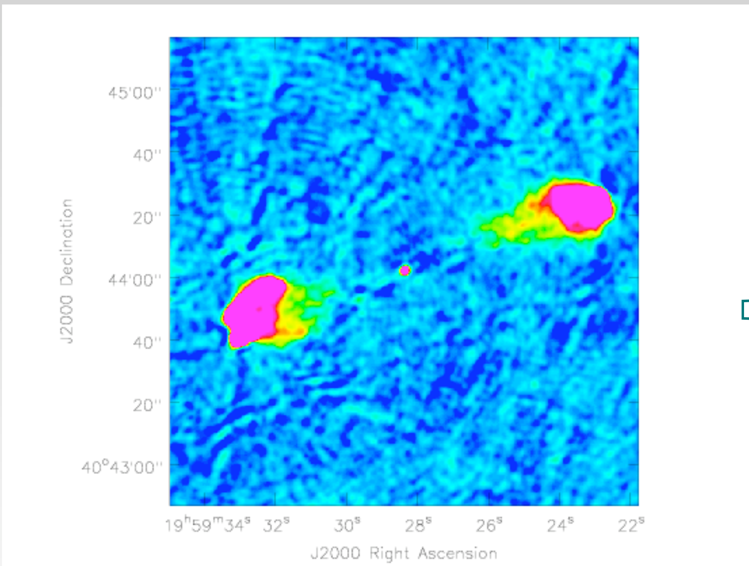
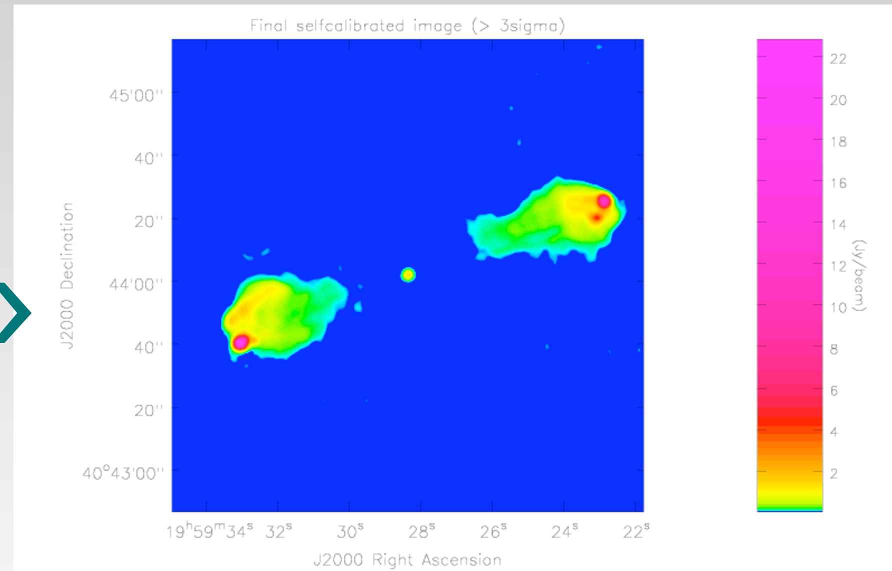
# Imaging Concepts: Self Calibration



## Intensidad

Cuanta luz hace falta

para que dejes de tropezarte con el miedo

de Rodrigo Troncoso

## Intensity

How much light do you need

to stop meeting your fear

by Rodrigo Troncoso

# 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

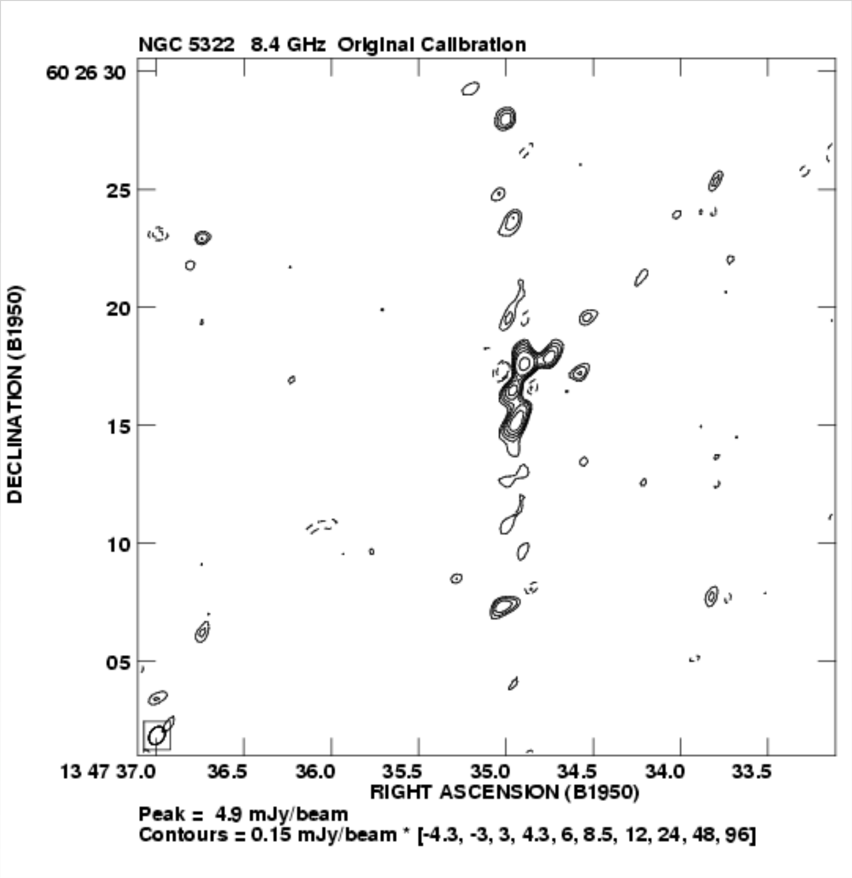
A number of methods lead to somewhat different results

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

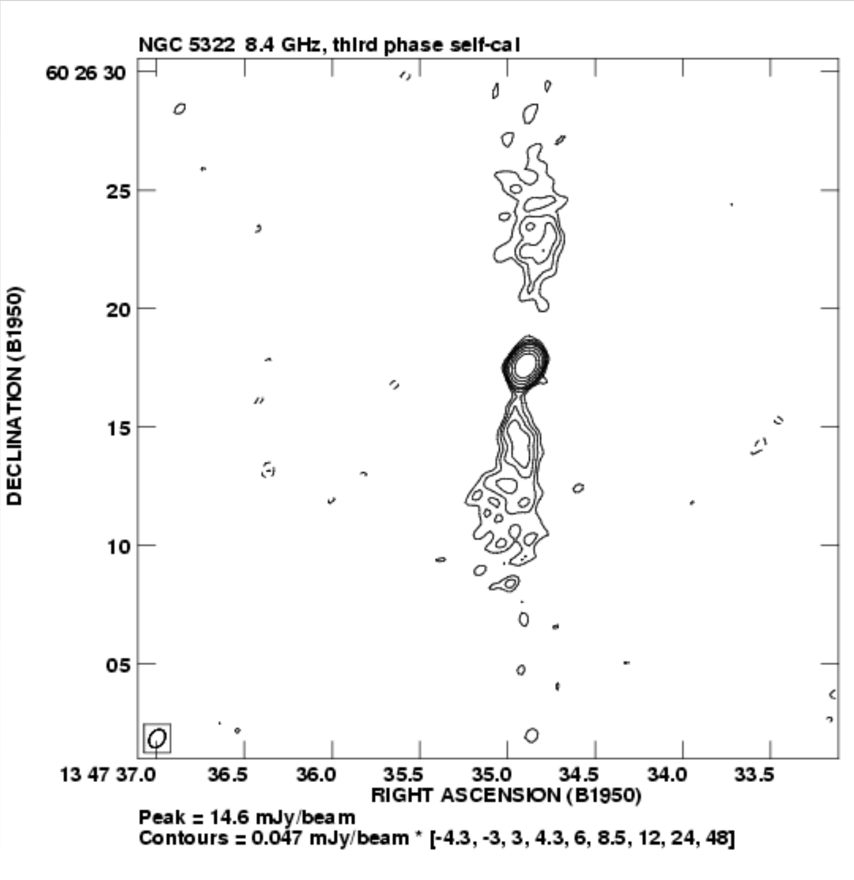
Improve on calibration (SNR permitting)

# Example:  Self-calibration of a VLA snapshot

Initial image




Final image



# 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

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

where S is the flux density of the source

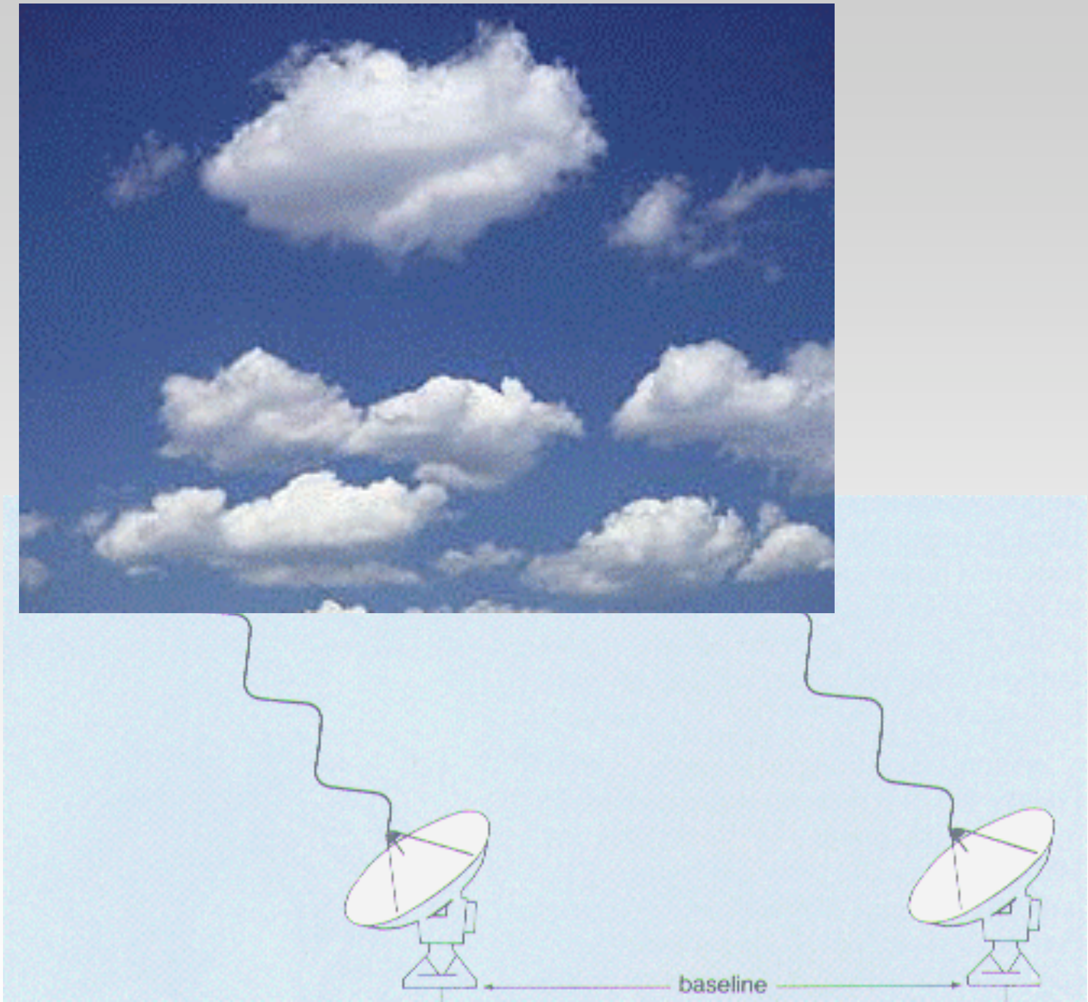
- Solve for antenna gains via least squares algorithm
- Works well - lots of redundancy
  - N-1 baselines contribute to gain estimate for any given antenna

# Why is the initial calibration insufficient?

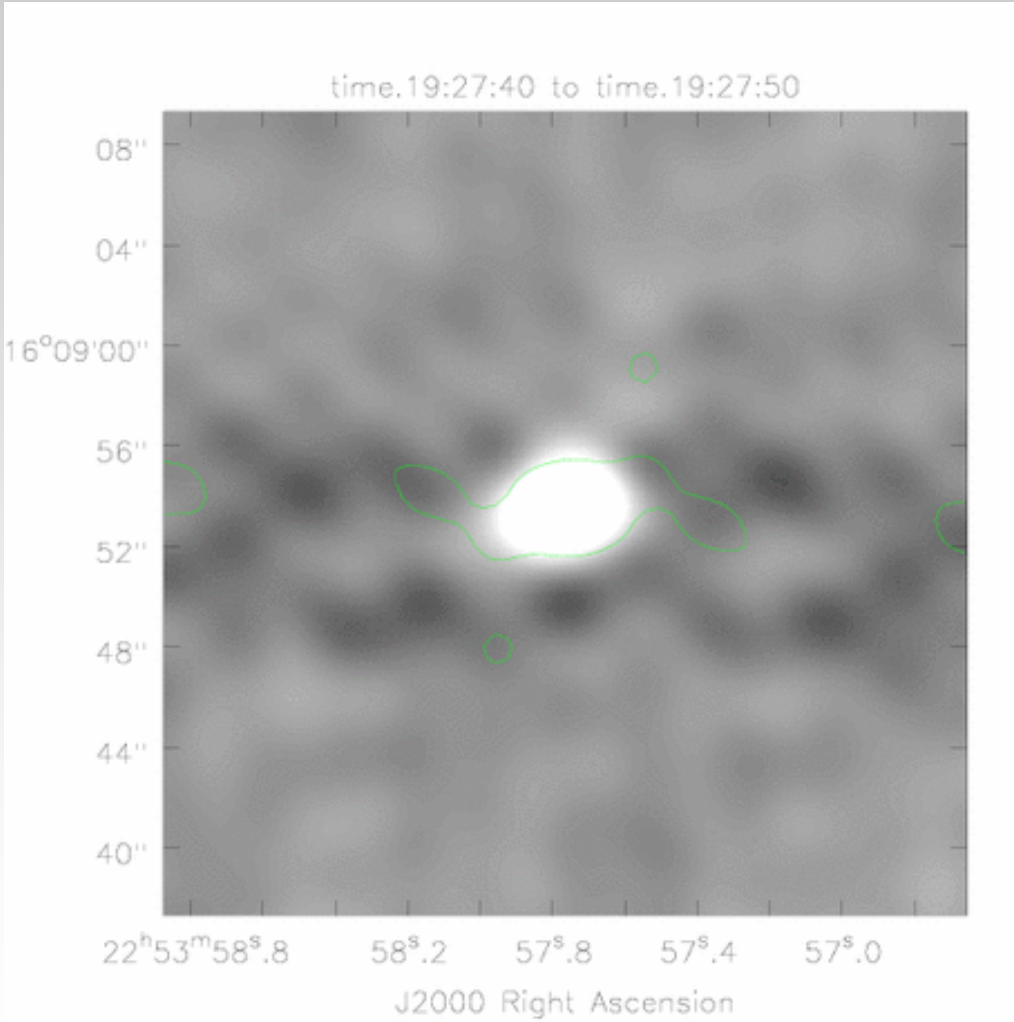
- The complex gains usually have been derived from an observation of a calibration source before/after the target source.
- The initial gain calibration is insufficient because:
  - Gains were derived at a different time
    - Troposphere and ionosphere are variable
    - Electronics may be unstable
  - Gains were derived for a different direction
    - Troposphere and ionosphere are not uniform
- Sensitivity (SNR) and frequency of the calibration might be insufficient

# What happens in the Troposphere?

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



# Movie of point source at 22GHz



# Calibration using a model of a complex source

- We do not need a point source!

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

$V_{ij}^{\text{model}}$ Model visibility

- Redundancy means that errors in the model will average

# Calibration using estimated antenna gains

- Correct for estimated gains:

$$V_{ij}^{\mathrm{cal}}(t) = \left(g_i(t) g_j^*(t)\right)^{-1} V_{ij}$$

- Can smooth or interpolate gains if desired

# Relationship to point source calibration

- Made a fake point source by dividing by model visibilities

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

where:

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

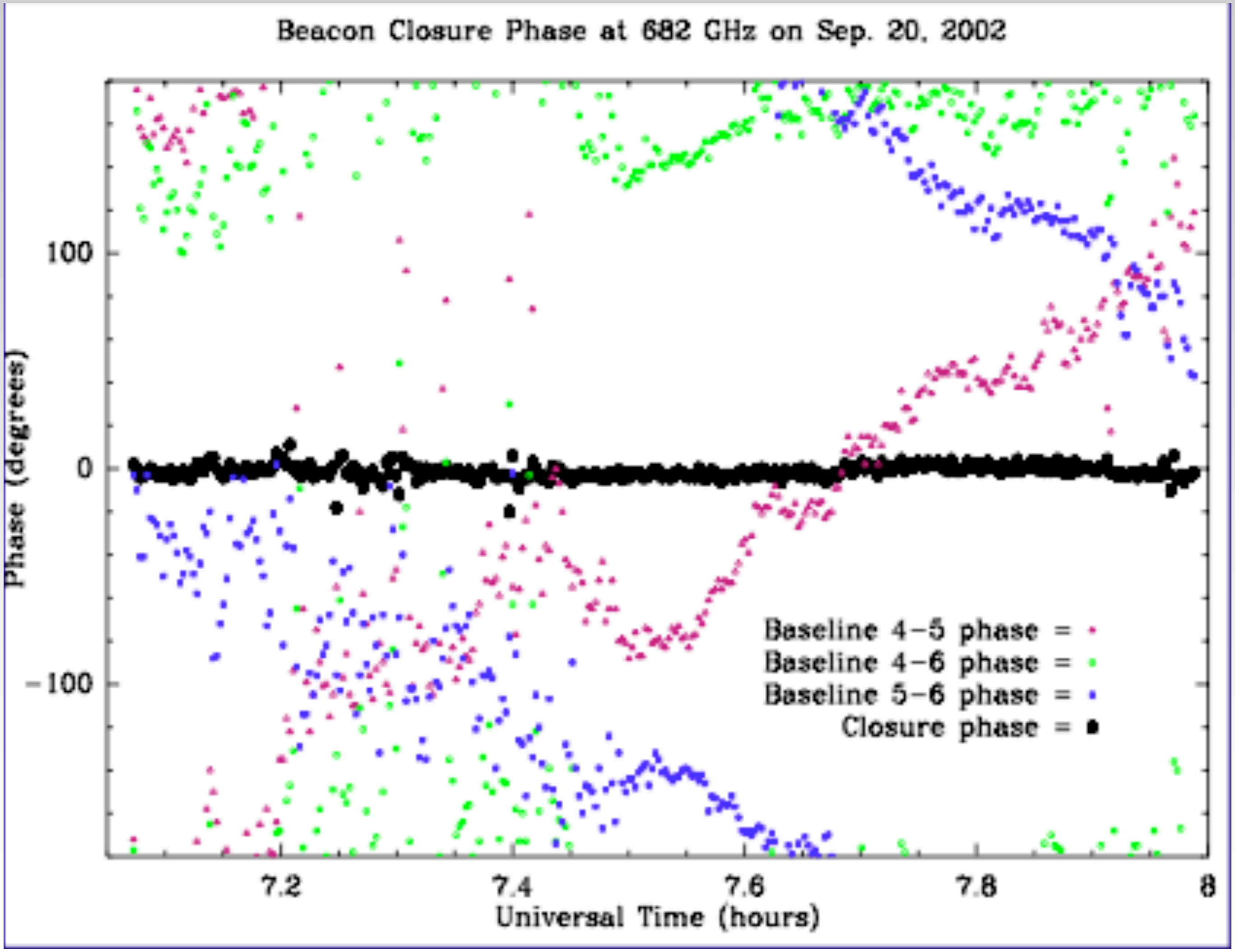
and $\varepsilon'_{ij}(t)$ is a modified noise term

# 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

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

# SMA closure phase measurements at 682GHz



# Advantages and disadvantages of self-calibration

- Advantages
  - Gains 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

# 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
  - Multiplicative fringes (due to deconvolution errors)
  - Deconvolution errors around moderately resolved sources

# Self-calibration procedure

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 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

# Choices in self-calibration

- Initial model?
  - Point source often works well
  - Clean components from initial image
    - Do not clean too deeply!
  - 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 observations, amplitude errors tend to be relatively unimportant at dynamic ranges < 1000

# 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 $$\sigma_g = \frac{1}{\sqrt{N-3}} \frac{\sigma_V}{S}$$

- where: $\sigma_V$ noise per visibility sample
  and $N$ number of antennas

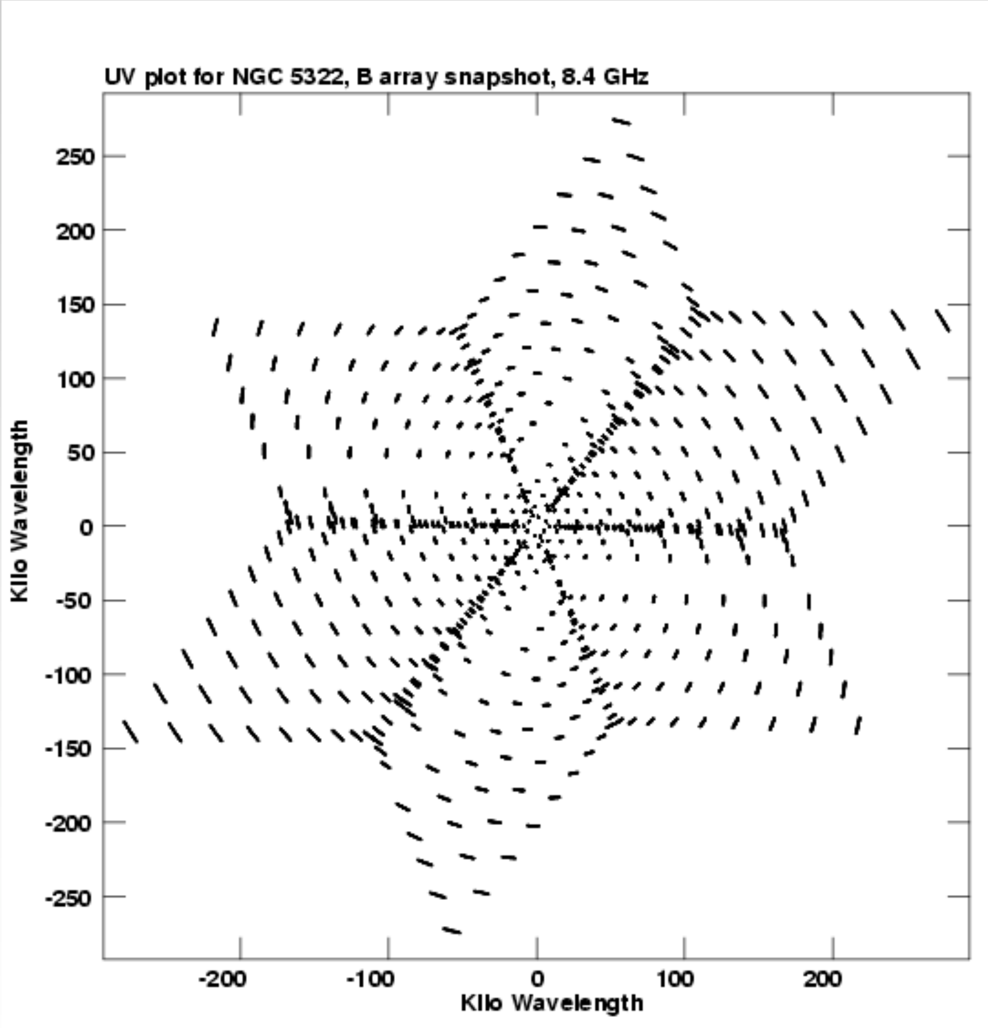
- If error in gain is much less than 1, then the noise in the final image will be close to theoretical
  - Actually, it can be a bit lower than theoretical!

# You can self-calibrate on weak sources!

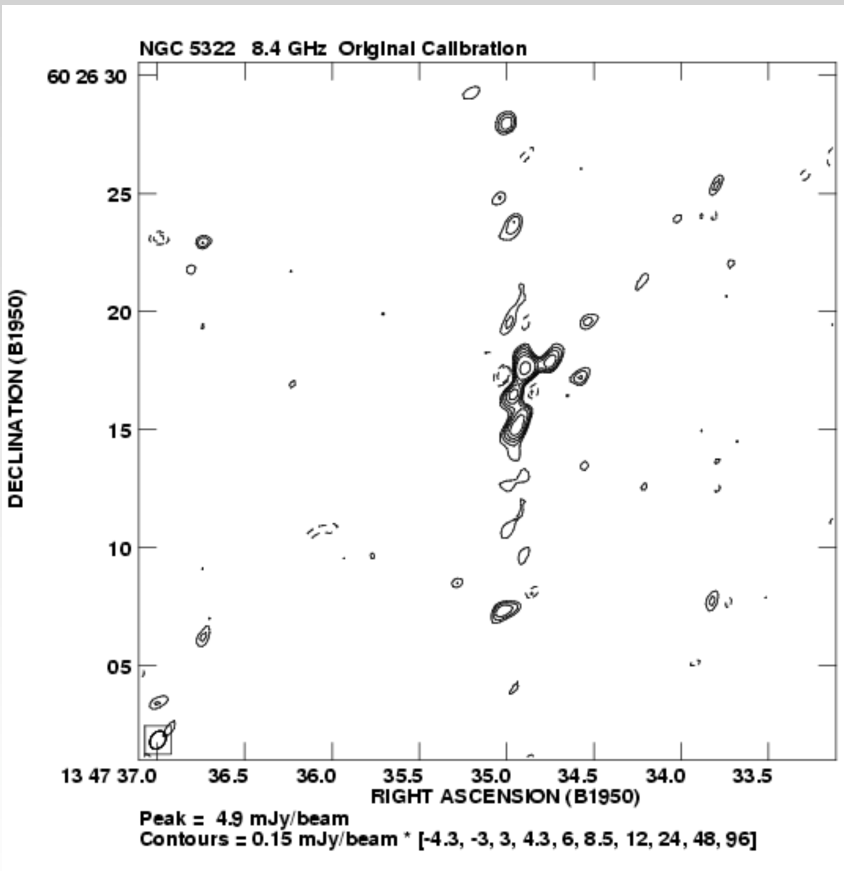
- For the VLA at 8 GHz, the noise in 10 seconds for a single 50 MHz IF is about 13 mJy on 1 baseline
  - Average 4 IFs (2 RR and 2 LL) for 60 seconds to decrease this by $(4 * 60/10)^{1/2}$ to 2.7 mJy
  - If you have a source of flux density about 5 mJy, you can get a very good self-cal solution if you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

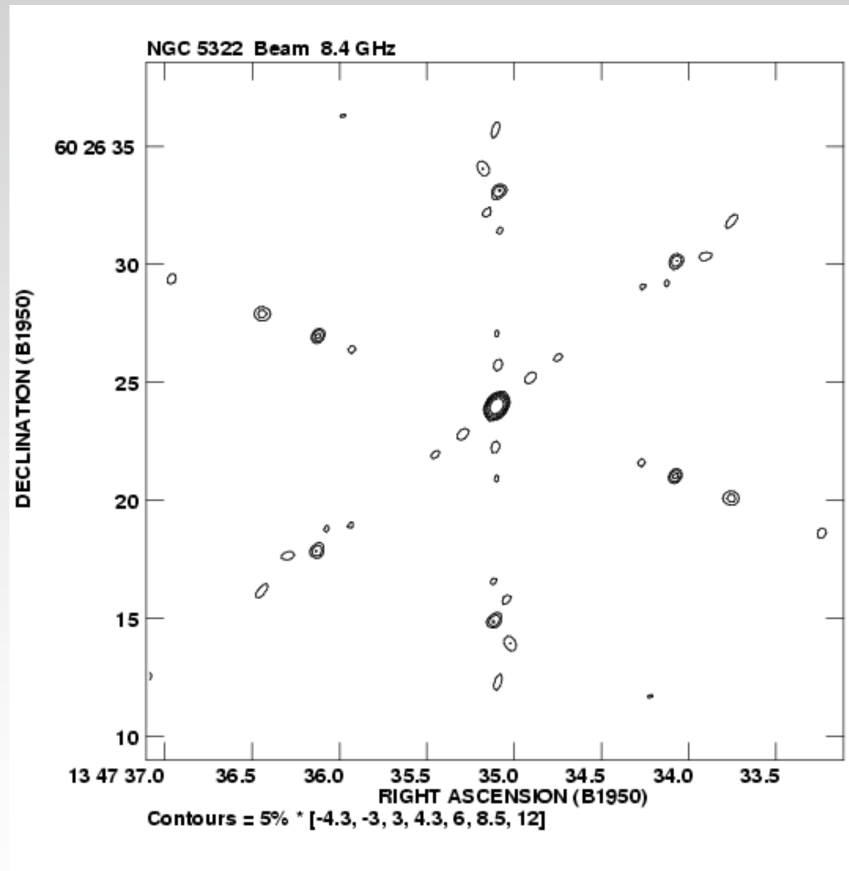
# Difficult example: VLA Snapshot, 8 GHz, B Array

- LINER galaxy NGC5322
- Data taken in October 1995
- Poorly designed observation
  - One calibrator in 15 minutes
- Can self-cal help?



# Initial NGC 5322 Imaging



# First pass

<u>Used 4 (merged) clean components in model</u>

❶ 10-sec solutions, no averaging, SNR > 5

CALIB1: Found 3238 good solutions

CALIB1: Failed on 2437 solutions

CALIB1: 2473 solutions had insufficient data

❷ 30-sec solutions, no averaging, SNR > 5

CALIB1: Found 2554 good solutions

CALIB1: Failed on 109 solutions

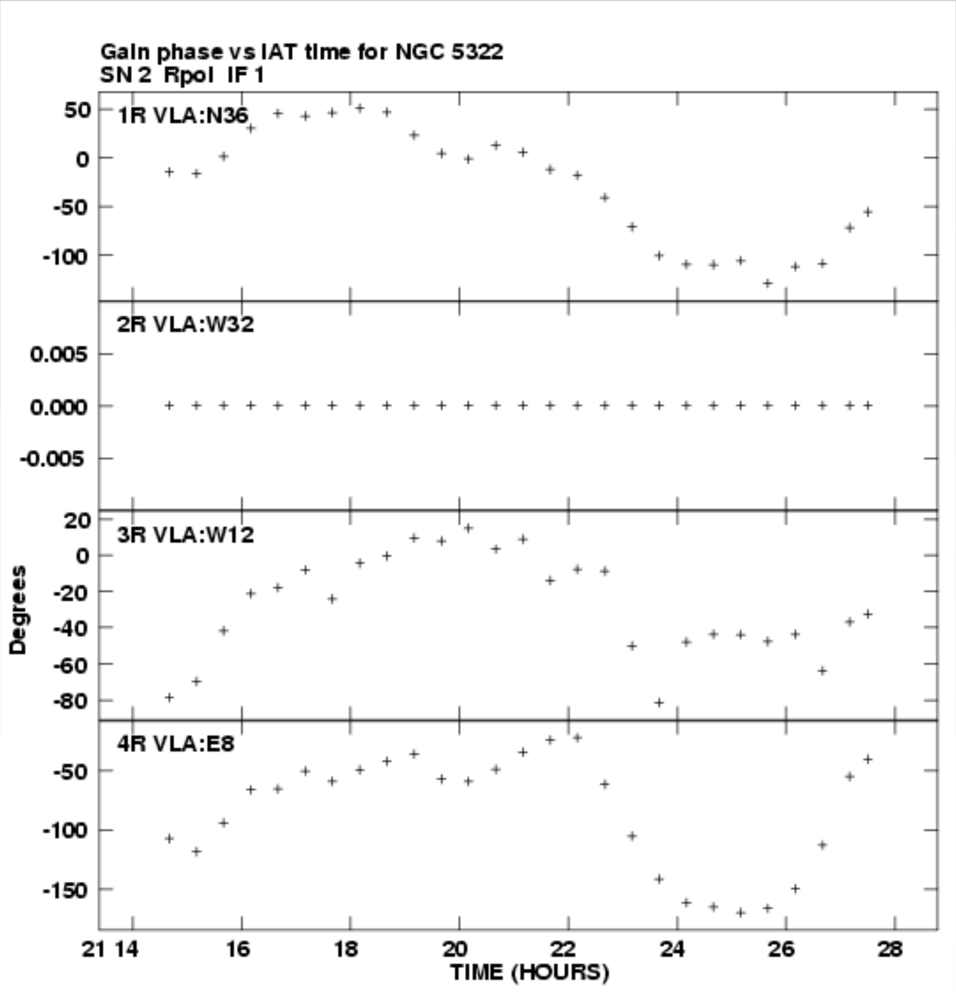
CALIB1: 125 solutions had insufficient data

❸ 30-sec solutions, average all IFs, SNR > 2

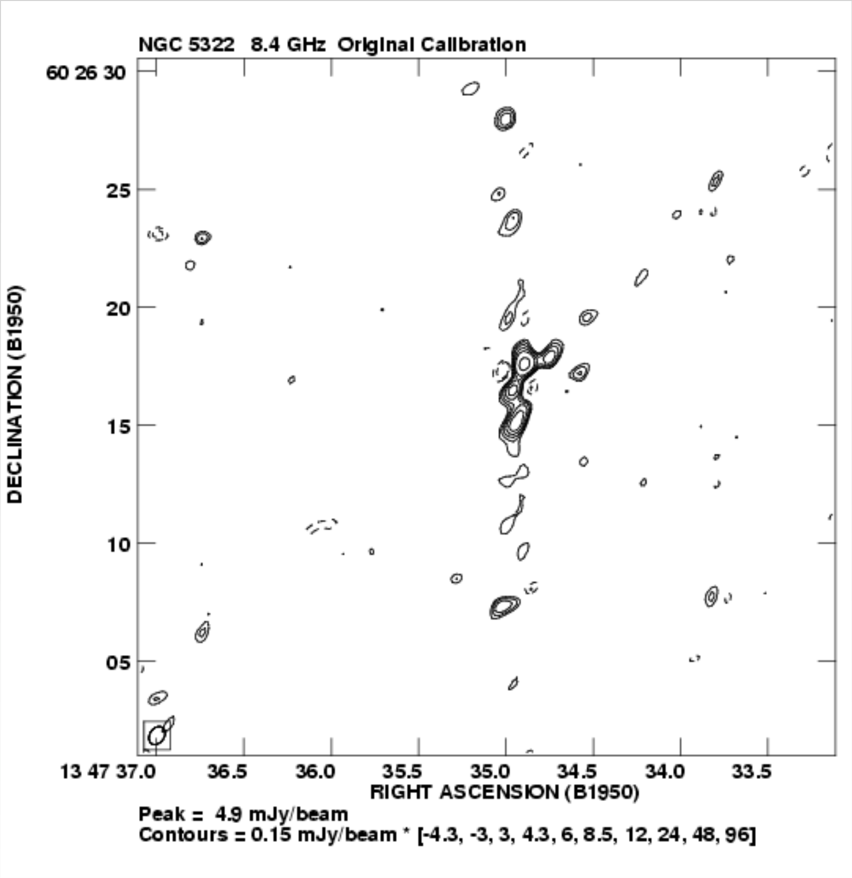
CALIB1: Found 2788 good solutions

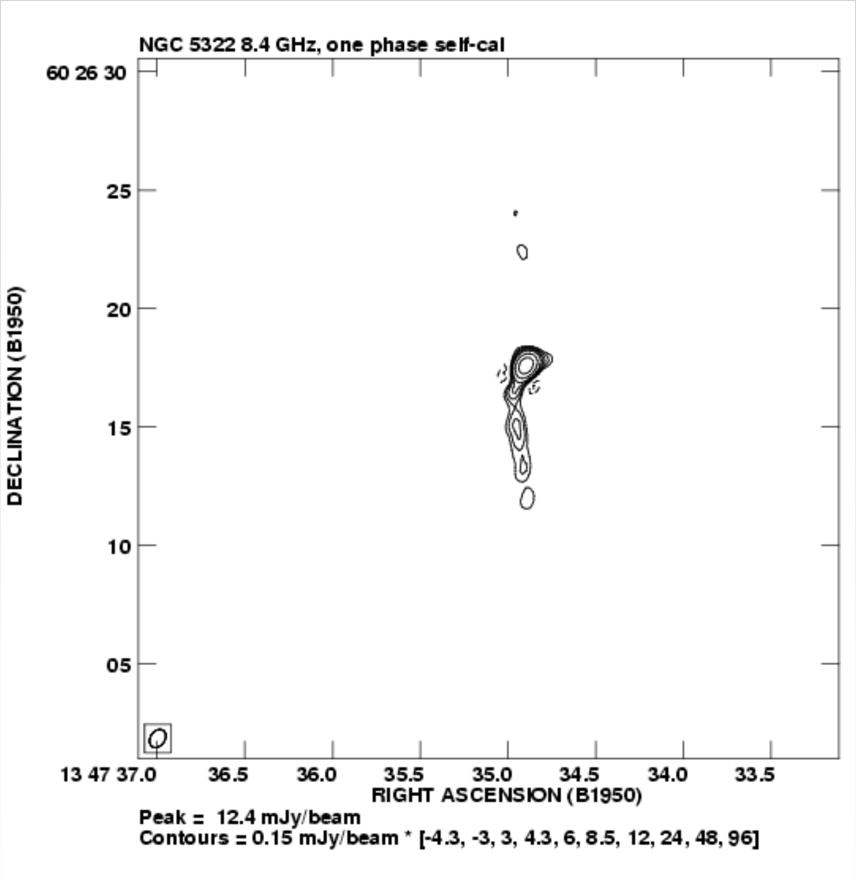
# Phase Solutions from 1st Self-Cal

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



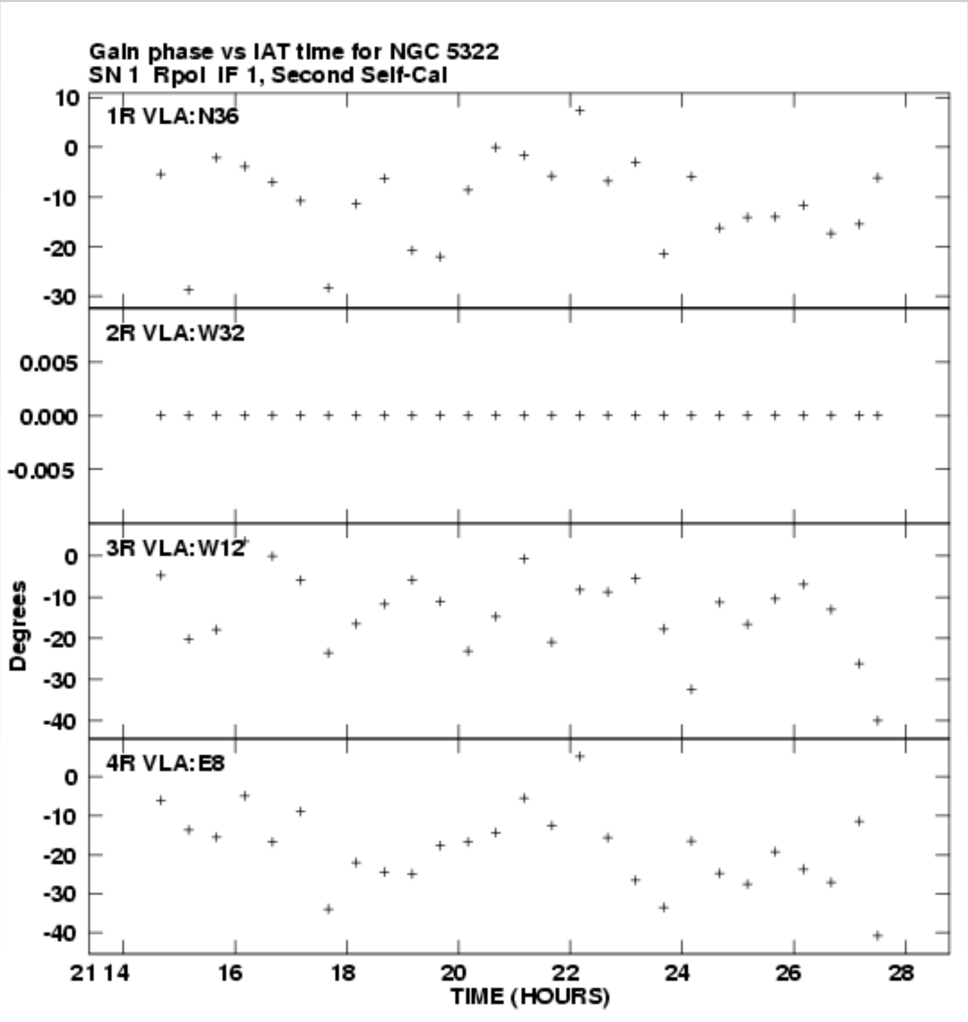
# Image after first pass



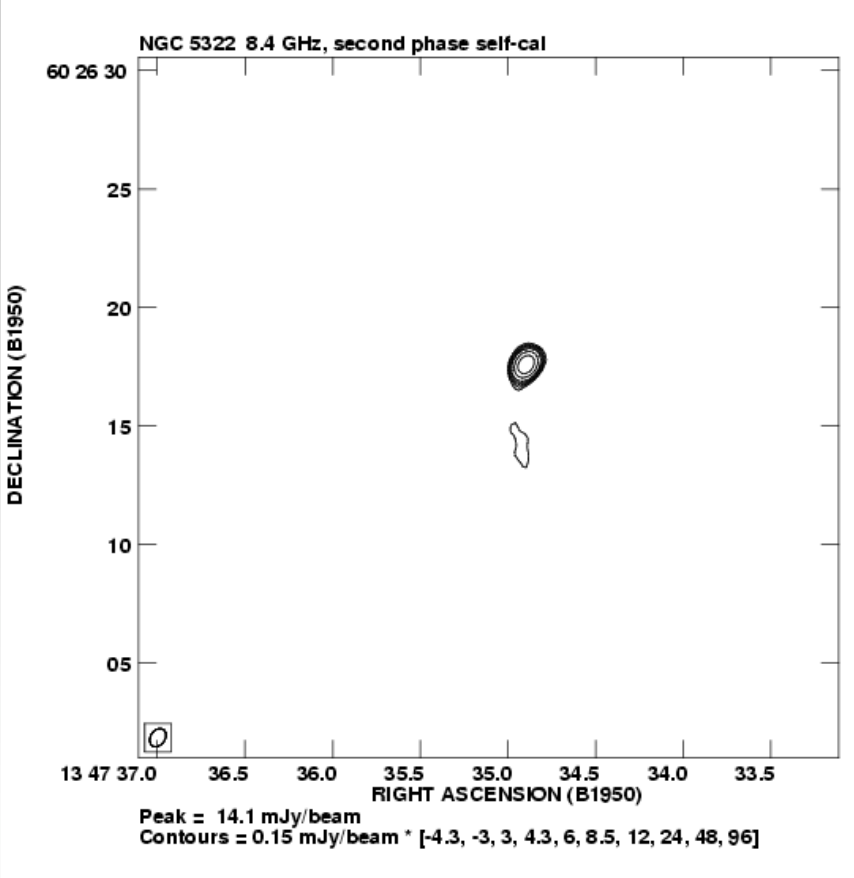



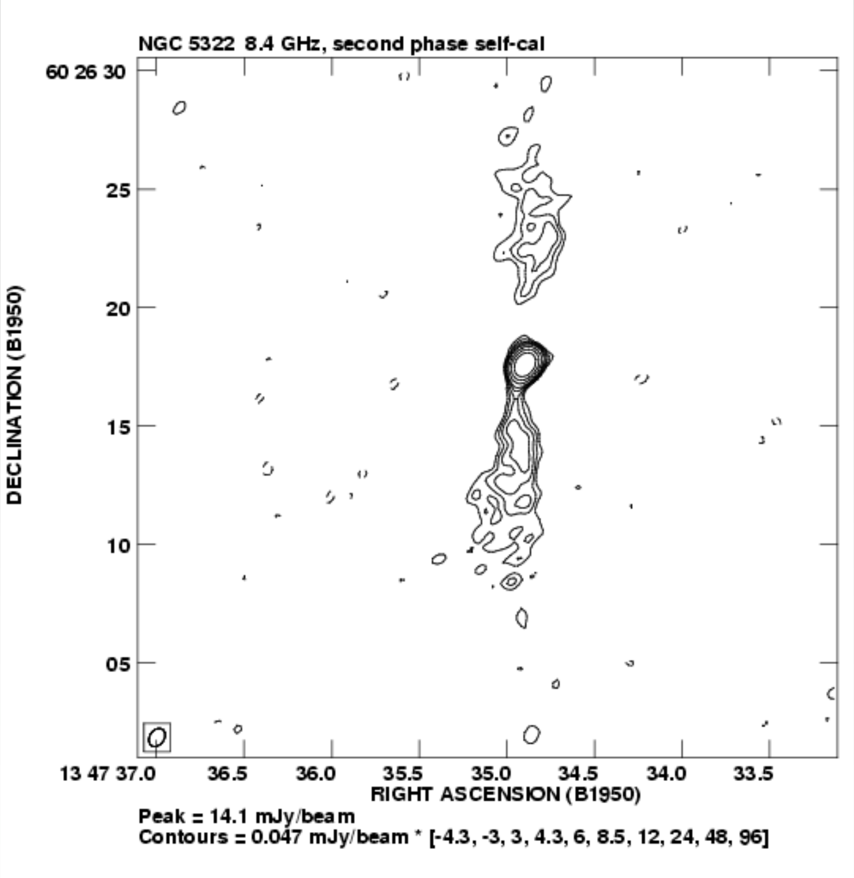
# Phase Solutions from 2nd Self-Cal

- 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



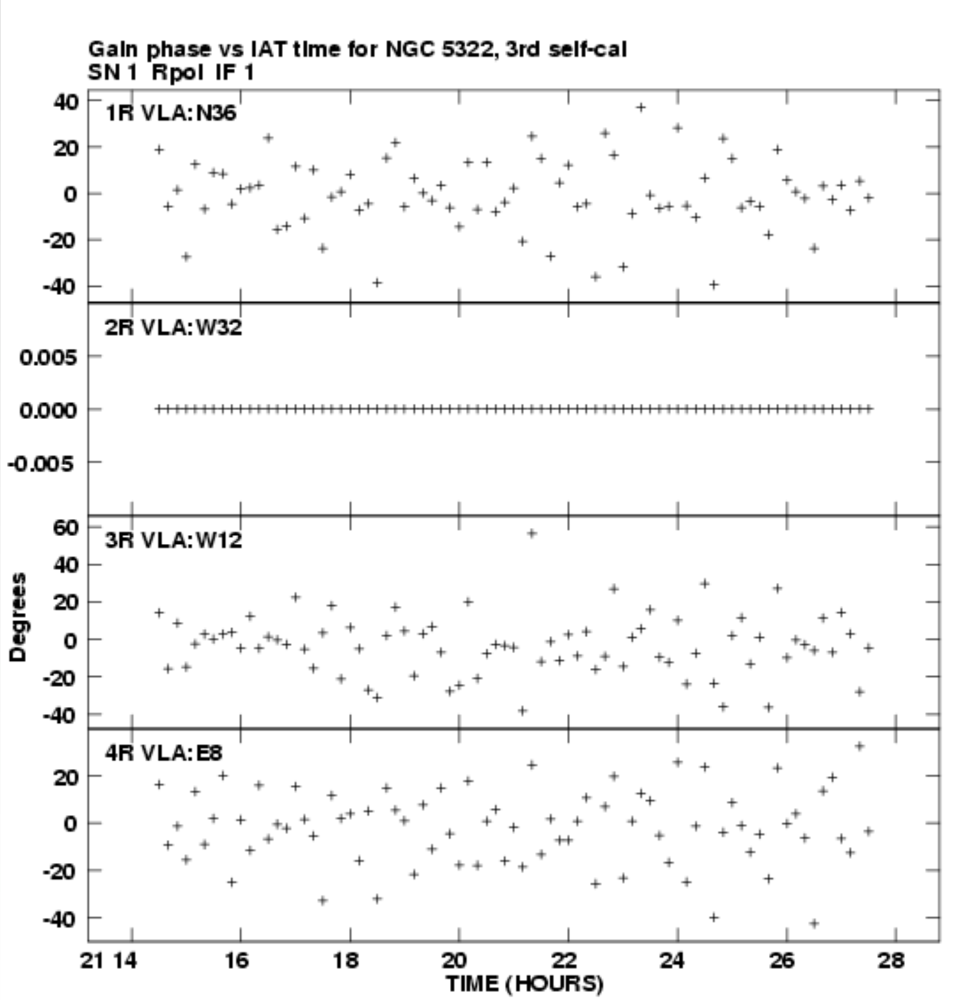



# Result after second self-calibration

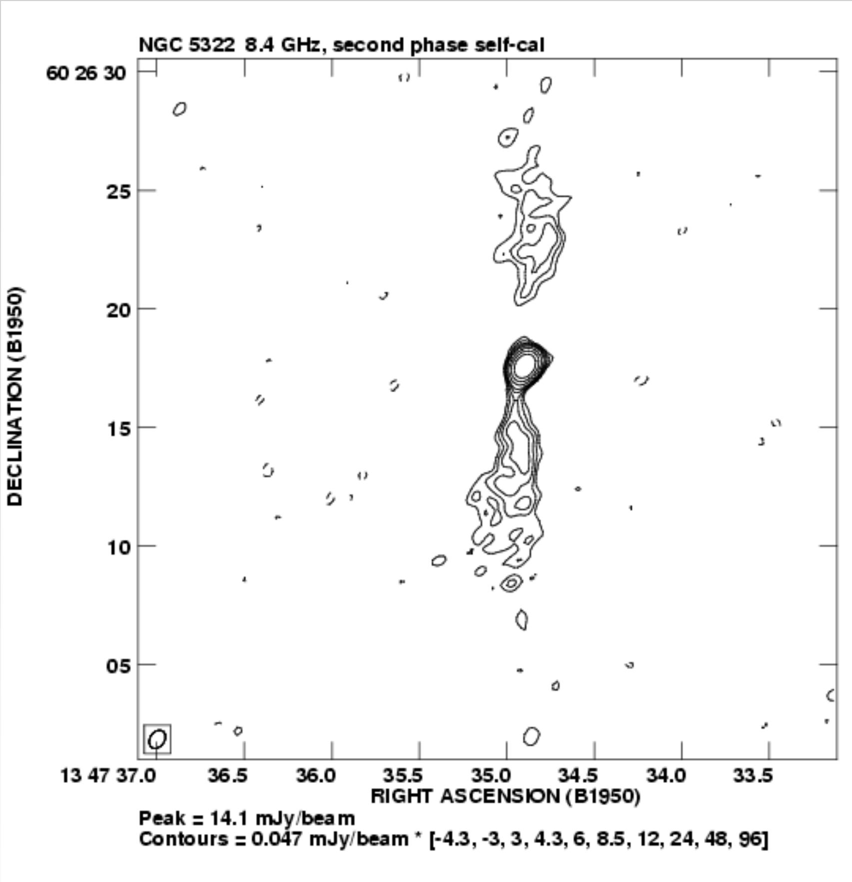
- Image noise is now 47 microJy/beam
  - Theoretical noise in 10 minutes is 45 microJy/beam for natural weighting
  - For 14 minutes, reduce by $(1.4)^{1/2}$ to 38 microJy/beam
  - For robust=0, increase by 1.19, back to 45 microJy/beam
- Image residuals look "noise-like"
  - Expect little improvement 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

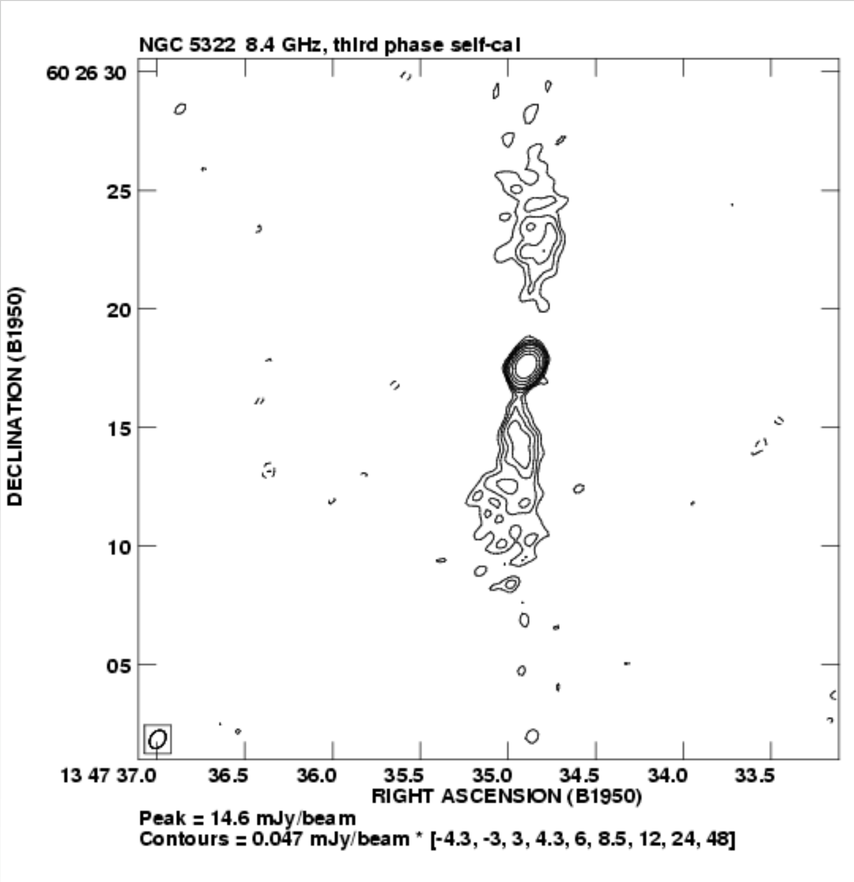
# Phase Solutions from 3rd Self-Cal

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



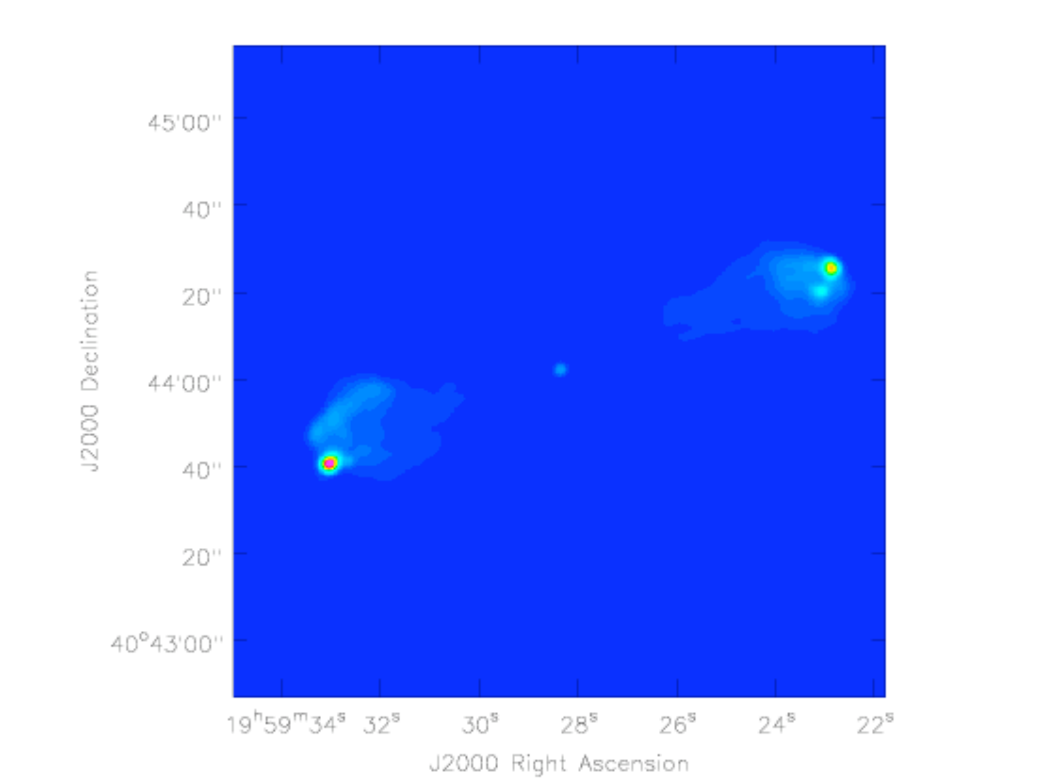
# Image Comparison



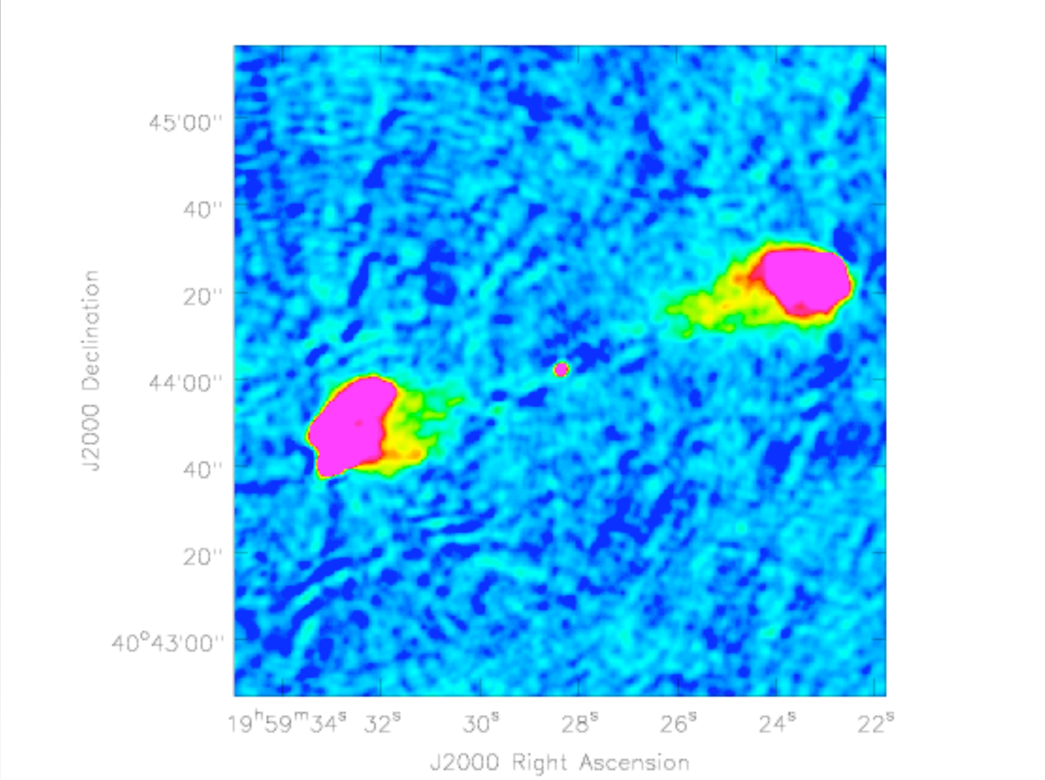
# Easy example

- 8.4GHz observations of Cygnus A
- VLA C configuration
- Deconvolved using multi-scale clean



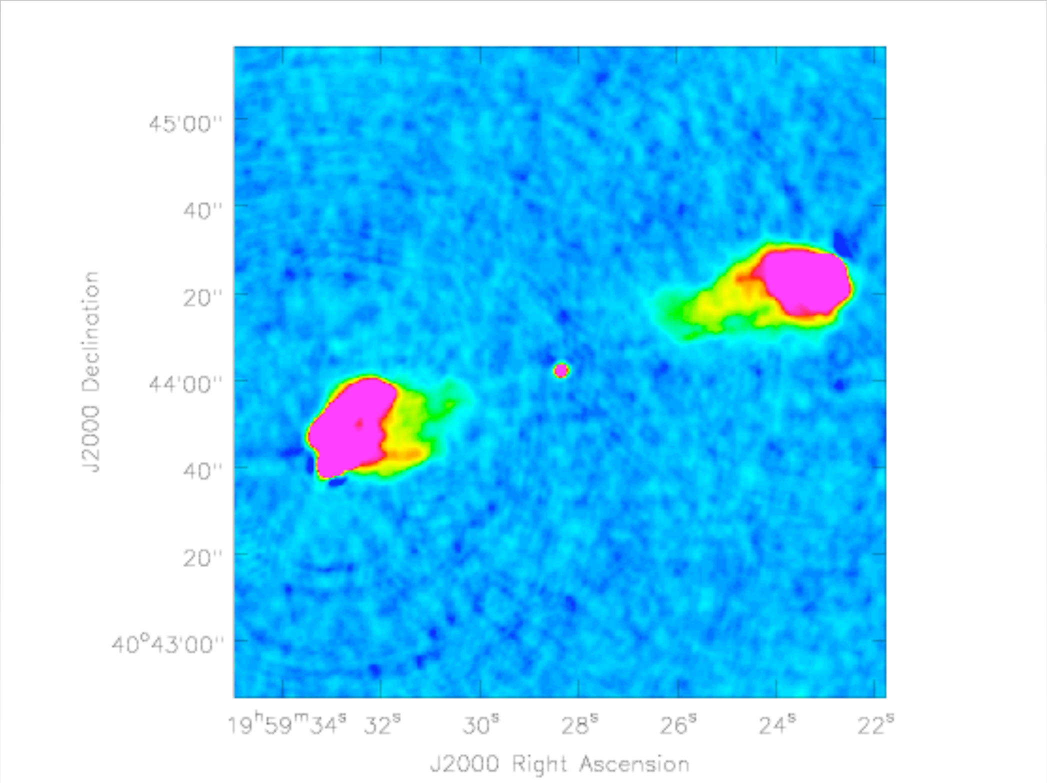
# Image without self-calibration

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

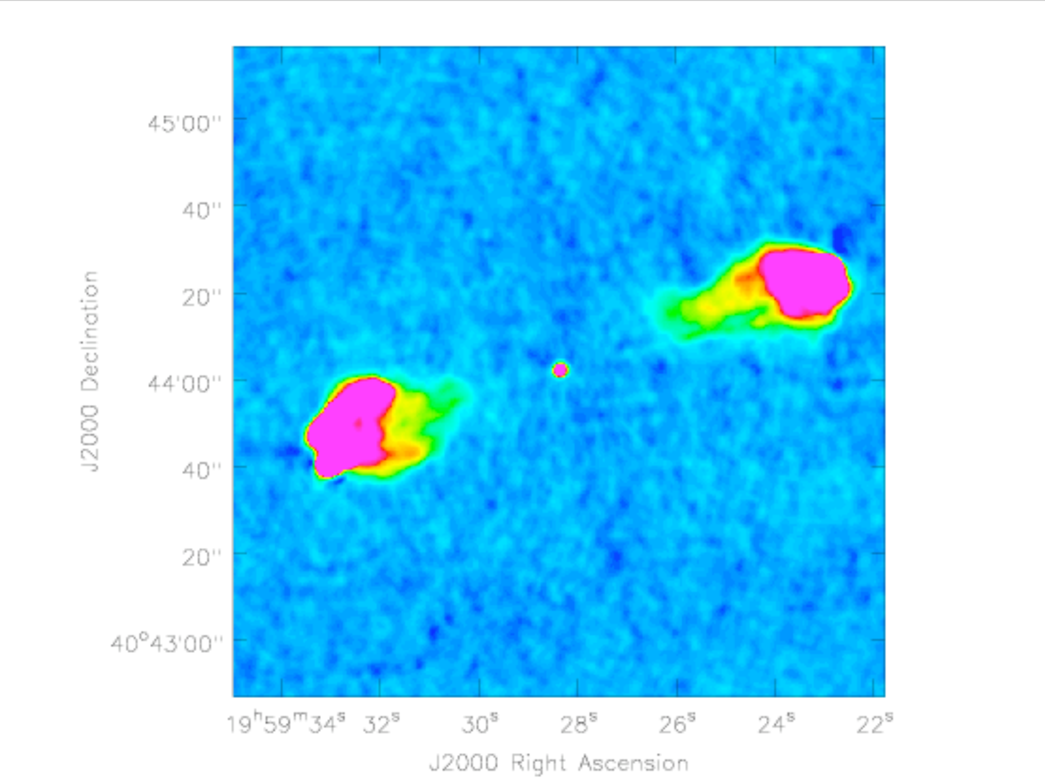


# After 1 phase-only self-calibration

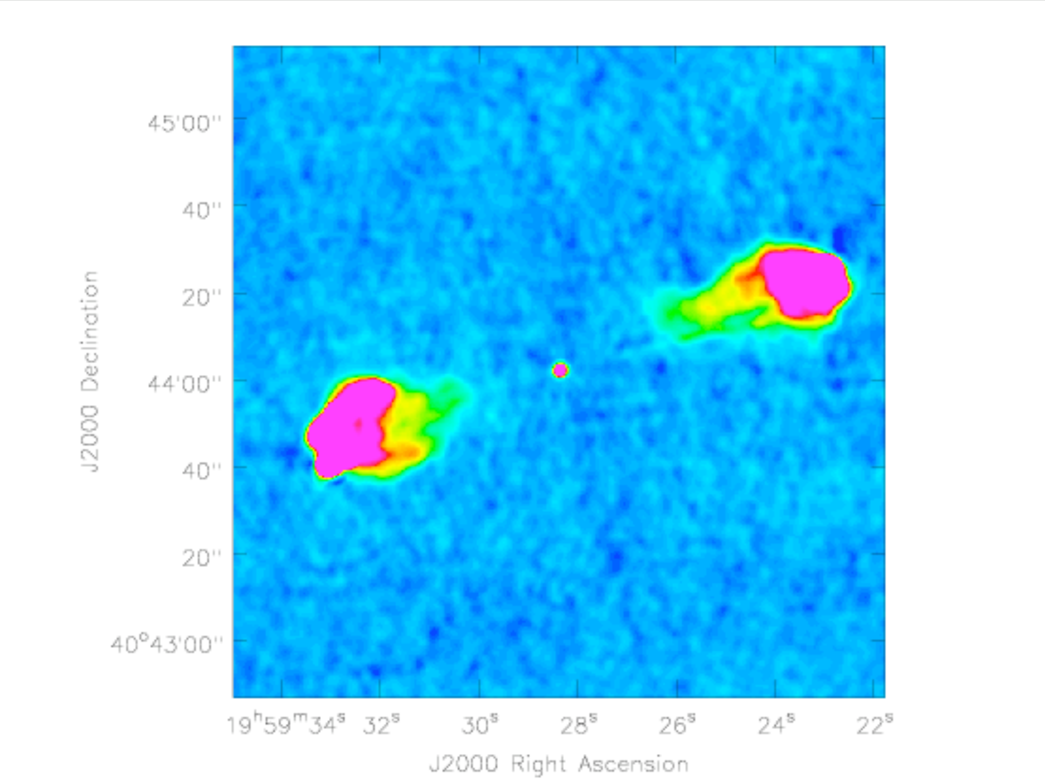
- Phase solution every 10s



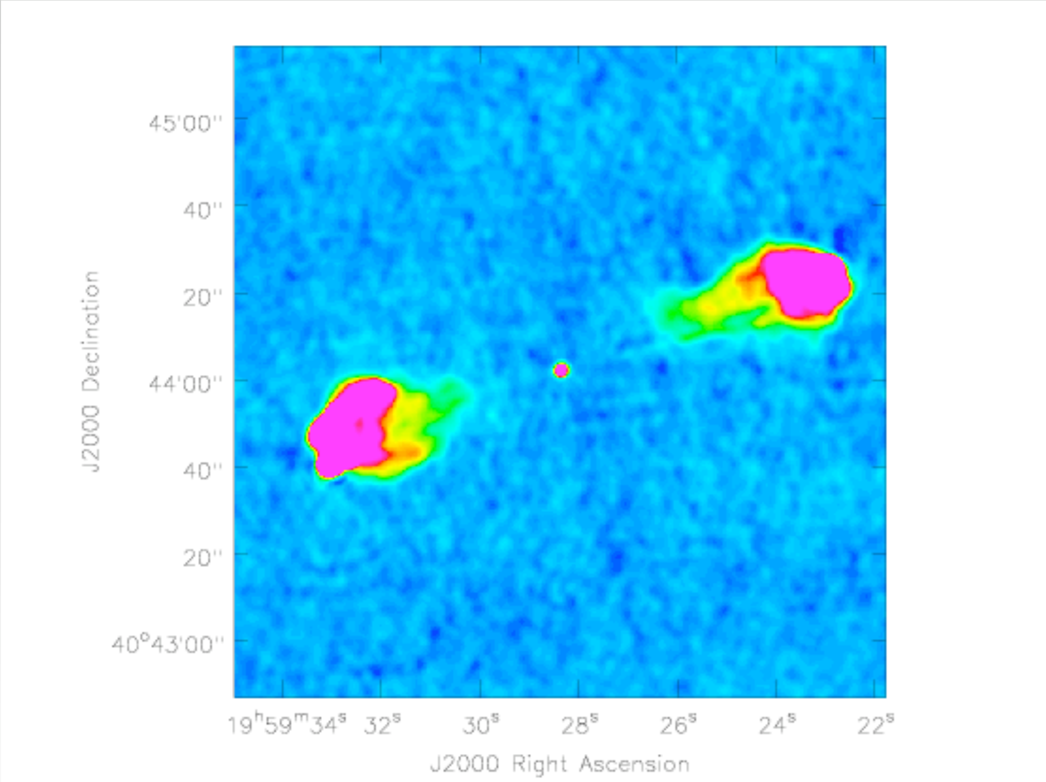
# After 1 amplitude and phase calibrations



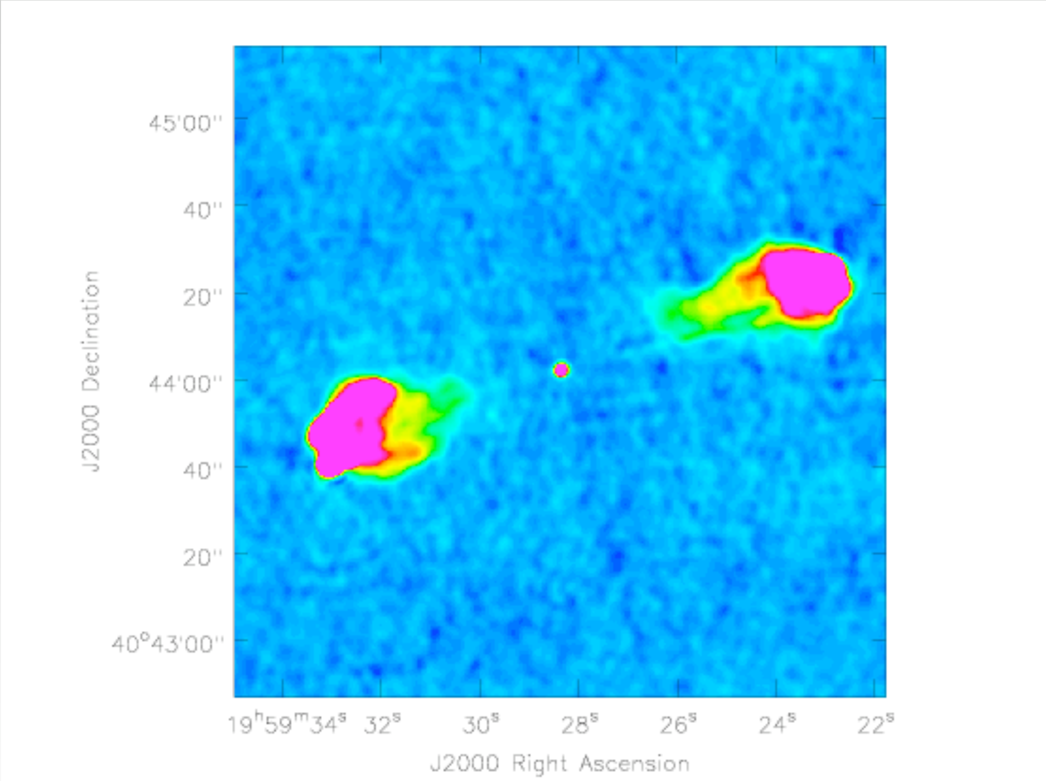
# After 2 amplitude and phase calibrations



# After 3 amplitude and phase calibrations



# After 4 amplitude and phase calibrations

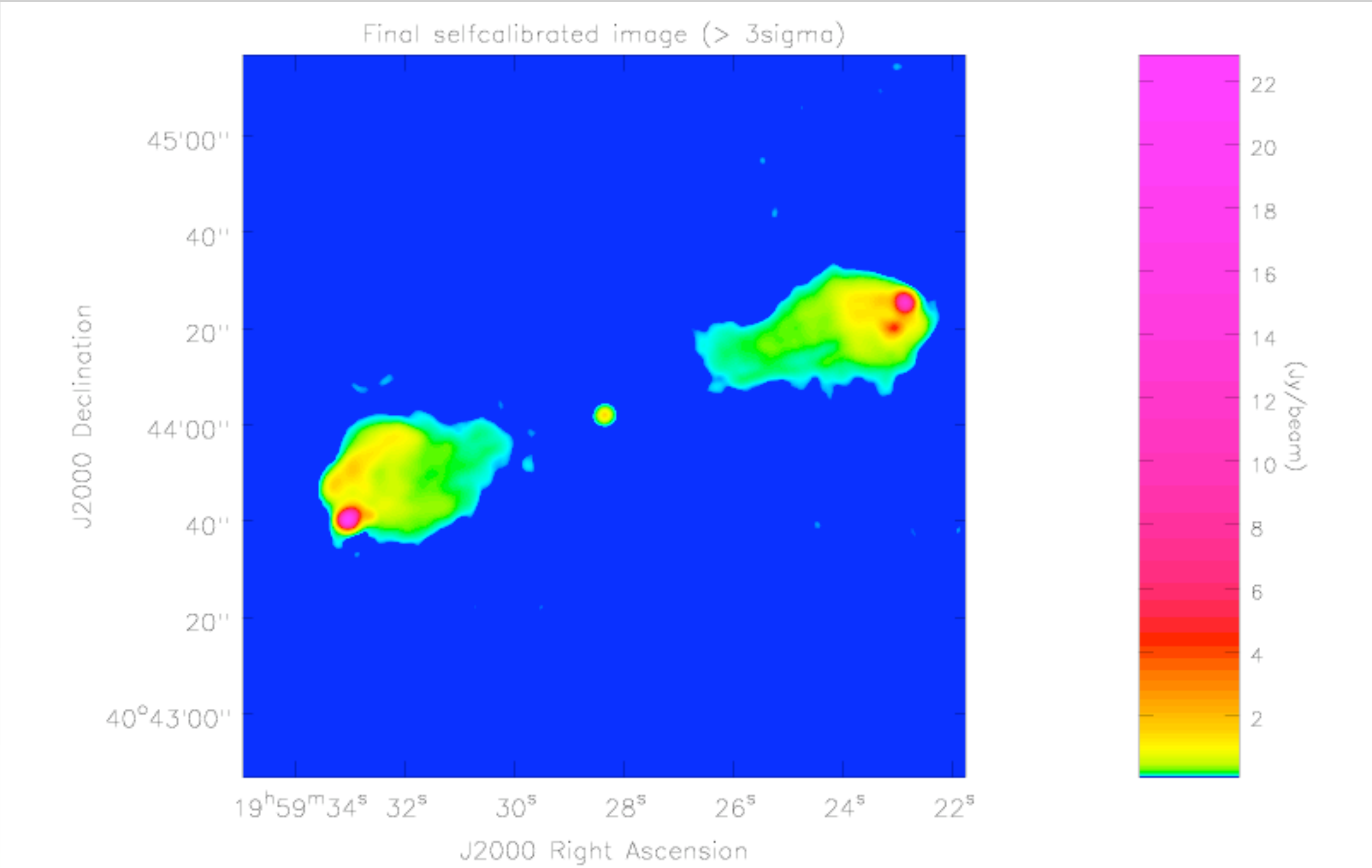


# Summary of Cygnus A example

| | 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.  Perhaps the (u,v) coverage is insufficient for the complexity of the source?

# Final image showing emission > 3σ



# How well does it work?

- 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 non-detection experiments
- Bad idea for detection experiments
  - Will manufacture source from noise
  - Use in-beam calibration for detection experiments

# Recommendations

- Edit your data carefully before self-calibration --remove corrupt data!
- Expect to self-calibrate most non-detection experiments (SNR $\geq$ 60)
- 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-calibration
  - 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 different solution intervals
  - Shorter intervals follow the atmosphere better
  - Don't be too afraid to accept low SNR in the solutions, statistics will help!

# Acknowledgements and references

Acknowledgements:

Developed by Tim Cornwell, Ed Fomalont and Jim Ulvestad.

References:

Interferometry and Synthesis in Radio Astronomy (2nd Edition) by A. R. Thompson, J. M. Moran & G. W. Swenson, Wiley (2001)

Synthesis Imaging in Radio Astronomy II. Eds. G. B. Taylor, C. L. Carilli & R. A. Perley, ASP Conference Series vol. 180 (1989)

Lectures of the 10th Synthesis Imaging Summer School (2006): http://www.aoc.nrao.edu/events/synthesis/2006/lectures/

## Poema XX.

Puedo escribir los versos más tristes esta noche.
Escribir, por ejemplo: “La noche está estrellada,
y tiritan, azules, los astros a lo lejos.”

(de “20 poemas de amor y una cancion desesperada” de Pablo Neruda)

## Poem XX.

Tonight I can write the saddest lines.
Write, for example, “The night is starry
and the blue stars shiver in the distance.”

(from “20 love poems and a desperate song” by Pablo Neruda)