

Self-calibration

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Astronomy 423 at UNM
Radio Astronomy



Announcements

- VLA/LWA tour on Wednesday, March 26 departing 7am!
- We will meet in PAIS back lot at 6:45am
- Drivers (5): Greg, Ella, Mark, Brett, Charlie
- Bring:
 - Sturdy shoes, pants, \$\$\$ for gift shop
 - Water, snack, sunscreen, sunglasses, camera
 - HW6
- For credit. If you can't go provide a 4 page paper about a radio telescope.
- HW7 is due Wednesday April 2nd

Outline

- Why self-calibrate?
- How to self-calibrate
- What to watch out for
- Limitations of self-calibration
- Practical examples of self-calibration in action
- Demo of self-calibration in AIPS for HW7

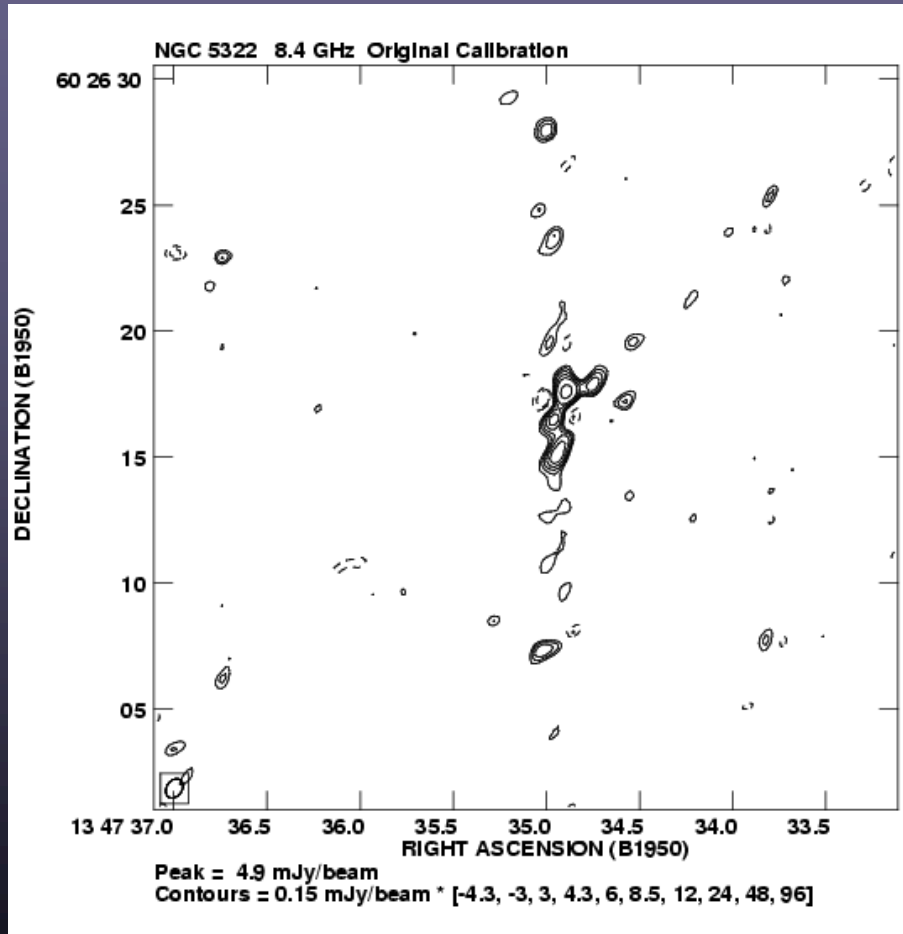
*This lecture is complementary to Chapter 10 of ASP 180
and is based on a lecture by Tim Cornwell*



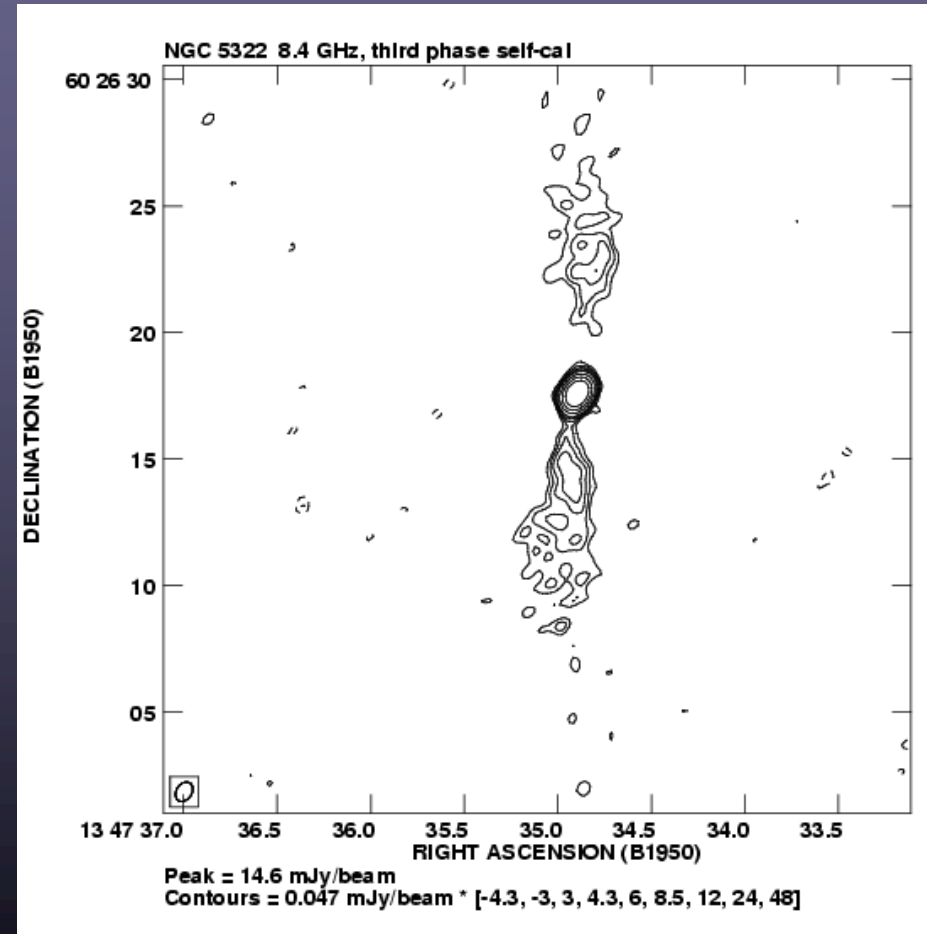
Self-calibration of a VLA snapshot

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Initial image



- Final image



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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



Calibration using a point source

- Calibration equation becomes

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

S Strength of point source

- Solve for antenna gains via least squares algorithm
- Works well - lots of redundancy
 - N-1 baselines contribute to gain estimate for any given antenna



Why is *a priori* calibration insufficient?

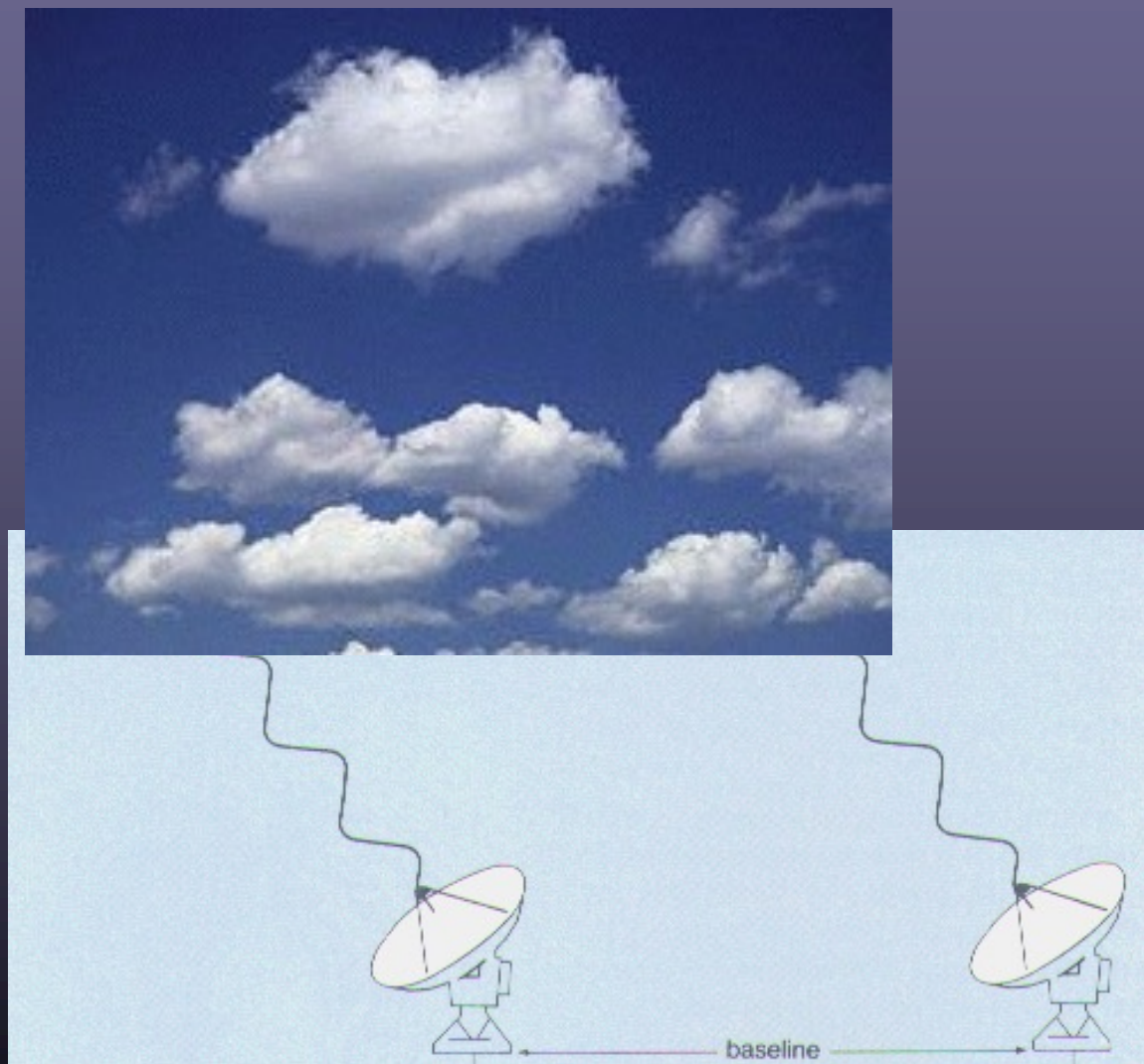
- The complex gains usually have been derived by means of observation of a calibration source before/after the target source
- Initial gain calibration is insufficient
 - Gains were derived at a different time
 - Troposphere and ionosphere are variable
 - Electronics may be variable
 - Gains were derived for a different direction
 - Troposphere and ionosphere are not uniform



What is the Troposphere doing?

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



Calibration using a model of a complex source

- Don't need point source - can use model

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

V_{ij}^{model}

Model visibility

- Redundancy means that errors in the model average down
- Can smooth or interpolate gains if desired



Relationship to point source calibration

- Made a fake point source by dividing by model visibilities

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

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

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



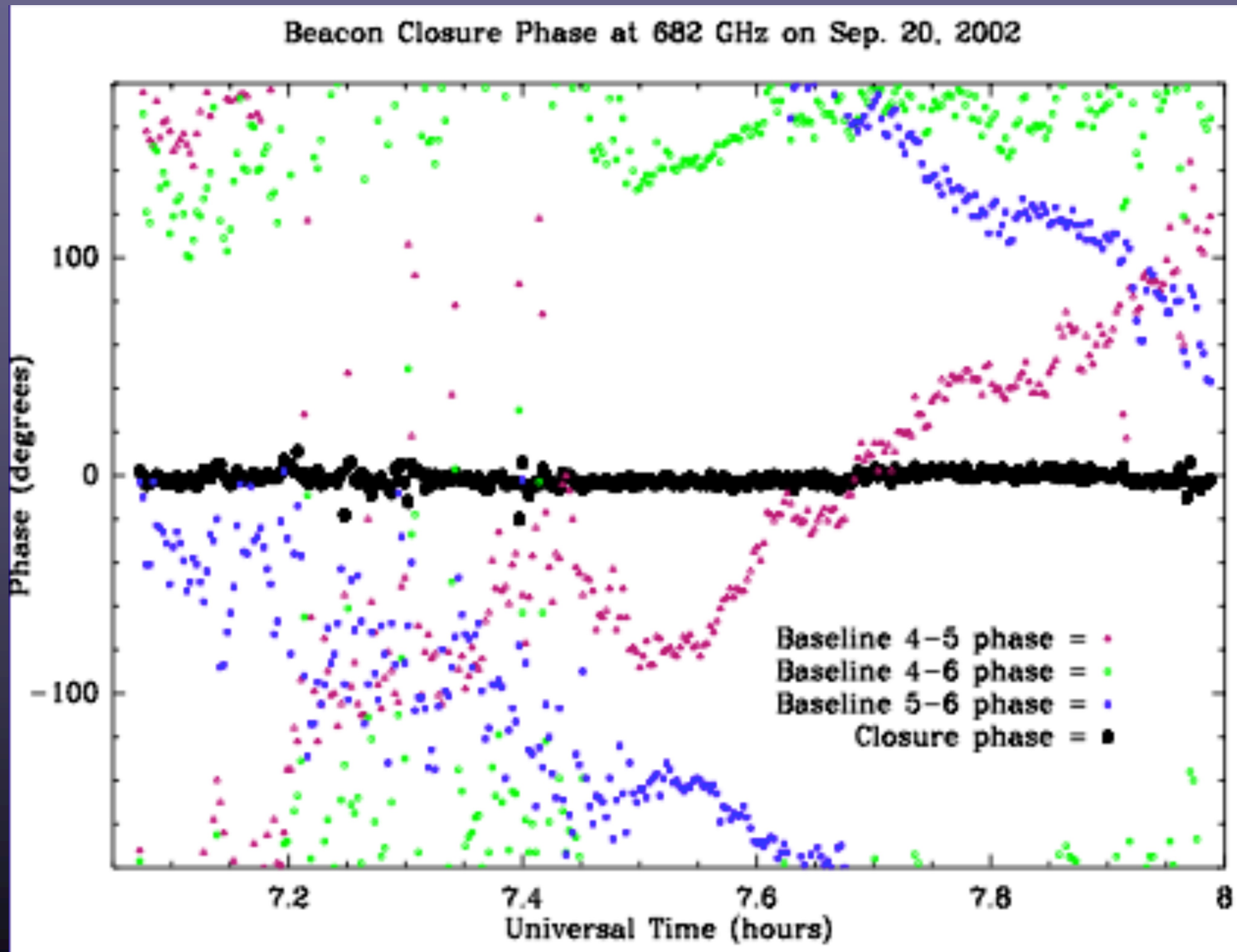
Why does self-calibration work?

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

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



SMA closure phase measurements at 682GHz



Advantages and disadvantages of self-calibration

- Advantages
 - Gains are derived for correct time, not by interpolation
 - Gains are derived for correct direction on celestial sphere
 - Solution is fairly robust if there are many baselines
- Disadvantages
 - Requires a sufficiently bright source
 - Introduces more degrees of freedom into the imaging so the results might not be robust and stable
 - Position information may be 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 due to lack of short spacings
 - Deconvolution errors around moderately resolved sources



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. Use Stokes ‘I’ (not enough SNR in Q, U or V)
3. Find antenna gains
 - Using least squares fit to visibility data
4. Apply gains to correct the observed data
5. Create a new model from the corrected data
 - Using for example Clean or Maximum Entropy
6. Go to (2), unless current model is satisfactory



Choices in self-calibration

- Initial model?
 - Point source often works well
 - Clean components from initial image
 - Don't go too deep!
 - Simple model-fitting in (u,v) plane
- Self-calibrate phases or amplitudes?
 - 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
 - Actually a bit lower than theoretical



You can self-calibrate on weak sources!

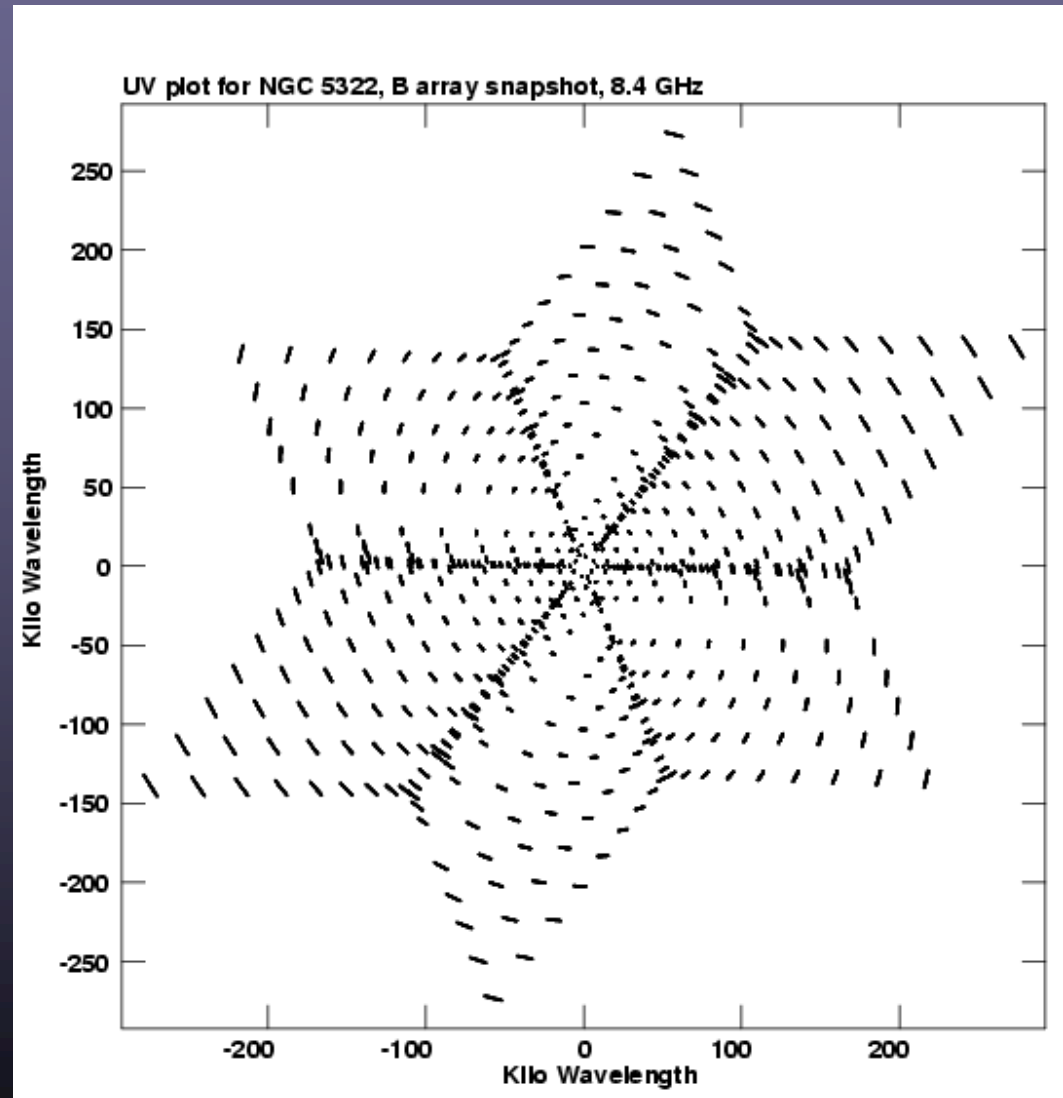
- For the VLA at 8 GHz, the noise in 10 seconds for a single 1024 MHz IF is about 4.5 mJy on a baseline
 - Average 4 IFs (2 RR and 2 LL) for 60 seconds to decrease this by $(4 * 60/10)^{1/2}$ to 1 mJy
 - If you have a source of flux density about 1.5 mJy, you can get a very good self-cal solution if you set the SNR threshold to 1.5.



Hard example: VLA Snapshot, 8 GHz, B Array

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



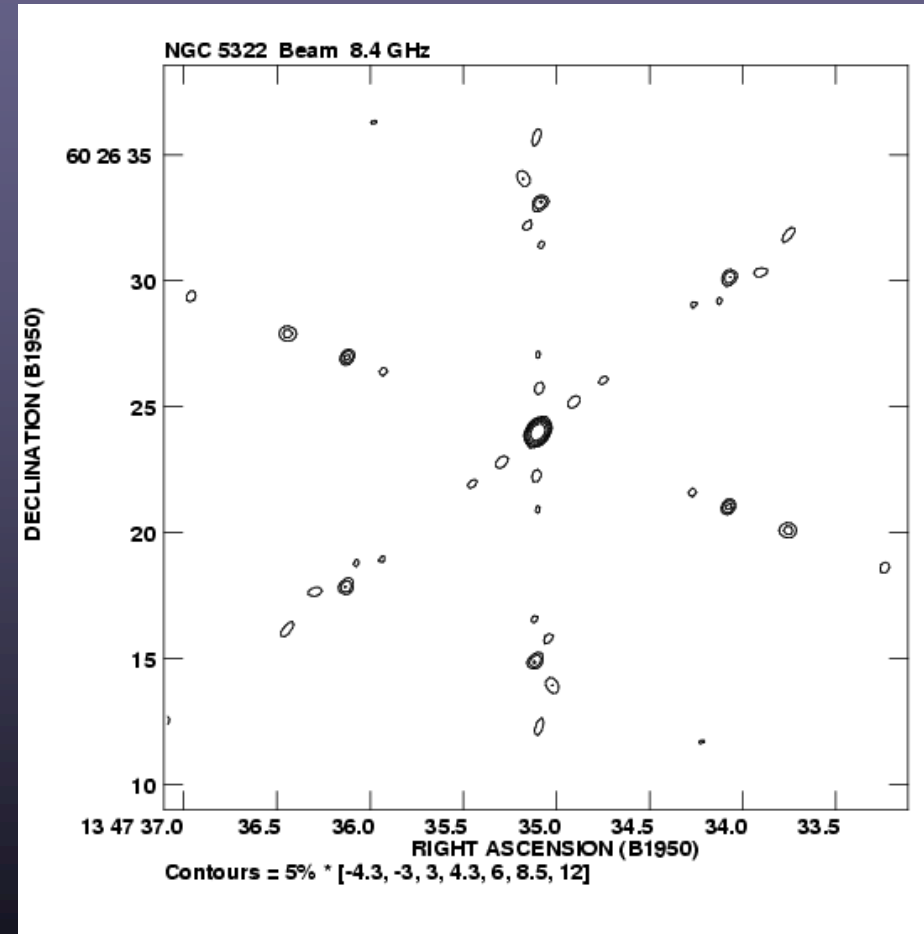
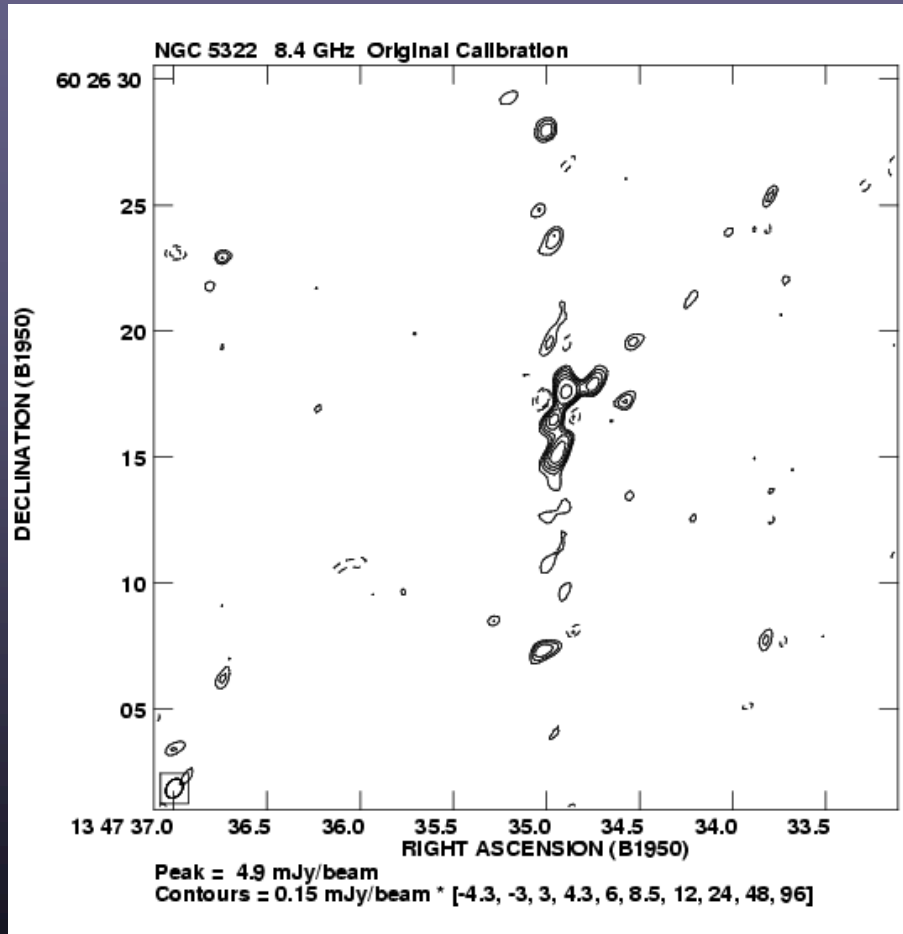
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Initial NGC 5322 Imaging

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Noise is 150 microJy/beam



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First pass

- Used 4 (merged) clean components in model
 1. 10-sec solutions, no averaging, $\text{SNR} > 5$
 - CALIB1: Found 3238 good solutions
 - CALIB1: Failed on 2437 solutions
 - CALIB1: 2473 solutions had insufficient data
 2. 30-sec solutions, no averaging, $\text{SNR} > 5$
 - CALIB1: Found 2554 good solutions
 - CALIB1: Failed on 109 solutions
 - CALIB1: 125 solutions had insufficient data
 3. 30-sec solutions, average all IFs, $\text{SNR} > 2$
 - CALIB1: Found 2788 good solutions



Phase Solutions from 1st Self-Cal

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

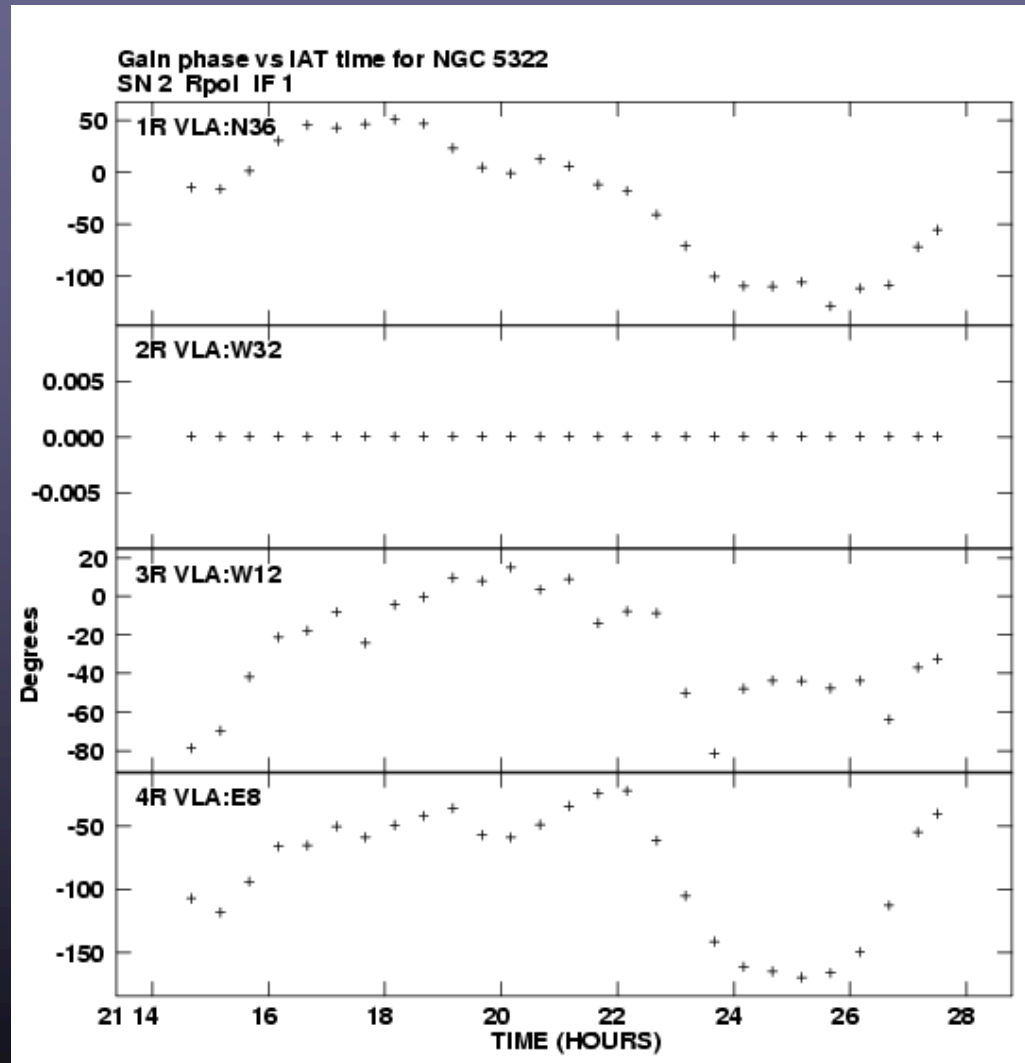
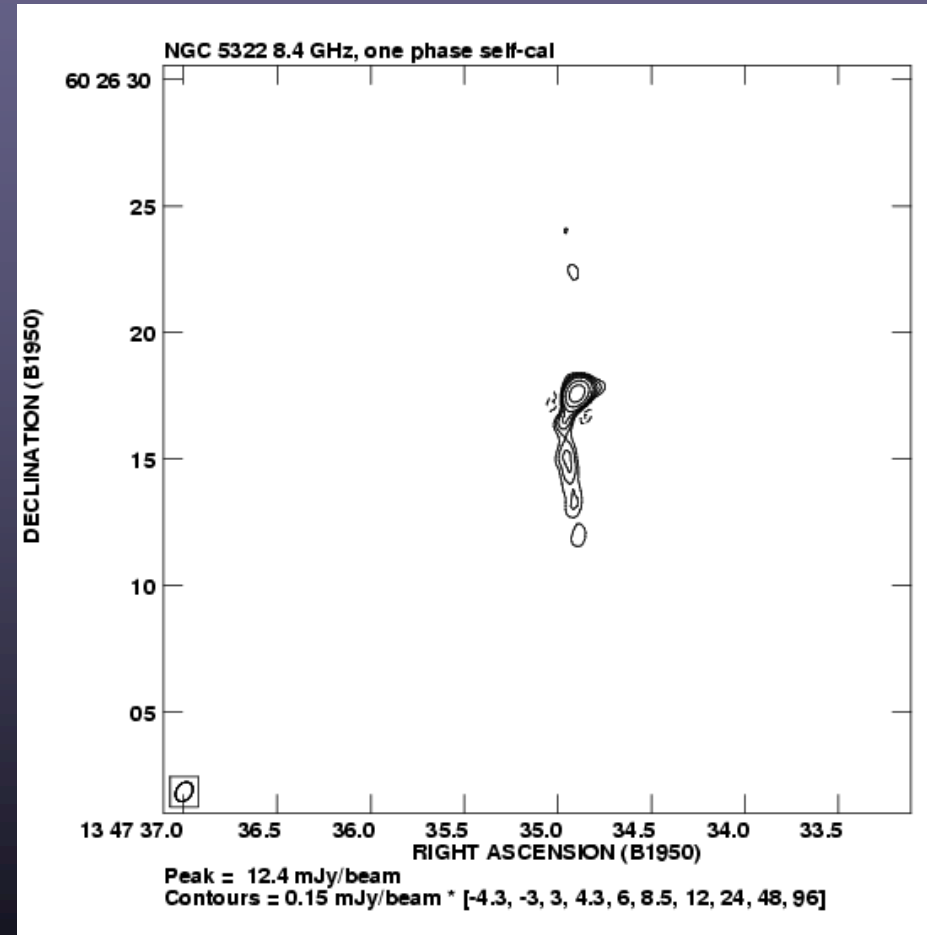
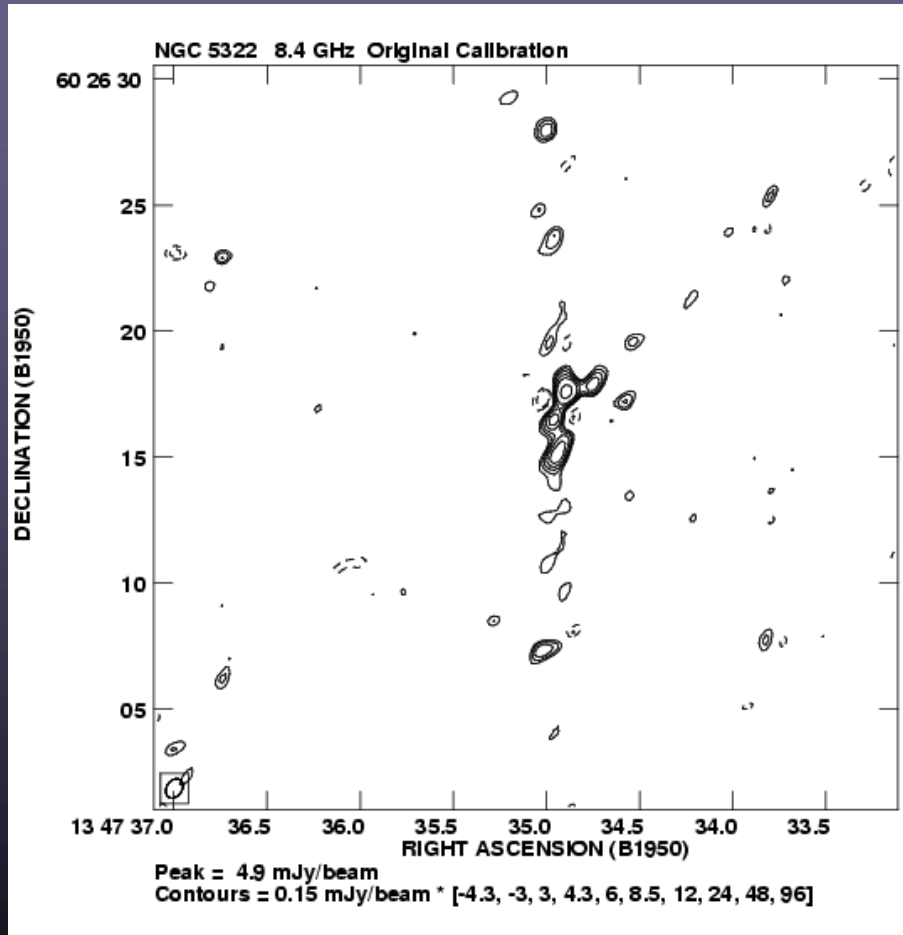


Image after first pass

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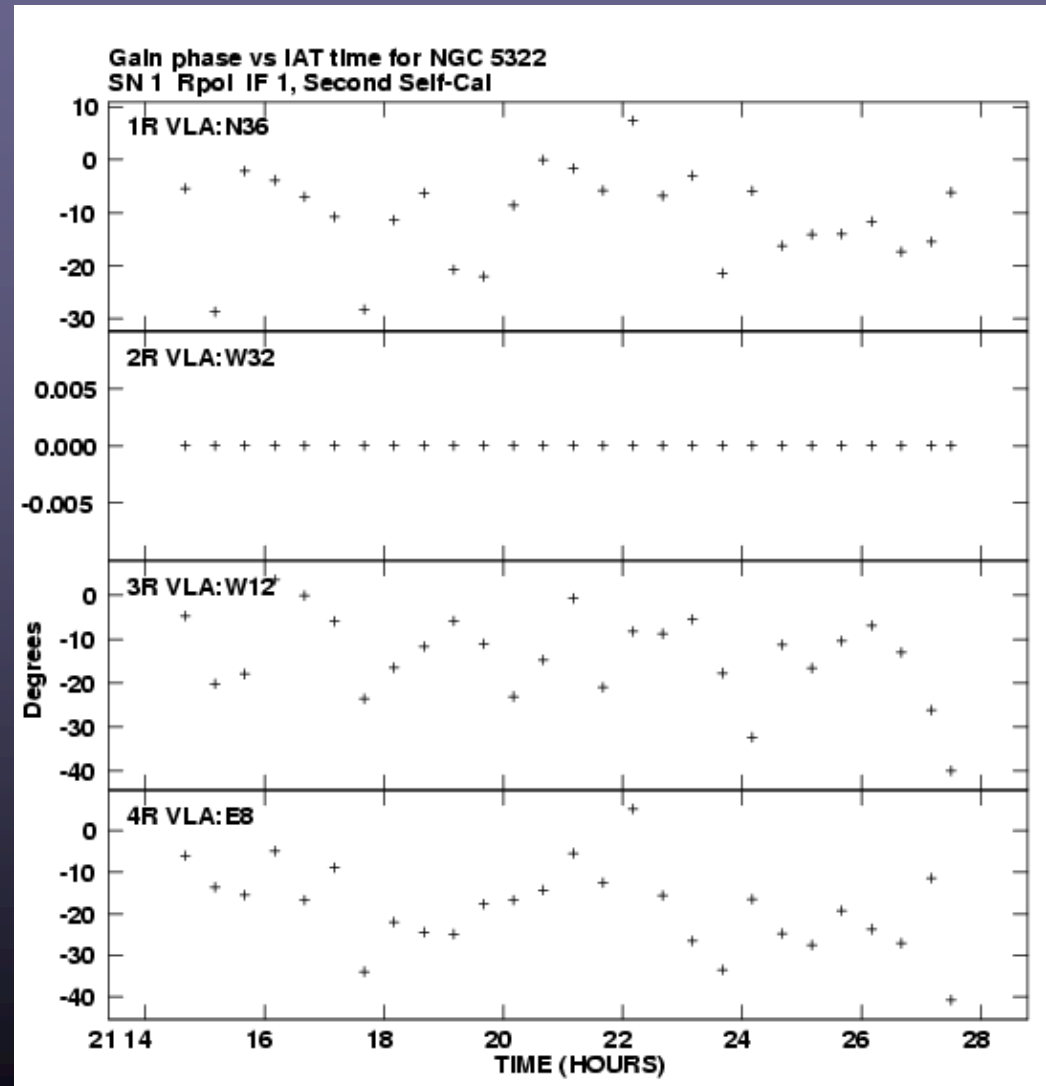
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Phase Solutions from 2nd Self-Cal

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

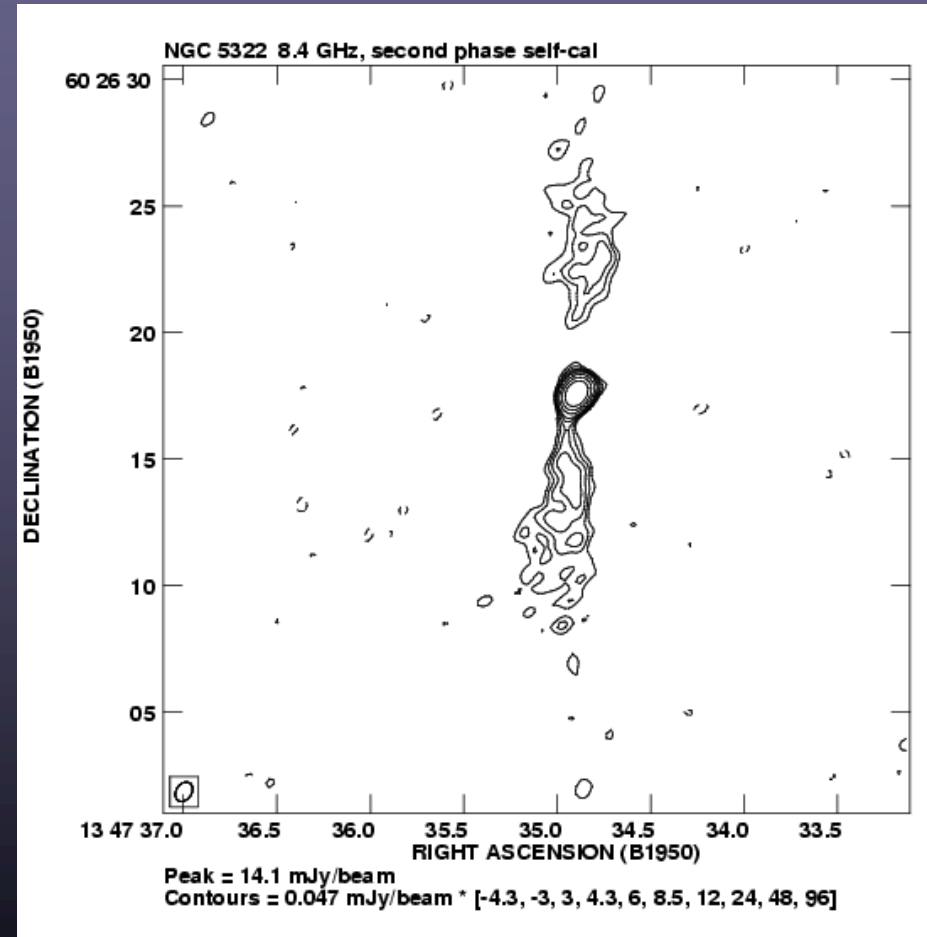
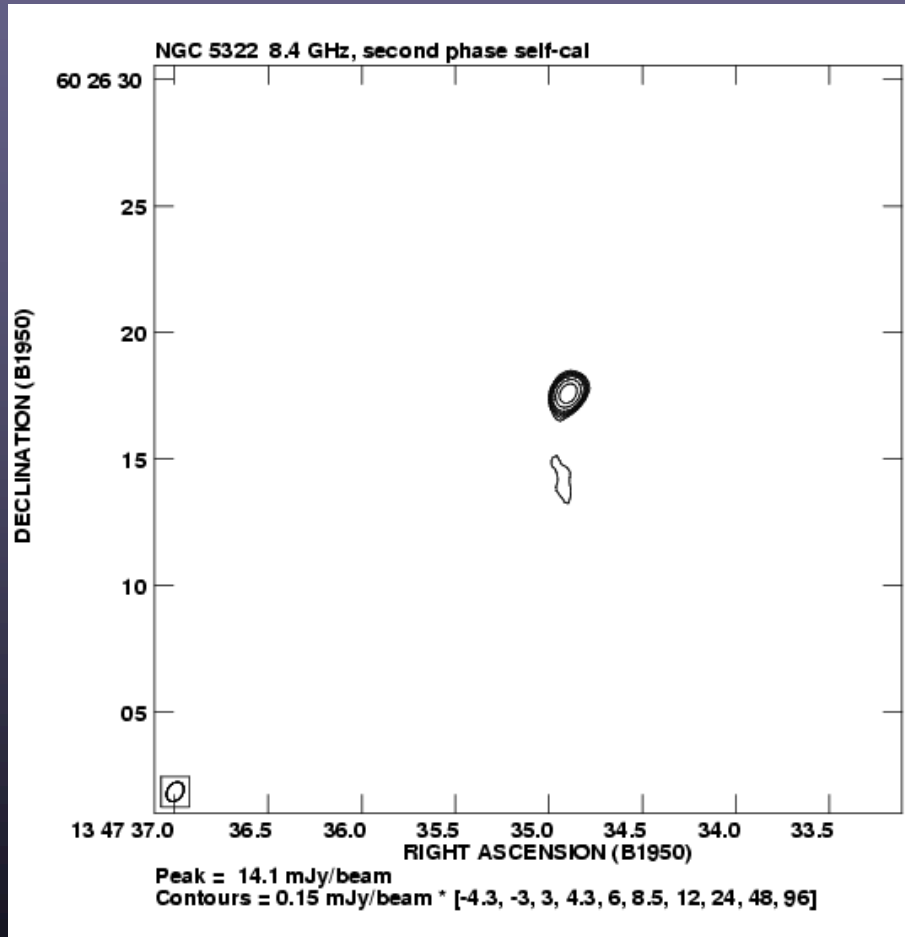


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Image after 2nd Self-Calibration

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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

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

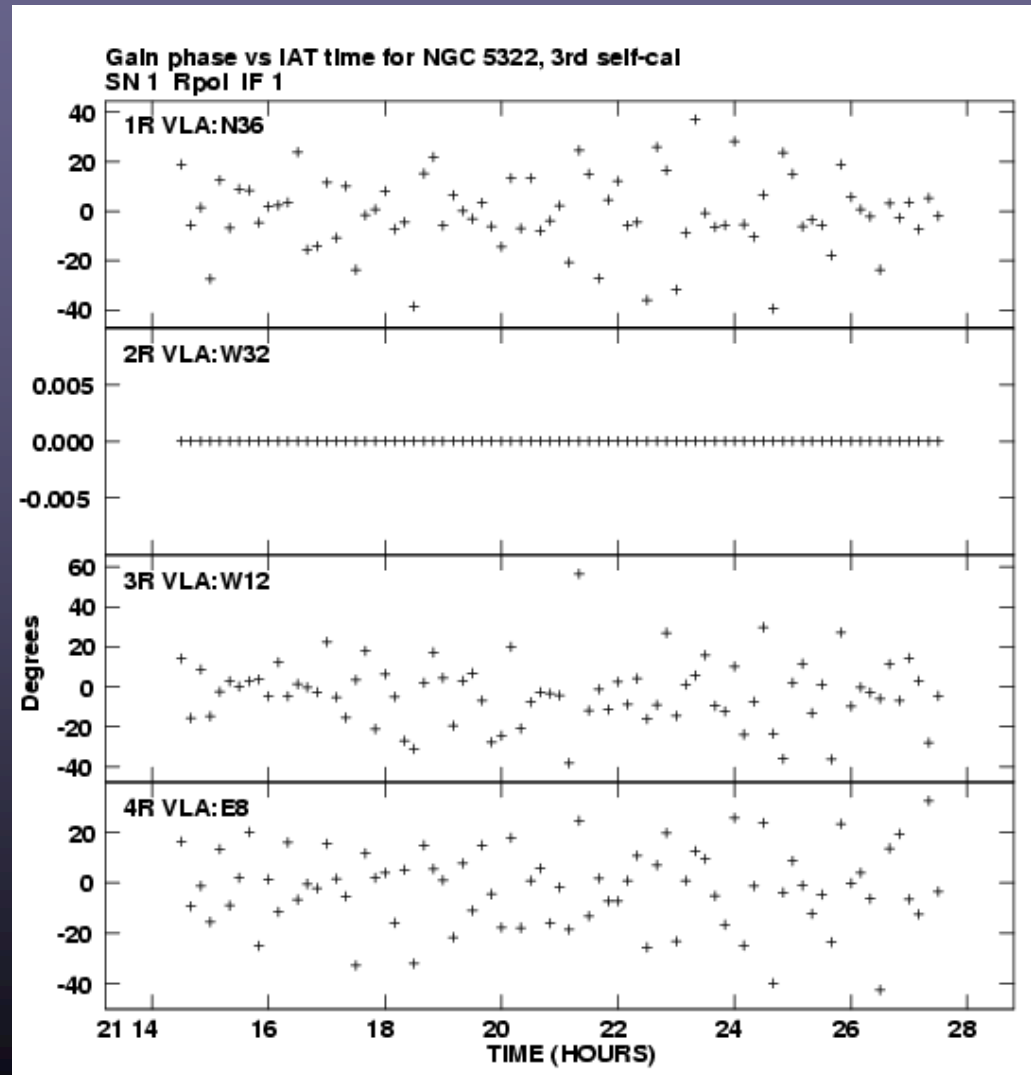
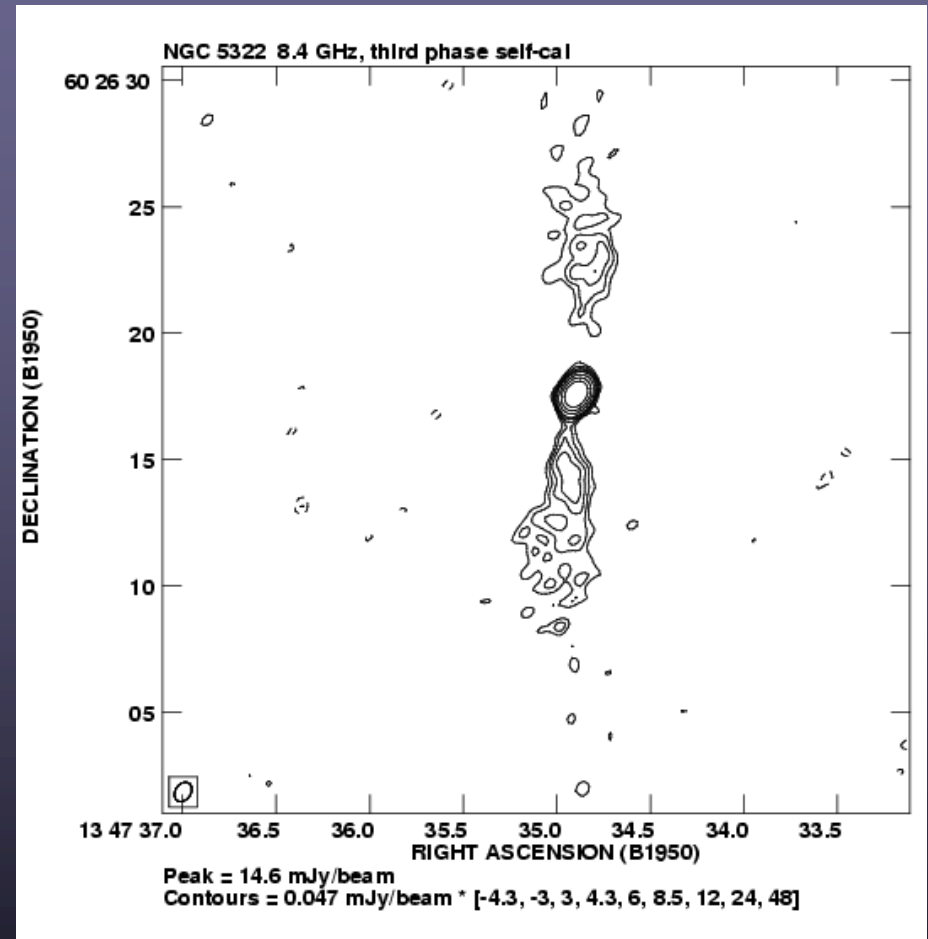
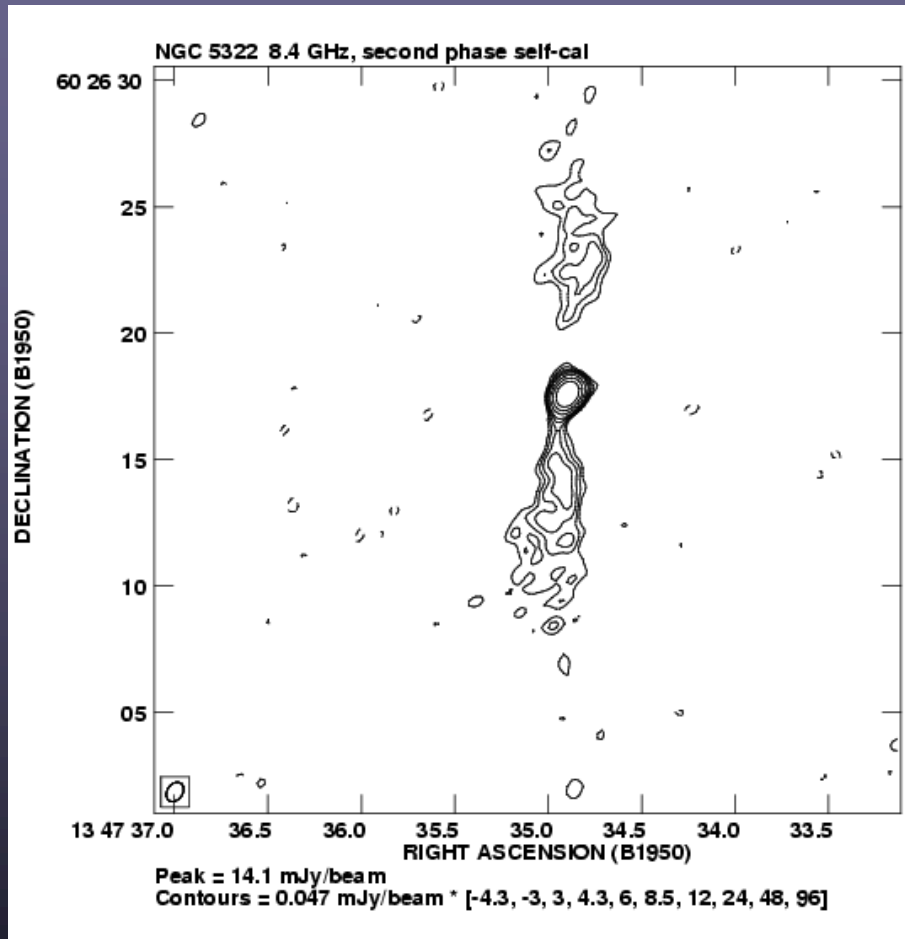


Image Comparison

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Easy example

- 8.4GHz observations of Cygnus A
- VLA C configuration
- Deconvolved using CASA multi-scale clean
- Calibration using CASA calibrator tool

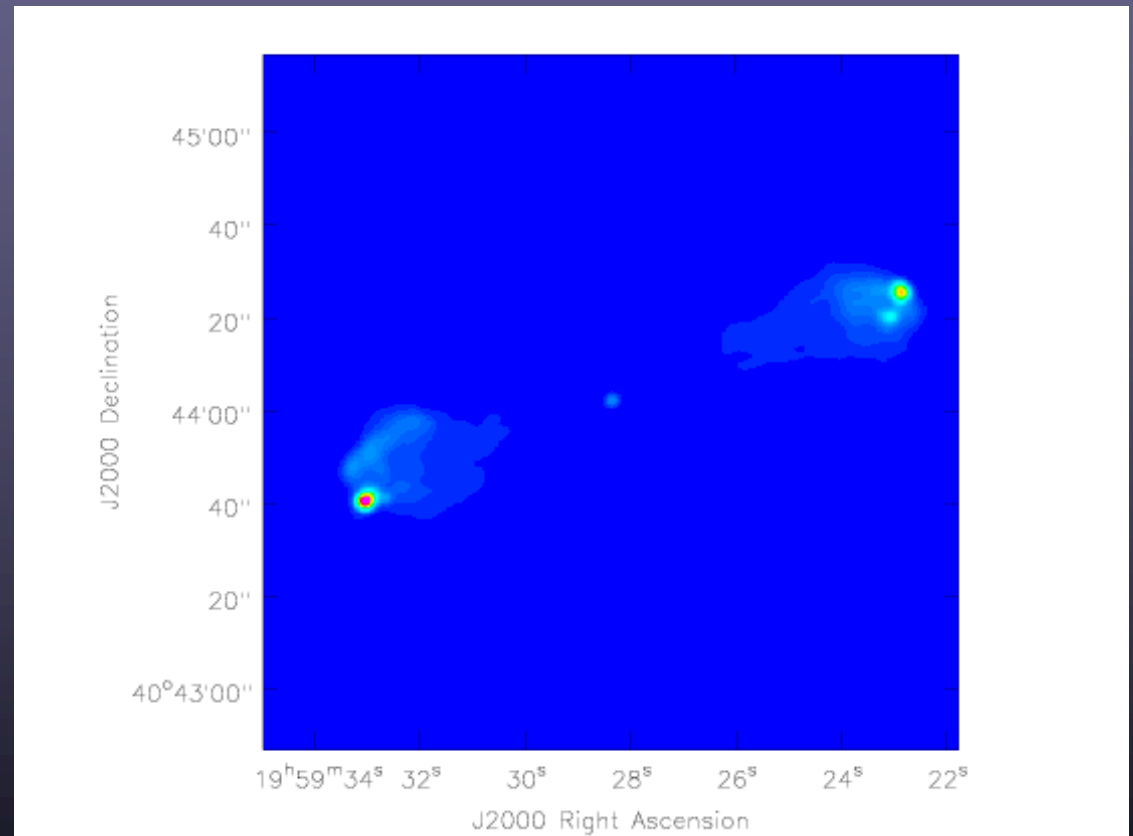
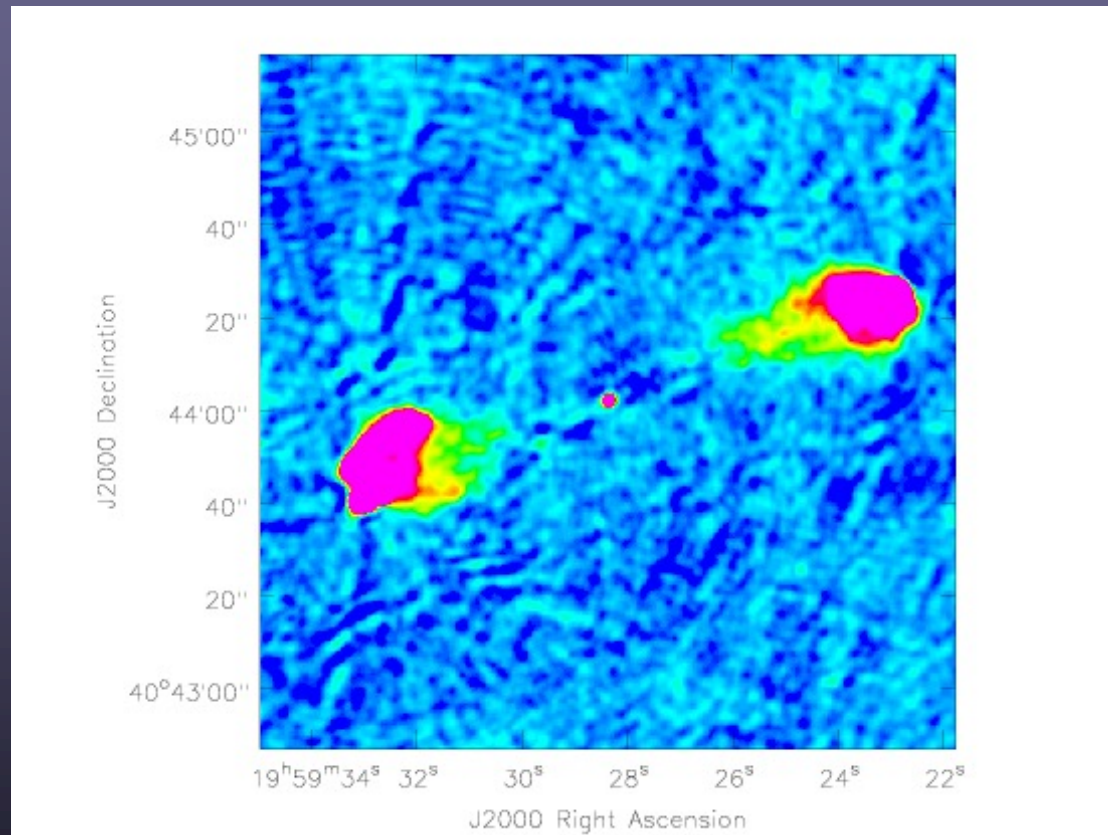


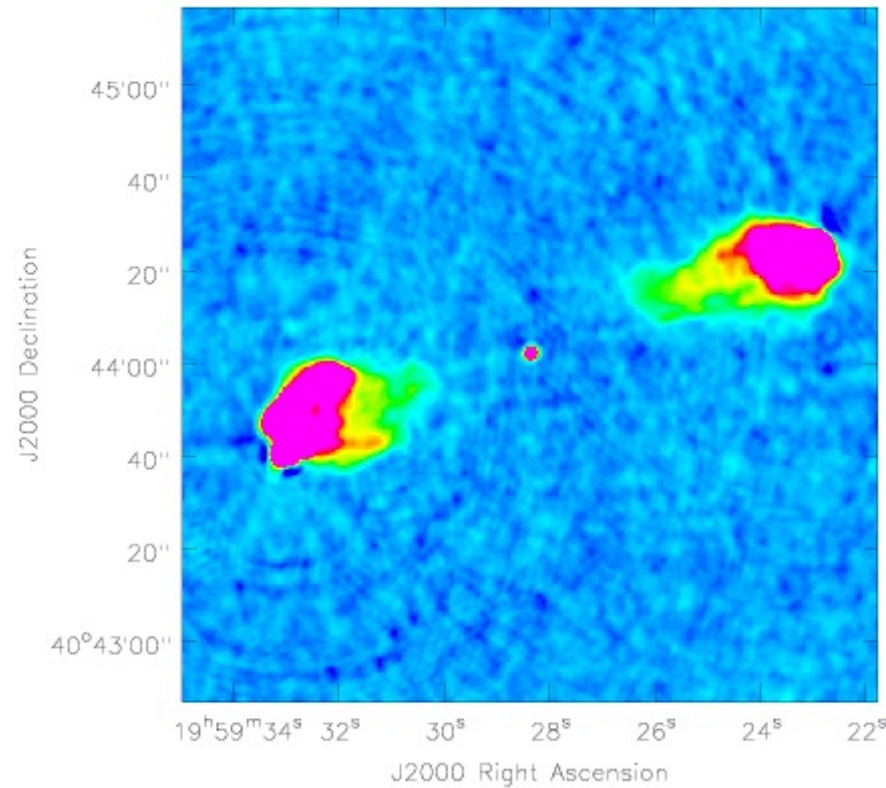
Image without self-calibration

- Phase calibration using nearby source observed every 20 minutes
- Peak $\sim 22\text{Jy}$
- Display shows - 0.05Jy to 0.5Jy

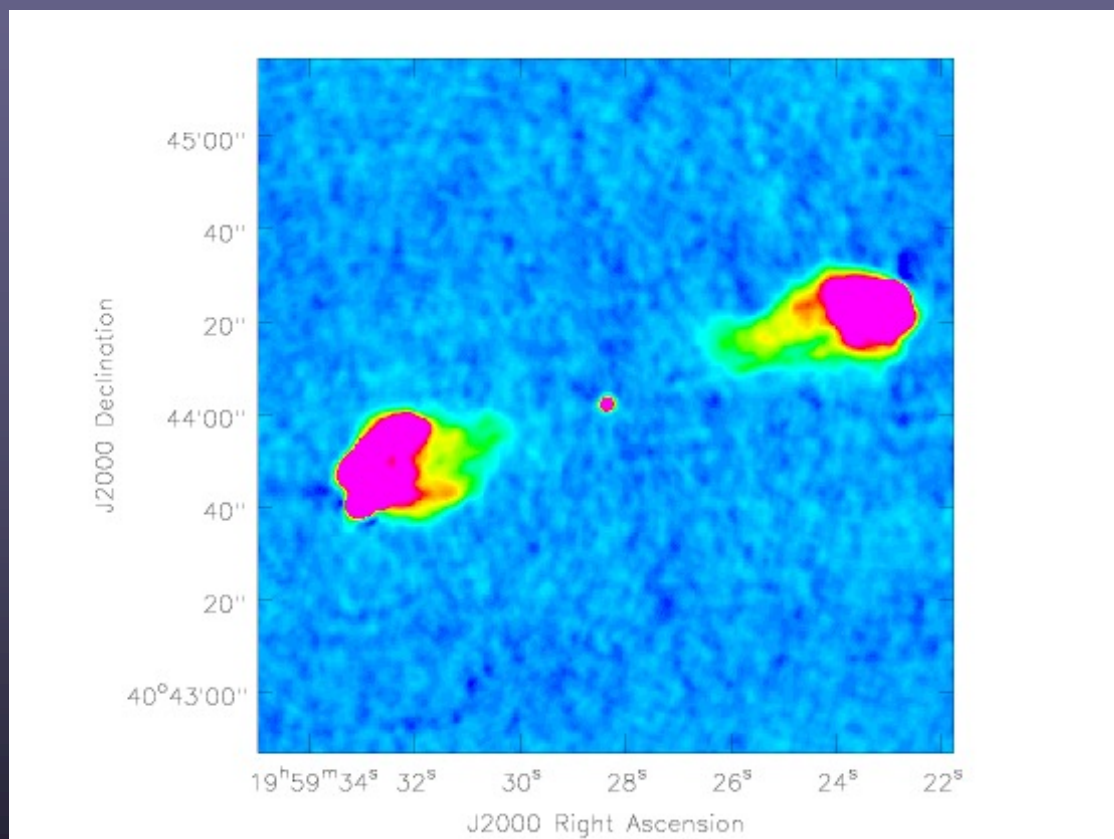


After 1 phase-only self-calibration

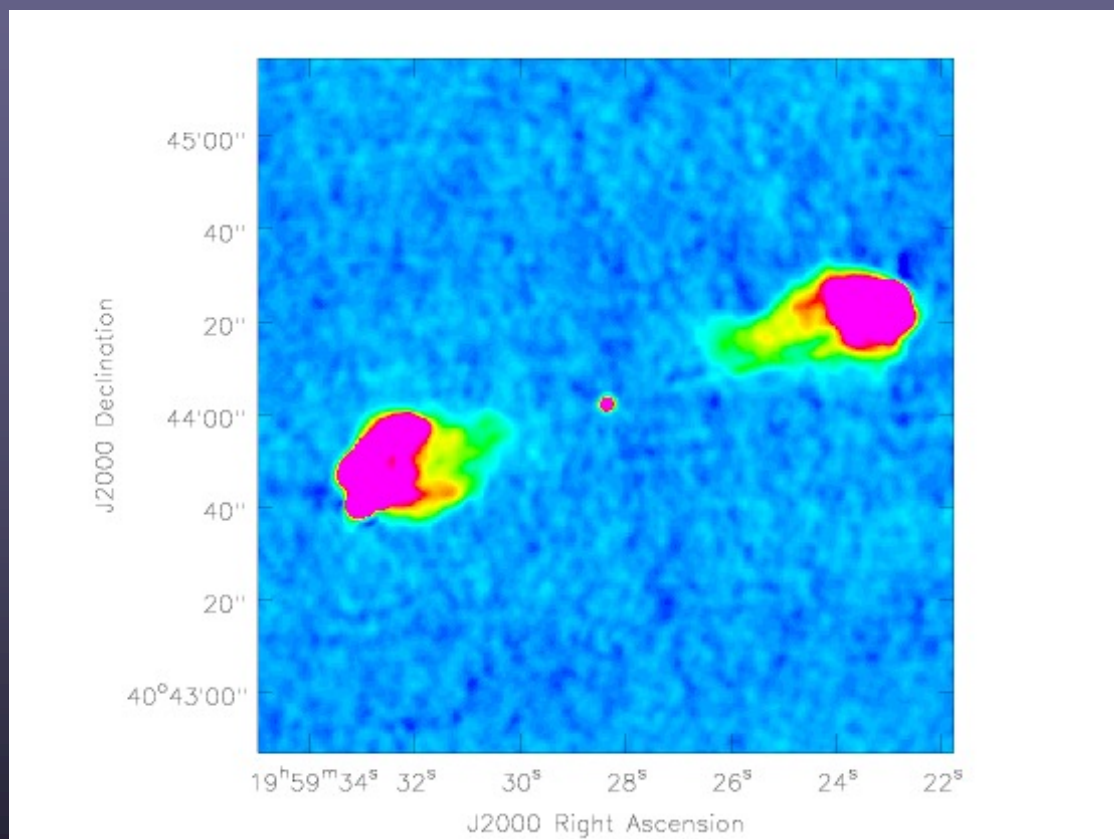
- Phase solution every 10s



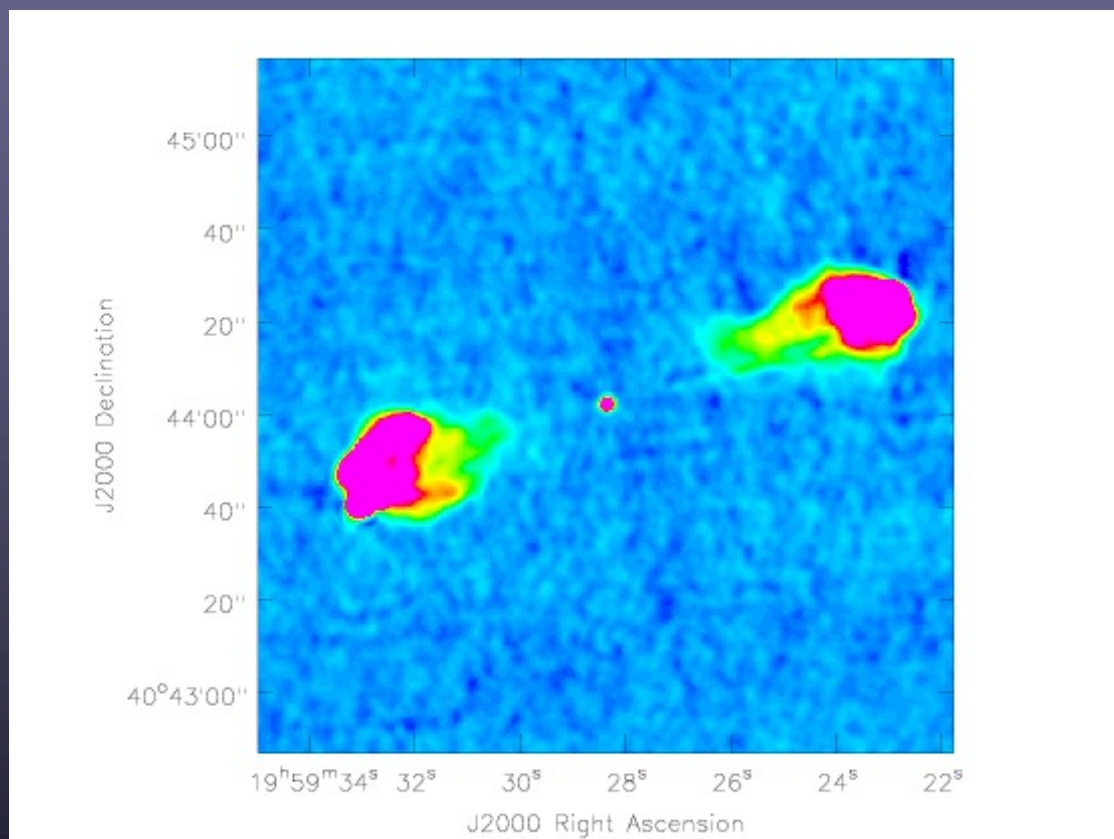
After 1 amplitude and phase calibrations



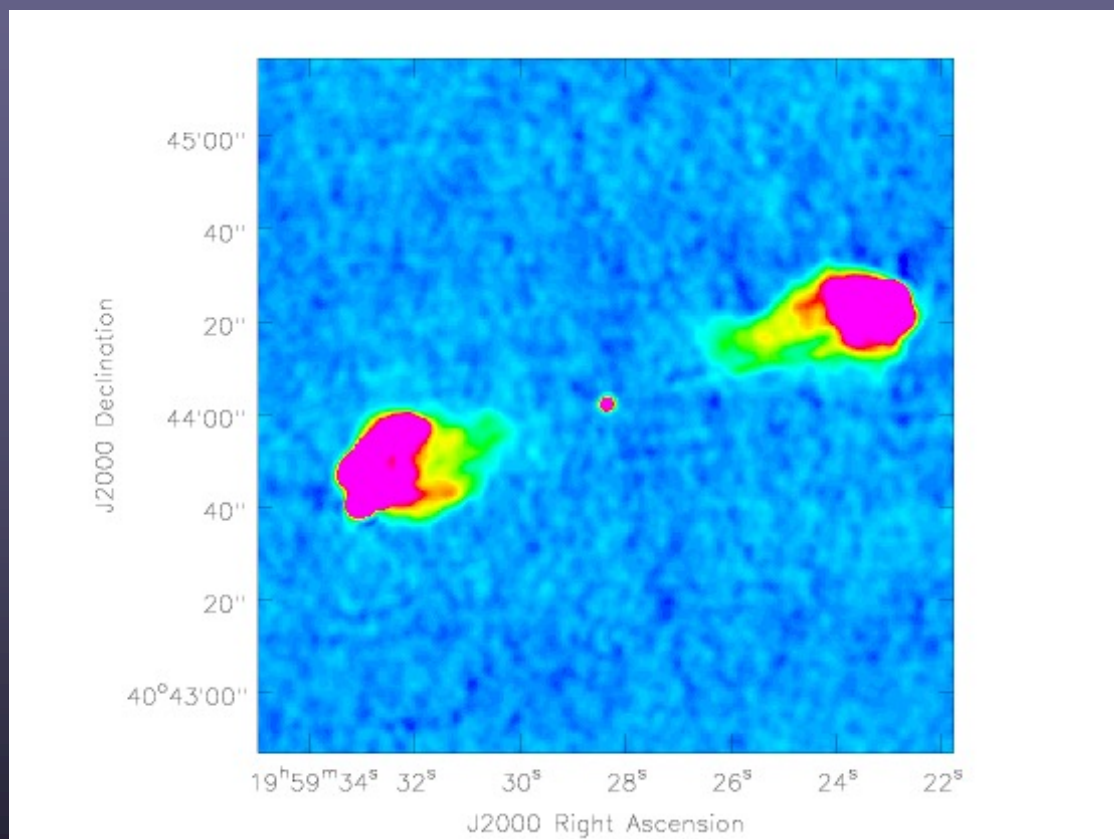
After 2 amplitude and phase calibrations



After 3 amplitude and phase calibrations



After 4 amplitude and phase calibrations



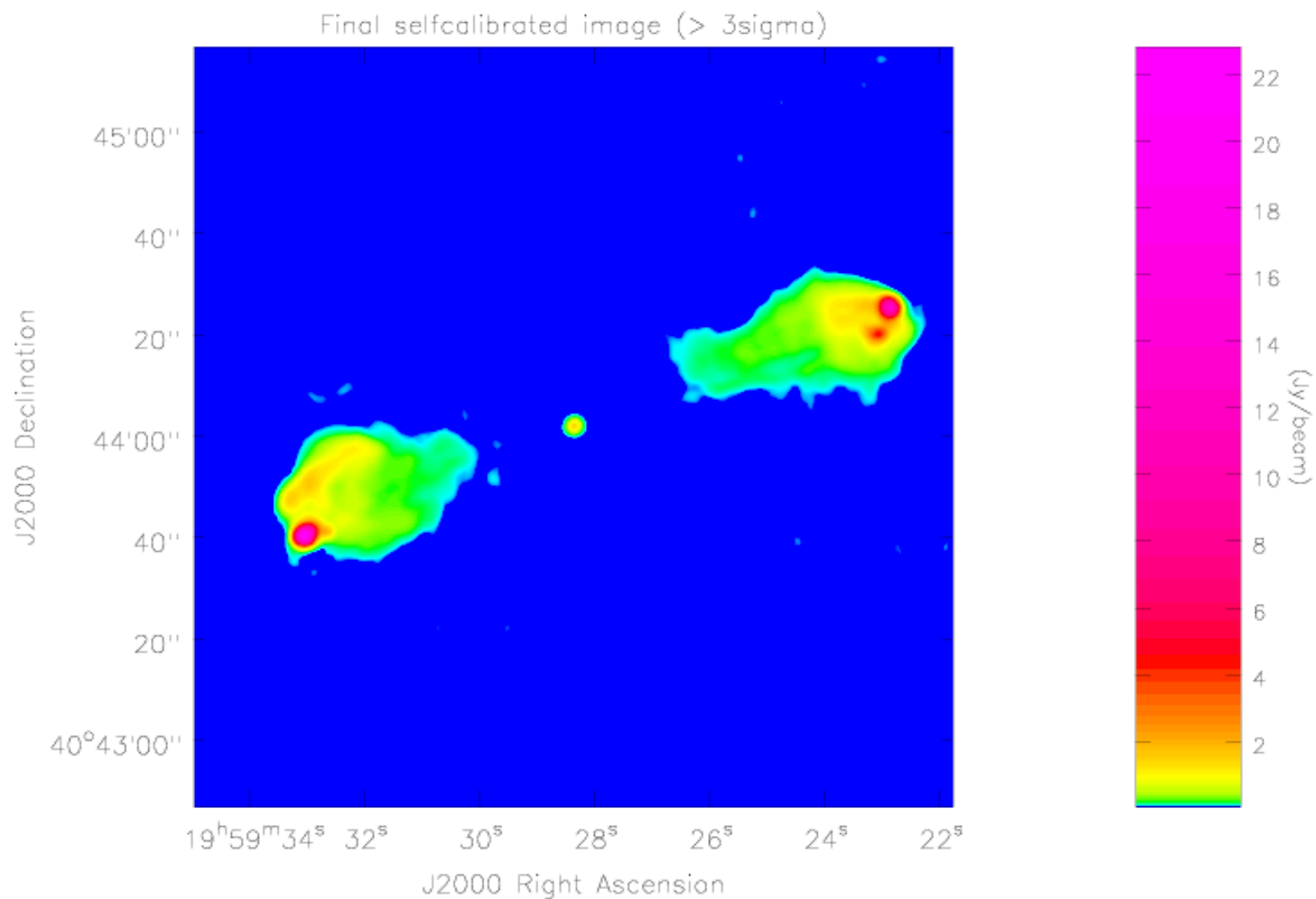
Summary of Cygnus A example

	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



Final image showing all emission > 3 sigma



How well it works

- Can be unstable for complex sources and poor Fourier plane coverage
 - VLA snapshots and VLBA observations
- Quite stable for well sampled VLA observations and appropriately complex sources
- Standard step in most experiments (except detection)
- 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 non-detection experiments
- For VLA observations, expect to see convergence in 3 - 5 iterations
- Monitor off source noise, peak brightness to determine convergence
- Few antennas (VLBI) or poor (u,v) coverage can require many more iterations of self-cal
 - Be careful with the initial model
 - Don't go too deep into your clean components!
 - If desperate, try a model from a different configuration or a different band
- Experiment with tradeoffs on solution interval
 - Shorter intervals follow the atmosphere better
 - Don't be too afraid to accept low SNRs



Demo

- Switch to AIPS and demo self-calibration on VLA data



Further Reading

- <http://www.nrao.edu/whatisra/mechanisms.shtml>
- <http://www.nrao.edu/whatisra/>
- www.nrao.edu
- Synthesis Imaging in Radio Astronomy
- ASP Vol 180, eds Taylor, Carilli & Perley

