Advanced Calibration Techniques

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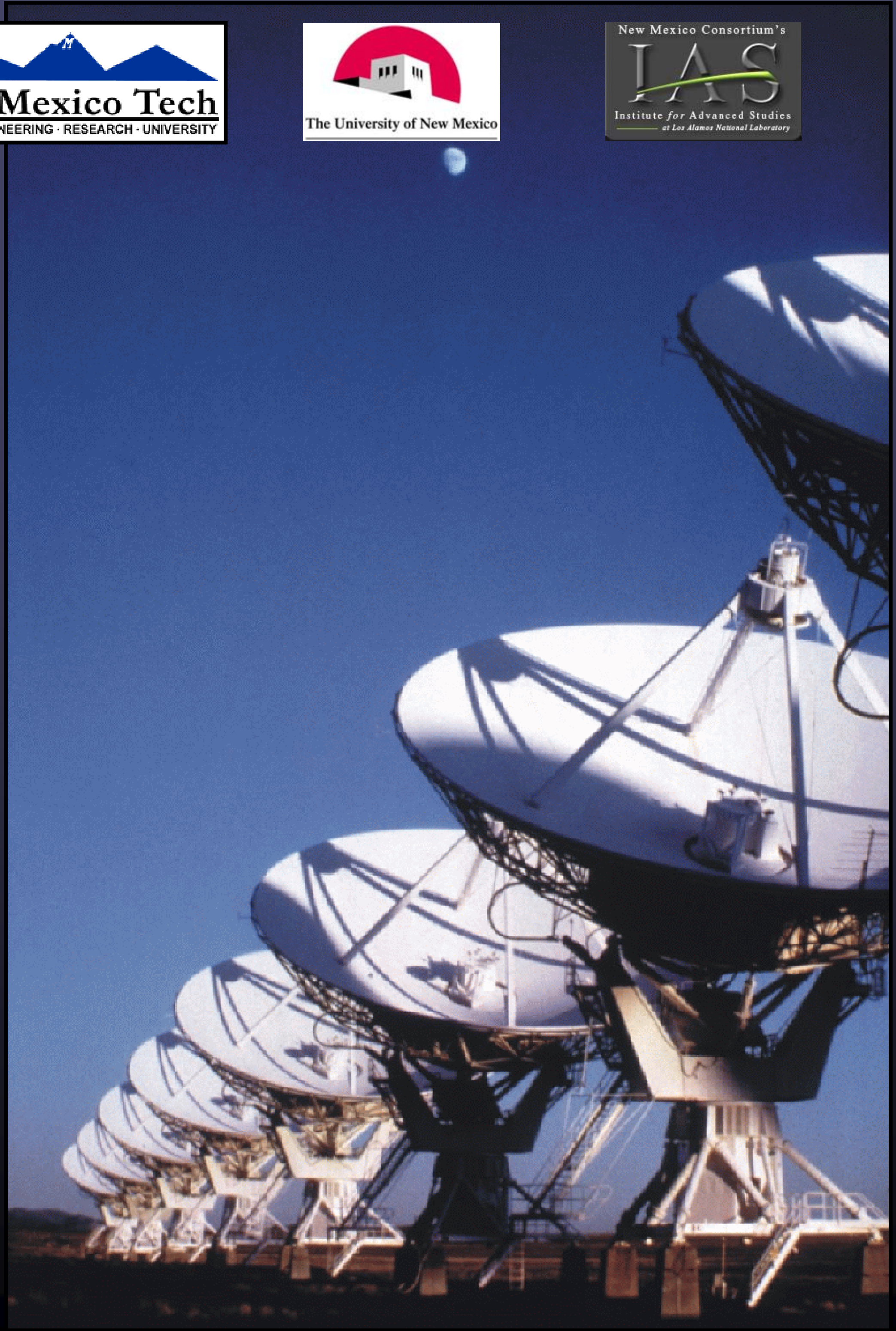
(based on previous self-calibration lectures)



Eleventh Synthesis Imaging Workshop

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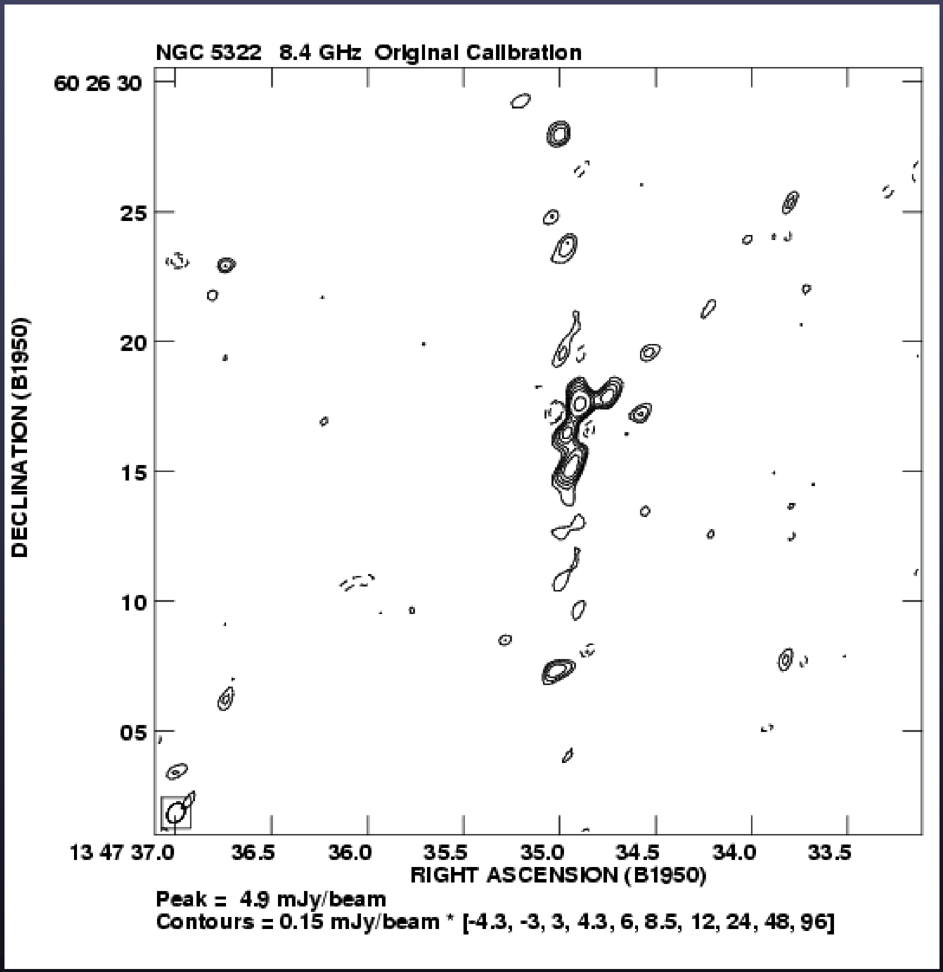
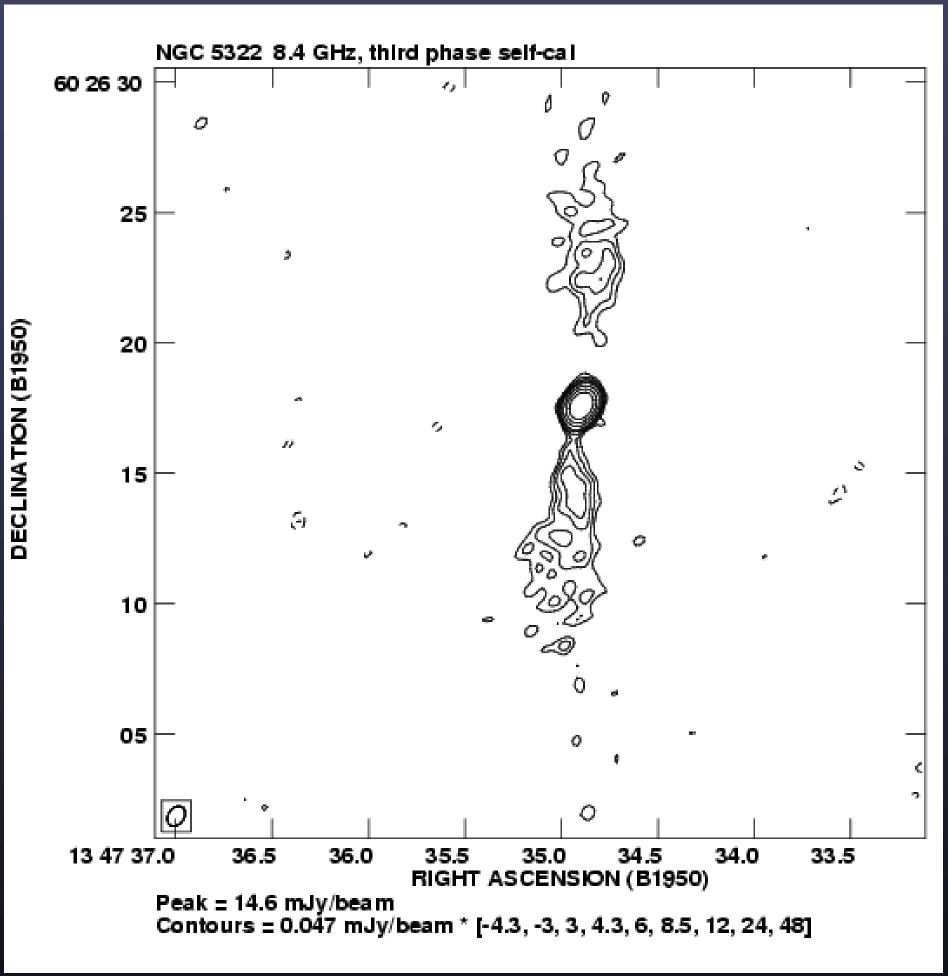
Self-calibration of a VLA snapshot

Initial image



Final image



Calibration equation

- Fundamental calibration equation

$$V_{ij}(t) = g_i(t) g_j^*(t) V^{true}(t) + \varepsilon_{ij}(t)$$

$V_{ij}(t)$ Visibility measured between antennas i and j

$g_i(t)$ Complex gain of antenna i

$V^{true}(t)$ True visibility

$\varepsilon_{ij}(t)$ Additive noise

Standard calibration using a point source calibrator

- Calibration equation becomes

$$V_{ij}(t) = g_i(t)g_j^*(t)S + \varepsilon_{ij}(t)$$

S Strength of point source

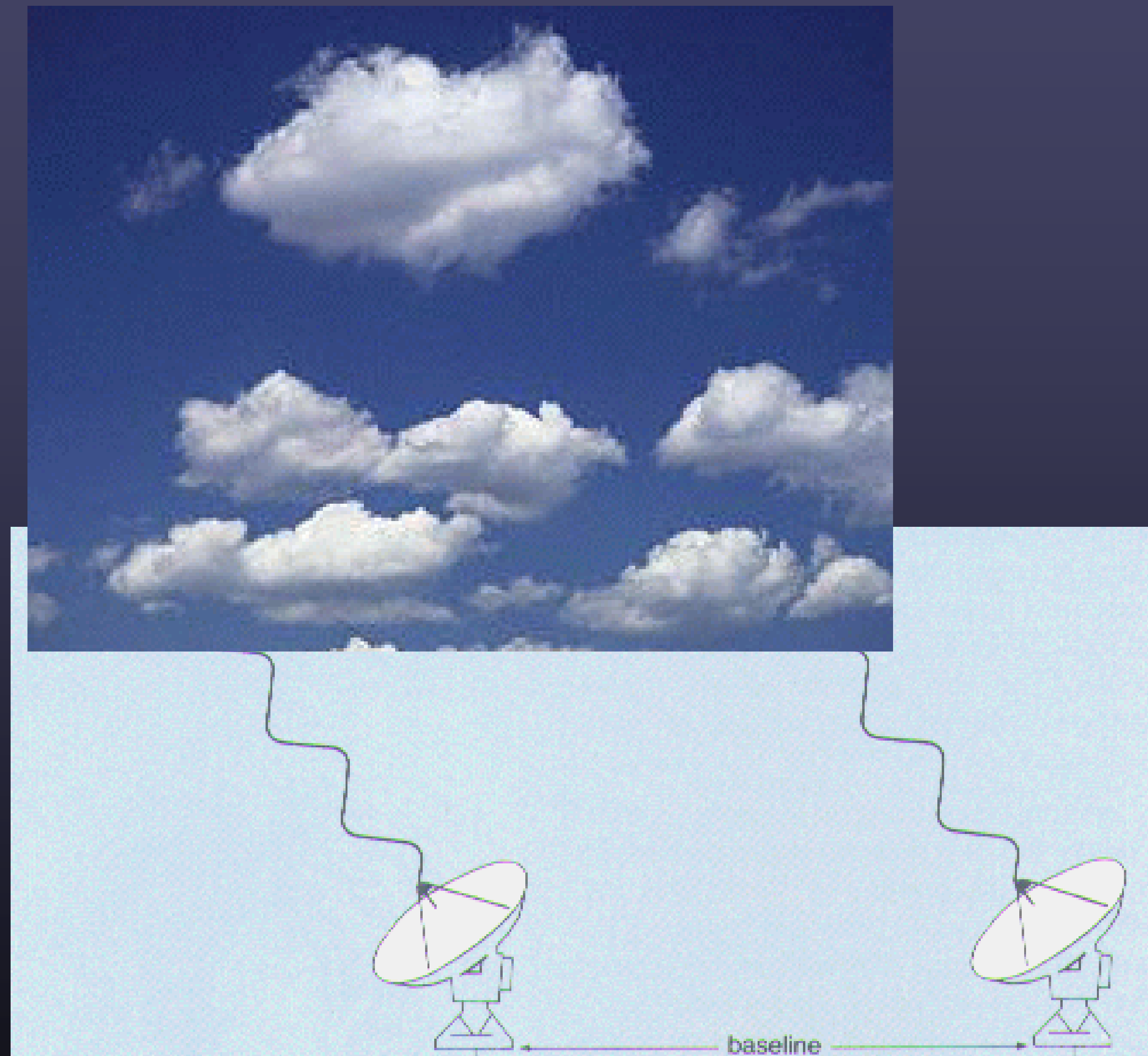
- These are calibrator visibilities; given a point source can solve for the complex gains
- Works well - lots of redundancy
  - N-1 baselines contribute to gain estimate for any given antenna

Why is *a priori* calibration insufficient?

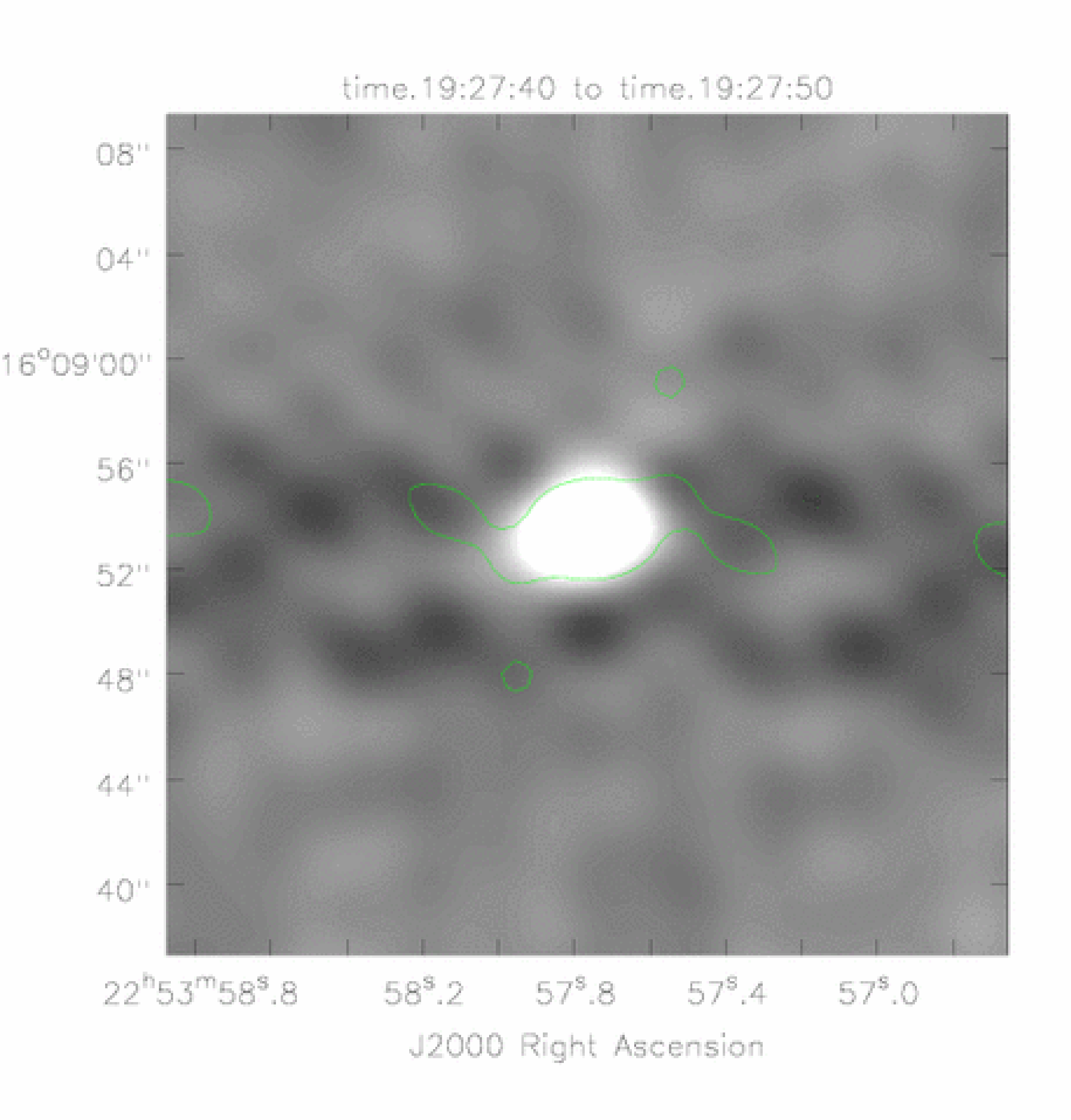
- Initial calibration based on calibrator observed before/after target
- Gains were derived at a different time
  - Troposphere and ionosphere are variable
  - Electronics may be variable
- Gains were derived for a different direction
  - Troposphere and ionosphere are not uniform
- Observation might have been scheduled poorly for the existing conditions
- Calibrator may have structure and may not be as strong as expected

What is the troposphere doing?

- Neutral atmosphere contains water vapor
- Index of refraction differs from “dry” air
- Variety of moving spatial structures



Movie of point source at 22GHz



Self-calibration

- Use *target* visibilities and allow the antenna gains to be free parameters.
- If all baselines correlated, there are N complex gain errors corrupting the N*(N – 1) / 2 complex visibility measurements for a given time.
- Therefore there are N * (N – 1) / 2 - N complex numbers that can be used to constrain the true sky brightness distribution.
- Even after adding the degrees of freedom from the antenna gains, the estimation of an adequate model of the target brightness is still overdetermined.

Self-Calibration using a model of a complex source

- So begin by using a *model* of the source visibilities:

$$V_{ij}(t) = g_i(t) g_j^*(t) V_{ij}^{\text{model}} + \varepsilon_{ij}(t)$$

V_{ij}^{model} Model visibility

- One can form a sum of squares of residuals between the observed visibilities and the product of gains and model visibilities and do some kind of minimization by adjusting the gains.

Relationship to point source calibration

- We can relate this to using a point source for calibration
- Made a fake point source by dividing by model visibilities

$$X_{ij}(t) = g_i(t)g_j^*(t) + \varepsilon'_{ij}(t)$$

$$X_{ij}(t) = \frac{V_{ij}(t)}{V_{ij}^{\text{model}}}$$

$\varepsilon'_{ij}(t)$ Modified noise term

How to self-calibrate

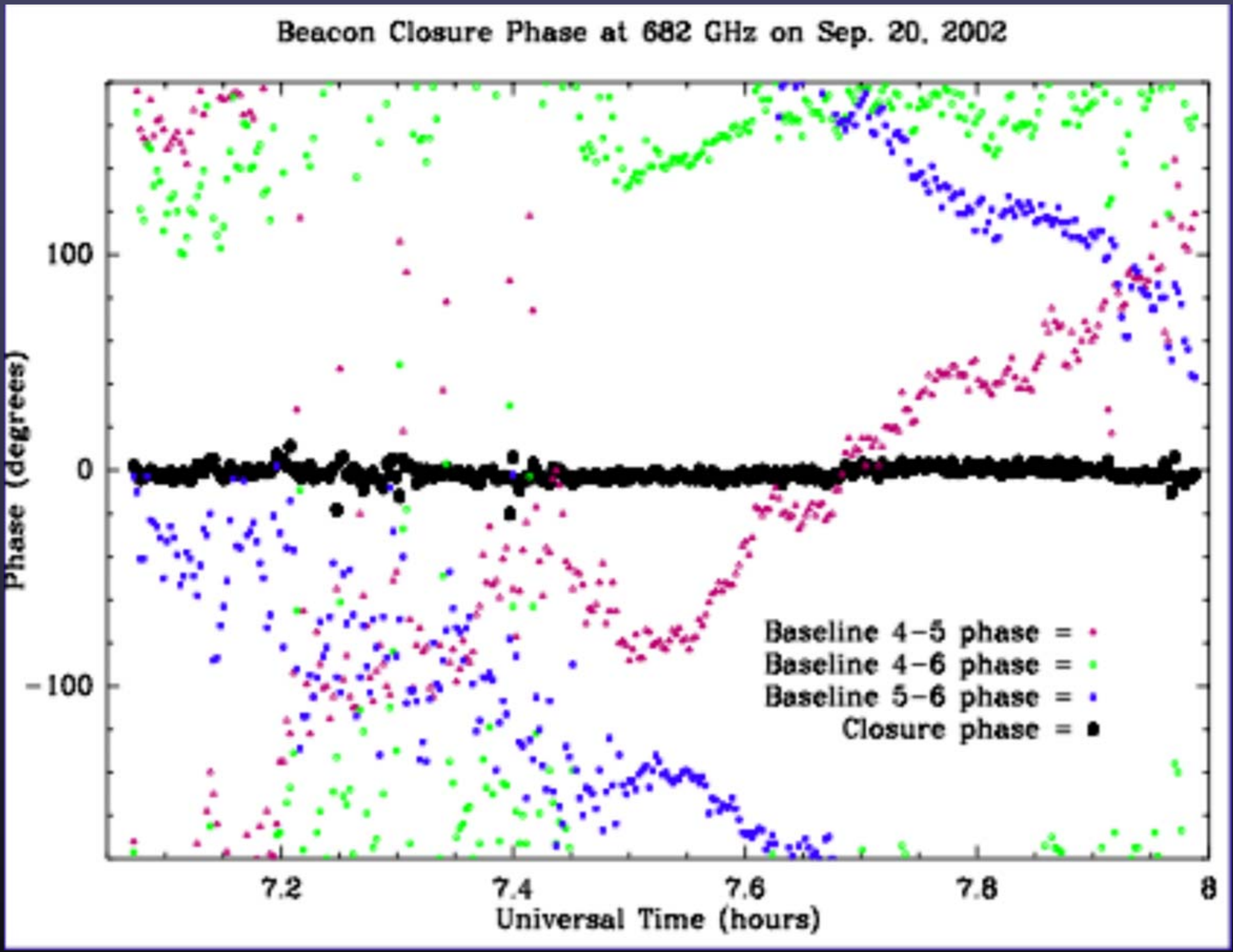
1. Create an initial source model, typically from an initial image (or else a point source)
   - Use full resolution information from the clean components or MEM image NOT the restored image
2. Find antenna gains
   - Using “least squares” (L1 or L2) fit to visibility data
3. Apply gains to correct the observed data
4. Create a new model from the corrected data
   - Using for example Clean or Maximum Entropy
5. Go to (2),unless current model is satisfactory
   - shorter solution interval, different uv limits/weighting
   - phase → amplitude & phase

Closure phase

- self-calibration preserves the *Closure Phase* which is a good observable even in the presence of antenna-based phase errors

$$
\begin{aligned}
\Phi_{ijk} &= \theta_{ij} + \theta_{jk} + \theta_{ki} \\
&= \theta_{ij}^{\text{true}} + \left(\phi_i - \phi_j\right) + \theta_{jk}^{\text{true}} + \left(\phi_j - \phi_k\right) + \theta_{ki}^{\text{true}} + \left(\phi_k - \phi_i\right) \\
&= \theta_{ij}^{\text{true}} + \theta_{jk}^{\text{true}} + \theta_{ki}^{\text{true}}
\end{aligned}
$$

SMA closure phase measurements at 682GHz



Advantages and disadvantages of self-calibration

- Advantages
  - Gains derived for correct time --- no interpolation
  - Gains derived for correct position --- no atmospheric assumptions
  - Solution is fairly robust if there are many baselines
  - More time on-source
- Disadvantages
  - Requires a sufficiently bright source
  - Introduces more degrees of freedom into the imaging: results might not be robust and stable
  - Absolute position information lost

When to and when not to self-calibrate

- Calibration errors may be present if one or both of the following are true:
  - The background noise is considerably higher than expected
  - There are convolutional artifacts around objects, especially point sources
- Don’t bother self-calibrating if these signatures are not present
- Don’t confuse calibration errors with effects of poor Fourier plane sampling such as:
  - Low spatial frequency errors (woofly blobs) due to lack of short spacings
  - Multiplicative fringes (due to deconvolution errors)
  - Deconvolution errors around moderately resolved sources

Choices in self-calibration

- Initial model?
  - Point source often works well
  - Simple fit (e.g., Gaussian) for barely-resolved sources
  - Clean components from initial image
    - Don't go too deep!
  - Simple model-fitting in (u,v) plane
- Self-calibrate phases or amplitudes?
  - Usually phases first
    - Phase errors cause anti-symmetric structures in images
  - For VLA and VLBA, amplitude errors tend to be relatively unimportant at dynamic ranges < 1000 or so

More choices….

- Which baselines?
  - For a simple source, all baselines can be used
  - For a complex source, with structure on various scales, start with a model that includes the most compact components, and use only the longer baselines
- What solution interval should be used?
  - Generally speaking, use the shortest solution interval that gives “sufficient” signal/noise ratio (SNR)
  - If solution interval is too long, data will lose coherence
    - Solutions will not track the atmosphere optimally

Sensitivity limit

- Can self-calibrate if SNR on most baselines is greater than one
- For a point source, the error in the gain solution is

Phase only $$\sigma_g = \frac{1}{\sqrt{N-2}} \frac{\sigma_V}{S}$$

Amplitude and phase $$\sigma_g = \frac{1}{\sqrt{N-3}} \frac{\sigma_V}{S}$$

σ_V Noise per visibility sample

N Number of antennas

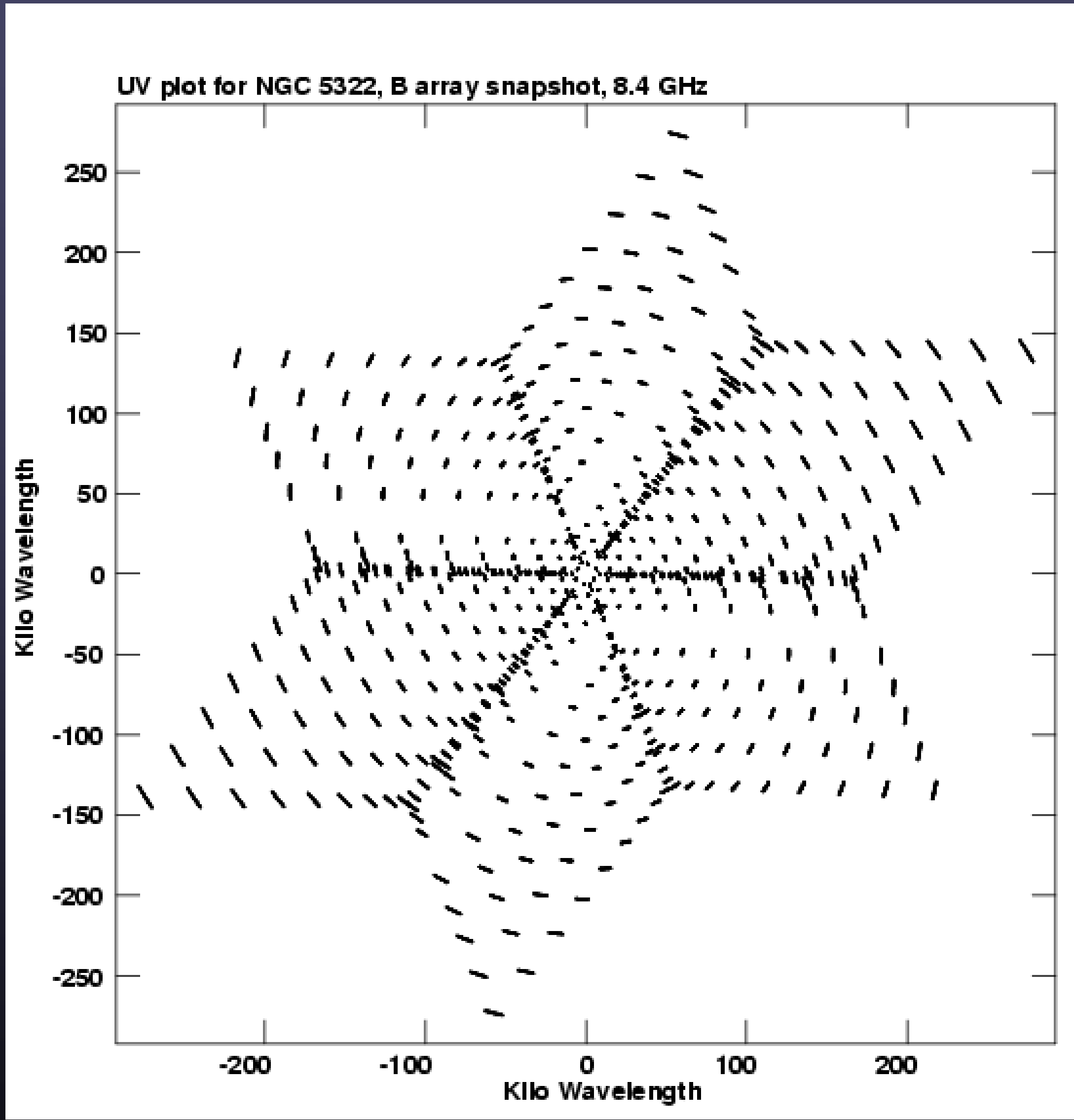
- If error in gain is much less than 1, then the noise in the final image will be close to theoretical

You can self-calibrate on weak sources!

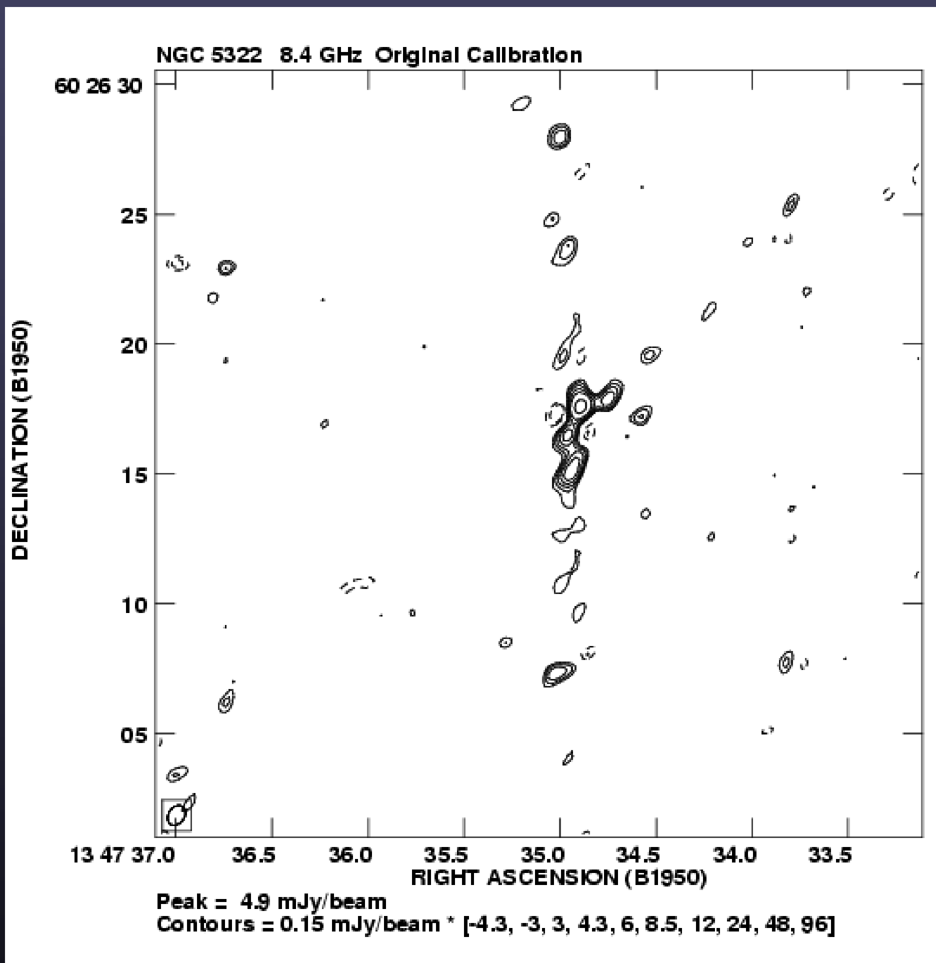
- For the VLA at 8 GHz, the noise in 10 seconds for a single 50 MHz IF is about 13 mJy on 1 baseline
  - Average 4 IFs (2 RR and 2 LL) for 60 seconds to decrease this by $(4 * 60/10)^{1/2}$ to 2.7 mJy
  - If you have a source of flux density about 5 mJy, you can get a very good self-cal solution if you set the SNR threshold to 1.5. For 5 min, 1.2 mJy gives SNR = 1
- For the EVLA at 8 GHz and up, the noise in 10 seconds for an *8 GHz* baseband will be about 1 mJy on 1 baseline!

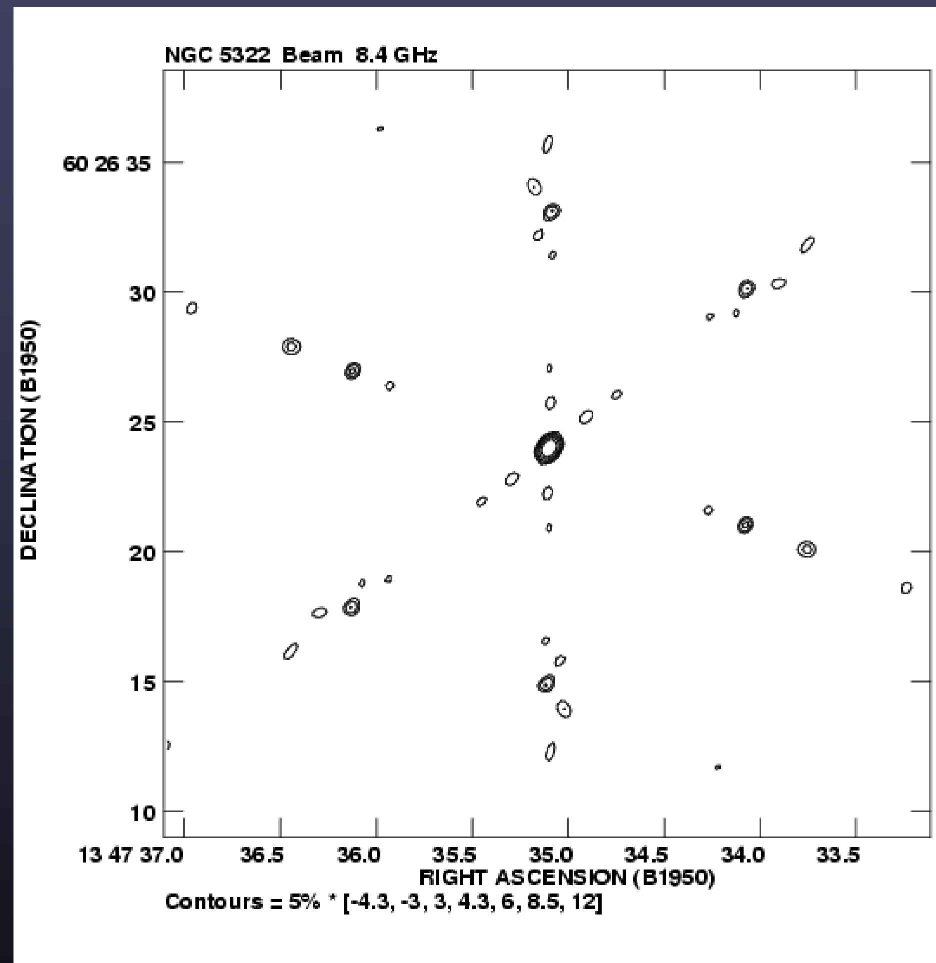
Hard example: VLA Snapshot, 8 GHz, B Array

- LINER galaxy NGC 5322
- Data taken in October 1995
- Poorly designed observation
  - One calibrator in 15 minutes
- Can self-cal help?



Initial NGC 5322 Imaging





First pass

Used 4 (merged) clean components in model

1. 10-sec solutions, no averaging, SNR > 5
   CALIB1: Found 3238 good solutions
   CALIB1: Failed on 2437 solutions
   CALIB1: 2473 solutions had insufficient data
2. 30-sec solutions, no averaging, SNR > 5
   CALIB1: Found 2554 good solutions
   CALIB1: Failed on 109 solutions
   CALIB1: 125 solutions had insufficient data
3. 30-sec solutions, average all IFs, SNR > 2
   CALIB1: Found 2788 good solutions

Phase Solutions from 1st Self-Cal

- Reference antenna has zero phase correction
  - ➔ **No absolute position info.**
- Corrections up to 150° in 14 minutes
- Typical coherence time is a few minutes

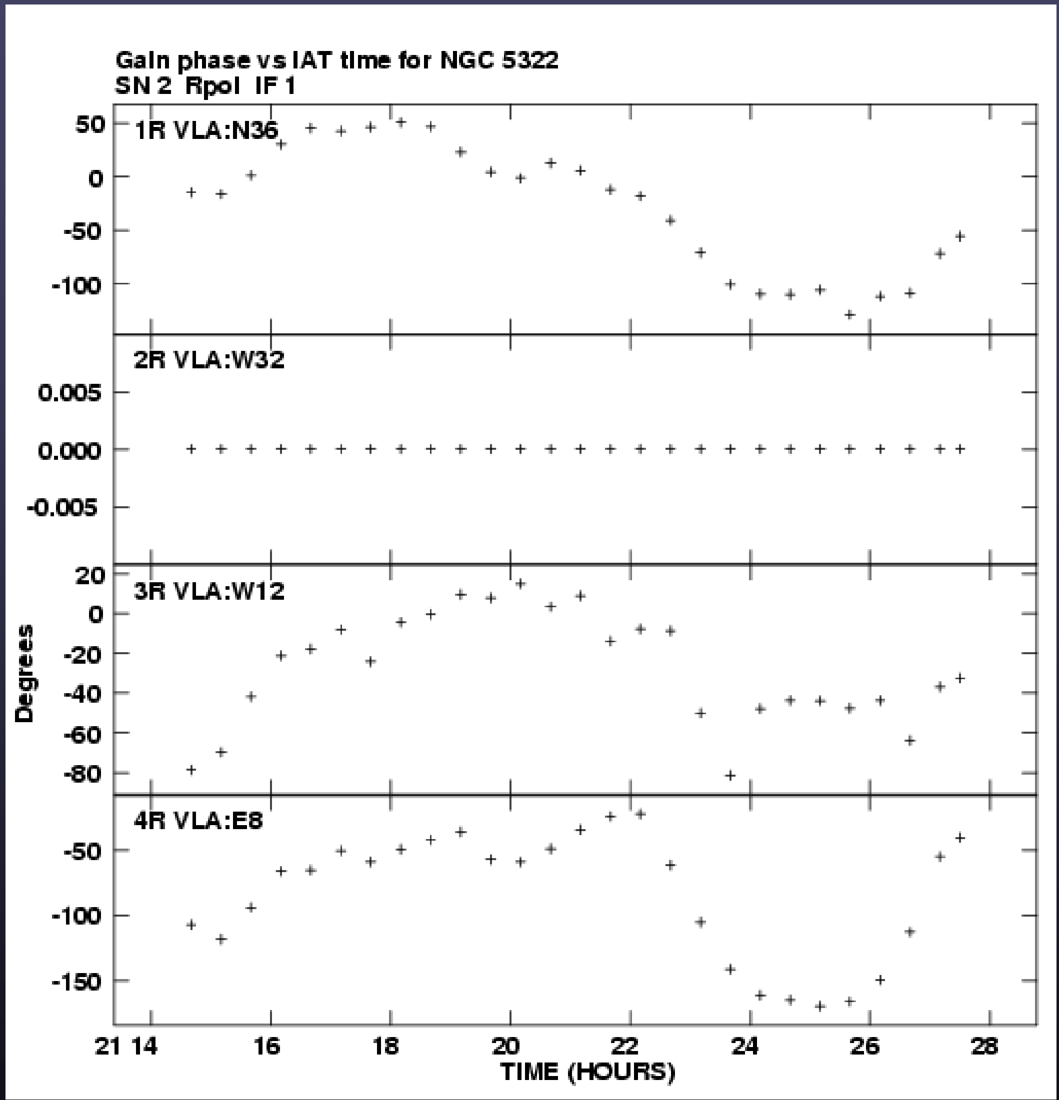
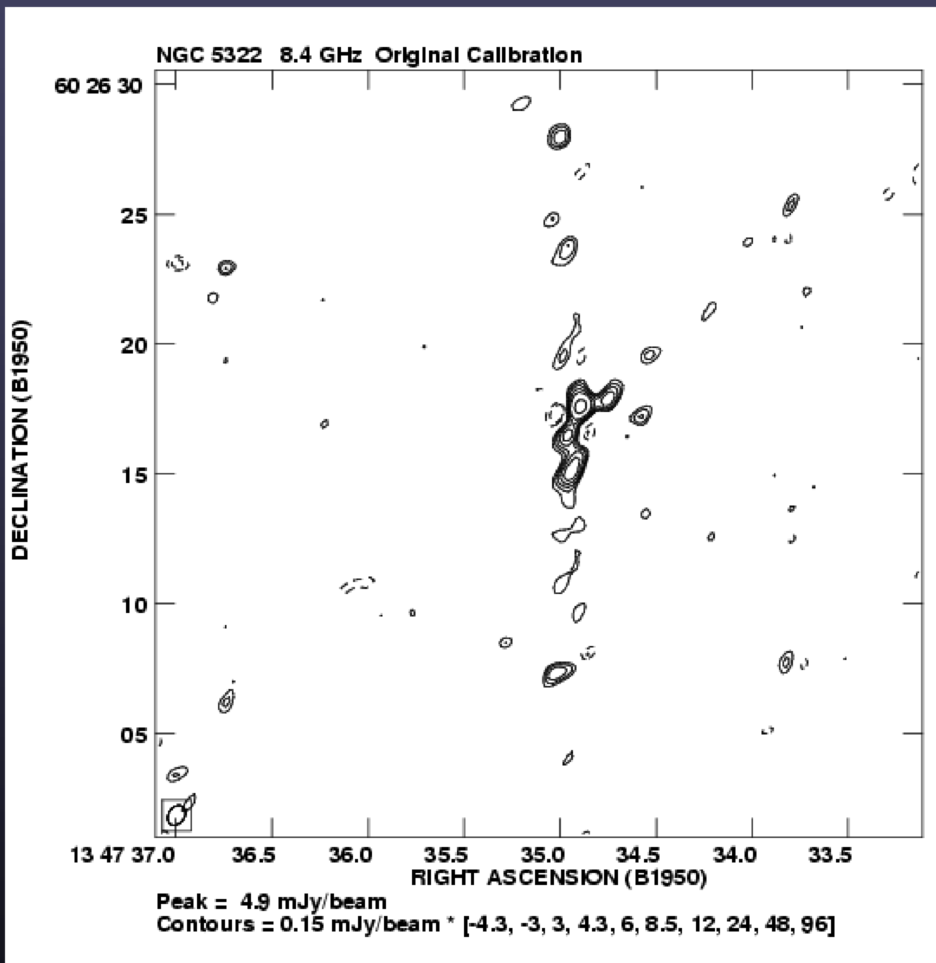
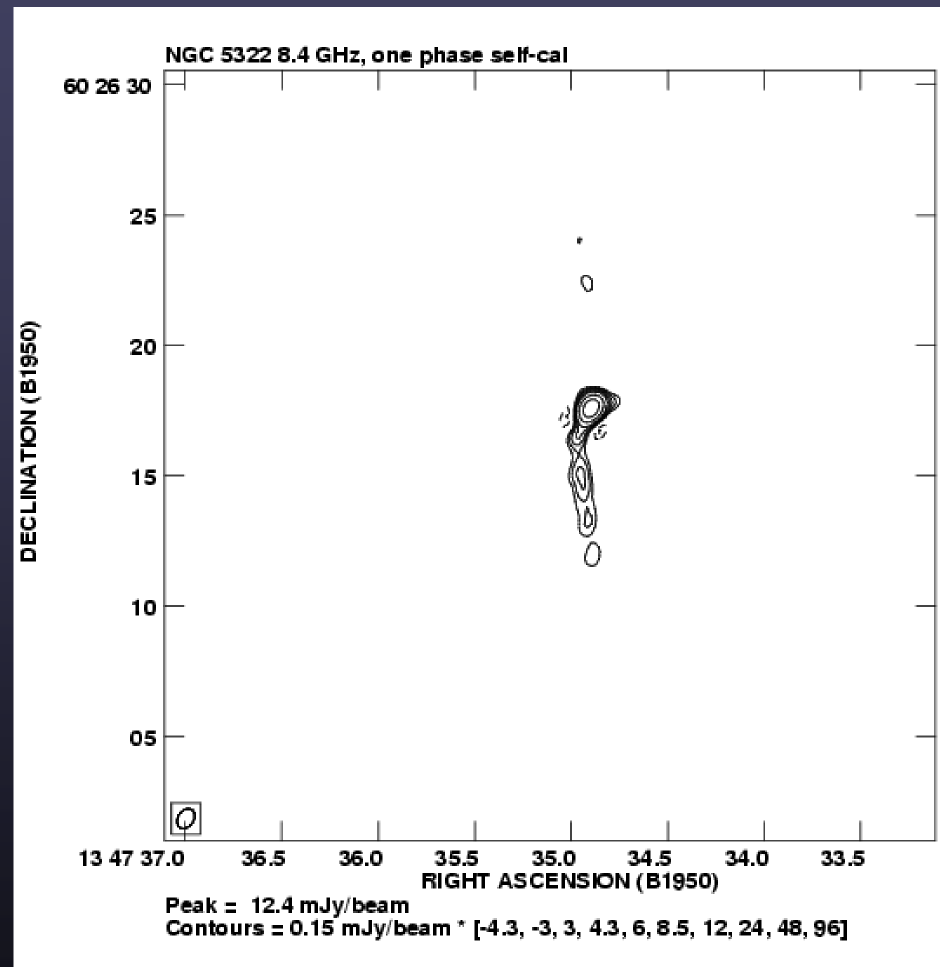


Image after first pass





Phase Solutions from 2nd Self-Cal

- Used 3 components
- Corrections are reduced to 40° in 14 minutes
- Observation now quasi-coherent
- Next: shorten solution interval to follow troposphere even better

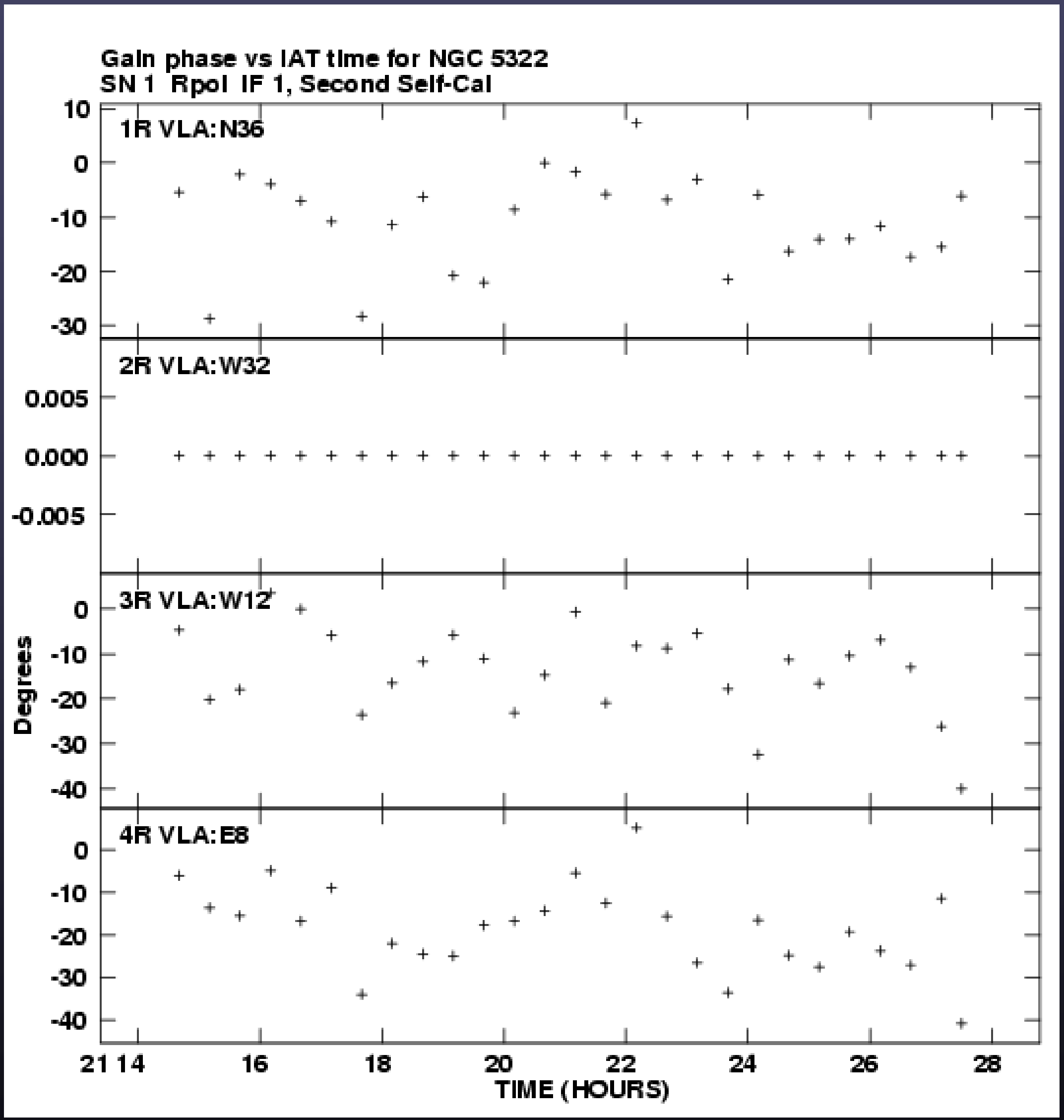
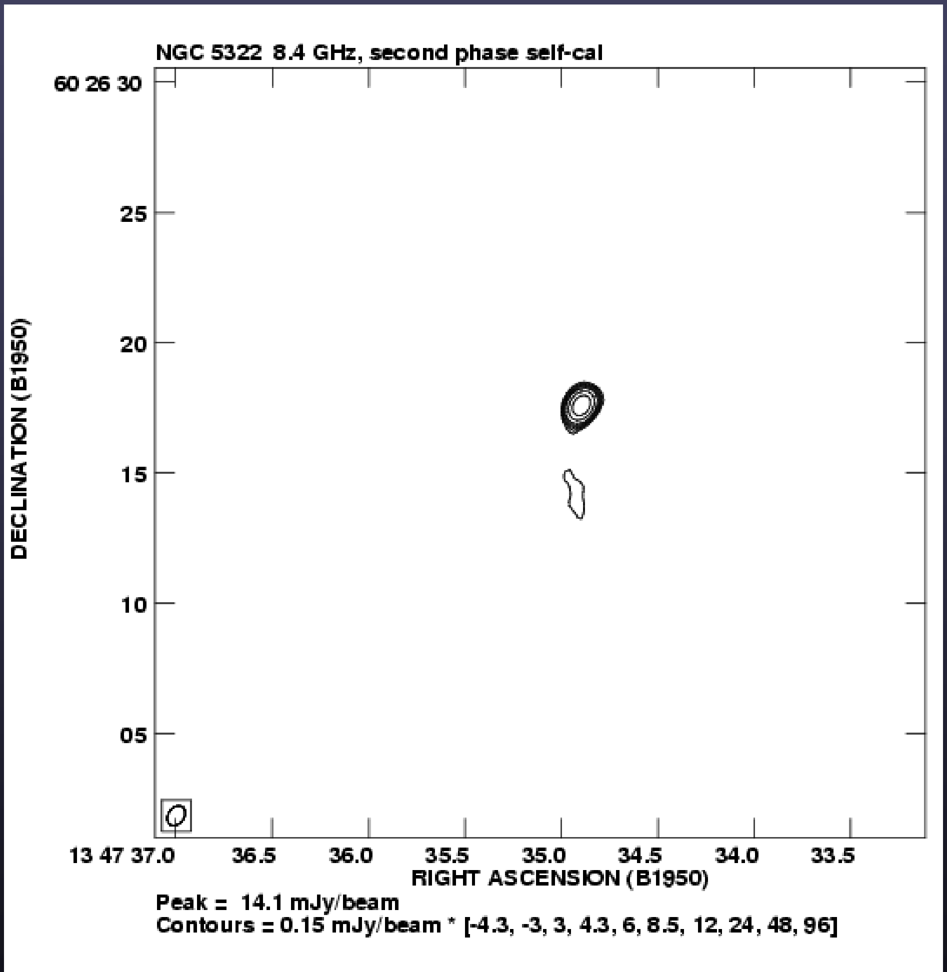
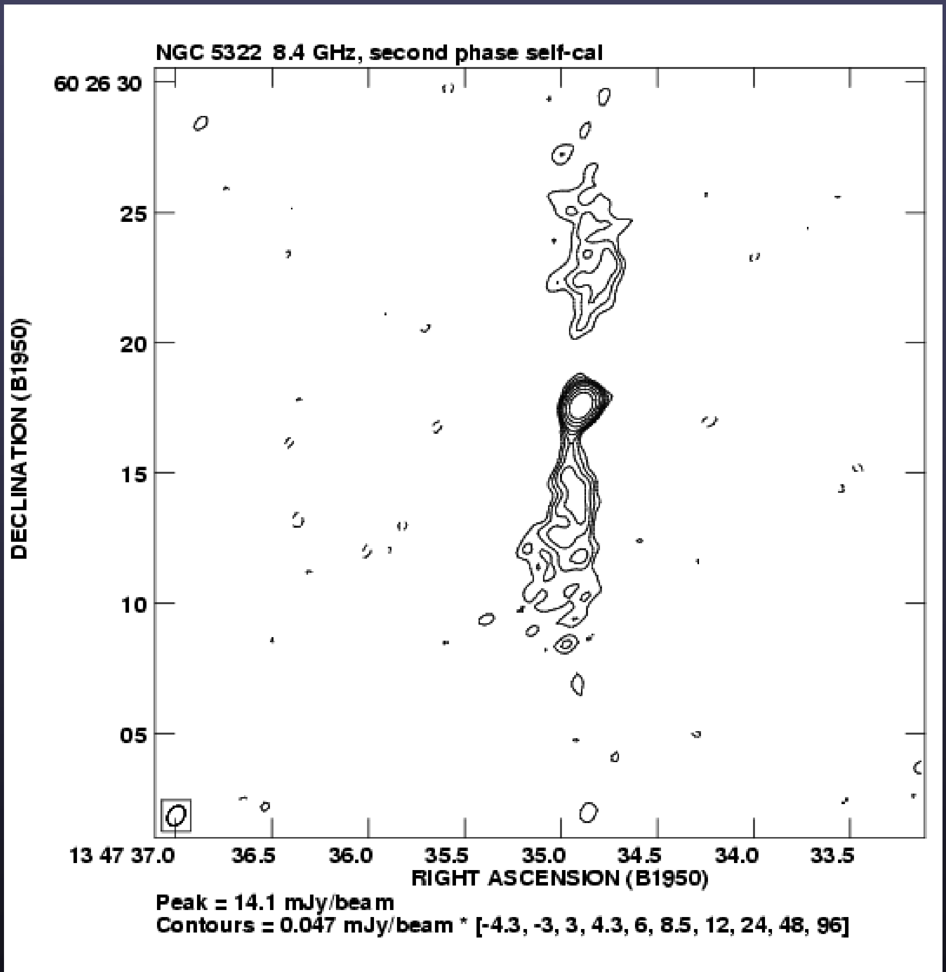


Image after 2nd Self-Calibration





Result after second self-calibration

- Image noise is now 47 microJy/beam
  - Theoretical noise in 10 minutes is 45 microJy/beam for natural weighting
  - For 14 minutes, reduce by $(1.4)^{1/2}$ to 38 microJy/beam
  - For robust=0, increase by 1.19, back to 45 microJy/beam
- Image residuals look “noise-like”
  - Expect little improvement from further self-calibration
  - Dynamic range is 14.1/0.047 = 300
    - Amplitude errors typically come in at dynamic range ~ 1000
- Concern: Source “jet” is in direction of sidelobes

Phase Solutions from 3rd Self-Cal

- 11-component model used
- 10-second solution intervals
- Corrections look noise-dominated
- Expect little improvement in resulting image

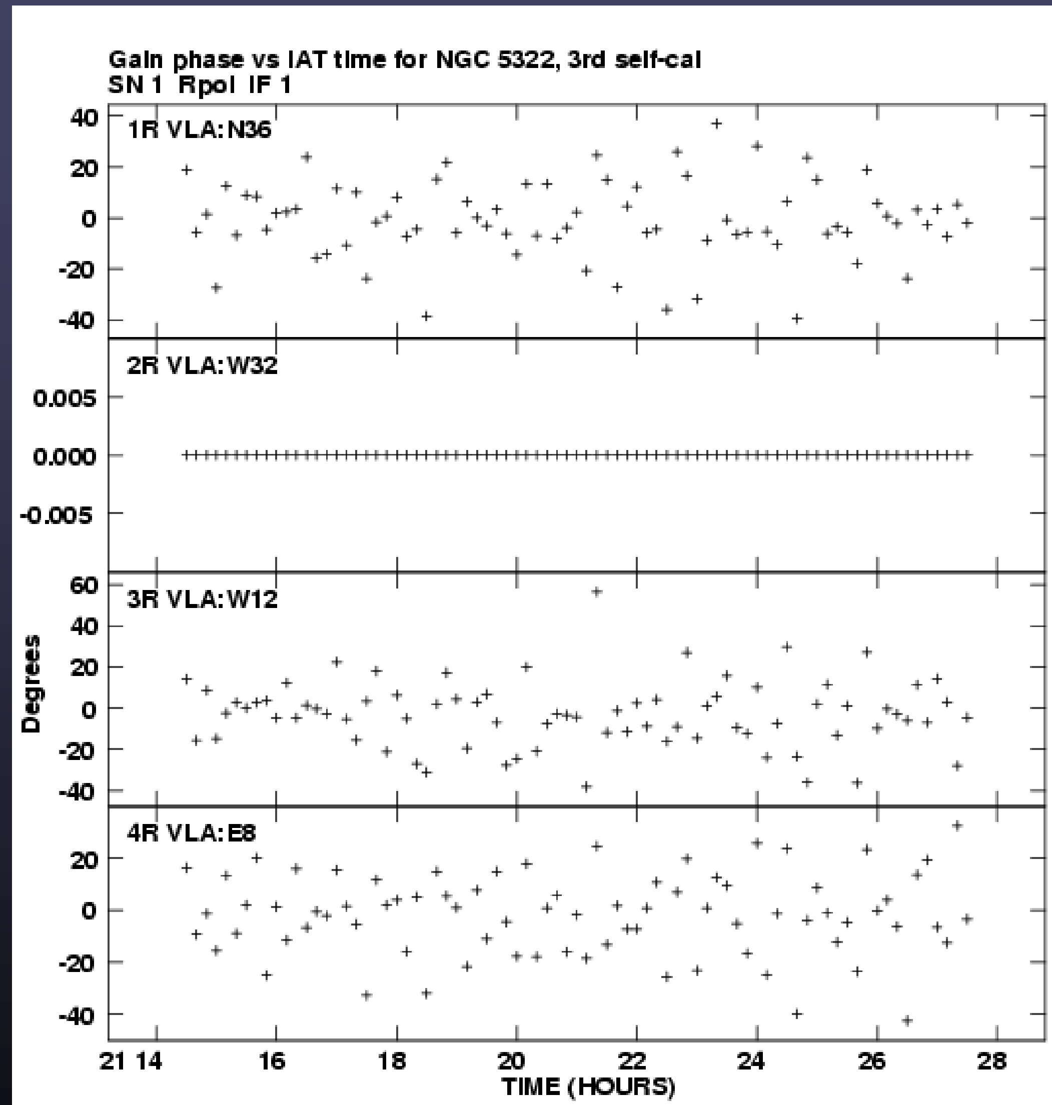
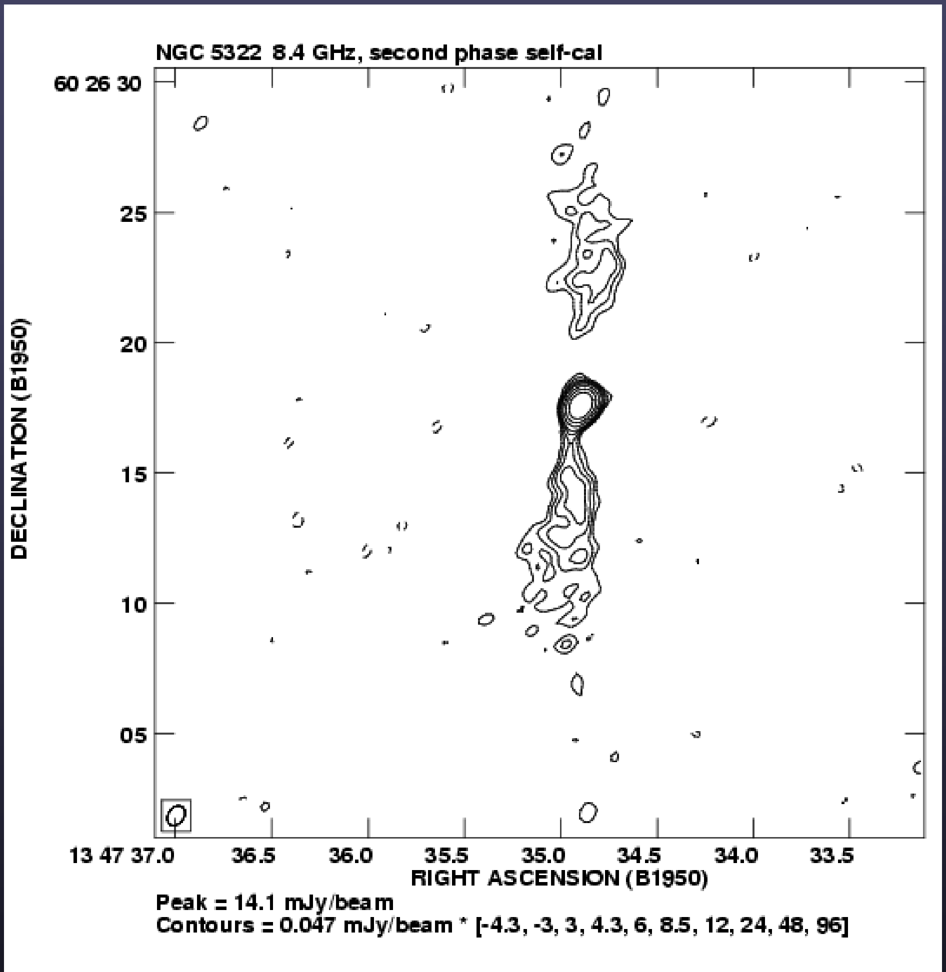
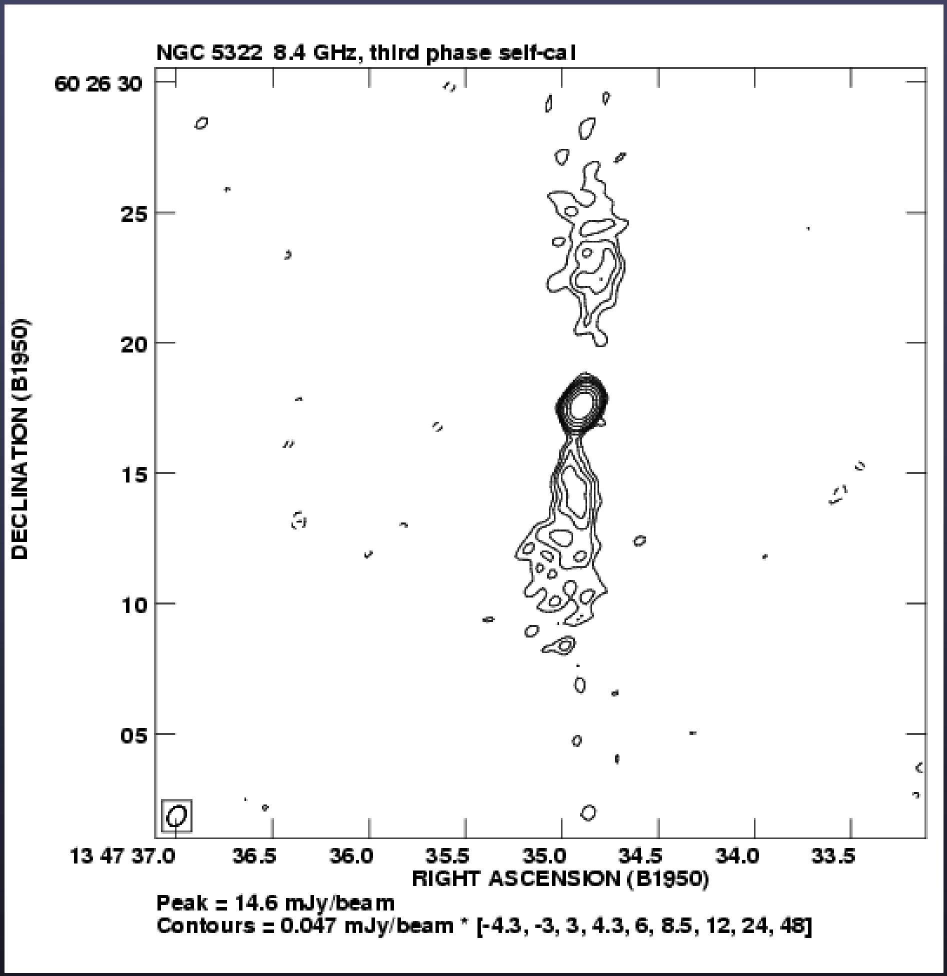


Image Comparison





When Self-cal Fails

- Astrometry (actually it just doesn't help)
- Variable sources
- Incorrect model
  - **barely-resolved sources**
  - **self-cal can embed mistakes in the data**
- Bad data
- Images dominated by deconvolution errors
  - **poor boxing**
  - **insufficient uv-coverage**
- Not enough flux density
  - **fast-changing atmosphere**
- Errors which are not antenna-based & uniform across the image
  - **baseline-based (closure) errors (e.g., bandpass mismatches)**
  - **imaging over areas larger than the isoplanatic patch**
  - **antenna pointing and primary beam errors**

How well it works

- Can be unstable for complex sources and poor Fourier plane coverage
  - VLA snapshots, sparse arrays (VLBA, MERLIN)
  - Basic requirement is that the total number of degrees of freedom (number of gains plus the number of free parameters in the model) should not be greater than the number of independent vis. measurements.
- Quite stable for well sampled VLA observations and appropriately complex sources
- Standard step in most non-detection experiments
- Bad idea for detection experiments
  - Will manufacture source from noise
  - Use in-beam calibration for detection experiments

Recommendations

- Flag your data carefully before self-cal
- Expect to self-calibrate most experiments (other than detection checks)
- For VLA observations, expect convergence in 3 - 5 iterations
- Monitor off-source noise, peak brightness, “unbelievable” features to determine convergence
- Few antennas (VLBI) or poor (u,v) coverage can require many more iterations of self-cal

Recommendations

- Be careful with the initial model
  - Don't go too deep into your clean components!
    - don't embed junk in your calibration
  - False symmetrization in phase self-cal (using, e.g., a point source model)
  - If it's important, leave it out: is this feature required by the data?
  - If desperate, try a model from a different configuration or a different band

- Experiment with tradeoffs on solution interval
  - Average IFs
  - Shorter intervals follow the atmosphere better
  - Don't be too afraid to accept low SNRs

More Calibration Techniques

- Water vapor radiometers
  22 GHz (EVLA) and 180 GHz (ALMA)
- Ionospheric measurements (TEC)
- Dual-frequency observations – calibration transfer

- Use self-cal to transfer phase solutions from narrow-band to broad-band (strong-line, weak continuum)

- Baseline-based calibration (removal of closure errors)
  antenna delay errors, antenna IF bandpasses

Finis

Easy example

- 8.4GHz observations of Cygnus A
- VLA C configuration
- Deconvolved using AIPS++ multi-scale clean
- Calibration using AIPS++ calibrater tool

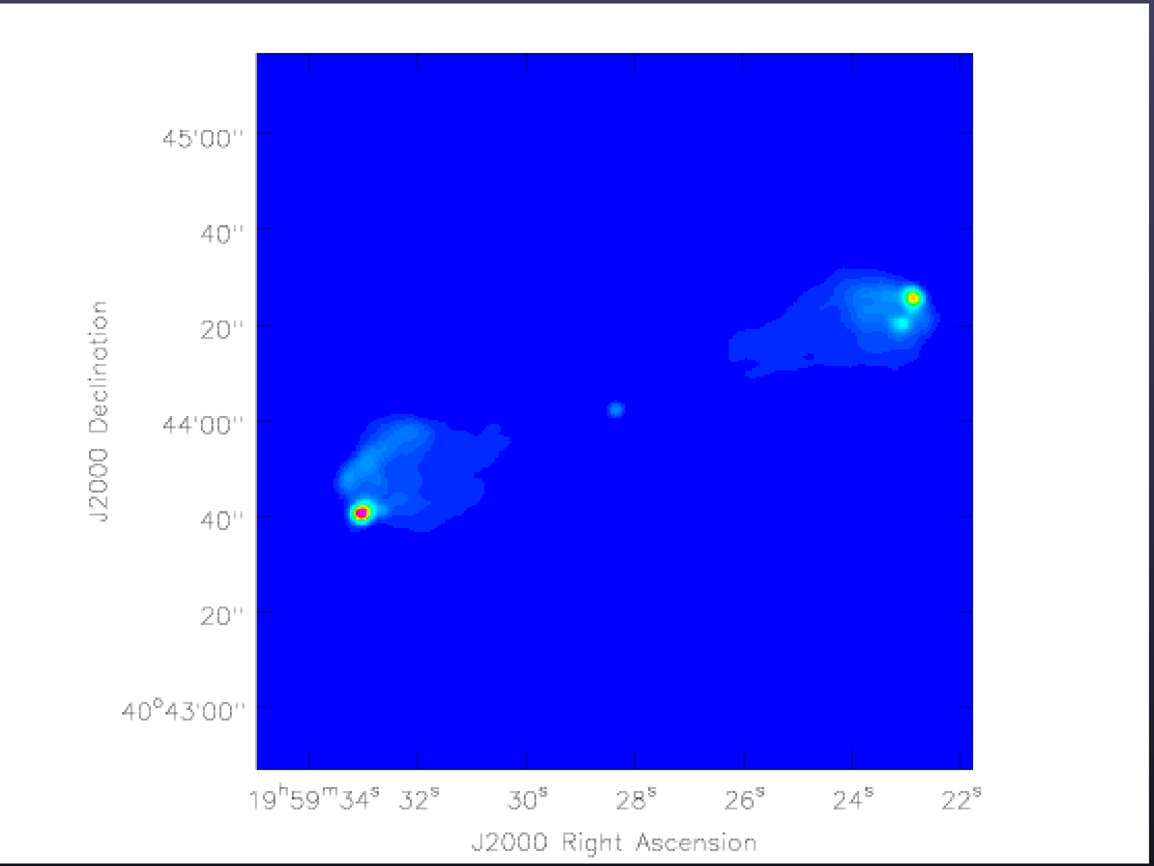
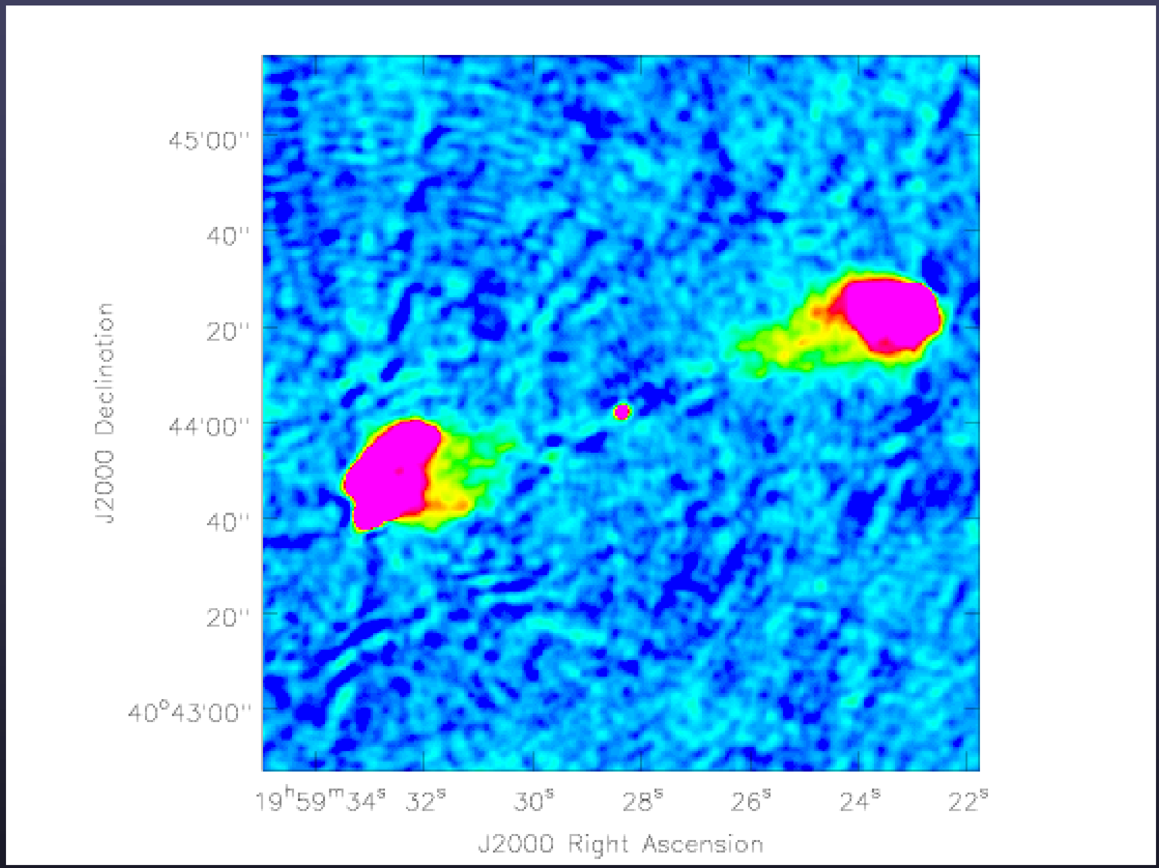


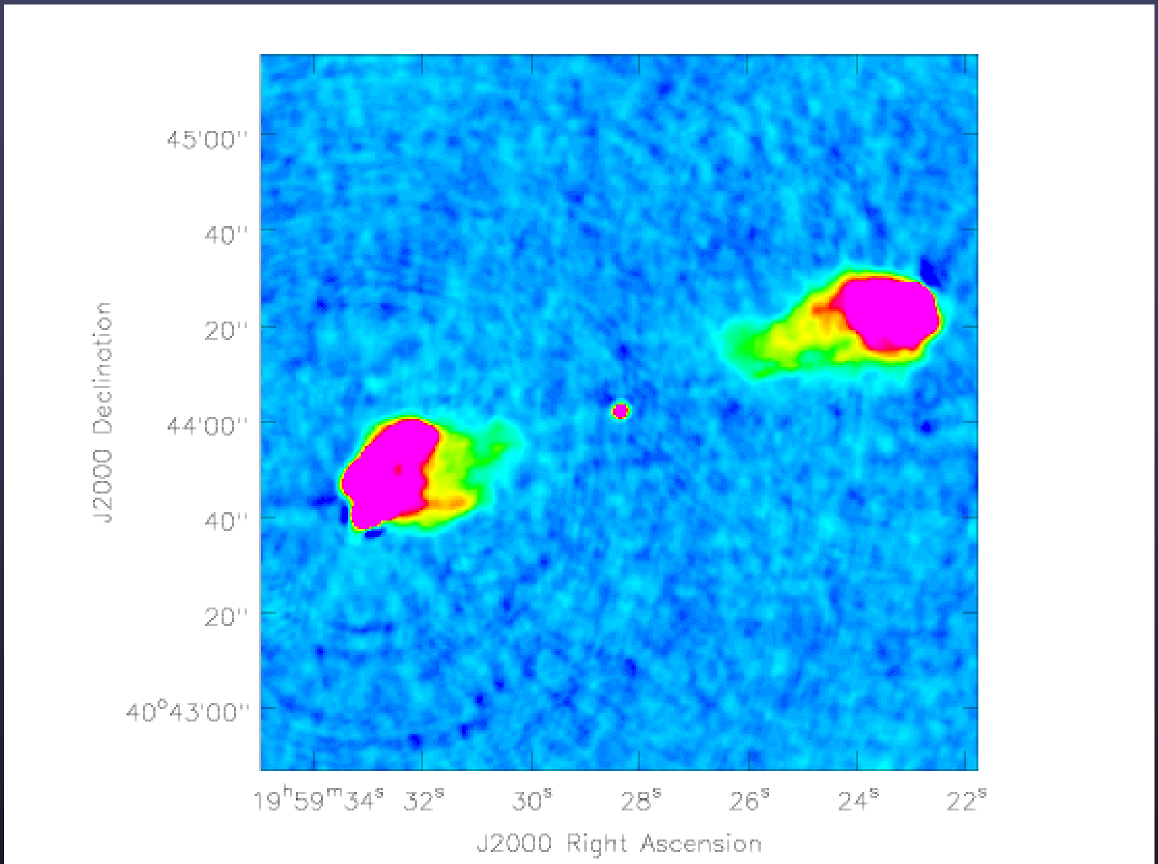
Image without self-calibration

- Phase calibration using nearby source observed every 20 minutes
- Peak ~ 22Jy
- Display shows - 0.05Jy to 0.5Jy

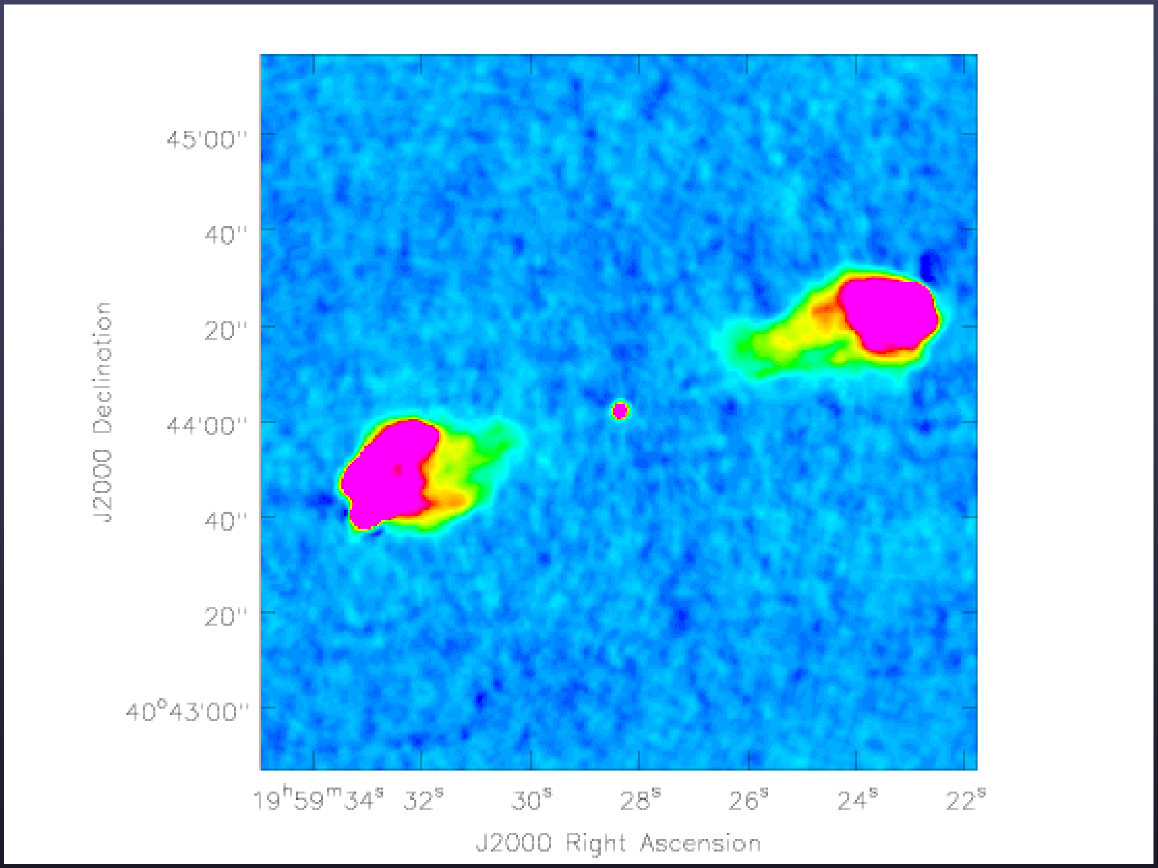


After 1 phase-only self-calibration

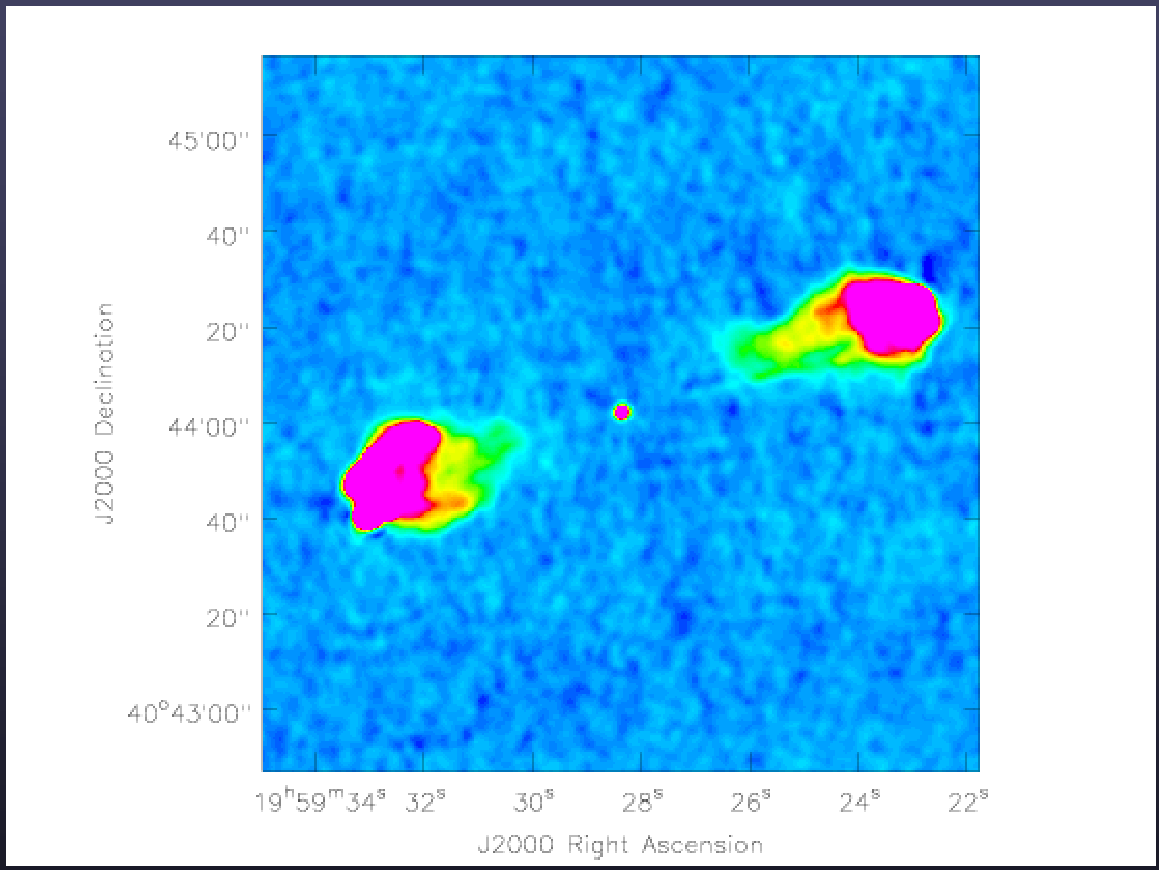
- Phase solution every 10s



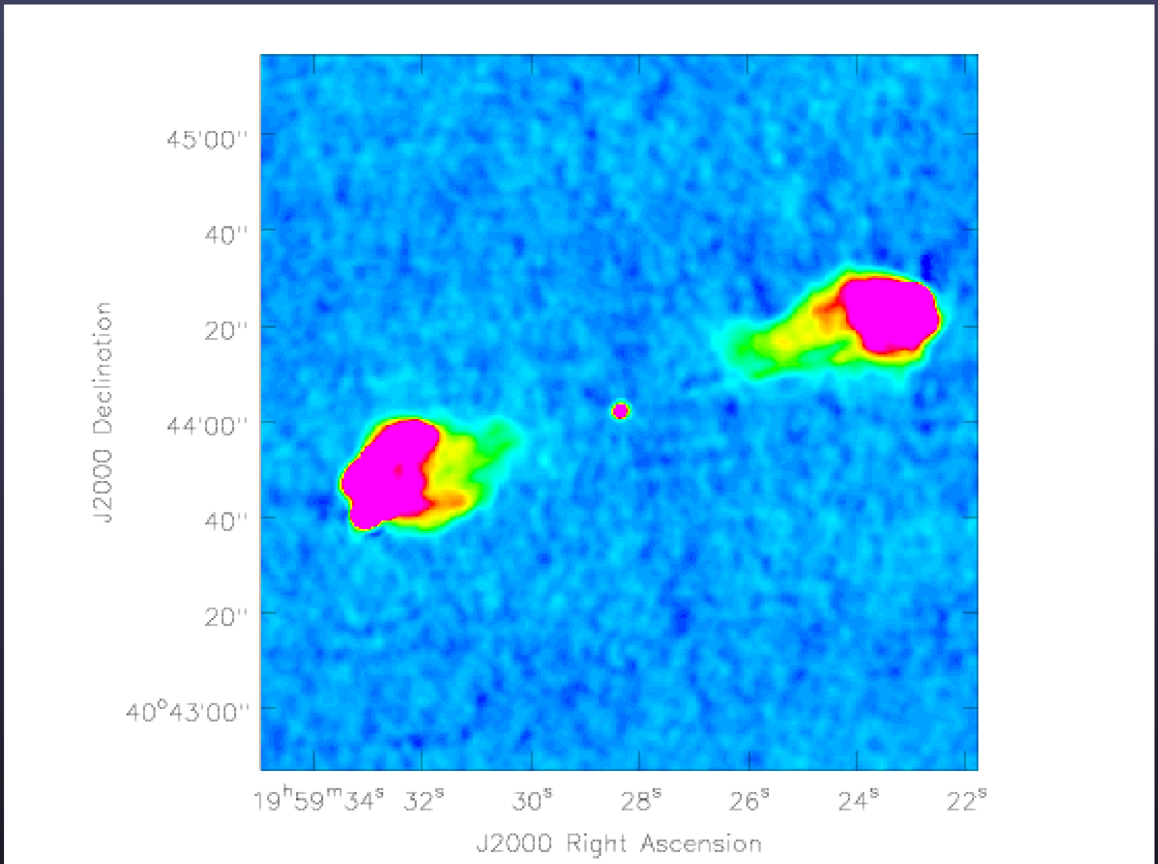
After 1 amplitude and phase calibrations



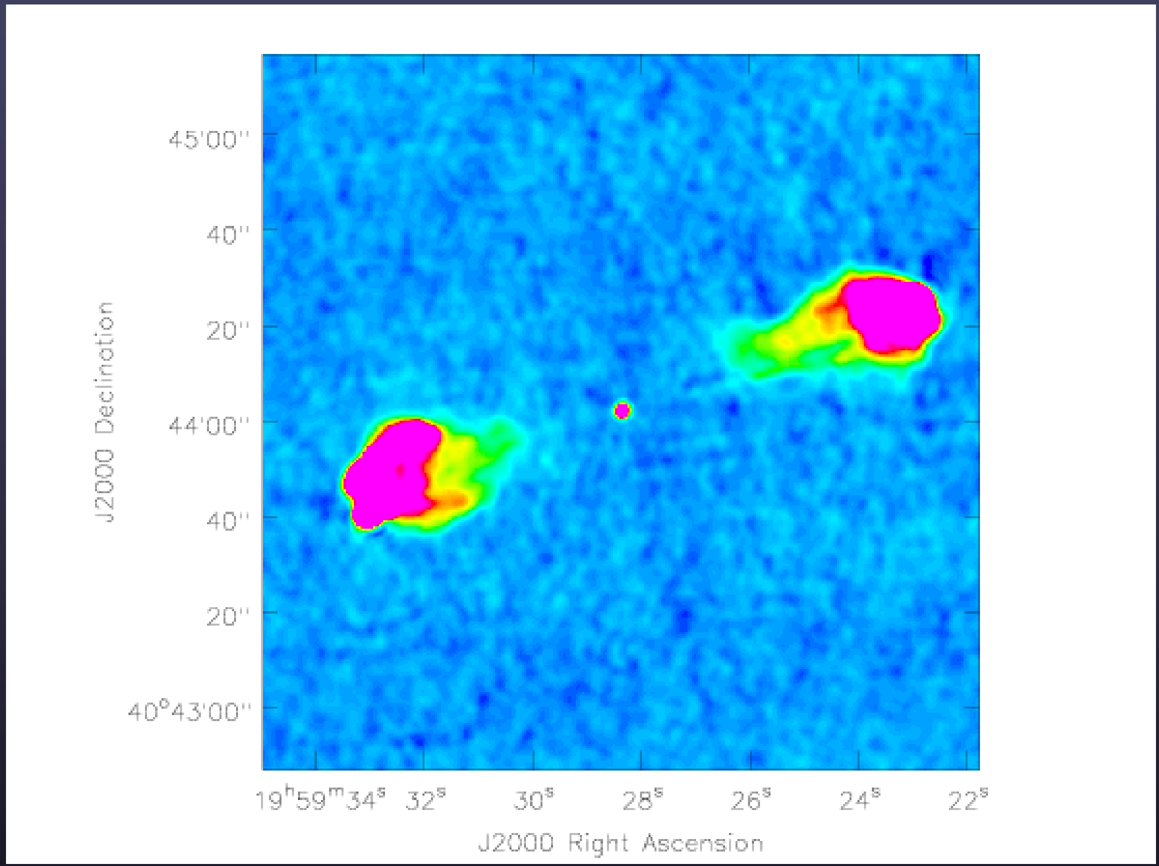
After 2 amplitude and phase calibrations



After 3 amplitude and phase calibrations



After 4 amplitude and phase calibrations



Summary of Cygnus A example

	Entire image			Off source		
	Max	**Minimum**	**RMS**	**Max**	**Minimum**	**RMS**
No selfcalibration	22.564	-0.179	0.409	0.072	-0.116	0.036
Phase only	22.586	-0.133	0.410	0.035	-0.035	0.013
1 Amp, Phase	22.976	-0.073	0.416	0.026	-0.033	0.012
2 Amp, Phase	22.912	-0.064	0.416	0.023	-0.033	0.012
3 Amp, Phase	22.887	-0.059	0.415	0.023	-0.033	0.012
4 Amp, Phase	22.870	-0.058	0.415	0.023	-0.032	0.012

- ~ Factor of three reduction in off source error levels
- Peak increases slightly as array phases up
- Off source noise is less structured
- Still not noise limited - we don’t know why

Final image showing all emission > 3 sigma