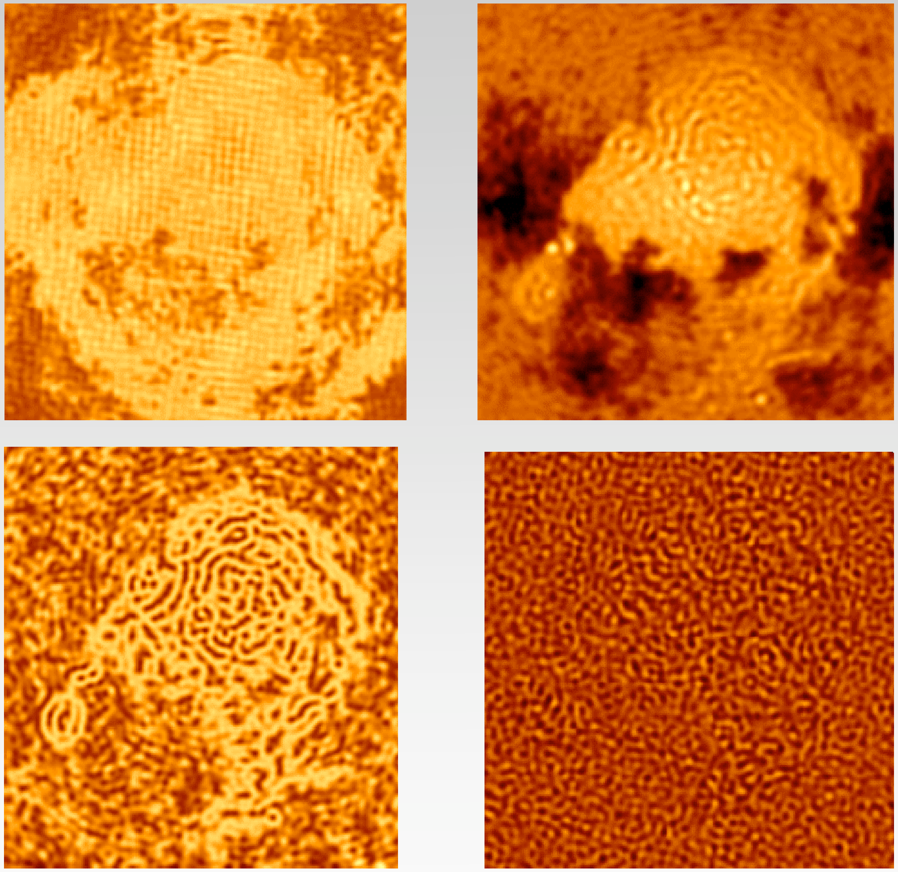
Other effects: Extended Emission

- 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!

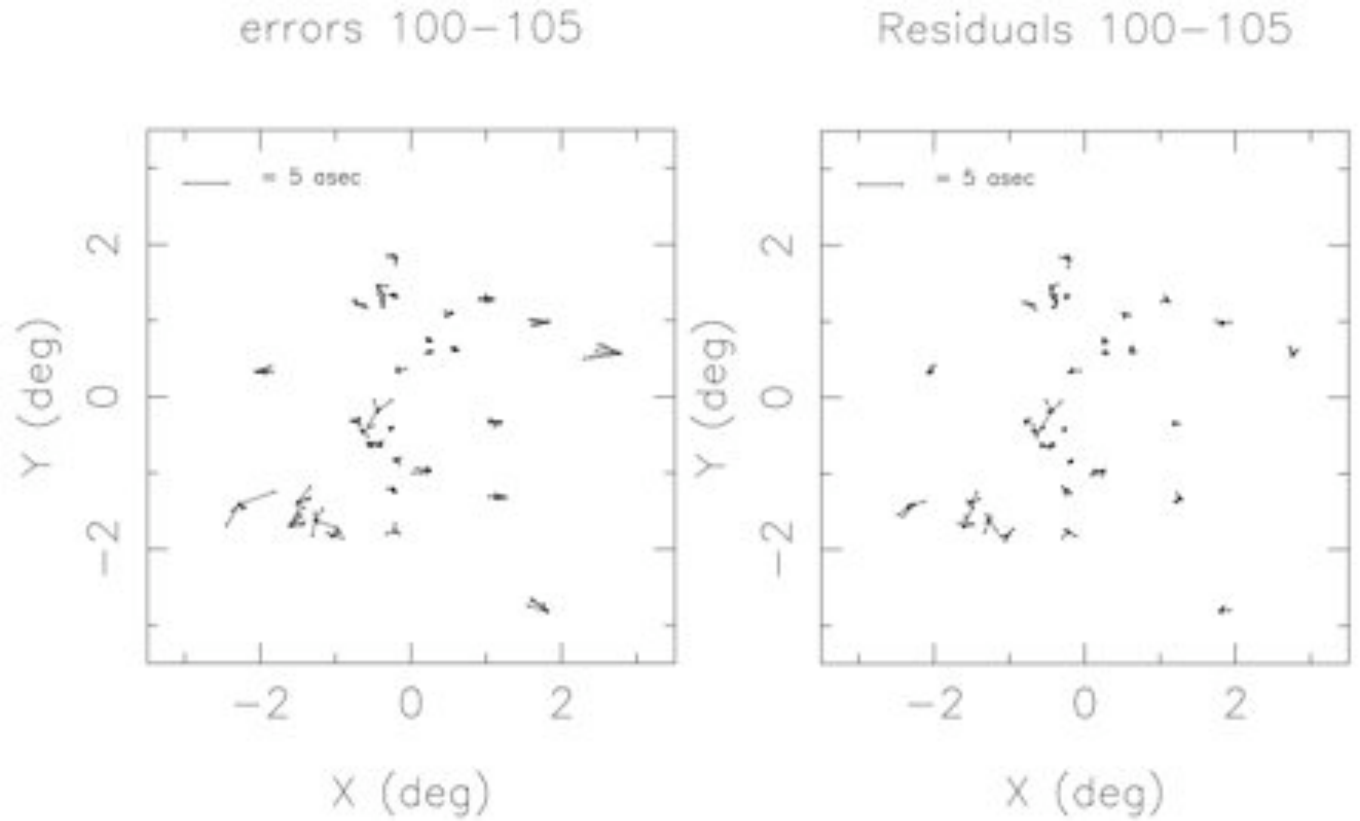
ASP deconvolution: Example

- Animation courtesy of Sanjay Bhatnagar.

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.

Ionospheric corrections: Distortions

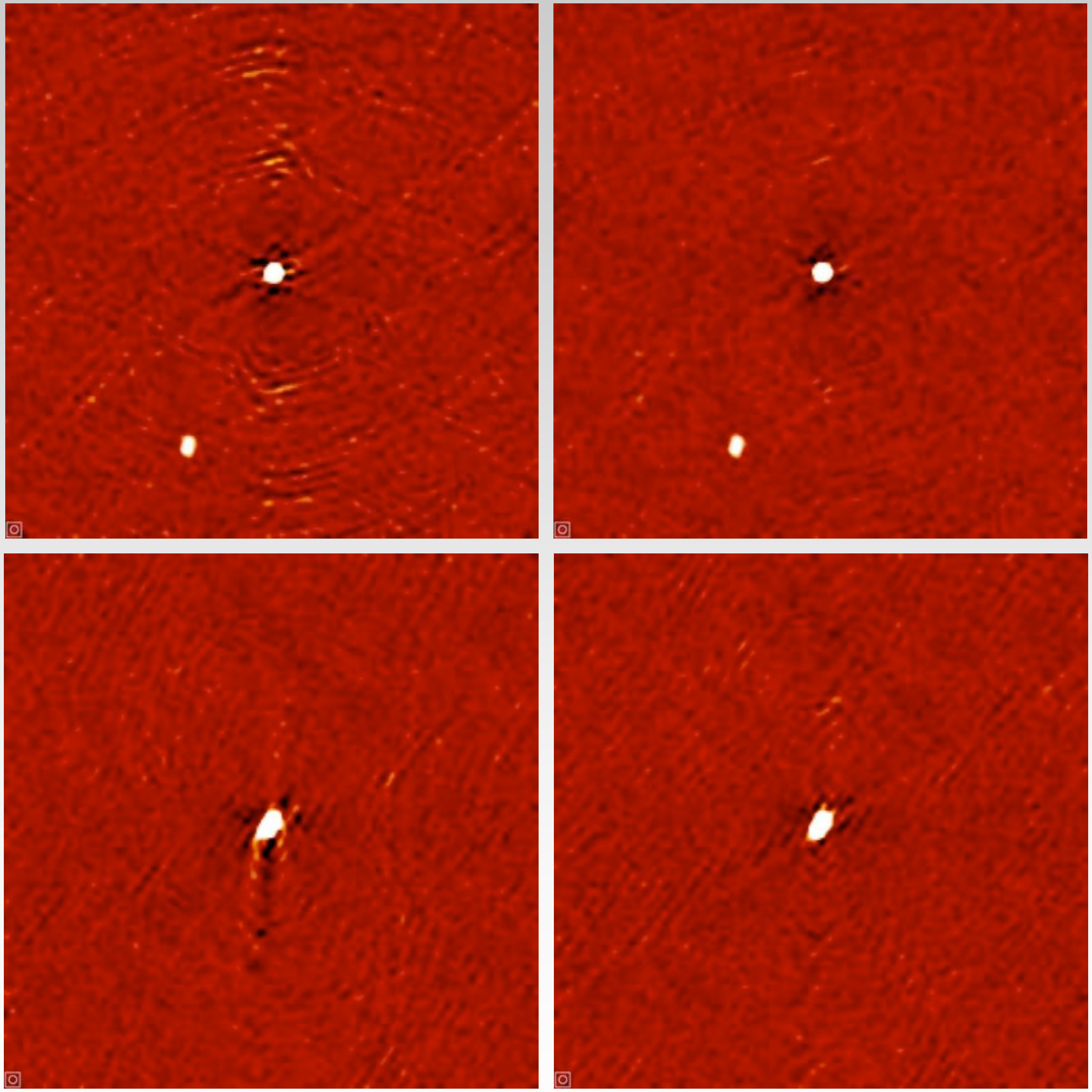


- Observations at 322 MHz with VLA A-configuration

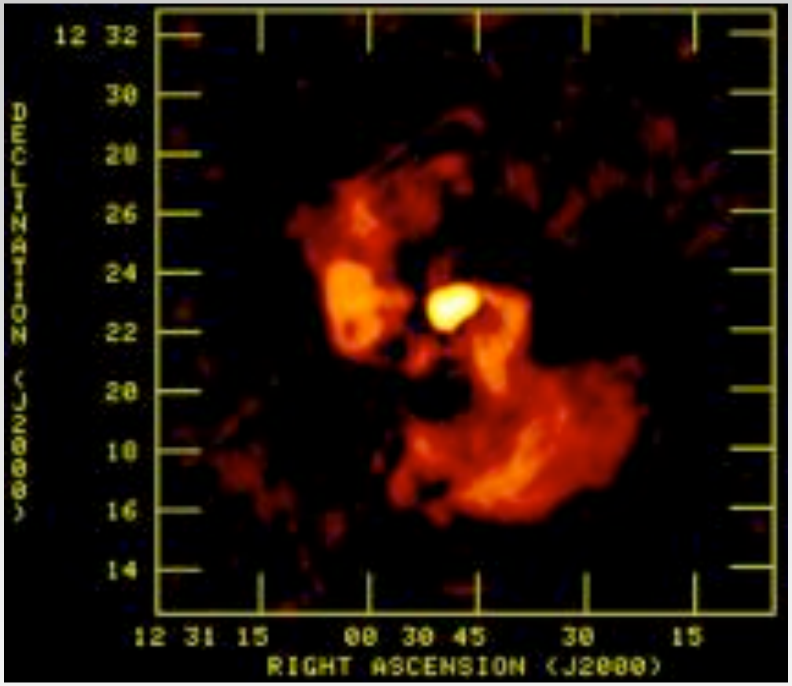
Non-isoplanaticity corrections

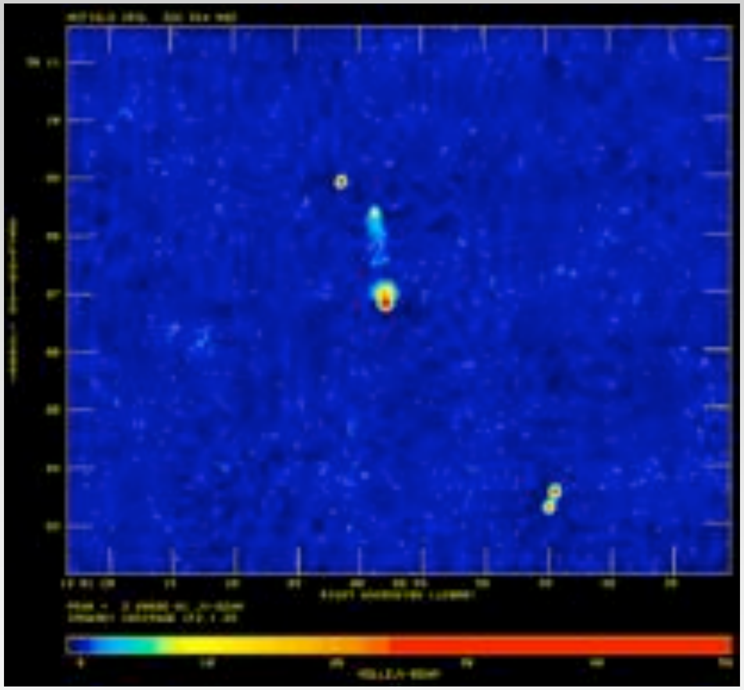
- Model ionosphere as a wedge over each antenna
  - Fit 2nd order Zernicke polynomials to strong-source positions
- Evaluate residual “seeing,” impose cutoff
  - Apply corrections to whole field.
- Center strong sources on separate “facets”
  - Apply corrections to whole field.
- Dynamic range still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

Ionospheric corrections: Images



Ionospheric corrections: Images





- Virgo A, 74 MHz, 25”

“Empty field,” 322 MHz, 6”

Dessine-moi

S’il vous plaît … dessine-moi un EVLA.
Hein!
Dessine-moi un ALMA …
Mais … qu’est-ce que tu fais là ?
S’il vous plaît … dessine-moi un SKA.

(avec mes excuses à Saint-Exupéry)

Draw me

Please … draw me an EVLA.
Eh!
Draw me an ALMA …
But … what are you doing there?
Please … draw me an SKA.

(with apologies to Saint-Exupéry)

Voyage a travers l’Univers celeste

Devant la grande toile
Où brillent les étoiles,
Tu rêves, toi l’artiste :
Tout seul sur la piste.

(d’un poème de Jean-Claude Brinette)

Journey through the Universe

Before the great canvas
Where stars are shining,
You dream, you the artist:
Alone on the stage.

(from a poem by Jean-Claude Brinette)

Acknowledgements and references

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

References:

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Uson, J. M. & Cotton, W. D. Astron & Astrophys. 486, 647 (2008)

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.
- Using 21 cm (HI) data on Stephan’s Quintet (courtesy of M. S. Yun).