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

• Basic theory
• Some choices
• Example
• Closing remarks

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 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

What is the Troposphere Really Doing?
• Clouds contain water vapor
• Index of refraction differs from “dry” air
• Variety of moving spatial structures

Fundamental calibration equation
\[ \tilde{V}_{ij}(t) = g_i(t)g_j^*(t)V_{ij}(t) + \varepsilon_{ij}(t) \]

• Definitions
  \[ \tilde{V}_{ij}(t) = \text{observed visibility at time } t \]
  \[ g_i(t) = \text{relative complex gain of antenna } i \]
  \[ V_{ij}(t) = \text{actual visibility at time } t \]
  \[ \varepsilon_{ij}(t) = \text{thermal noise on } i-j \text{ baseline} \]
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?
  \[ \sigma_U^2 = \frac{\sigma_L^2}{(N - 3)F^2} \]
  \( \sigma_L^2 \) = variance in gain estimates
  \( \sigma_U^2 \) = variance of visibilities (square of noise)
  \( N \) = number of array elements
  \( F \) = source flux density

You Can Self-Calibrate on Weak Sources!
\[ \sigma_U^2 = \frac{\sigma_L^2}{(N - 3)F^2} \]
• 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 \((4 \times 60/10)^{1/2}\) 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?
**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\textsuperscript{nd} Self-Calibration**

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

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

**Image Comparison**

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<th>2\textsuperscript{nd} Self-Calibration</th>
<th>3\textsuperscript{rd} Self-Calibration</th>
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**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!