Self-calibration

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Ninth Synthesis Imaging Summer School
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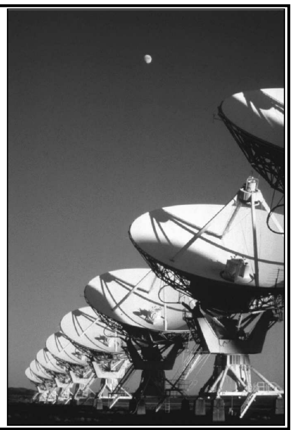
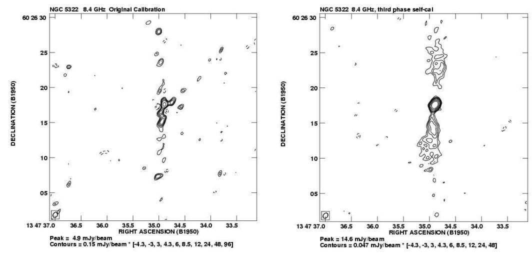


Self-calibration of a VLA snapshot

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

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

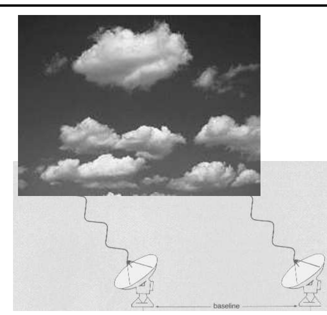
- Solve for antenna gains via least squares algorithm
- Works well - lots of redundancy
  - N-1 baselines contribute to gain estimate for any given antenna

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
- Observation might have been scheduled poorly for the existing conditions

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

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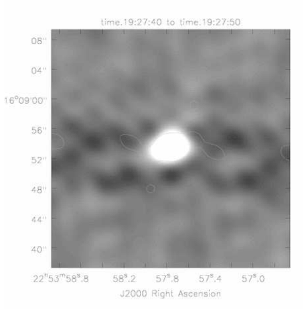

Calibration using a model of a complex source

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- 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

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Calibration using estimated antenna gains

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- Correct for estimated gains:

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

- Can smooth or interpolate gains if desired

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Relationship to point source calibration

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- 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

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Why does self-calibration work?

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

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

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SMA closure phase measurements at 682GHz

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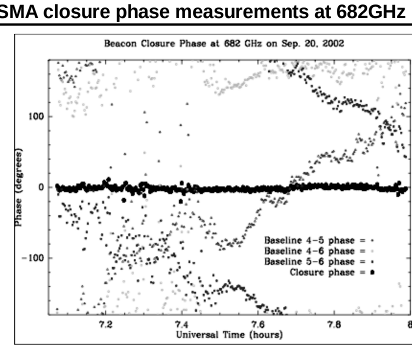

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Advantages and disadvantages of self-calibration

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- 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

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- 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

How to self-calibrate

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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

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- 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?
  - 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….

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- 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

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- 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!

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- 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

Hard example: VLA Snapshot, 8 GHz, B Array

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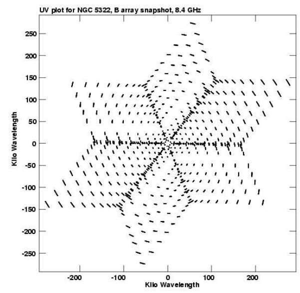
- LINER galaxy NGC 5322
- Data taken in October 1995
- Poorly designed observation
  - One calibrator in 15 minutes
- Can self-cal help?



Initial NGC 5322 Imaging

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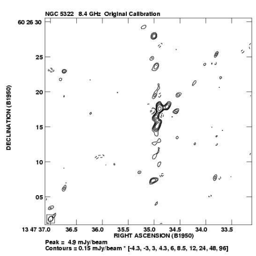

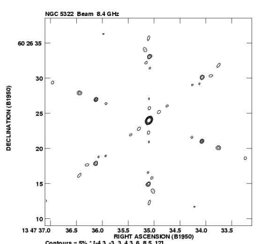

First pass

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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

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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

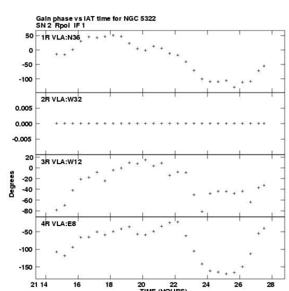

Image after first pass

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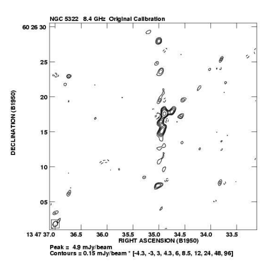
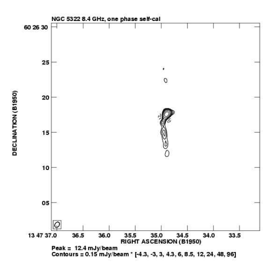




Phase Solutions from 2nd Self-Cal

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

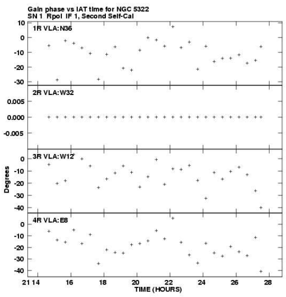
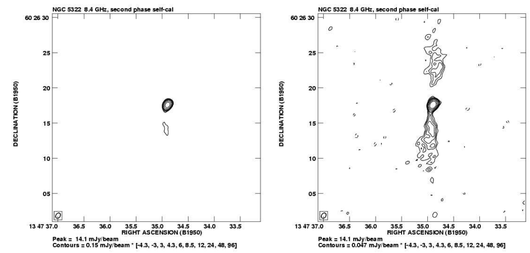


Image after 2nd Self-Calibration



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

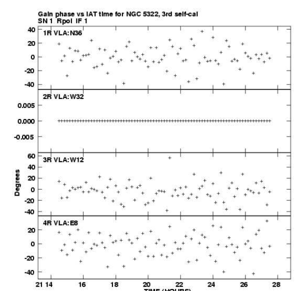
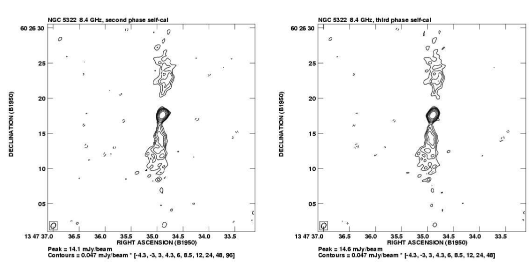


Image Comparison



Easy example

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

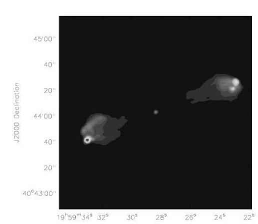
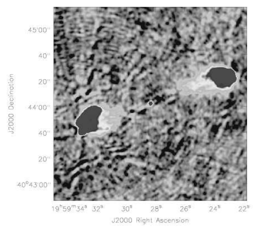


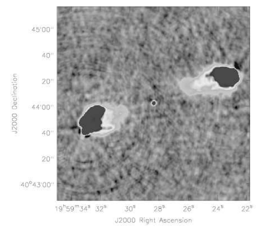
Image without self-calibration

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

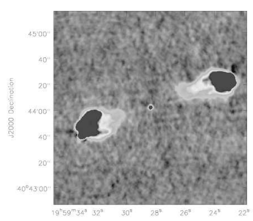


After 1 phase-only self-calibration

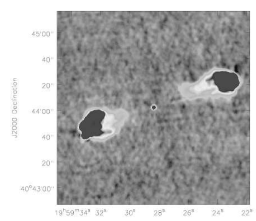
- Phase solution every 10s



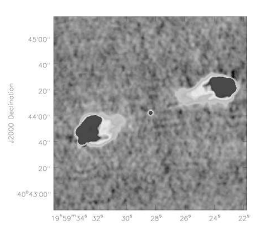
After 1 amplitude and phase calibrations



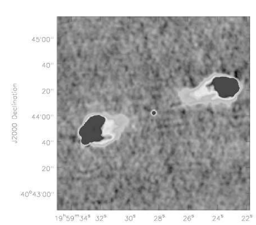
After 2 amplitude and phase calibrations



After 3 amplitude and phase calibrations



After 4 amplitude and phase calibrations



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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

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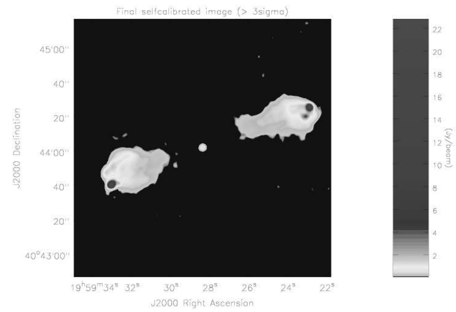
Final image showing all emission > 3 sigma



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

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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

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