Self-Calibration

Jim Ulvestad

(Lecture 10, Synthesis Imaging II, p. 187; Cornwell & Fomalont)

- Basic theory
- Some choices
- Example
- Closing remarks

- Fundamental calibration equation

$$\tilde{V}_{ij}(t) = g_i(t) g_j^*(t) V_{ij}(t) + \epsilon_{ij}(t)$$

- Definitions

$\tilde{V}_{ij}(t)$ = observed visibility at time t

$g_i(t)$ = relative complex gain of antenna i

$V_{ij}(t)$ = actual visibility at time t

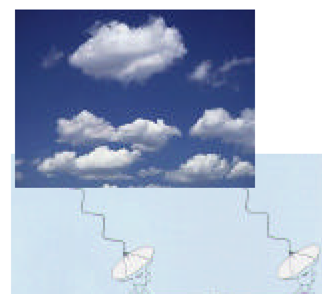
$\epsilon_{ij}(t)$ = thermal noise on i-j baseline

What's Wrong with the Initial Calibration?

- The complex gains usually have been derived by means of observation of a calibration source before/after the target source
- Initial gain calibration is incorrect
  - 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 Really Doing?

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



What is Self-Calibration?

- Self-calibration uses a model of the target source to solve for improved values for the complex gains of the individual antennas
  - 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
    - Results depend on the assumed model. If the model is incorrect, it will be "built into" the derived gains, leading to incorrect visibilities and images

- The gains are solved for in self-calibration by a least-squares solution that minimizes the difference between the model and observed visibilities

$$S = \sum_k \sum_{\substack{i,j \\ i \neq j}} w_{ij}(t_k) \left| \tilde{V}_{ij}(t_k) - g_i(t_k) g_j^*(t_k) \hat{V}_{ij}(t_k) \right|^2$$

- Define $\hat{V}_{ij}(t)$ = model $\qquad X_{ij}(t) = \frac{\tilde{V}_{ij}(t)}{\hat{V}_{ij}(t)}$
- Then

$$S = \sum_k \sum_{\substack{i,j \\ i \neq j}} w_{ij}(t_k) \left| \hat{V}_{ij}(t_k) \right|^2 \left| X_{ij}(t_k) - g_i(t_k) g_j^*(t_k) \right|^2$$

Iterative Self-Calibration

1. Create an initial source model, typically from an initial image (or else a point source)
2. Use model to convert observed visibilities into a "pseudo-point source"
3. Find least-squares solution to complex gains
4. Find corrected visibility
5. Create a new model from the corrected data
6. Go to (2), unless current model is satisfactory

Choices-1

- 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

Choices-2

- 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

Choices-3

- How weak a source can be self-calibrated?

$$\sigma_G^2 = \frac{\sigma_V^2}{(N-3)F^2}$$

σ_G^2 = variance in gain estimates

σ_V^2 = variance of visibilities (square of noise)

N = number of array elements

F = source flux density

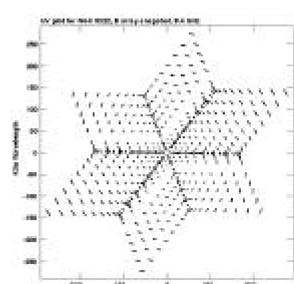
You Can Self-Calibrate on Weak Sources!

$$\sigma_G^2 = \frac{\sigma_V^2}{(N-3)F^2}$$

- 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
- *Caveat:* Make sure there's a detected source!

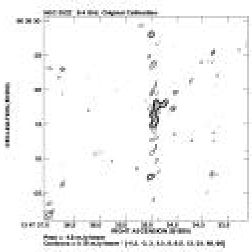
Example: VLA Snapshot, 8 GHz, B Array

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

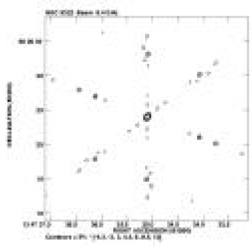


Initial NGC 5322 Imaging

Cleaned Image



Synthesized Beam



First Phase Self-Calibration

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

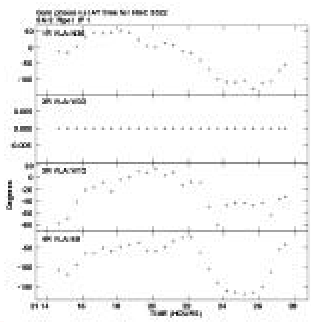
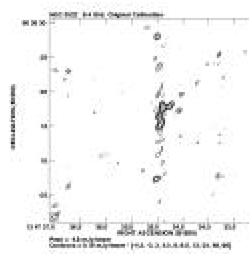
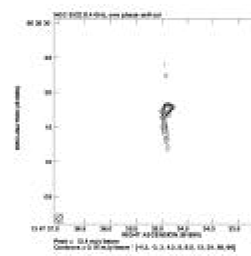


Image after 1st Self-Calibration

Original Image



Self-Calibrated Image



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

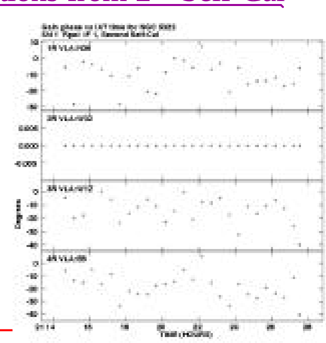
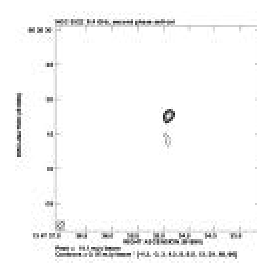
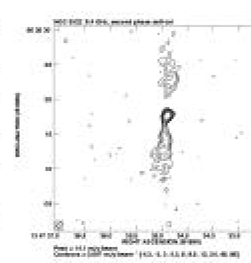


Image after 2nd Self-Calibration

Original Contour Level



Deeper Contouring



Status after 2^{nd} Self-Calibration

- Image noise is now 47 μJy/beam
  - Theoretical noise in 10 minutes is 45 μJy/beam for natural weighting
  - For 14 minutes, reduce by $(1.4)^{1/2}$ to 38 μJy/beam
  - For robust=0, increase by 1.19, back to 45 μJy/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 3^{rd} Self-Cal

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

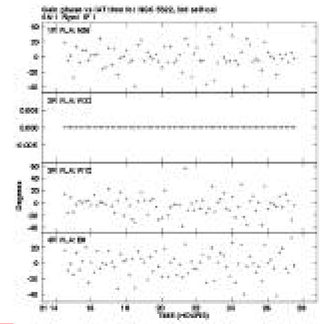
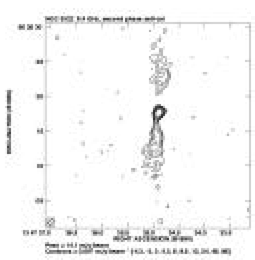
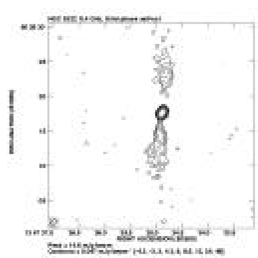


Image Comparison

2^{nd} Self-Calibration

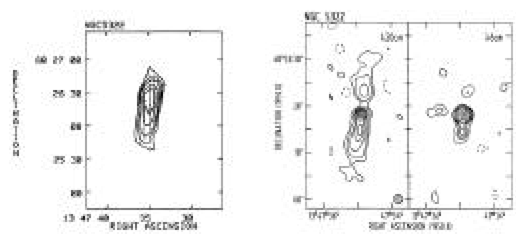


3^{rd} Self-Calibration



Is the Structure Believable?

- WSRT and VLA imaging by Feretti et al. 1984
  - Lesson: If in doubt, look for other evidence!



Concluding Remarks

- Flag your data carefully before 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
- Few antennas (VLBI) or poor (u,v) coverage often require many more iterations of self-cal
- Experiment with tradeoffs on solution interval
  - Shorter intervals follow the atmosphere better
  - Don’t be too afraid to accept low SNRs
- Check your results any way you can!

Lots of Topics Weren’t Covered

- Error recognition (Myers lecture, Chapter 15)
- Model-fitting (Pearson lecture, Chapter 16)
  - Closure quantities and their conservation in self-calibration
- Amplitude self-calibration
  - Initial calibration offsets can be important
- How do you know when your solution has gone wrong, or your model is corrupting your gains?
- Self-calibration is not a rigorous mathematical operation
  - Experience, intuition, and being careful really count!