Self Calibration

Newton DARA

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Talk based on A. Richards ALMA workshop lecture 2012

Introduction

1. a priori calibration
    - Sources of corruption (atmospheric effects)
    - Error effects on data

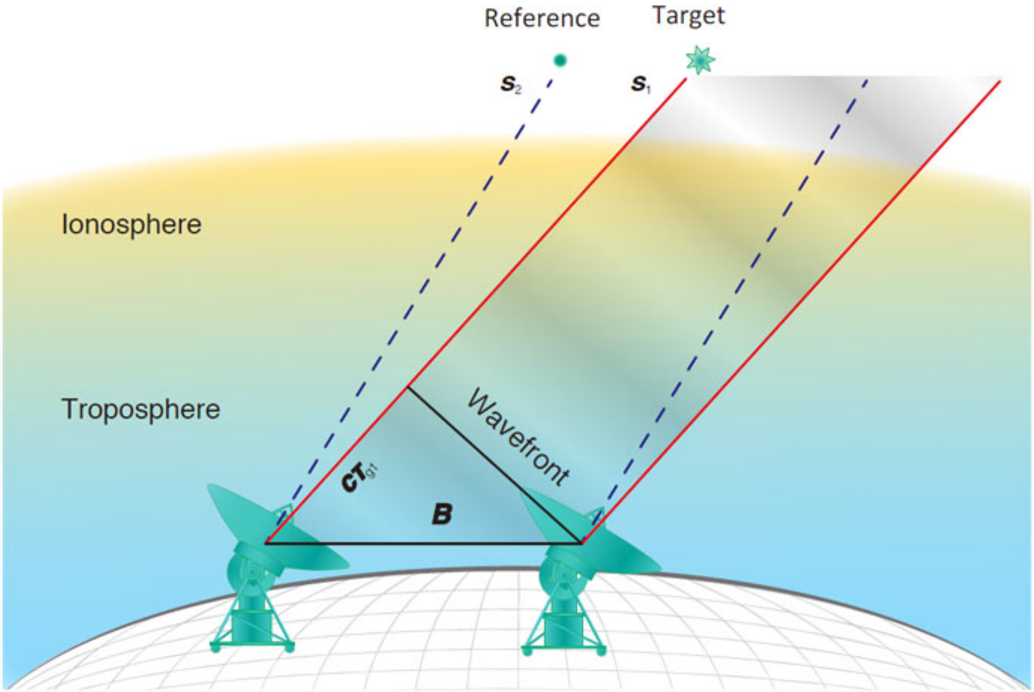
2. Self-calibration
    - Principle
    - Generalised method

3. Self-calibration in practice (and its implementation in CASA)
    - Phase referencing
    - Guided self calibration

4. Choices in self-calibration

a Priori Calibration

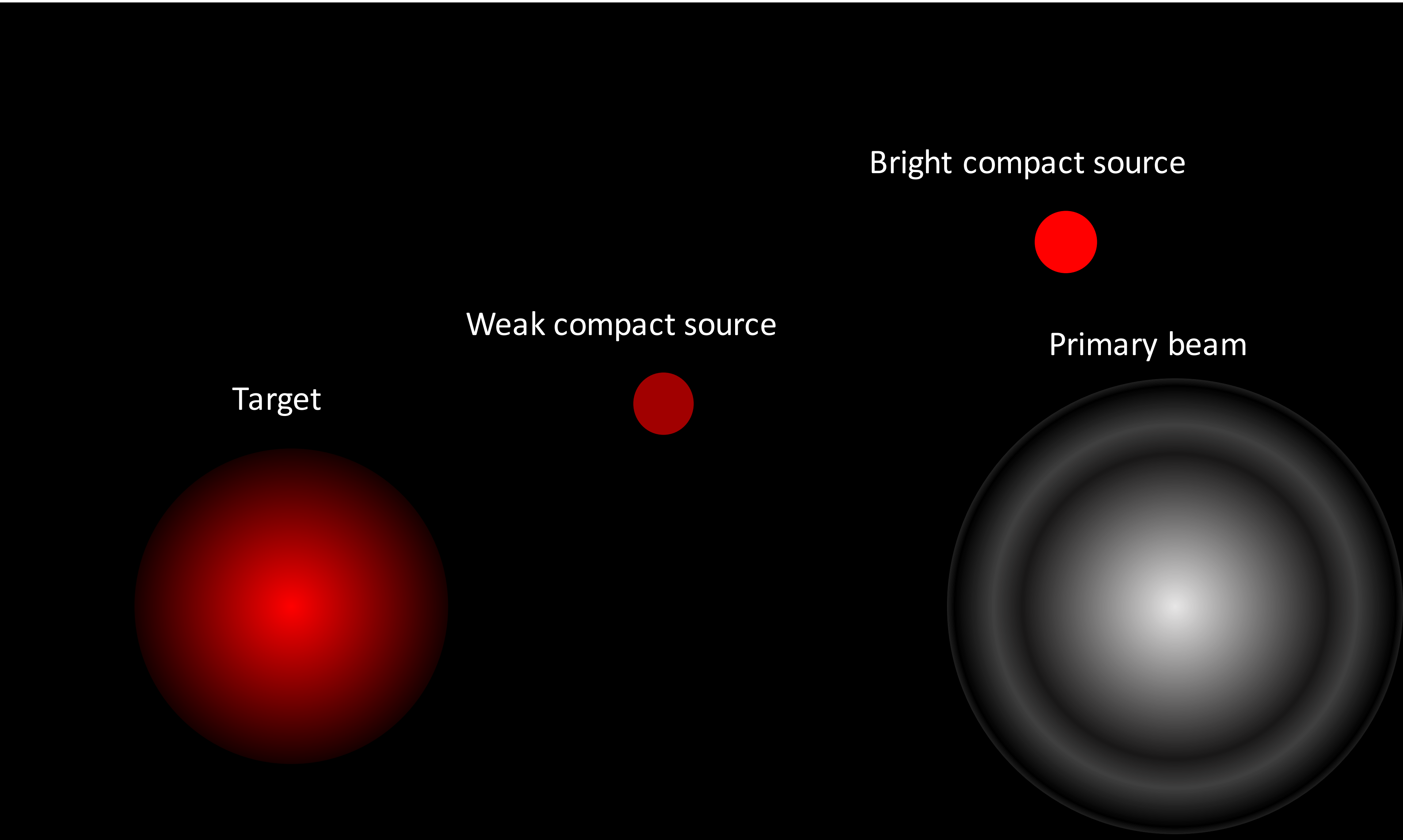
Recap



- Apply instrumental corrections: e.g. T_{sys}
- Edit the data as required
- Apply bandpass, (polarization) corrections
- Apply phase and (fluxscaled) amplitude corrections derived from phase reference
- Close enough to see similar atmosphere
- Nod on suitable timescale e.g. 10:2min
- Derive time-dependent corrections to make phase-ref visibilities match model
- Apply same corrections to target

a Priori Calibration

Phase Referencing Recap



a Priori Calibration

Why is a priori calibration insufficient?

- Initial calibration based on calibrator observed before/after target

- 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.

- Calibrator may have structure and may not be as strong as expected

a Priori Calibration

Why are atmospheric effects important?

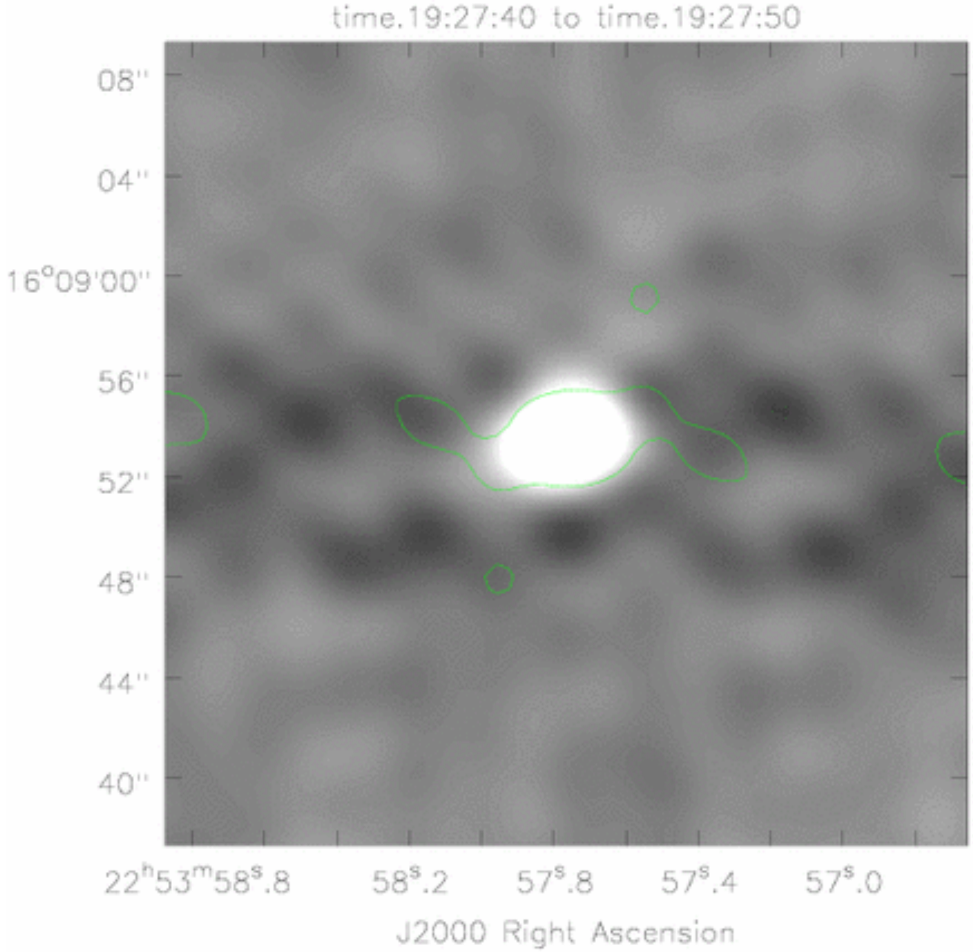
- The atmosphere is similar, not identical, above the target and above the phase-reference.

- There are offsets in distance and in time.

- Neutral atmosphere contains water vapour
- Index of refraction differs from "dry" air
- Variety of moving spatial structures in the atmosphere.

- Typically worse for low frequencies ~100sMHz (ionosphere) & high frequencies ~20+GHz (water vapour)

Example 22GHz point source observed with the EVLA



a Priori Calibration

The atmosphere is not our only worry, our true visibilities are corrupted by all these other effects!:

1. Atmospheric attenuation
2. Radio "seeing"
3. Variable pointing offsets
4. Variable delay offsets
5. Electronic gain changes
6. Electronic delay changes
7. Electronic phase changes
8. Radiometer noise
9. Correlator malfunctions
10. Most interference signals

Antenna based

Baseline

Let's see what these errors do to our data!

a Priori Calibration

What is the effect of a priori calibration errors?

- Dt is interval after which phase errors independent
  - Dt > scan (phase-ref:target cycle)
  - $Dt \sim$ duration of Scheduling Block, $\sim$20-30 min?
- Phase errors e_f affecting all baselines limit dynamic range of M intervals

$$Dt \sim \frac{\sqrt{M}N}{\sqrt{2}e_f}$$

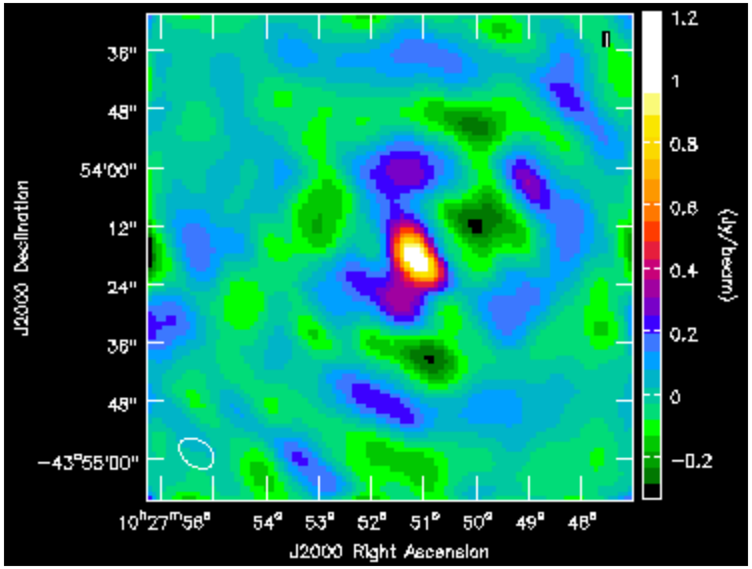
e.g. $M = 6, N = 7, e_f = 10°$ = $p/18$ rad

  - Dynamic range < 70
  - Phase errors are asymmetric, sine function

- An amplitude error of 20% is equivalent to $e_f = 10°$
  - Amplitude errors are symmetric, cosine function
  - Dt may be longer so M is smaller – effect worse

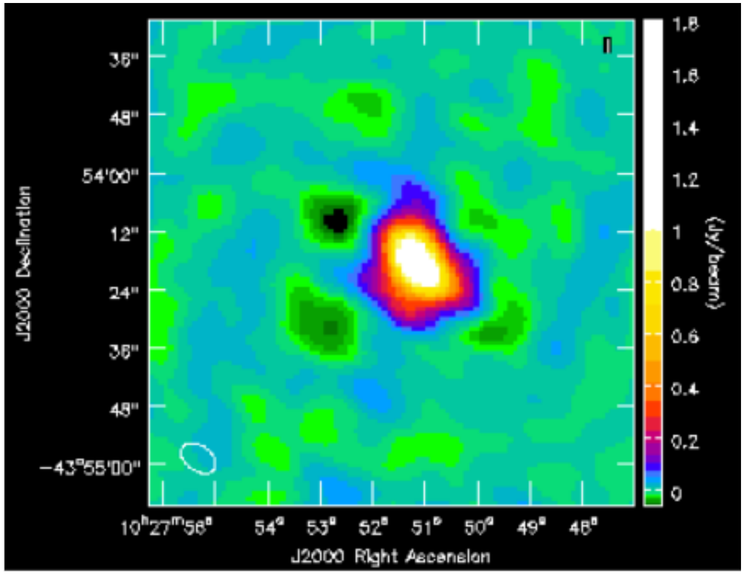
a Priori Calibration

What is the effect of a priori calibration errors?



Phase referencing solutions only

Anti-symmetric (phase) errors dominate

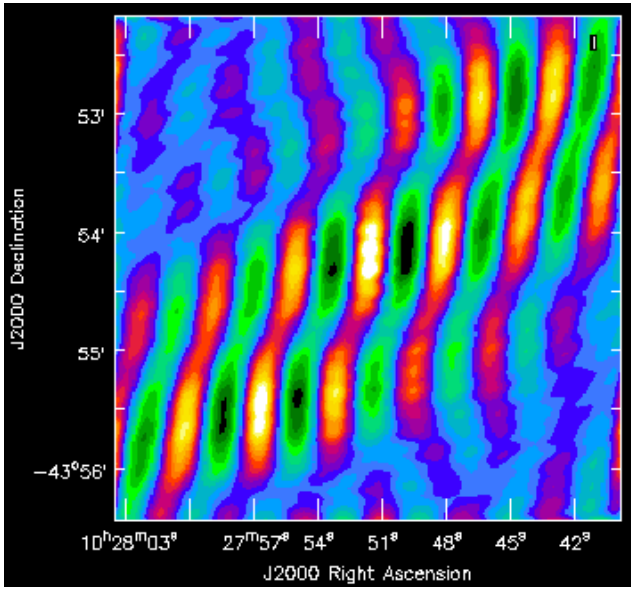


Phase self-cal only (i.e. removal of phase errors)

Symmetric (amplitude) errors dominate!

a Priori Calibration

What is the effect of a priori calibration errors?



A few high amps (easily flagged) cause symmetric stripes

Asymmetric stripes are usually delay errors! (cannot self-calibrate these out easily…)

Now you can see why a priori calibration is insufficient…

We need to use Self Calibration!

Self Calibration

Quick recap of the measurement equation

Our observed visibilities can be represented by:

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

$V_{ij}(t)$ - visibility measured between antenna i and j

$g_i(t)$ - complex gain of antenna i

$\epsilon_{ij}(t)$ - additive noise/ baseline error

$V^{\mathrm{true}}(t)$ - 'true' visibility = $\iint I(l,m) e^{-2\pi i(ul+vm)} dl dm$

This equation can be represented in matrix form & the complex gain terms decomposed into Jones matrices which correspond to various sources of error.

Self Calibration

The Radio Interferometer Measurement Equation (RIME)

$$\vec{V}_{ij} = M_{ij}B_{ij}G_{ij}D_{ij}\iint E_{ij}P_{ij}T_{ij}F_{ij}S\vec{I}(l,m)e^{-2\pi i(u_{ij}l+v_{ij}m)}dldm + \vec{\epsilon}_{ij}(t)$$

Vectors

$\vec{V}$isibility = f(u,v)
$\vec{I}$ mage to be calculated
$\vec{\epsilon}$ - Additive baseline error

Scalars

S (mapping I to observer polarisation)
l, m image plane coordinates
u, v Fourier plane coordinates
i, j telescope pair

Jones Matrices

Multiplicative baseline error
Bandpass response
Generalised electronic gain
D term (polarisation leakage)
E - antenna voltage pattern
Parallactic angle
Tropospheric effects
Faraday rotation

Self Calibration

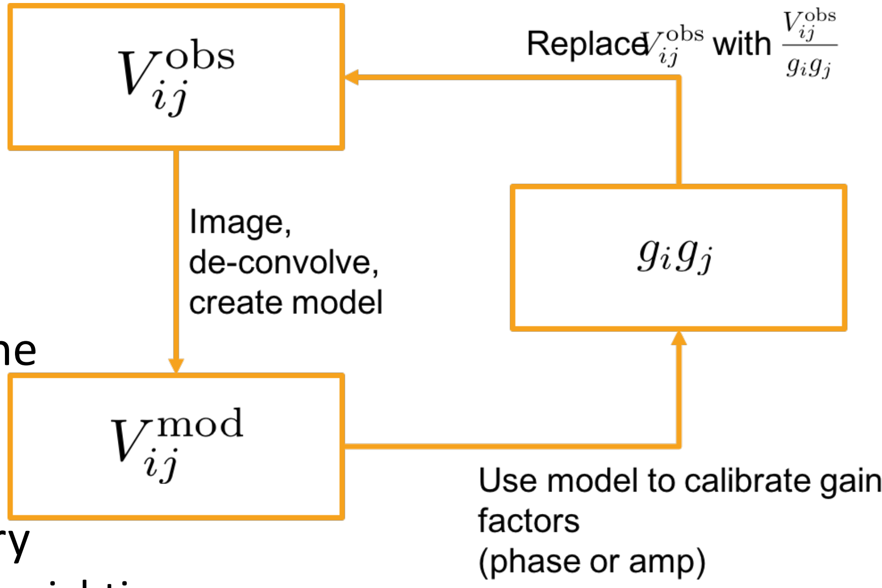
Principles of Self-calibration

- Use *target* visibilities and allow the antenna gains to be free parameters.
- If all baselines correlated, there are N complex gain errors corrupting the N*(N – 1) / 2 complex visibility measurements for a given time.
- Therefore there are N * (N – 1) / 2 - N complex numbers that can be used to constrain the true sky brightness distribution.
- Even after adding the degrees of freedom from the antenna gains, the estimation of an adequate model of the target brightness is still overdetermined.
- The improved model created from constraining these parameters can then be used to constrain the visibilities & remove residual phase & amp errors

Self Calibration

The Self Calibration Method

1. Create an initial source model, typically from an initial image (or else a point source)
   - Use full resolution information from the model image NOT the restored image (ie. CLEAN +residuals)
2. Find antenna gains
   - Using "least squares" fit to visibility data
3. Apply gains to correct the observed data
4. Create new model visibilities (V^{mod}) from the corrected data
5. Go to (2), unless current model is satisfactory
   - shorter solution interval, different uv limits/weighting
   - phase → amplitude & phase



V_{ij}^{obs}

Replace V_{ij}^{obs} with $\frac{V_{ij}^{\mathrm{obs}}}{g_i g_j}$

Image,
de-convolve,
create model

$g_i g_j$

V_{ij}^{mod}

Use model to calibrate gain
factors
(phase or amp)

Self Calibration in Practice **(and implementing it in CASA)**

Method

1. Apply prior corrections.

2. Image target
   - FT of Clean Components stored in MS Model column if usescratch = True in CASA clean (or use task **ft** to store Clean components from a model image into the MS)

   - Compare target visibilities with the model
     Any differences are due to either/both of
     1. Deficiencies in the model
     2. Atmospheric or other errors affecting the visibilities

3. Estimate corrections for phase visibility errors
   - Use CASA task **gaincal** with calmode ‘p’

Self Calibration in Practice

Method

4. Apply and make another image
    - This should provide an improved model

5. Repeat until phase corrections converge then do a amplitude & phase self calibration.

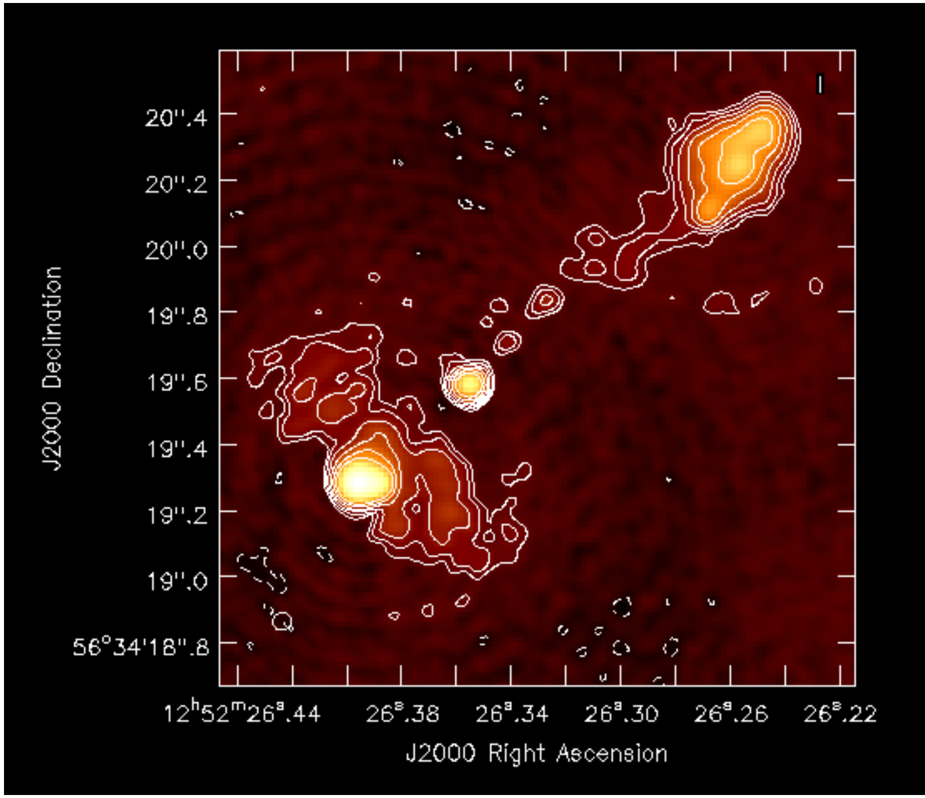
Remember that:

- Phase correcting first allows longer averaging times for amplitudes

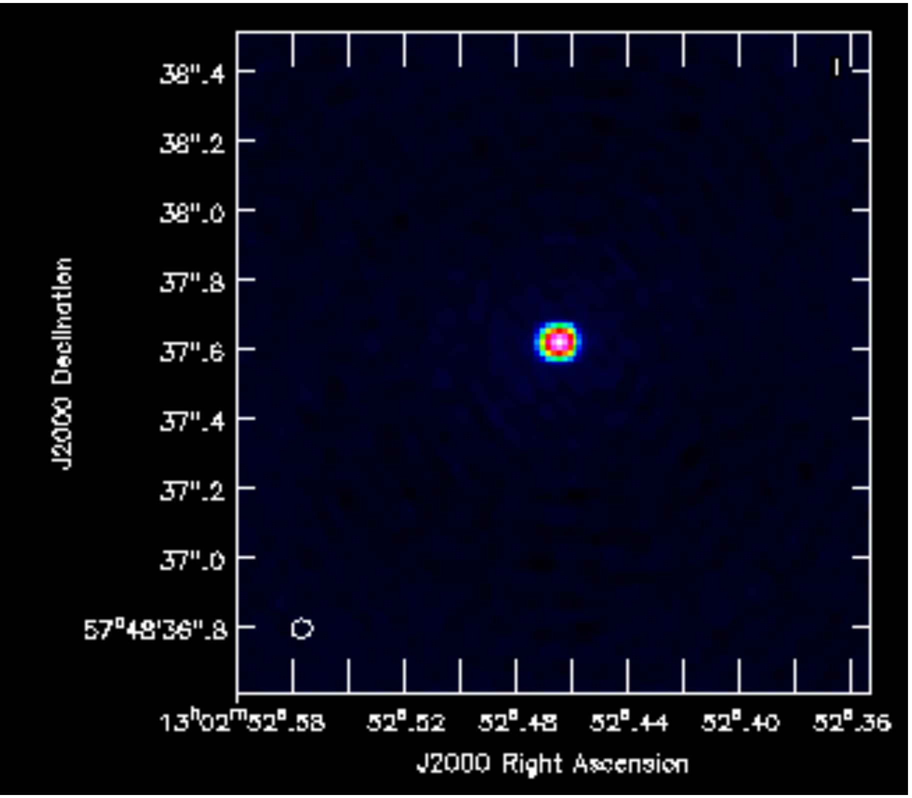
- Apply your phase solutions when using calmode 'ap’ as residual phase solutions should be small.

Self Calibration in CASA

Example (finally some pictures!):



Target 3C277.1 observed using MERLIN at 1.6 cm (bright, extended structure)

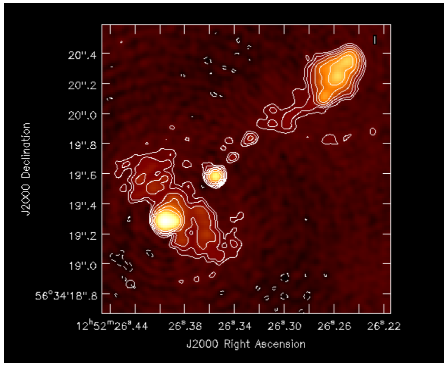


Phase-ref 1300+580
~3° from target

Unresolved point!

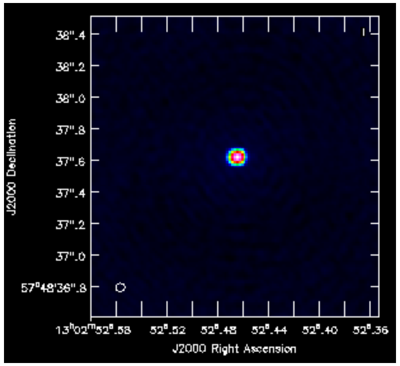
Self Calibration in Practice

Phase referencing: Source structure



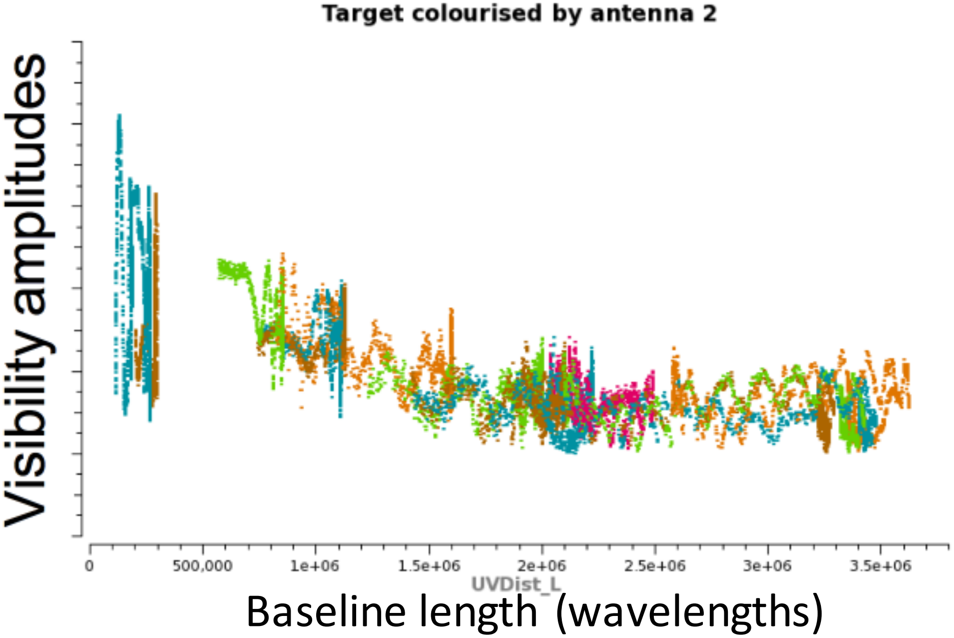
Extended source:

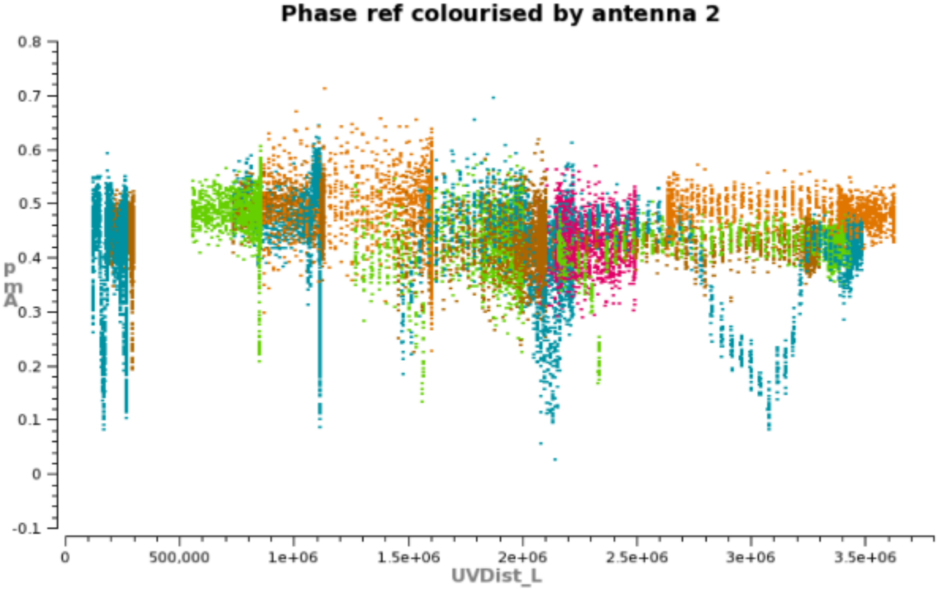
More flux on short baselines



Point source:

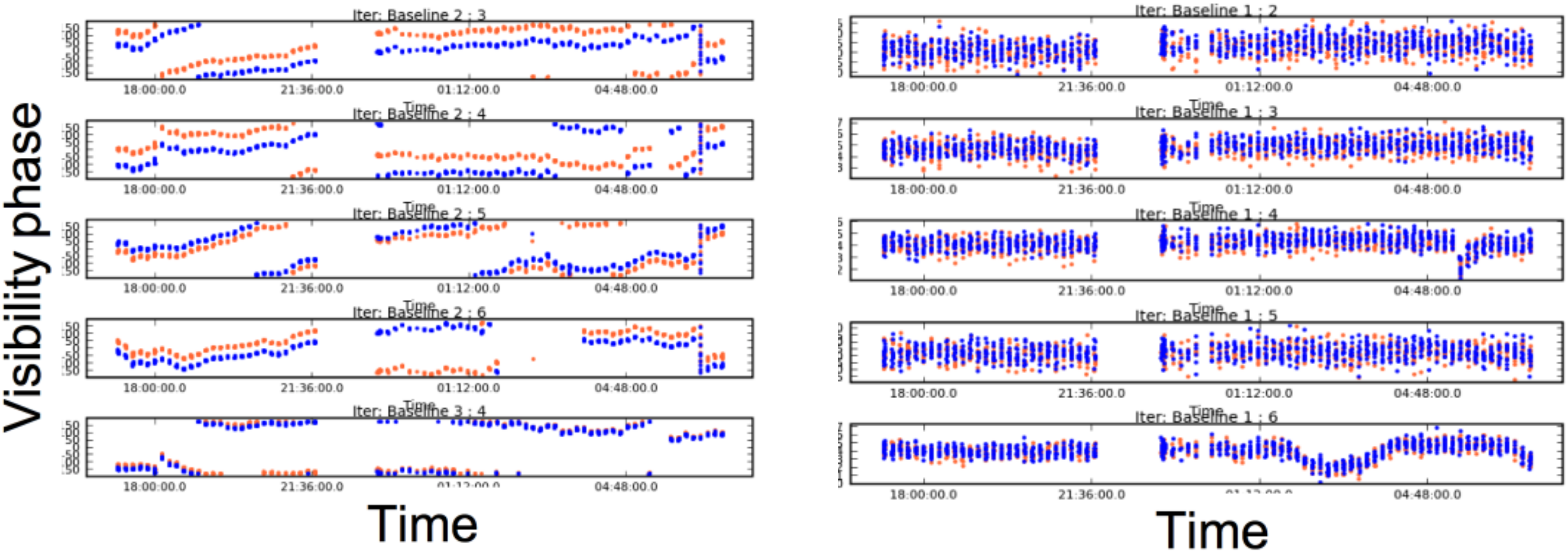
Same flux density on all baselines (within errors)





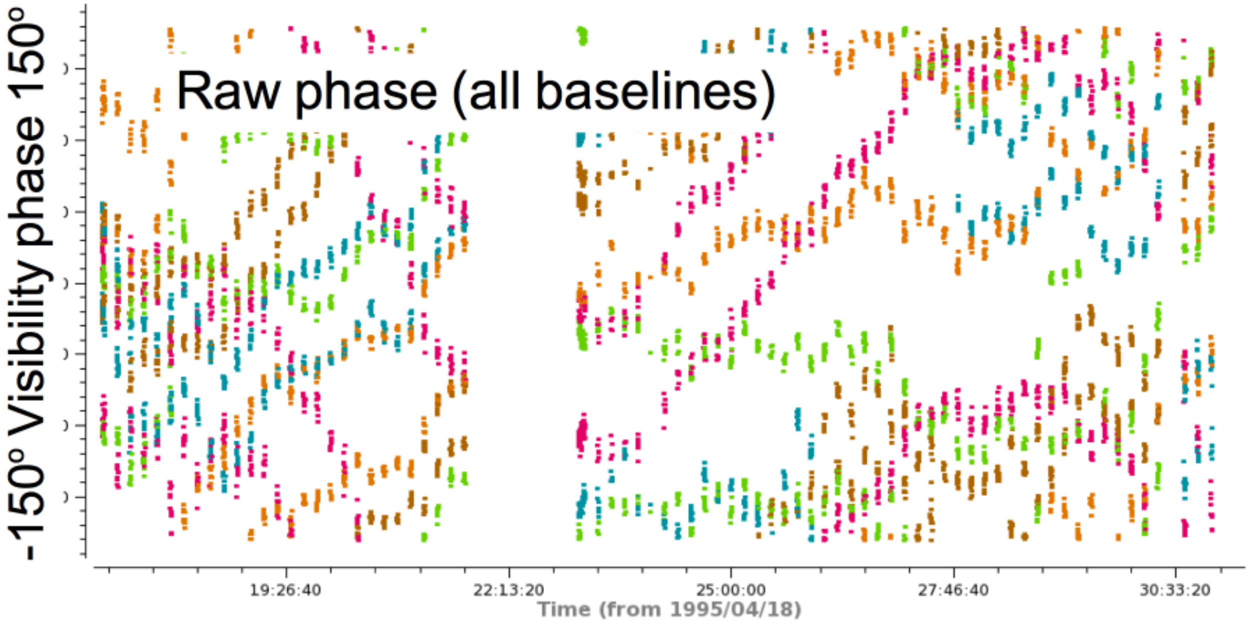
Self Calibration in Practice

Phase referencing: point source visibilities



Self Calibration in Practice

Phase referencing: Correcting phase reference visibilities



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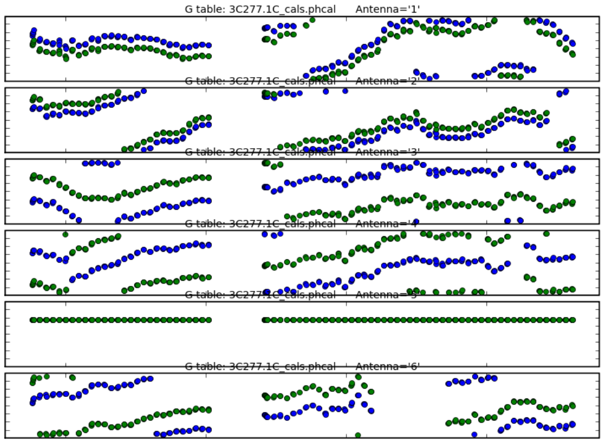
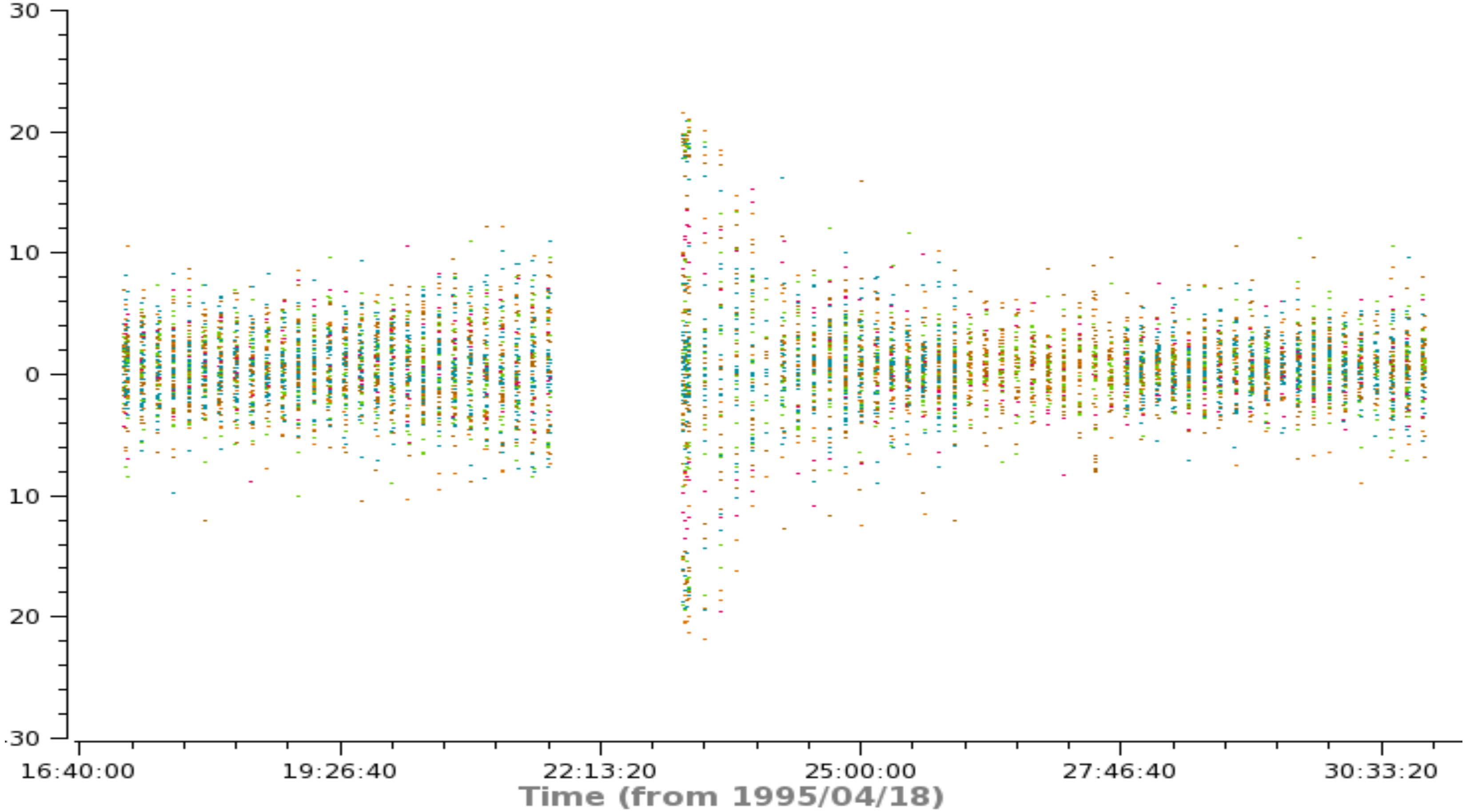


Corrections (per antenna) results in …

Self Calibration in Practice

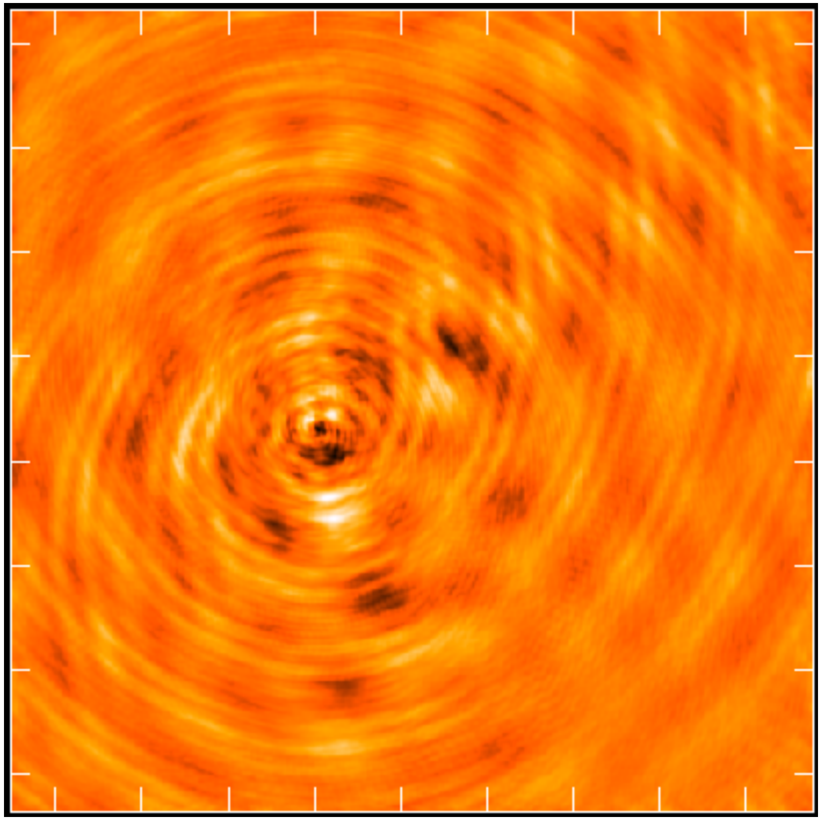
Results in corrected phase for point source!



- Scatter reduced
- Phases aligned close to 0

Self Calibration in Practice

First image of the target



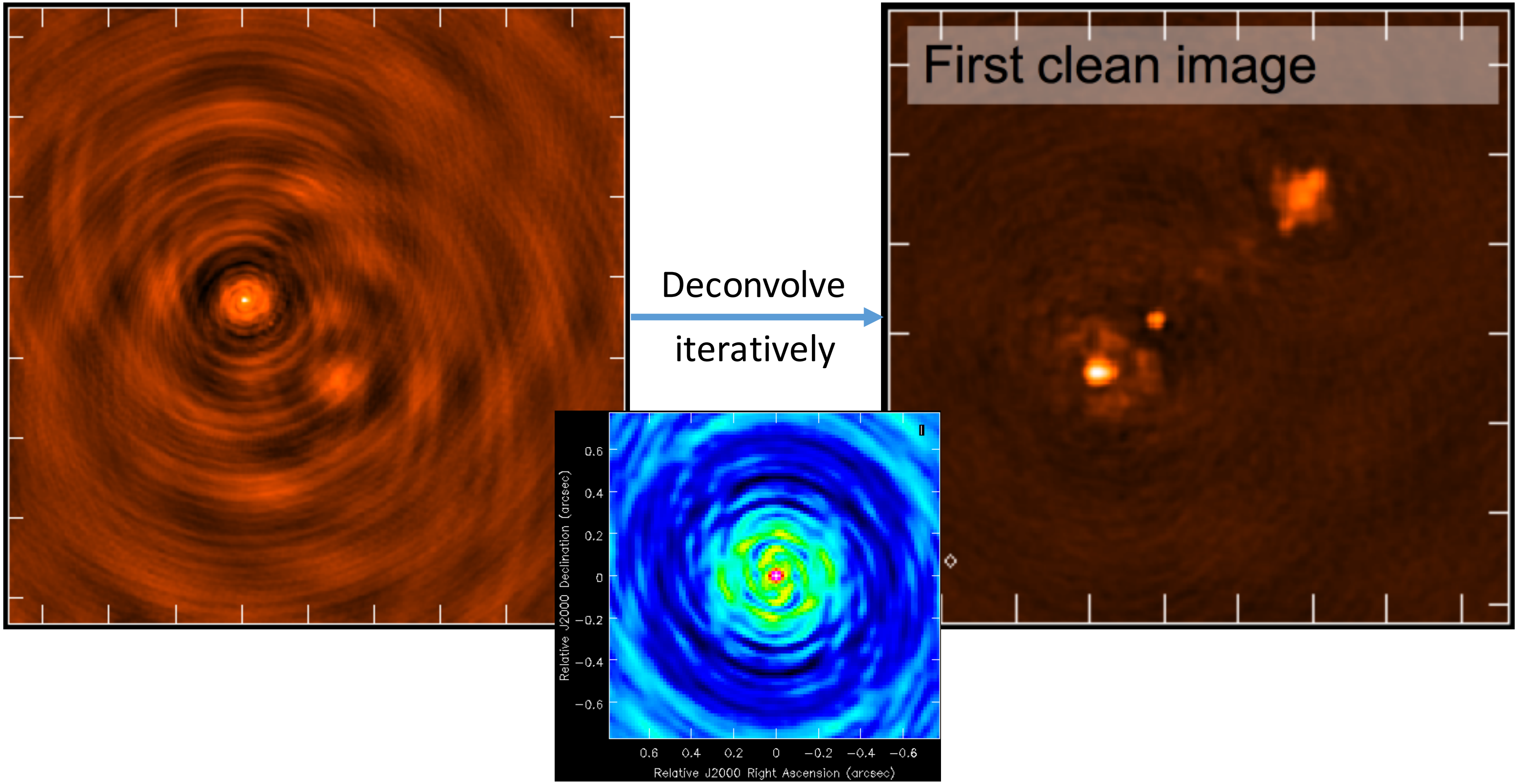
Dirty map

- Raw phase (not corrected)
- Holes and smearing
- No peaks

Apply phase referencing corrections to visibility data and Fourier transform to image plane….

Self Calibration in Practice

First image of the target

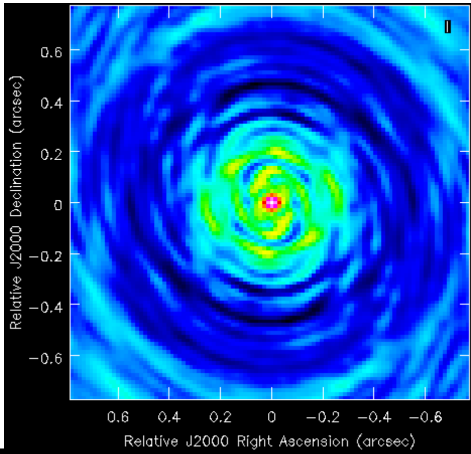


Deconvolve

iteratively

with the dirty beam!

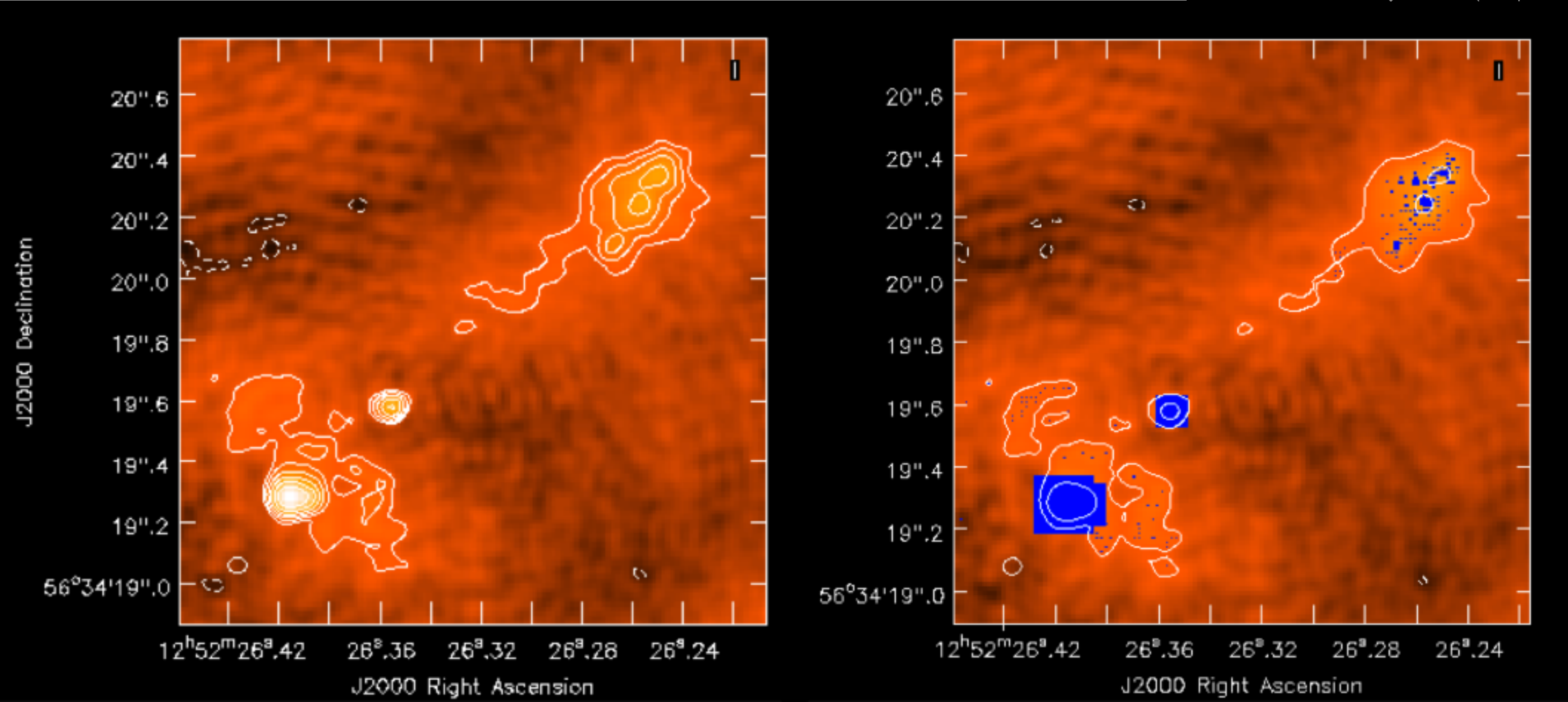
Self Calibration in Practice



Preparing the model for self calibration

Take care in setting mask (clean boxes)!

- Clean Components will be used as model
- Plot dirty beam to help avoid sidelobes



Self Calibration in Practice

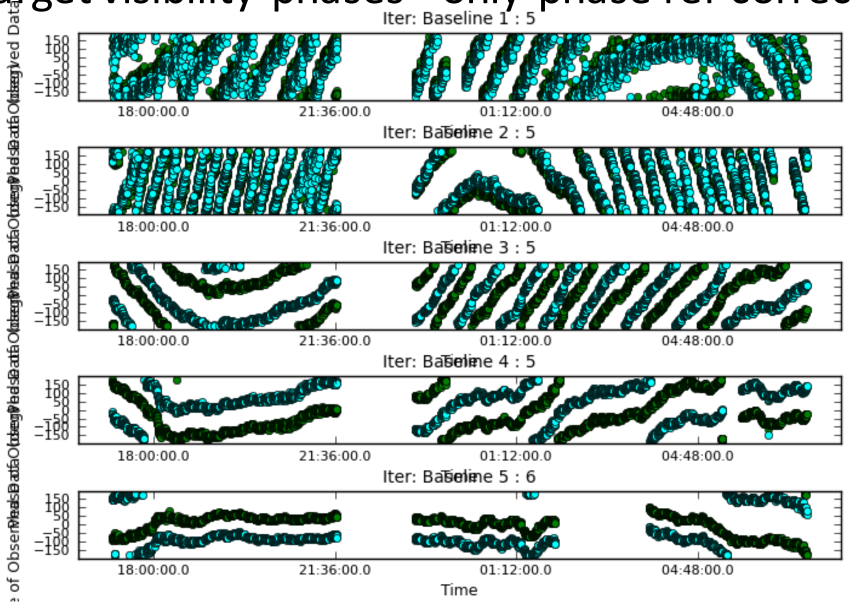
Phase self-calibration

FT of Clean Components stored in MS 'model' column if usescratch in CASA clean is set to True

Alternatively use task **ft** to convert .model file into model visibilities!

Use **gaincal** to obtain phase solutions contained in a calibration file - **gaincal** compares model with target visibility data

Target visibility phases - only phase ref correction



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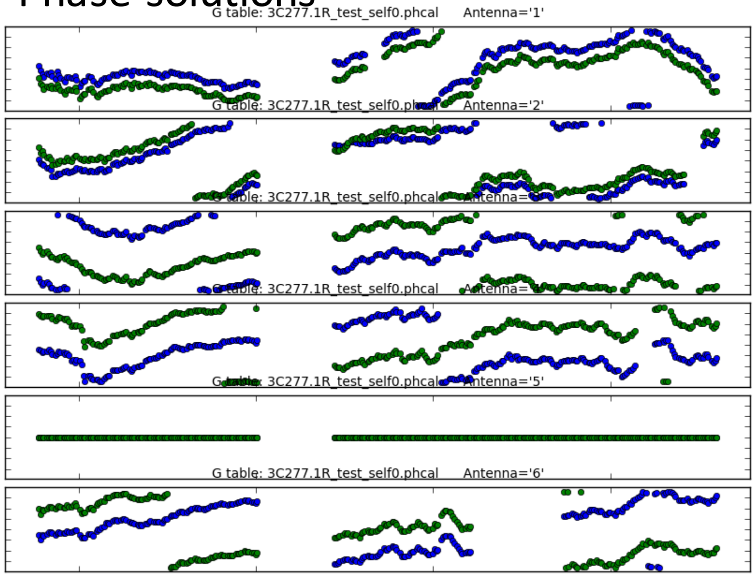
Phase solutions

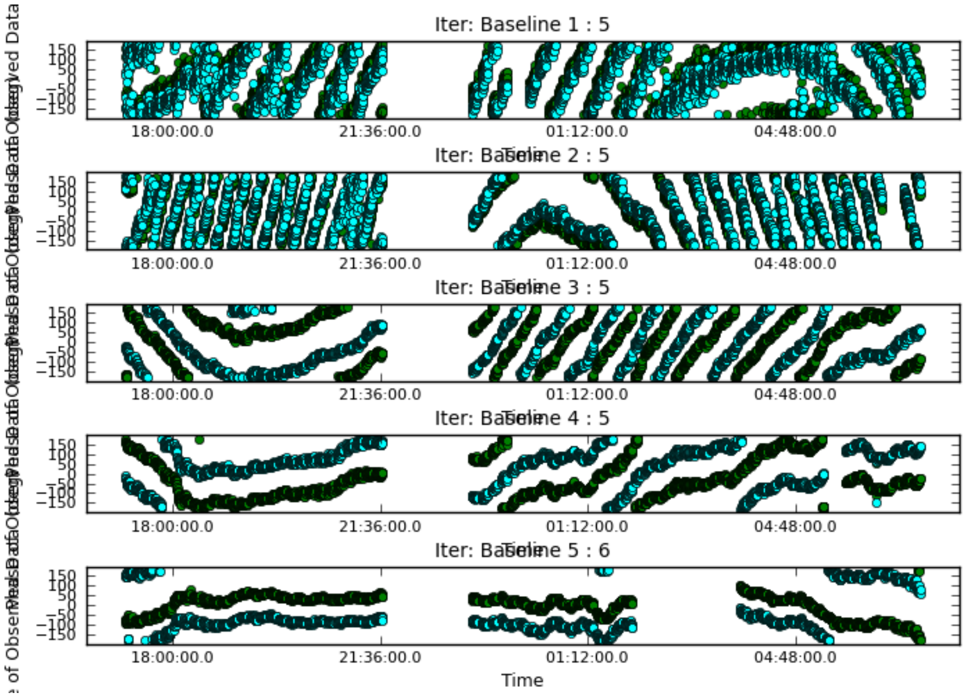


Self Calibration in Practice

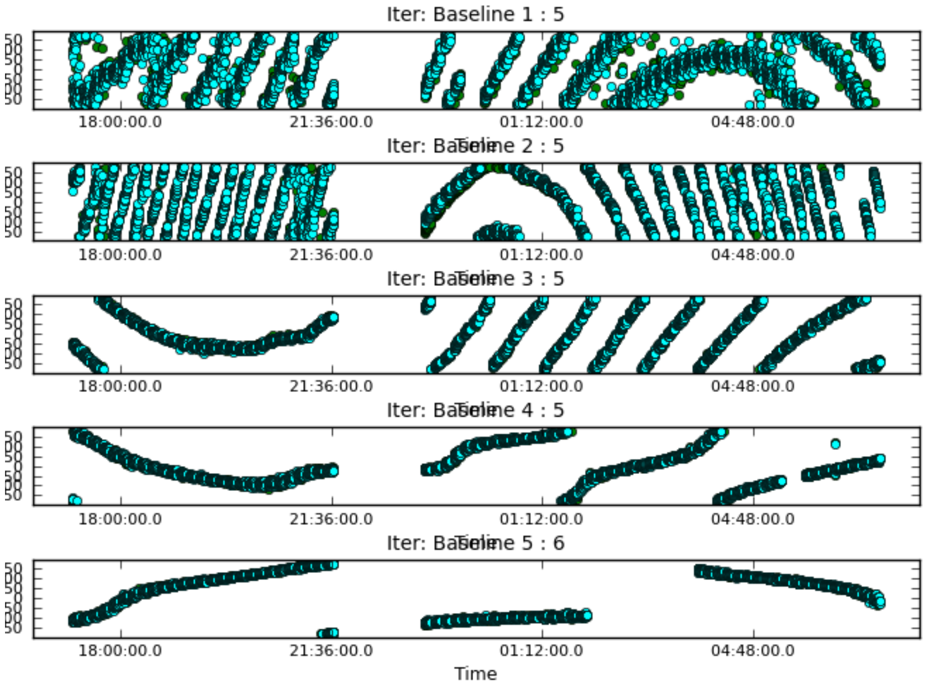
Phase self-calibration

- Use CASA task **applycal** to apply calibration file (containing self-cal solutions) to the MS

Target visibility phases - only phase referencing correction



Target with phase self cal solutions applied



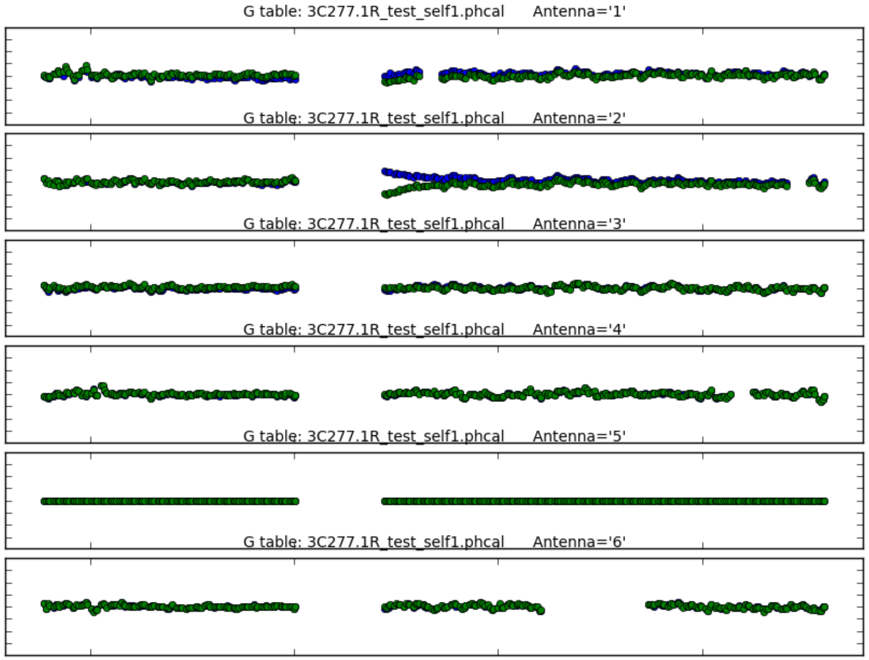
- Much improved and smoother target phases - reduced scatter!
- Offset between pols has been removed!

Self Calibration in Practice

Iterative self-calibration

- Once solutions have been applied, image again!

  Note that:
  - The old model column is overwritten
  - Use task **ft** (with previous model image) if you want to go back to a previous Clean model
- Repeat this process until residual phase solutions converge on zero.



Small residual phase solutions from next gaincal

Self Calibration in Practice

Iterative self-calibration

A good iterative self-cal cycle to follow is outlined below

First image

Phase calibration

Shallow CLEAN (avoid CLEAN bias)

Phase calibration

Deep CLEAN

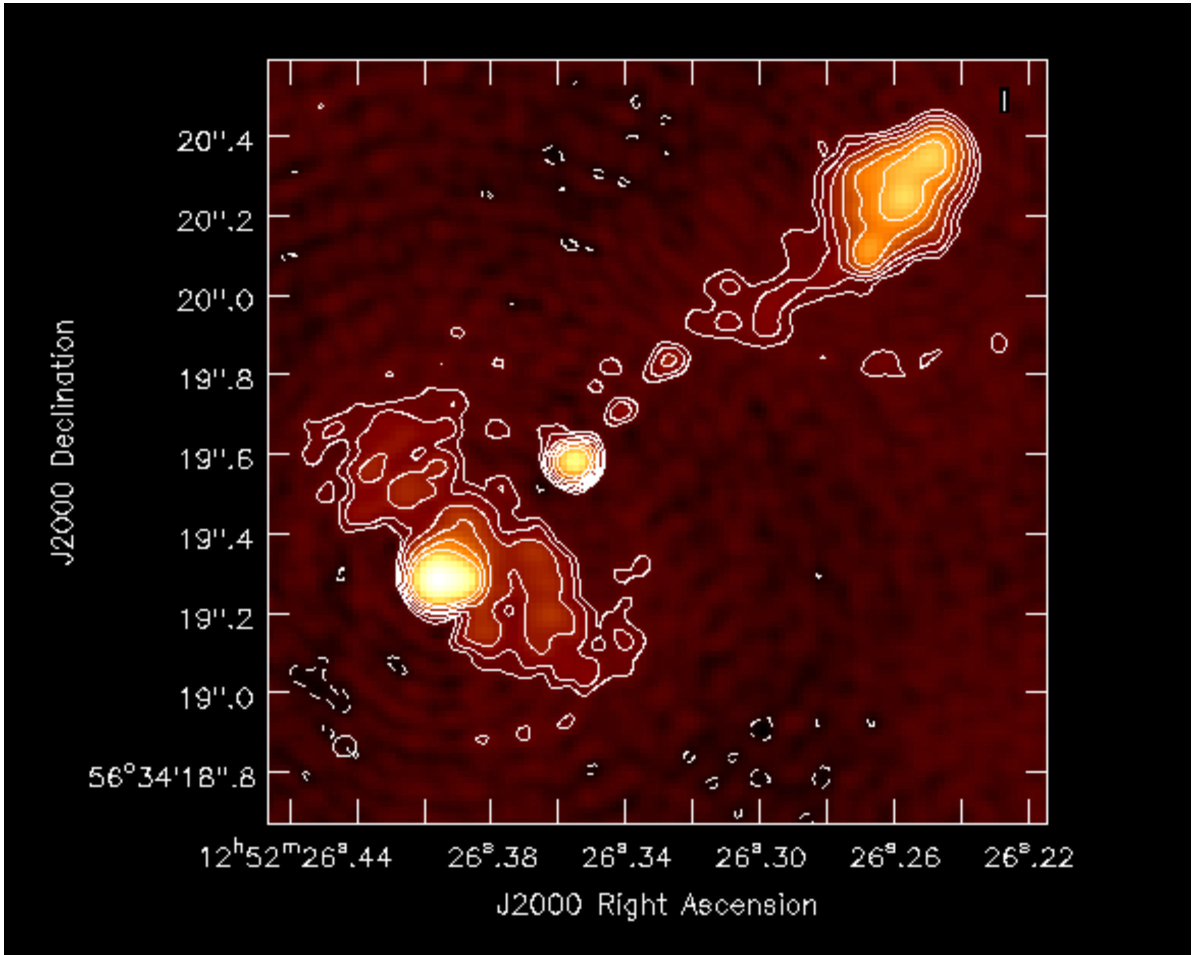
Amplitude & phase calibration *Nb. Amplitude solutions should be close to 1*

Deep CLEAN

Self Calibration in Practice

Iterative self-calibration

After rounds of self-calibration, you get a vastly improved image with increased signal to noise



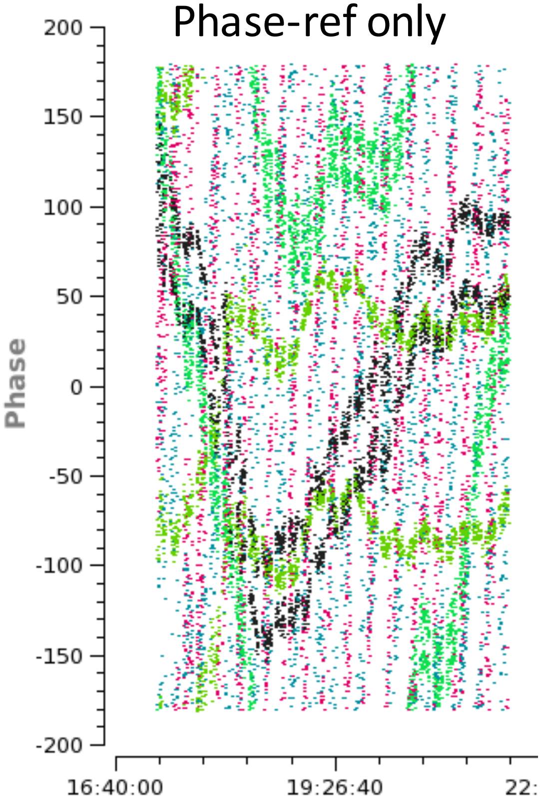
Beautiful!

Self Calibration in Practice

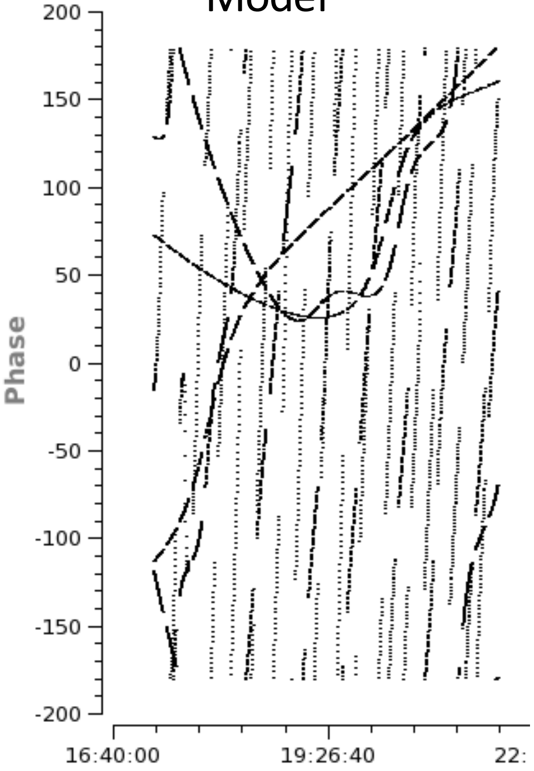
HEALTH WARNING: Check solutions, models at each round!

- Solutions should not look like pure noise!
- Zoom in in case of a fast phase rate
- Data should get less noisy

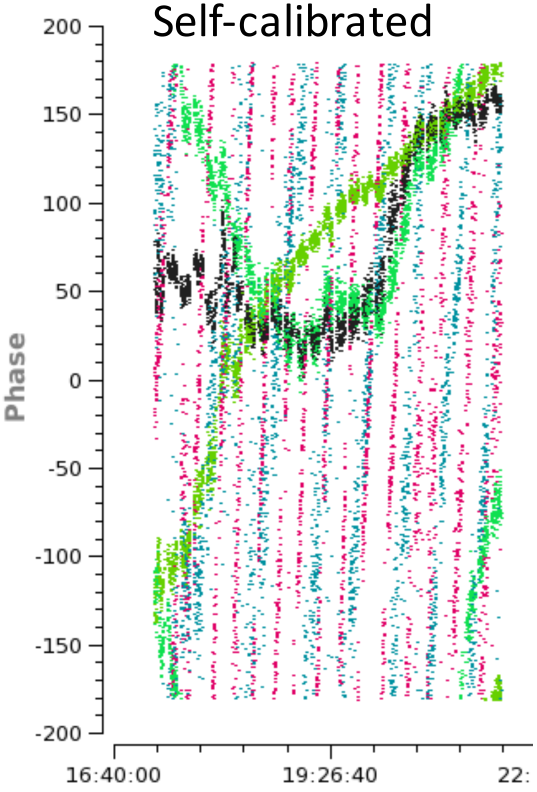
Phase-ref only



Model

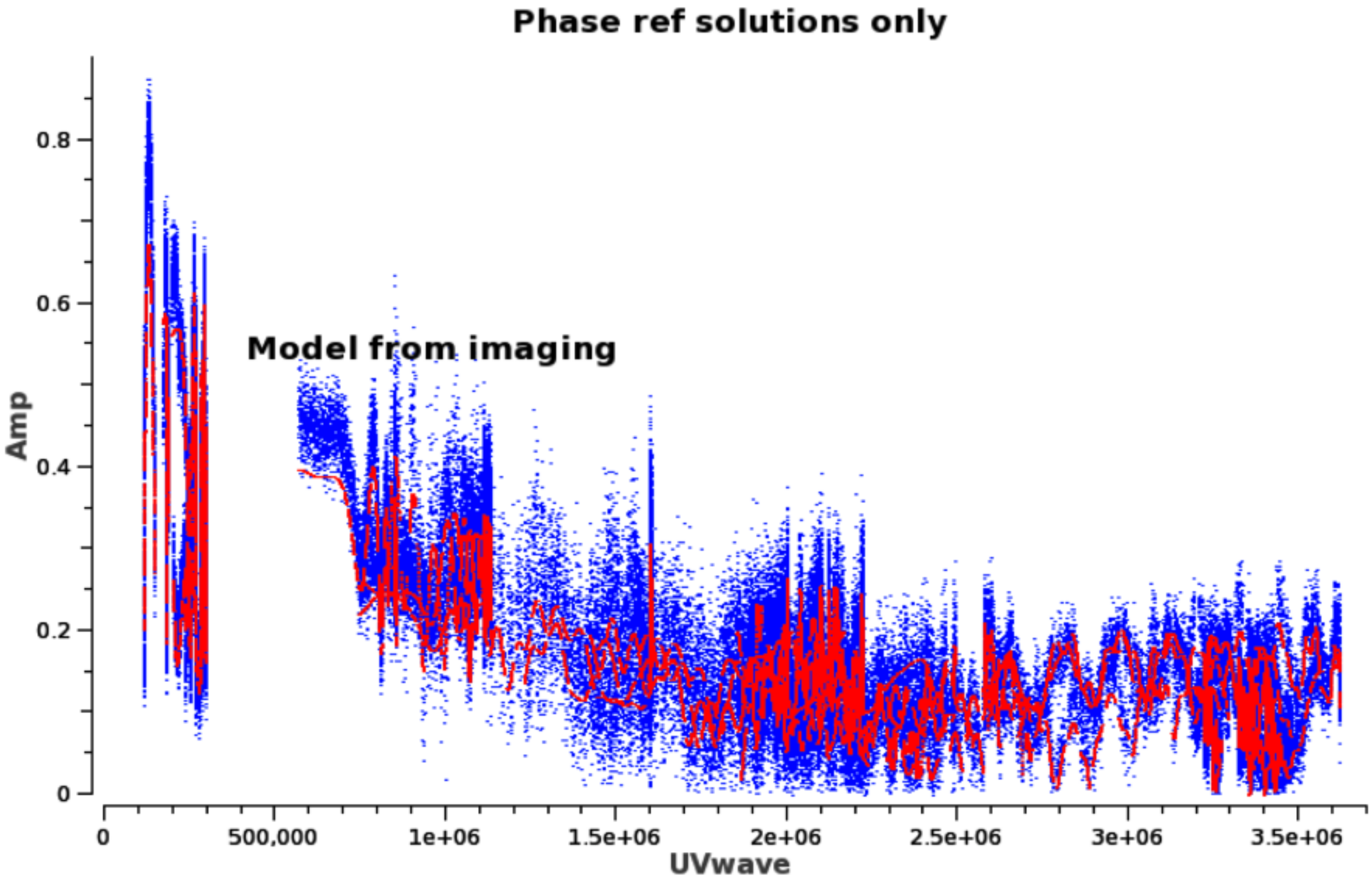


Self-calibrated



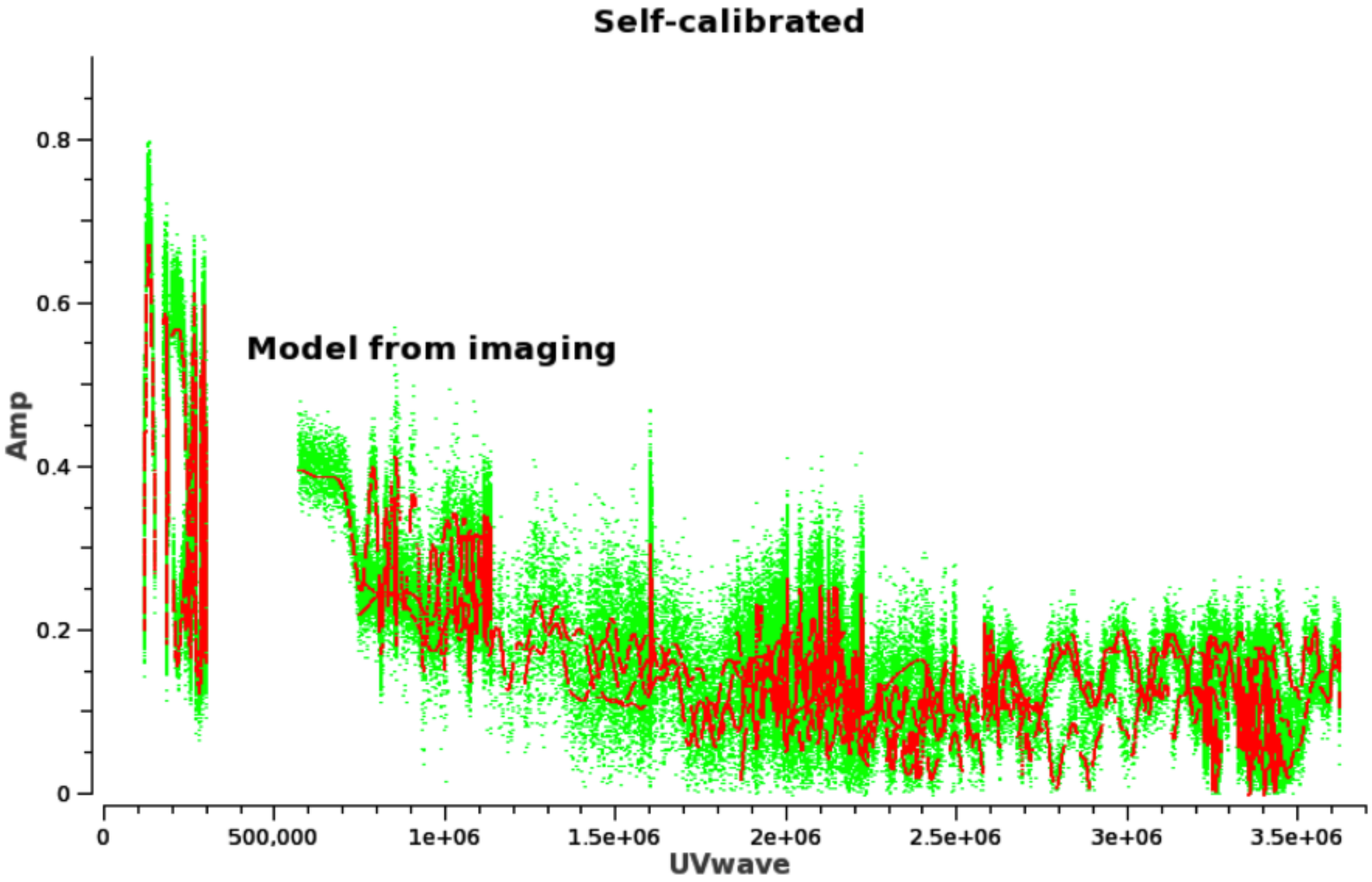
Self Calibration in Practice

Self-calibration improvement



Self Calibration in Practice

Self-calibration improvement



Choices in Self-calibration

1. *Initial model?*

    - Point source often works well
    - Simple fit (e.g., Gaussian) for barely-resolved sources
    - Clean components from initial image

        Note: Don't go too deep!
    - Simple model-fitting in (u,v) plane

2. *Self-calibrate phases or amplitudes?*

    - Usually phases first
        - Phase errors cause anti-symmetric structures in images

    e.g. For VLA and VLBA, amplitude errors tend to be relatively unimportant at dynamic ranges < 1000 or so
    - Safe bet is to follow iterative self calibration cycle shown on previous slide.

Choices in Self-calibration

Some more choices!

3. *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

4. *What solution interval should be used?*

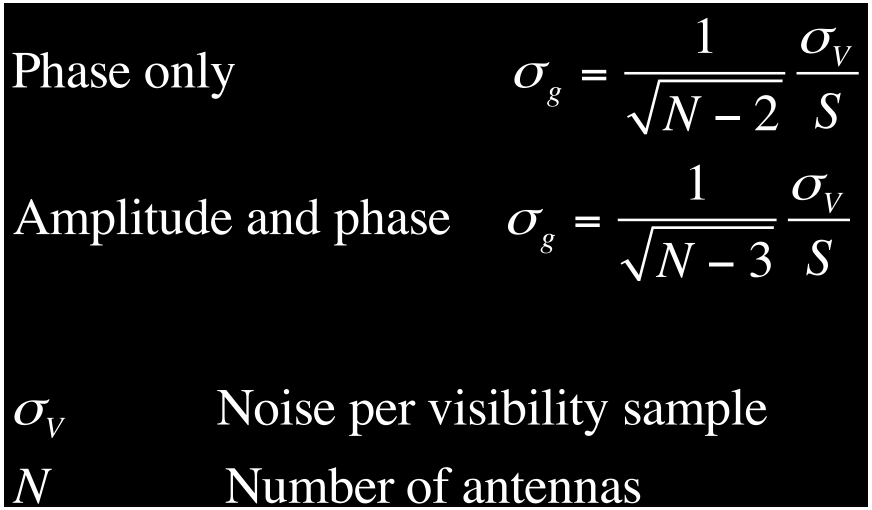
   - Generally speaking, use the shortest solution interval that gives "sufficient" signal/noise ratio (SNR)
   - If solution interval is too long, data will lose coherence - Solutions will not track the atmosphere optimally

Choices in Self-calibration

Sensitivity limit

- Can self-calibrate if signal to noise ratio (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 can be close to theoretical
- If you are desperate you can average polarisations to get enough SNR