



High Dynamic Range Imaging

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High Dynamic Range Imaging

Introduction

Review of Clean

Self-Calibration

Direction Dependence

Other Advanced Techniques

An image's *dynamic range* is the ratio of the peak brightness to the noise floor

$$DR = \frac{S_{\text{peak}}}{\sigma}$$

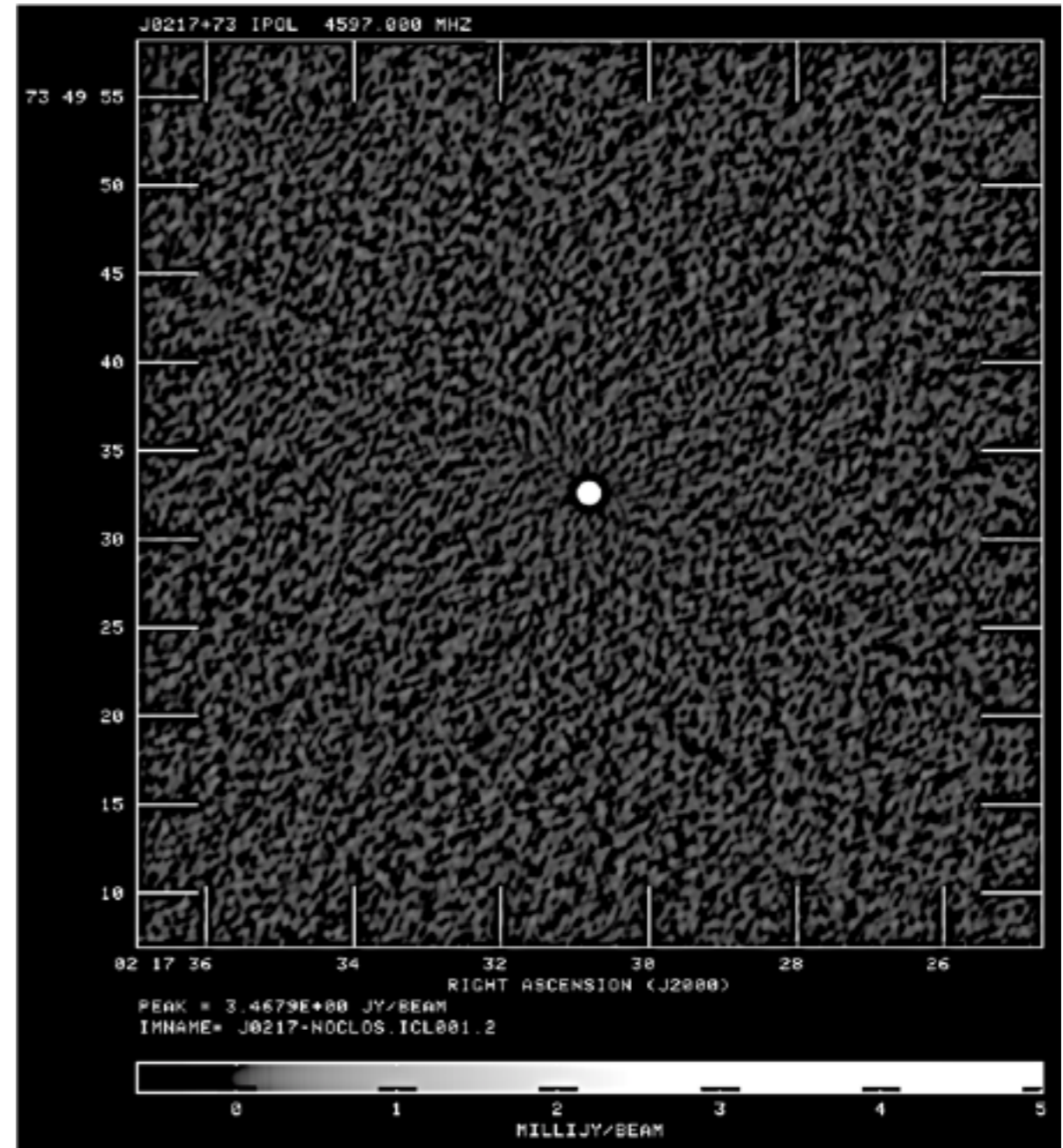


Image by R. Perley

An image's *dynamic range* is the ratio of the peak brightness to the noise floor

$$DR = \frac{S_{\text{peak}}}{\sigma}$$

$$S_{\text{peak}} = 3.5 \text{ Jy}$$

$$\sigma = 42 \mu\text{Jy}$$

$$DR \simeq 83,000$$

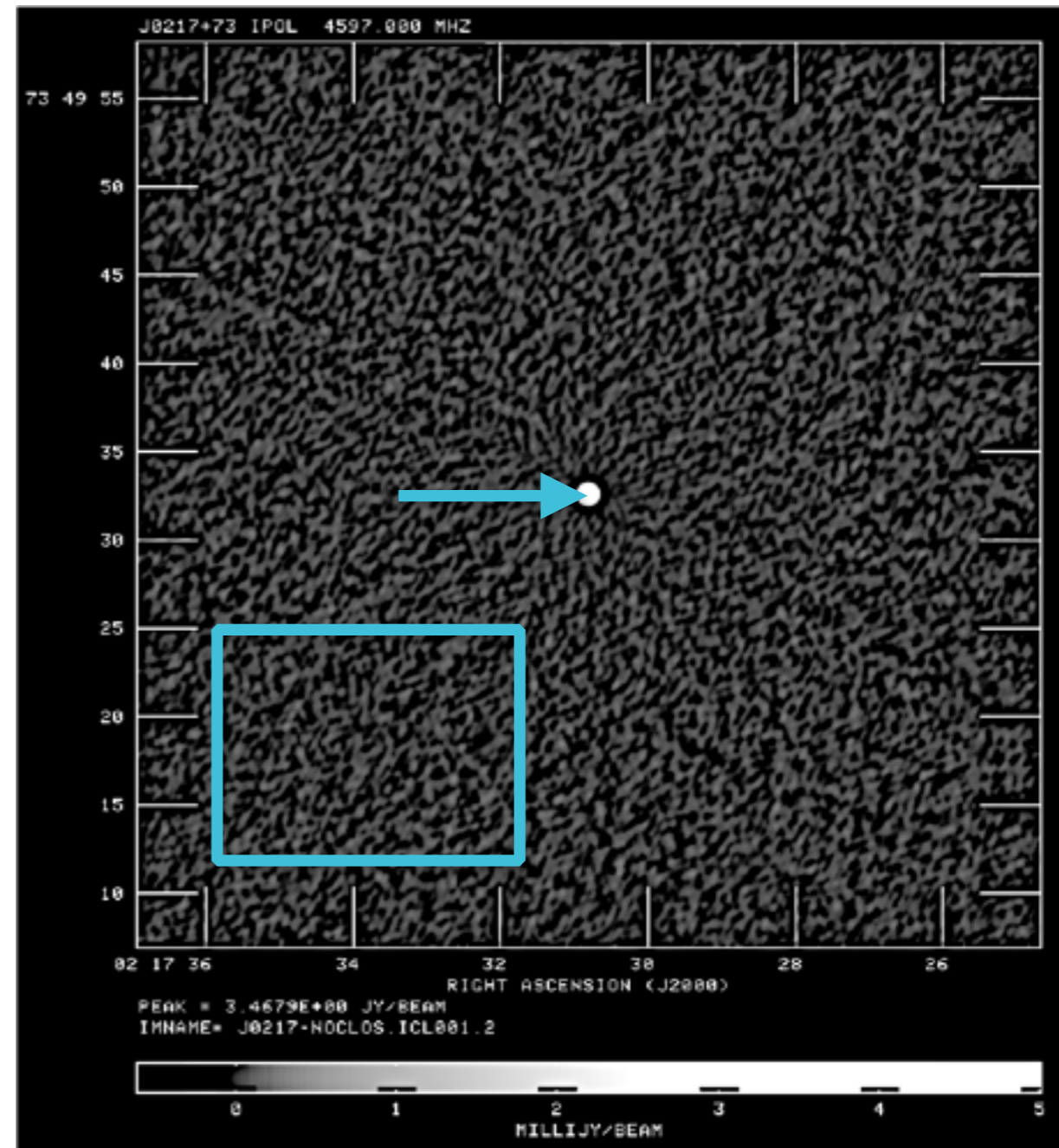


Image by R. Perley

Requirements for high dynamic range:

$$DR = \frac{S_{\text{peak}}}{\sigma}$$

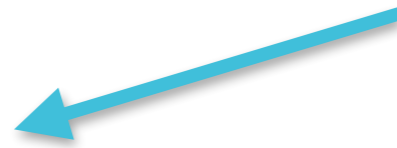


Bright sources in the field of view

- Your target is bright
- Bright source(s) near your target
- Your data are part of a survey

Requirements for high dynamic range:

$$DR = \frac{S_{\text{peak}}}{\sigma}$$



Low noise

- Sensitive instrument
- Large bandwidth
- Long integration time

$$\sigma_S = \frac{2kT_{\text{sys}}}{A_{\text{eff}}[N(N-1)\Delta\nu_{\text{RF}}\tau]^{1/2}}$$

Sensitivity Equation

$$\left(\frac{\sigma_c}{\text{mJy beam}^{-1}}\right) \approx 0.2 \left(\frac{\nu}{\text{GHz}}\right)^{-0.7} \left(\frac{\theta}{\text{arcmin}}\right)^2$$

Confusion Limit

Let's design the ultimate high dynamic range image

10 Jy point source

1 μ Jy thermal noise

Avoid confusion limit

Reach DR of 10 Million to One

What could go wrong?

Image artifacts around bright sources limit dynamic range

Achieving high dynamic range requires advanced calibration and proper imaging

Standard Calibration: 10^3
Self-Calibration: $10^{4\sim5}$
Advanced Calibration: $10^{5\sim6+}$

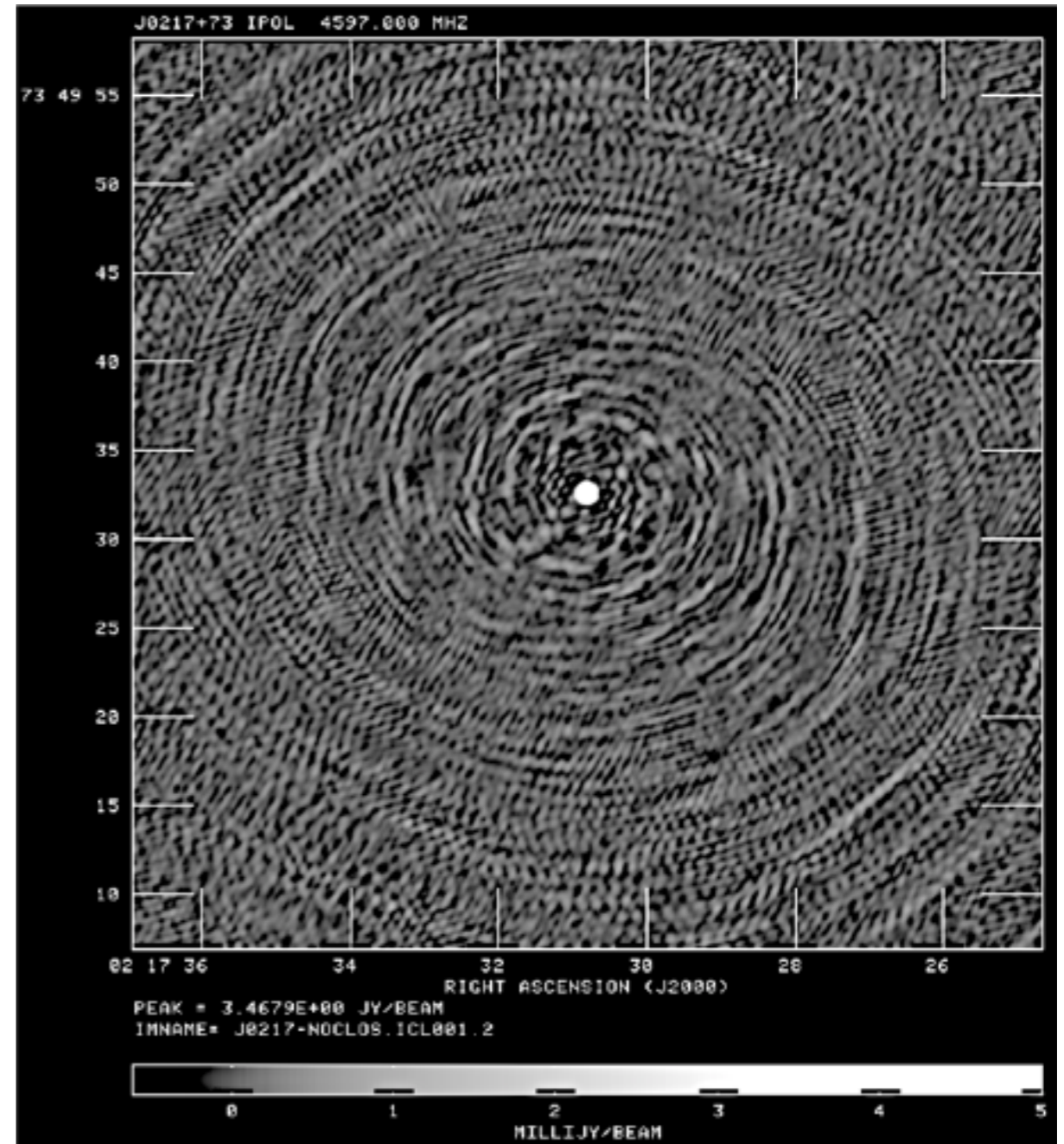


Image by R. Perley

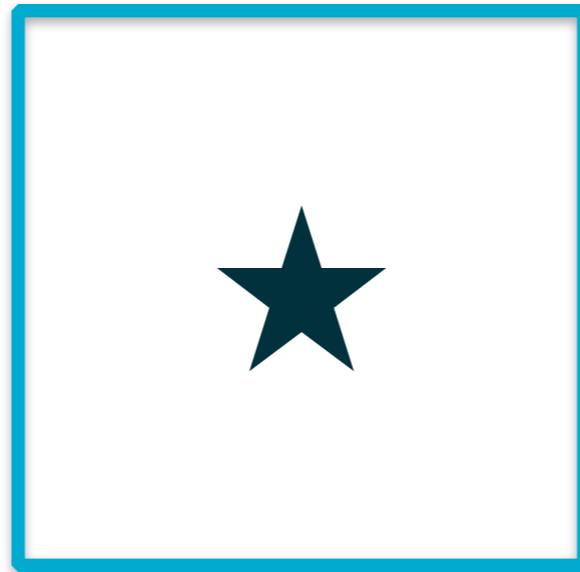
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Review of the *clean* algorithm



Dirty Image

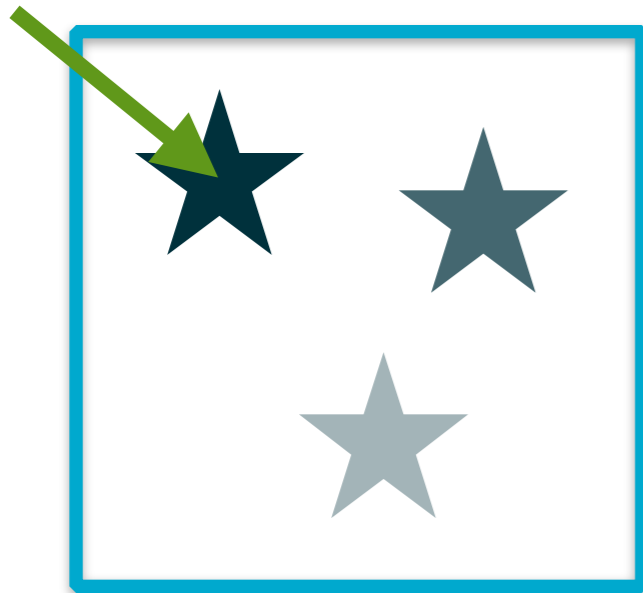


Dirty Beam



Model Image

Review of the *clean* algorithm



Dirty Image



Dirty Beam



Model Image

**Find the
brightest peak**

Review of the *clean* algorithm



Dirty Image

**Find the
brightest peak**



Dirty Beam

**Subtract the
dirty beam**



Model Image

Review of the *clean* algorithm

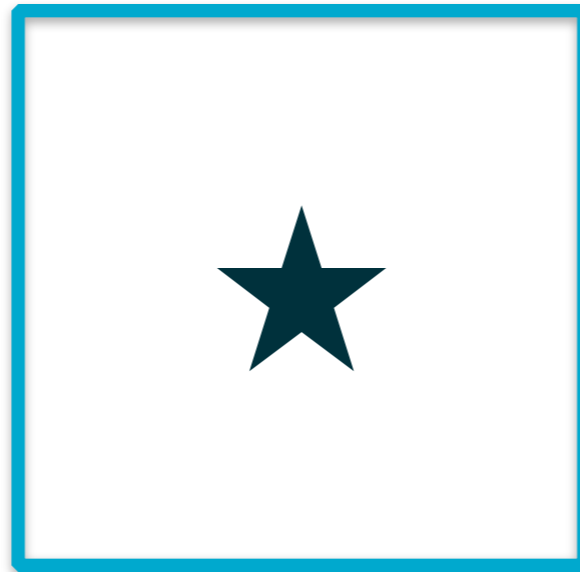


Review of the *clean* algorithm



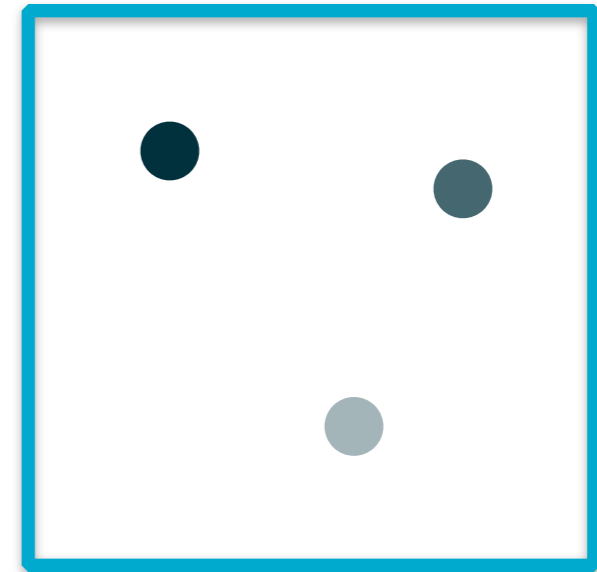
**Dirty Image
(Residual)**

**Find the
brightest peak**



Dirty Beam

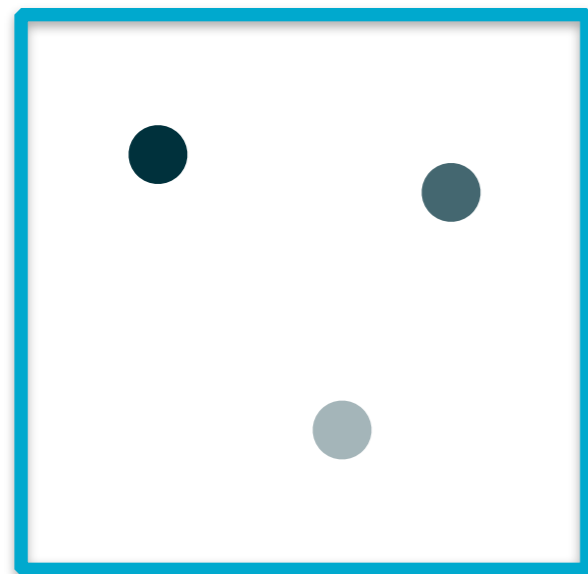
**Subtract the
dirty beam**



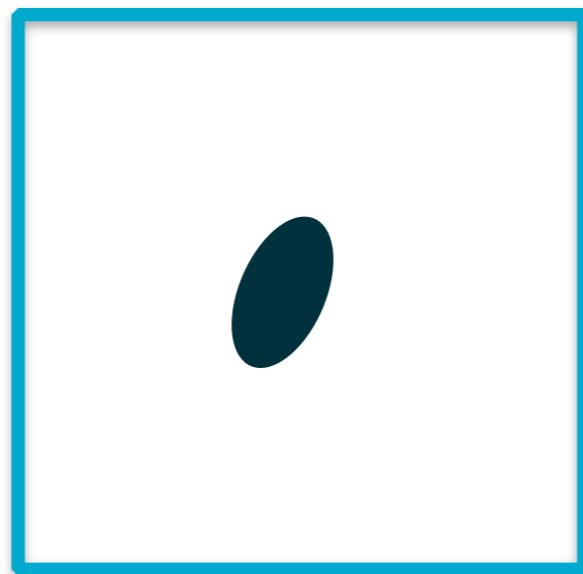
Model Image

**Add component
to model**

Review of the *clean* algorithm



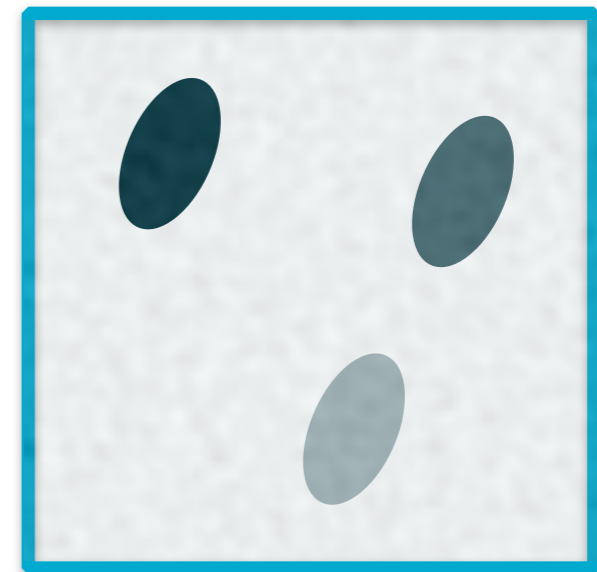
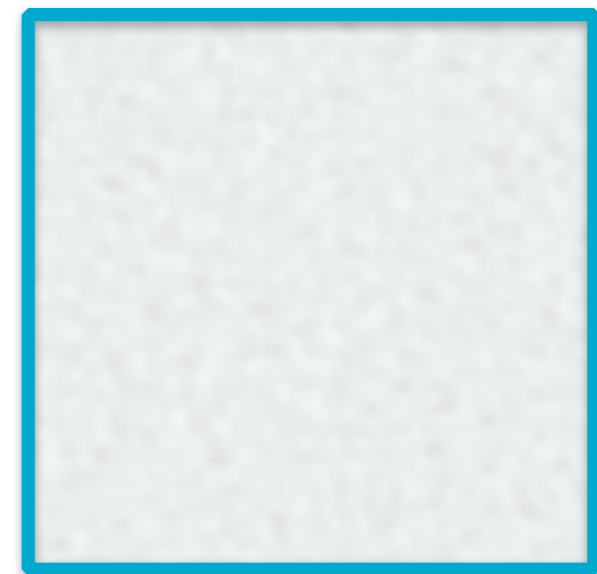
Model Image



Clean Beam



Residual Image



Restored Image

Best case:

Residual image is noise-like with a Gaussian distribution

Typical case:

Residual image has substantial non-Gaussian structures

Sources of image errors:

Refer to previous talks

Especially Emil's talk on Error Recognition

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Self-calibration is just like regular calibration

Use source's visibilities and model image (from clean) to solve for antenna-based gains

Works because complex gains are factored into $O(N)$ antenna-based quantities using $N(N-1)/2$ baseline-based quantities

Requires adequate signal-to-noise and decent model image

Self-calibration recipe

- 1. Solve and apply standard (external) calibration**
- 2. Split and clean the target field**
- 3. Solve for gain corrections using the clean model**
- 4. Apply corrections, split, re-image**
- 5. Solve for new gain corrections using the new clean model**
- 6. Apply new corrections, split, re-image**
- 7. Iterate**

Self-calibration recipe (a variant)

- 1. Solve and apply standard (external) calibration**
- 2. Split and clean the target field**
- 3. Solve for gain corrections using the clean model**
- 4. Apply corrections, split, re-image**
- 5. Return to step (3) but use model image from step (4)**
- 6. Iterate**

Self-calibration tips

Inspect the gain solutions for coherence

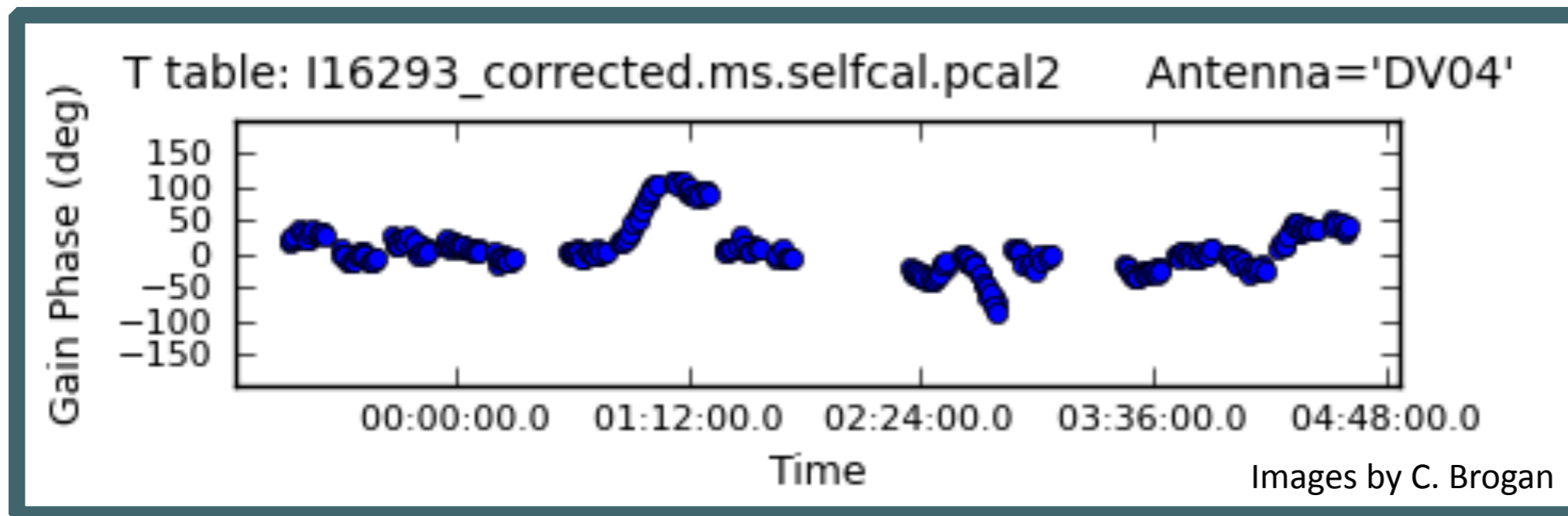
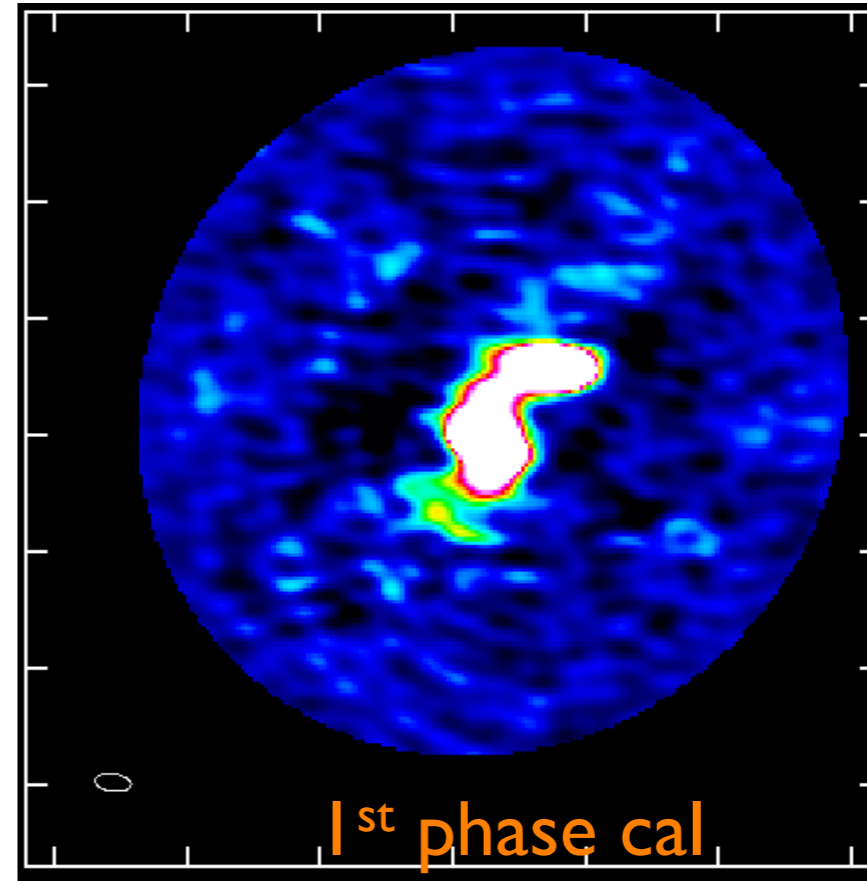
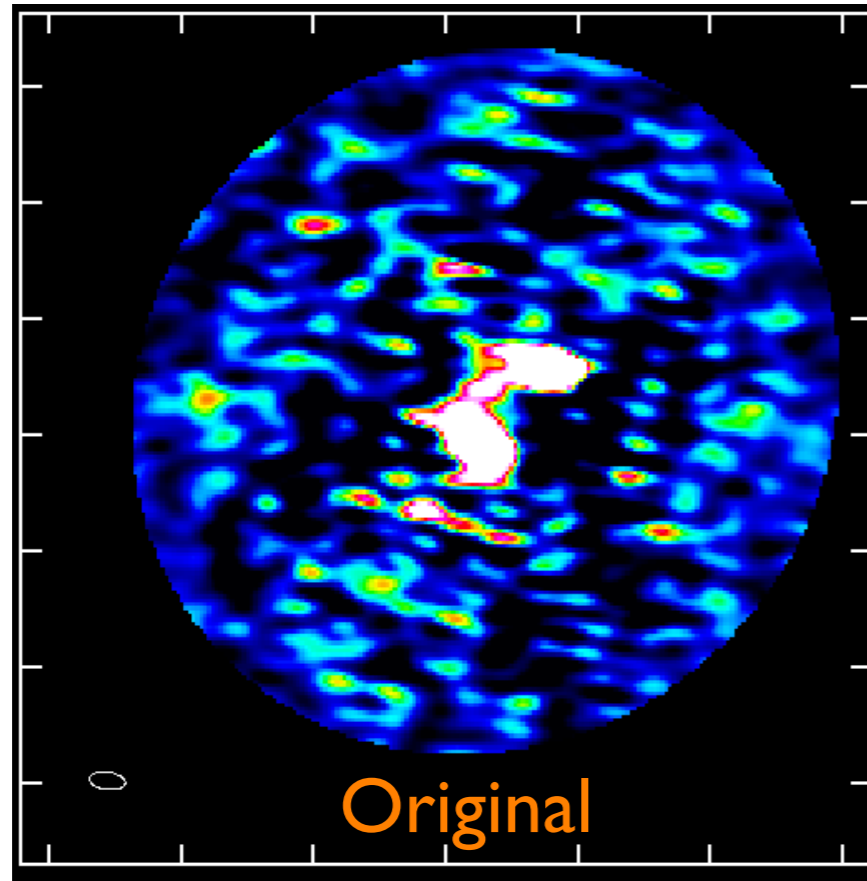
Apply phase-only corrections during initial iterations

Try including amplitude corrections in final iteration

Experiment with different averaging: time, freq, pol

Peak fluxes should increase and image RMS decrease

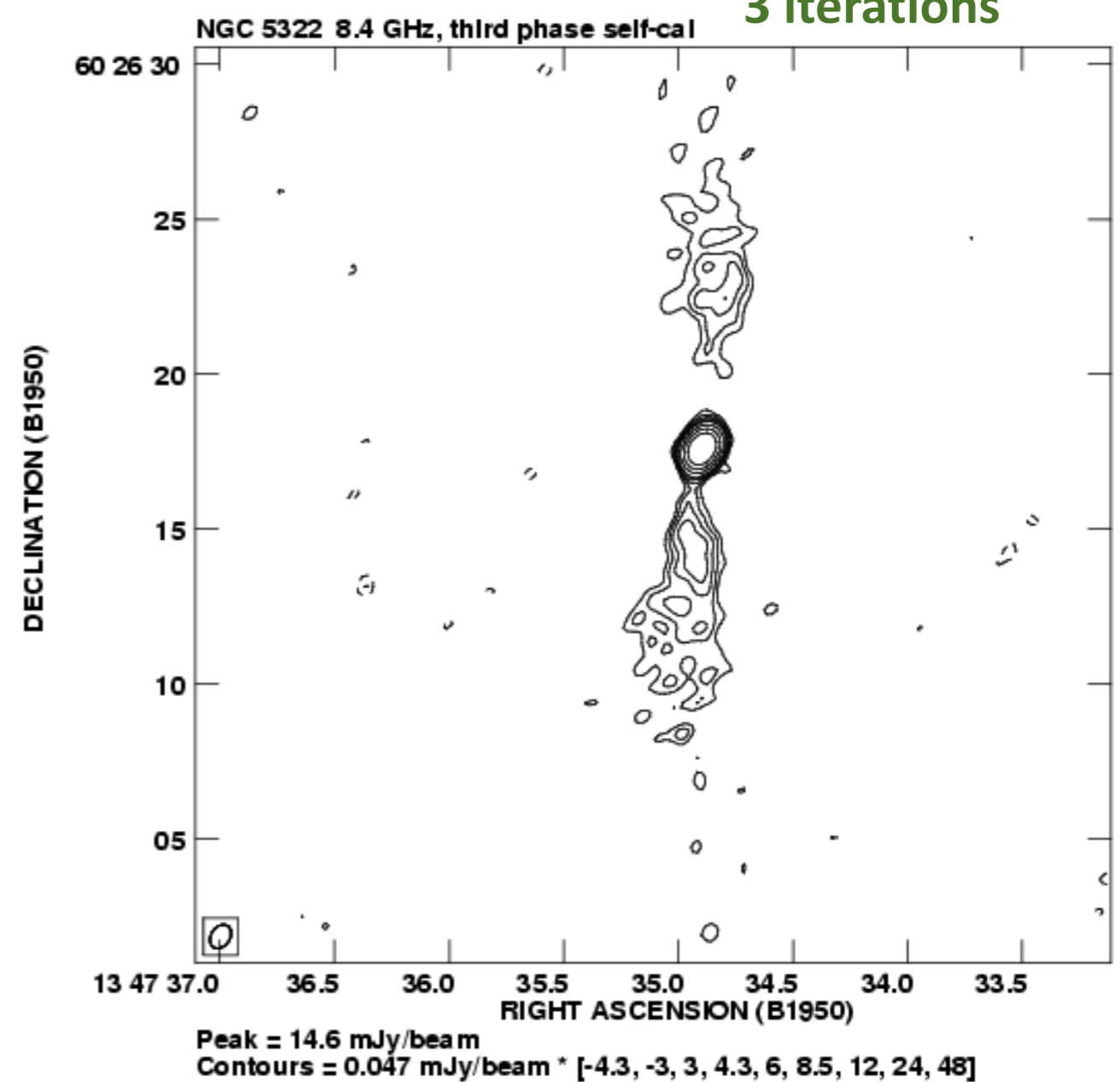
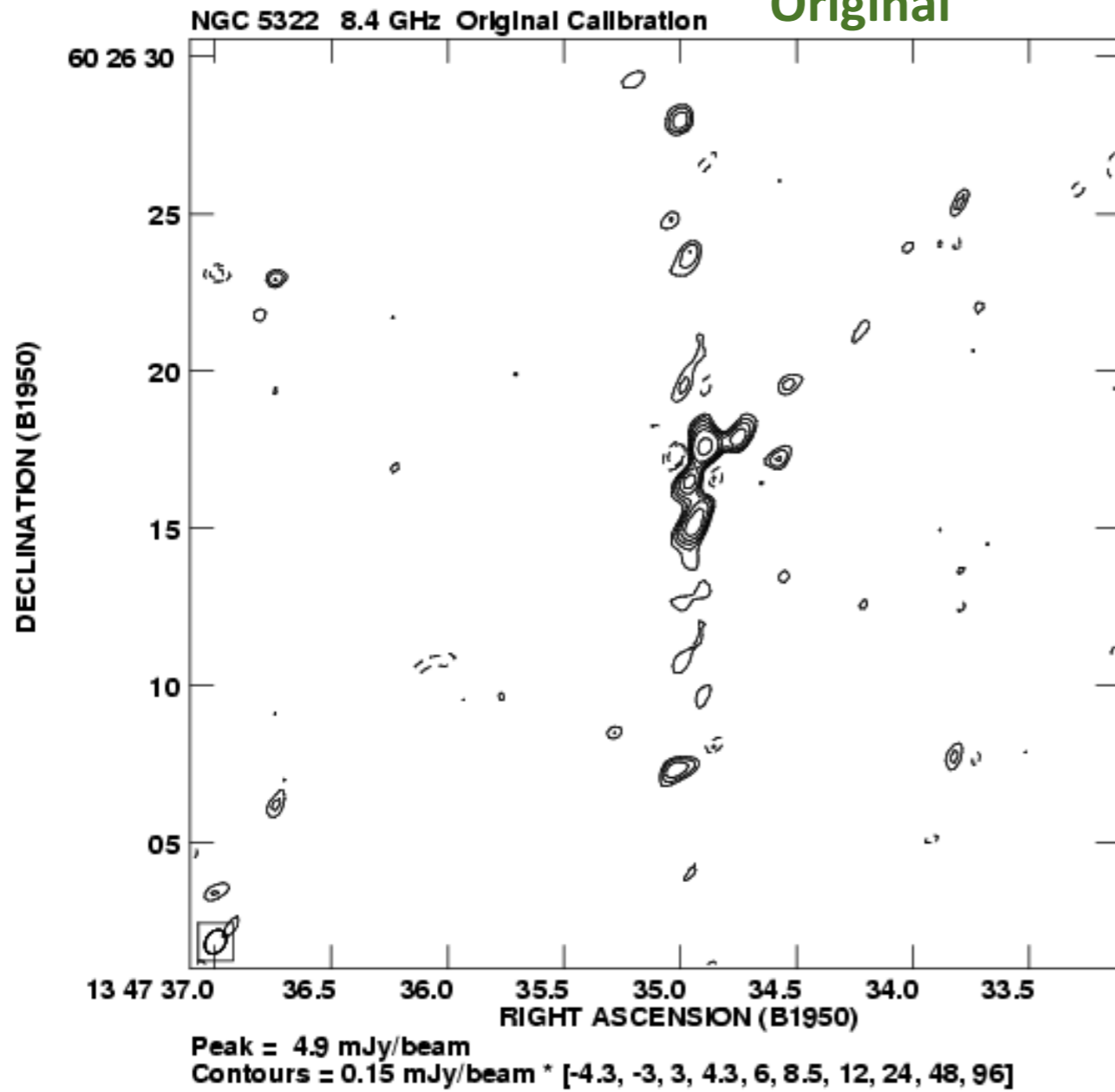
Self-calibration- example results



Self-calibration- example results

Original

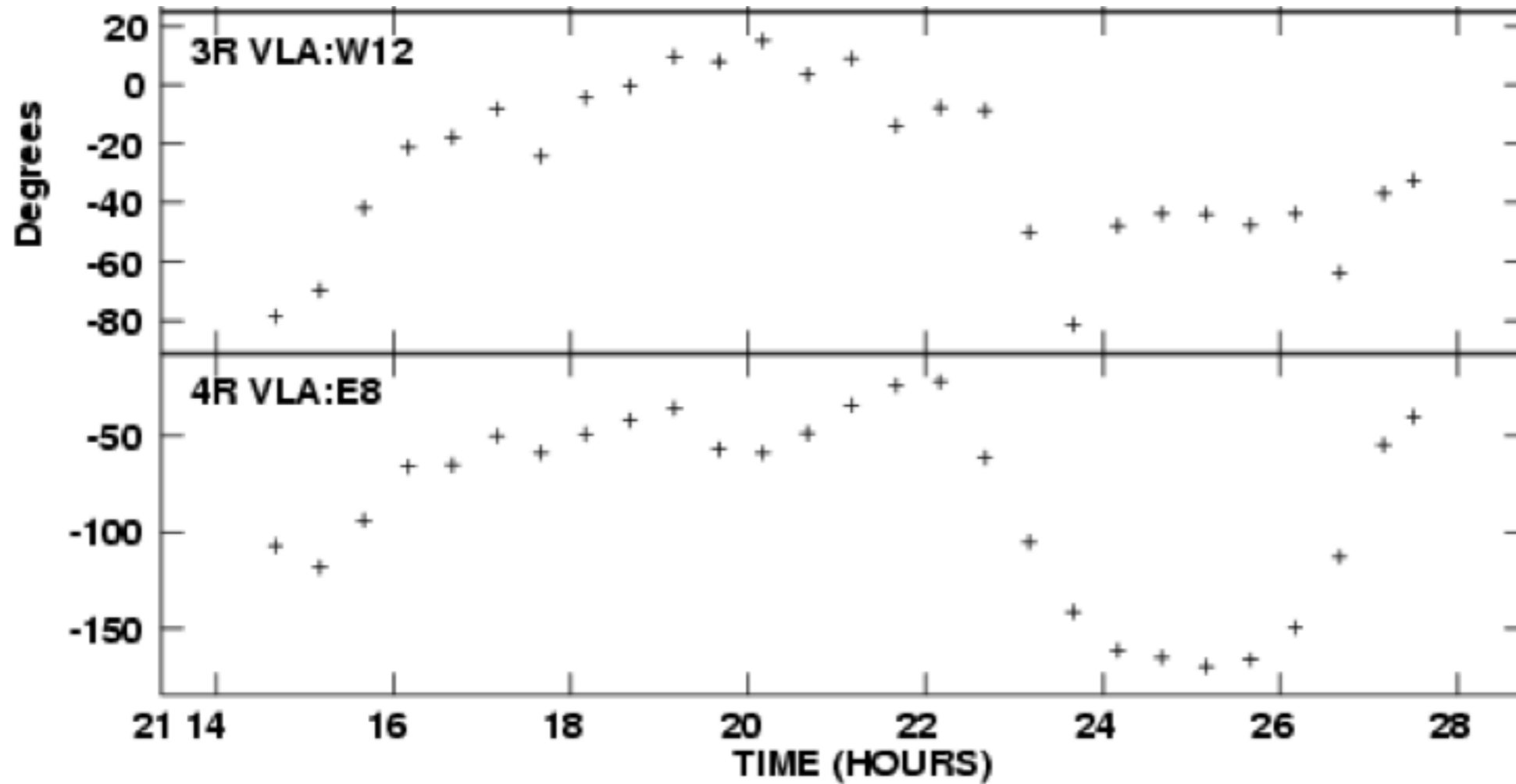
3 iterations



Images by M. Bietenholz

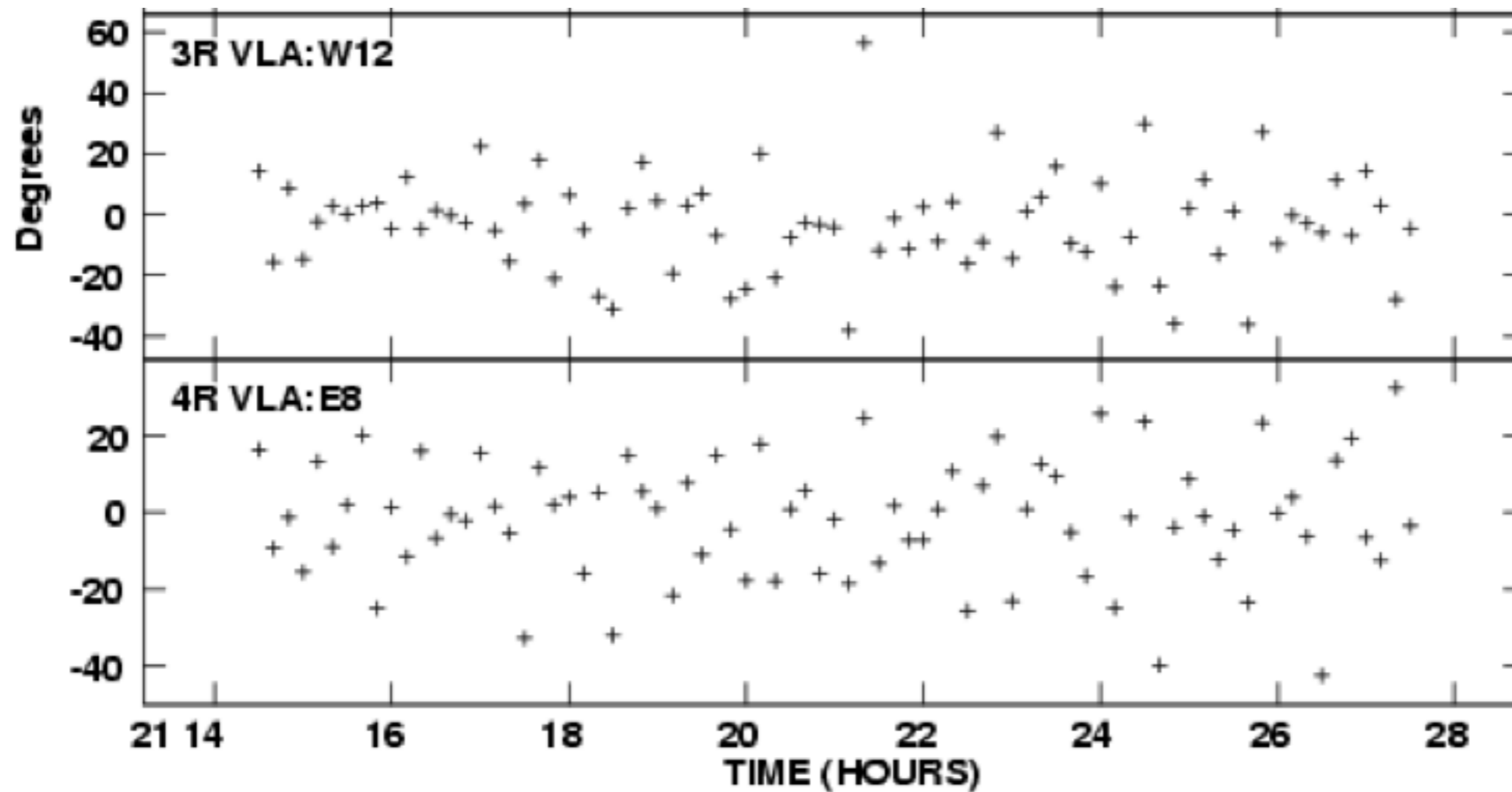
Self-calibration- example results

Good coherence



Self-calibration- example results

Higher order solutions



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Direction-dependent imaging errors

Errors are larger for bright sources further from the image center

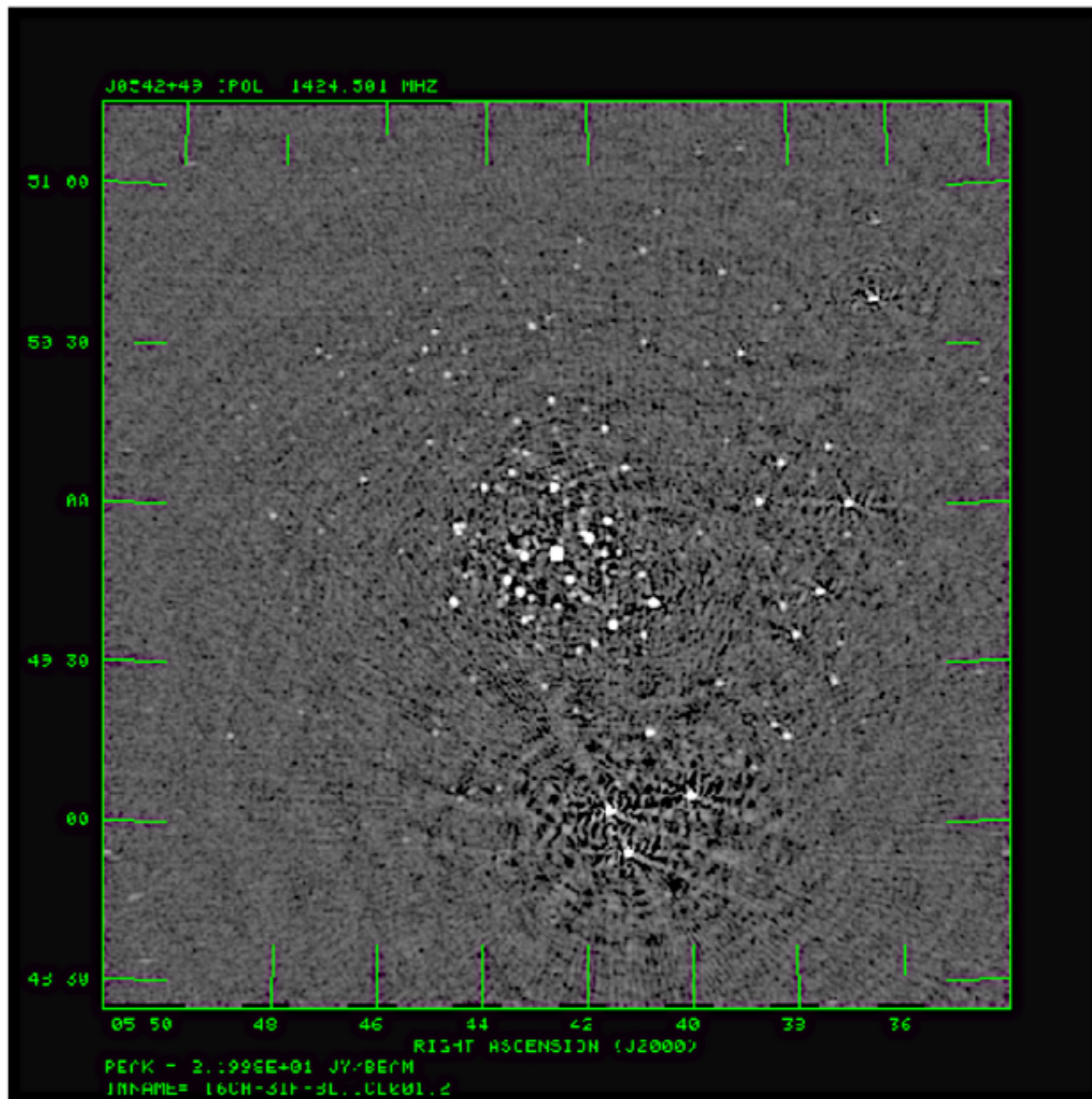
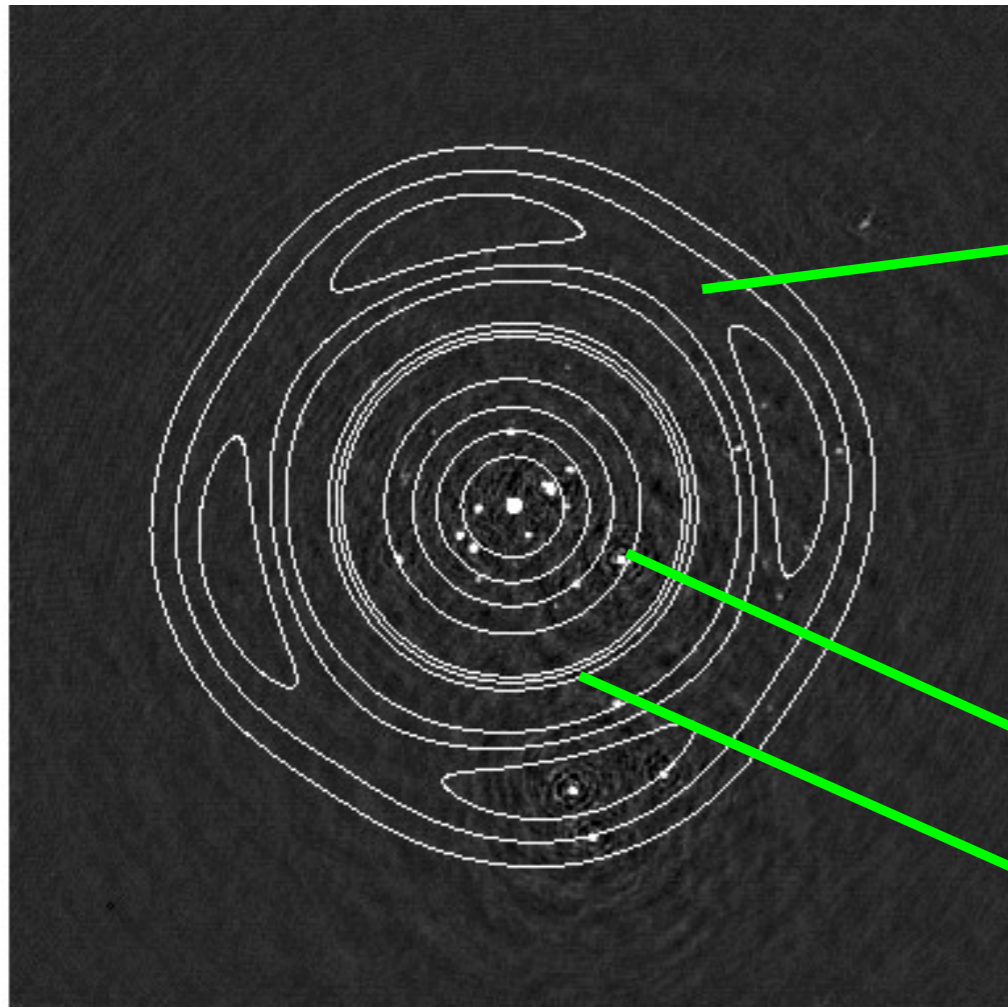


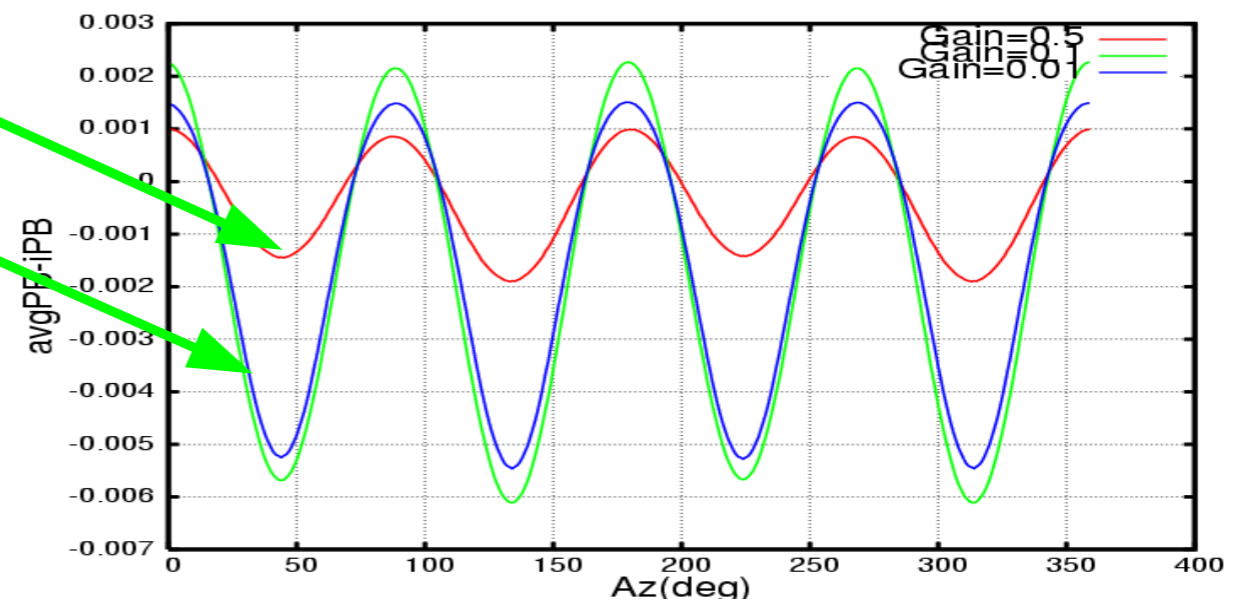
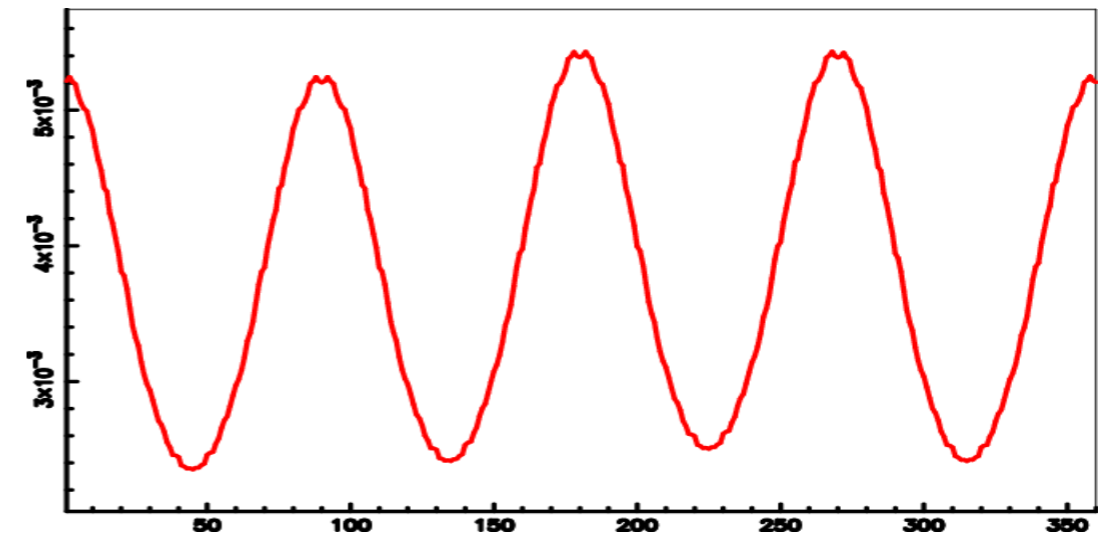
Image by R. Perley

Effect of the rotating primary beam pattern



Images by S. Bhatnagar

Time varying gain



A-Projection Algorithm

Incorporates the primary beam convolution function into the imaging algorithm

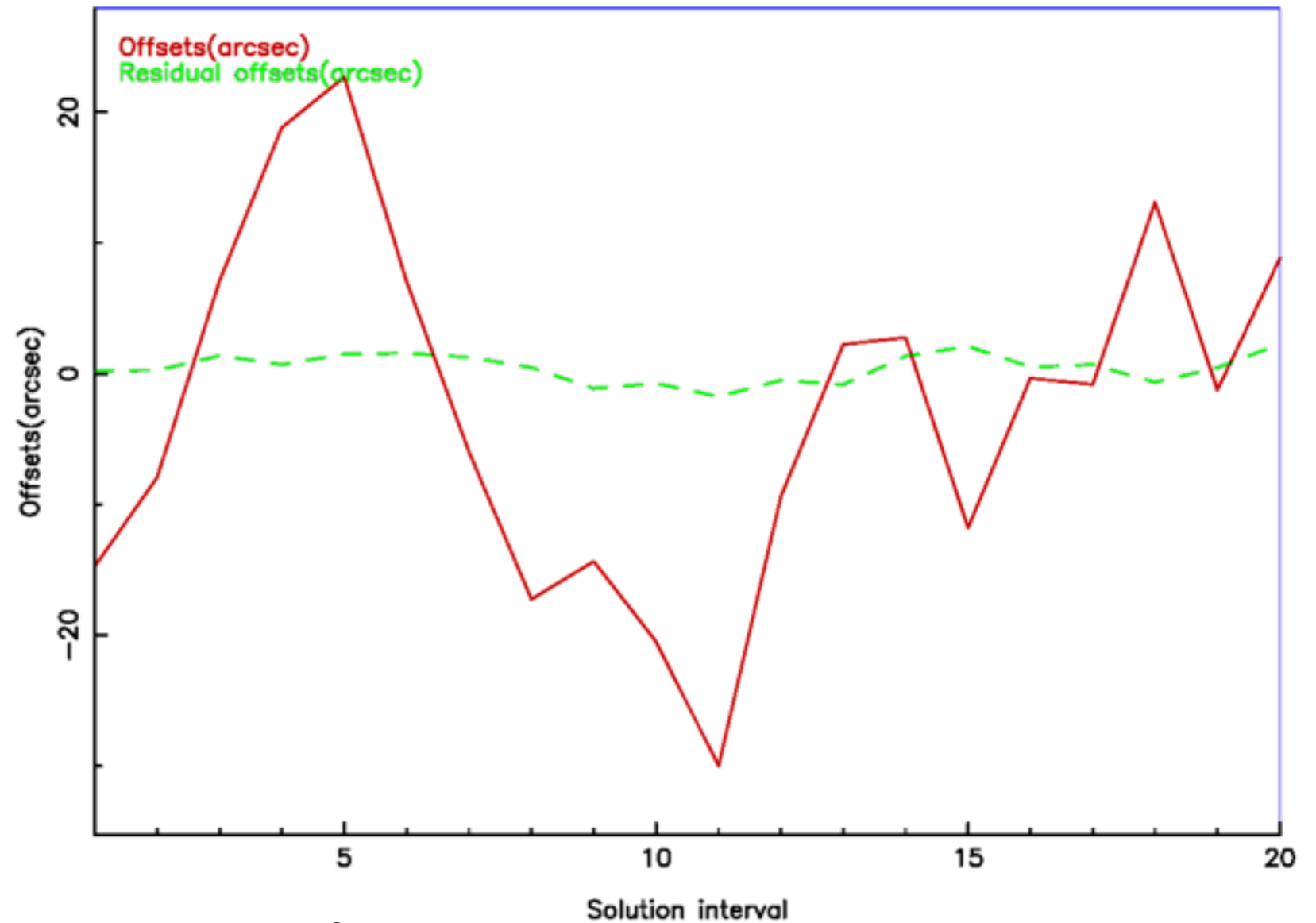
Accounts for rotation of (asymmetric) beam on the sky

Some implementations are available but not fully integrated with other imaging algorithms (eg. wideband)

Pointing Self-calibration

Solves for antenna, time based primary beam translation

Not yet implemented in
common data reduction
packages



EVLA Memo #84

Peeling

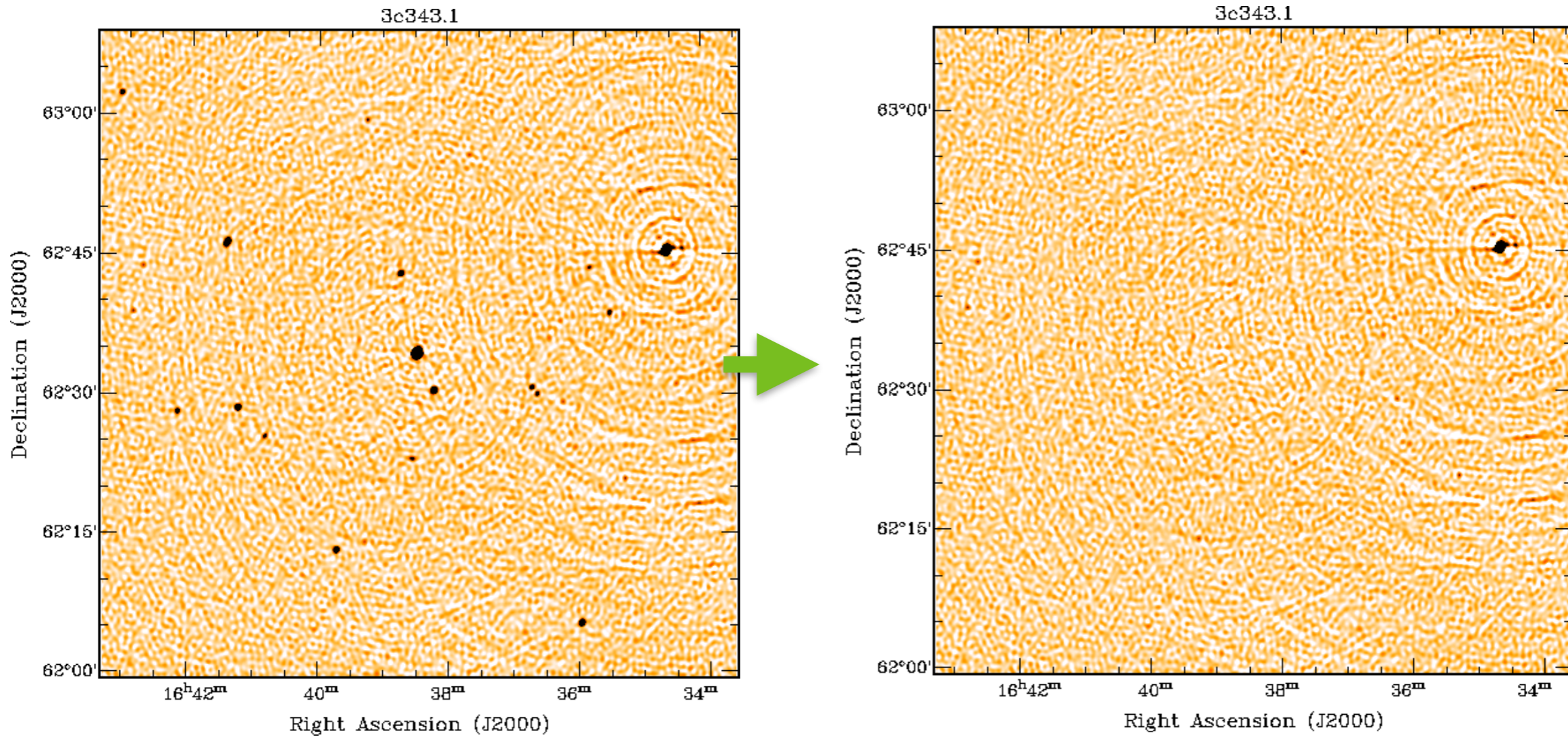
Works like self-cal but on one source at a time

Does not discriminate between sources of errors

Can be tedious to run on more than a couple sources

Peeling Recipe

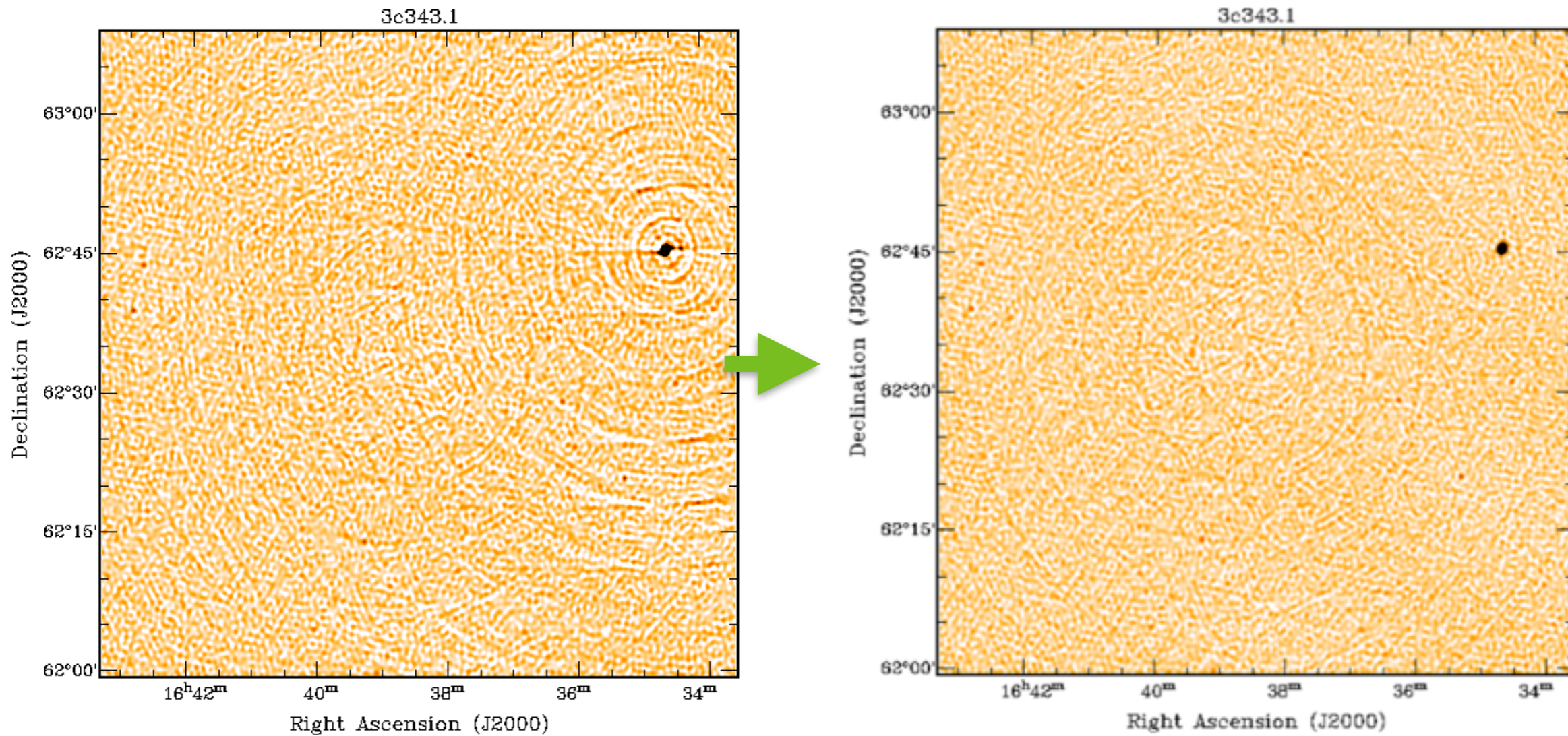
Model and UV-subtract all but one bright source



Images by T. Oosterloo

Peeling Recipe

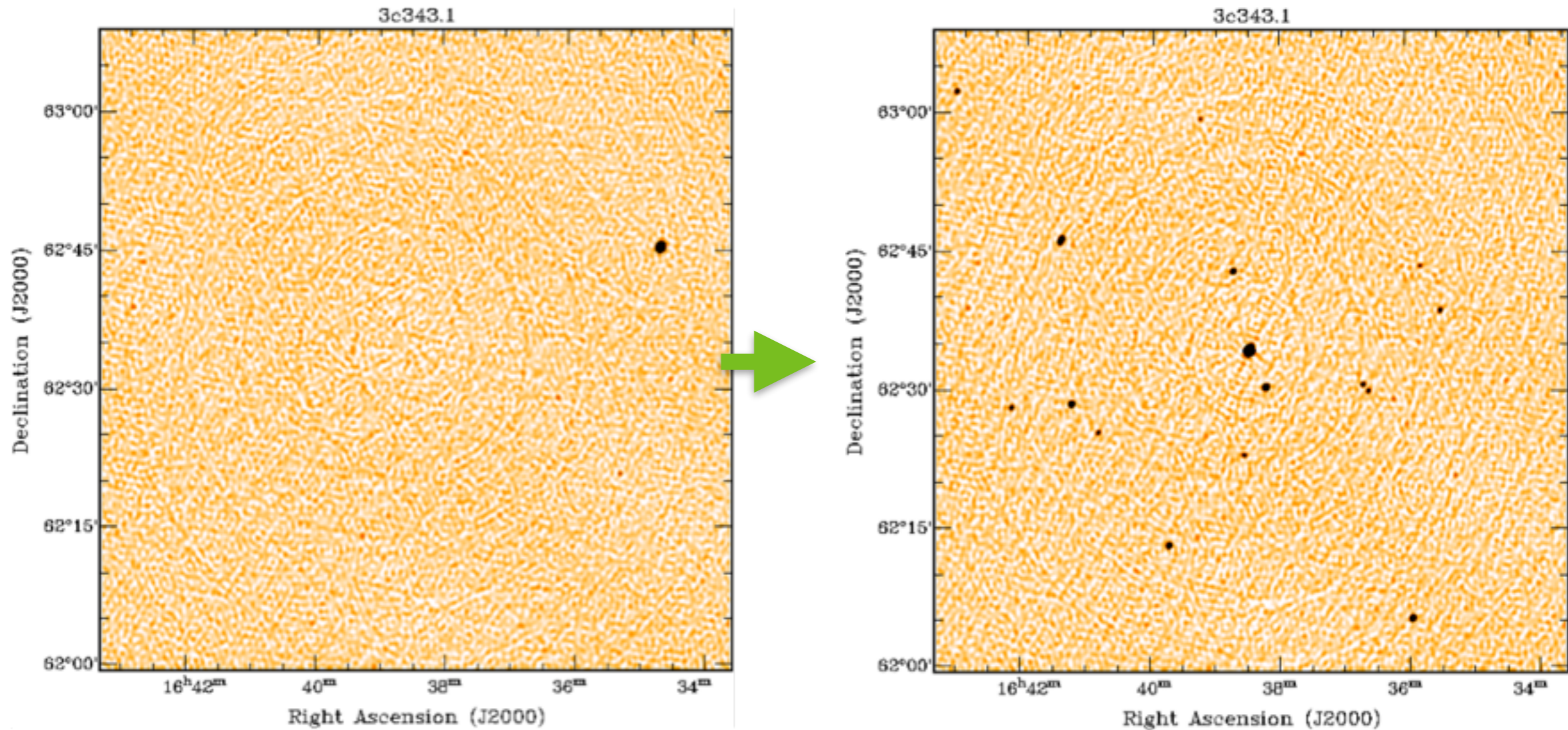
Self-calibrate and apply solutions



Images by T. Oosterloo

Peeling Recipe

Apply solutions to previous data, subtract far-field source, undo gain corrections



Images by T. Oosterloo

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Baseline-based Calibration

Visibilities are corrupted by *closure* errors (C_{ij})

$$V_{ij} = G_i G_j^* (1 + C_{ij}) S_{ij} + O_{ij} + n_{ij}$$

Closure errors are multiplicative
(larger error around brighter sources)

Closure errors do not factor out into antenna-based gains

Recipe for BL Calibration

Solve for baseline-based amplitude and phase

Use a bright calibrator field and a *very* good model

Divide the visibilities by the FT of the model

Average the remainder in time

Polarization Calibration

Flux of polarized sources can leak into Stokes I image

Flux of unpolarized sources can leak into Stokes I image

Off-axis unpolarized sources can appear polarized by the primary beam response and leak into Stokes I image

Full Direction-Dependent Jones Matrix Calibration

Solutions can address many effects without separating them by origin (eg. antenna pointing, pol leakage)

Can solve for calibration simultaneously and independently in multiple directions

Implemented in the MeqTrees package

This approach is essential for reaching the highest dynamic ranges

Full Direction-Dependent Jones Matrix Calibration

3.2 Million Dynamic Range

Current 'world record'

Calibrated with MeqTrees

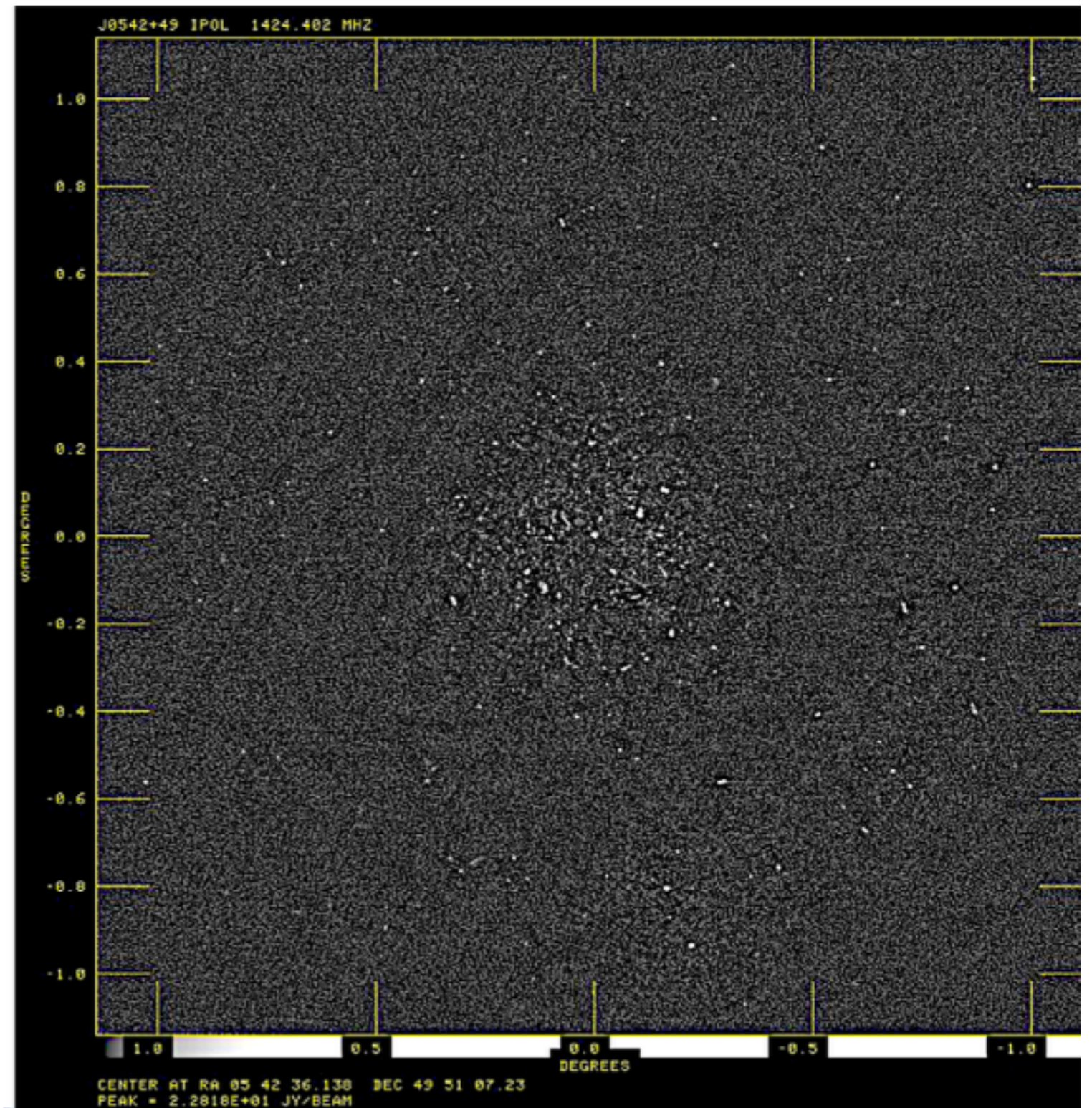


Image by R. Perley and O. Smirnov

Summary

Self calibration is not scary
Advanced methods are available
New algorithms are being developed

Only go as far as required by your science