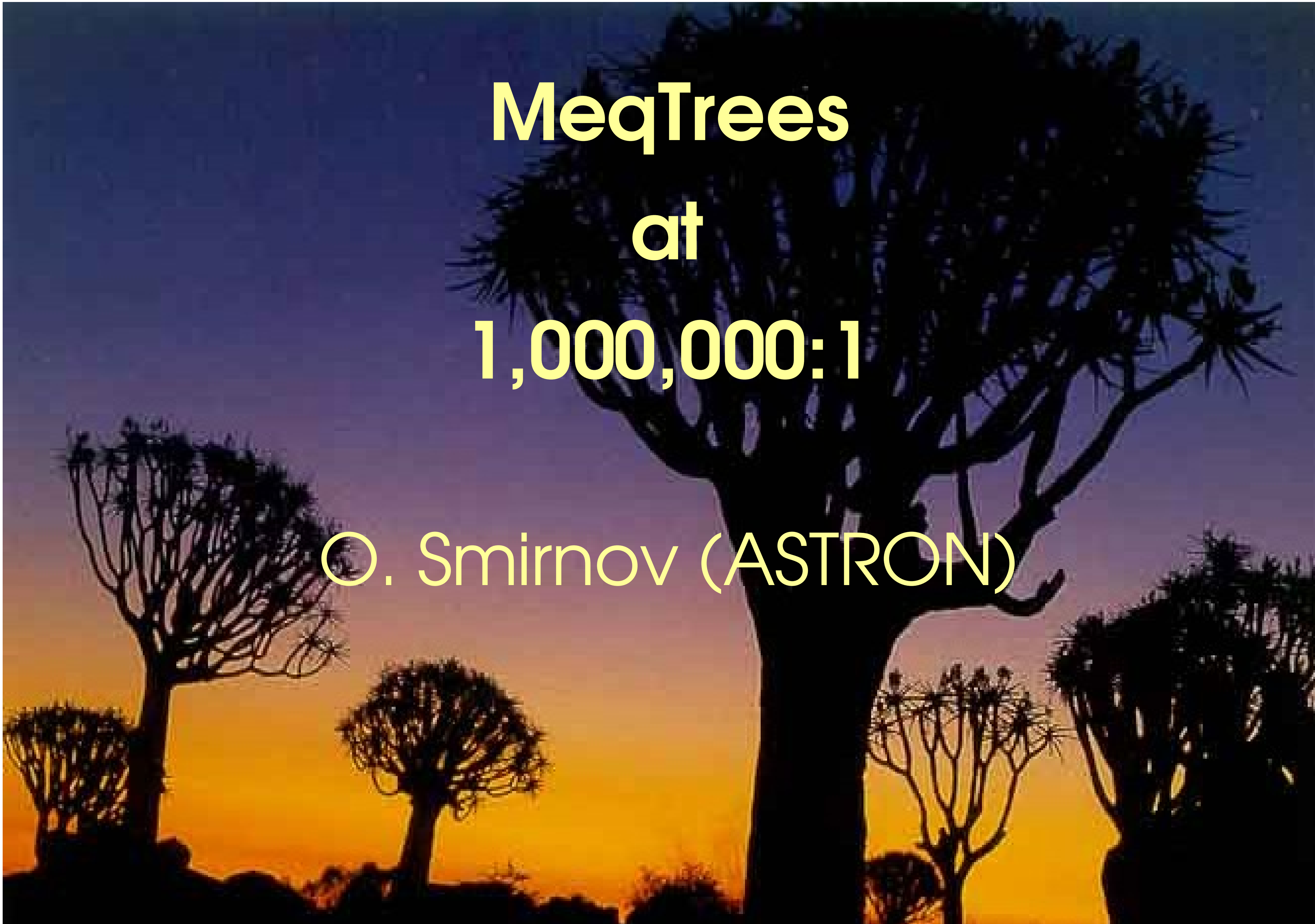


MeqTrees at 1,000,000:1

O. Smirnov (ASTRON)

NWO
Netherlands Organisation for Scientific Research

ASTRON

Introduction: Calibration In MeqTrees

- MeqTrees is (mostly) about building measurement equations, e.g.:

$$\boldsymbol{V}_{pq} = \boldsymbol{G}_p \left(\sum_s \boldsymbol{E}_p^{(s)} \boldsymbol{Z}_p^{(s)} \boldsymbol{K}_p^{(s)} \boldsymbol{B}^{(s)} \boldsymbol{K}_q^{(s)\dagger} \boldsymbol{Z}_q^{(s)\dagger} \boldsymbol{E}_q^{(s)\dagger} \right) \boldsymbol{G}_q^{\dagger}$$

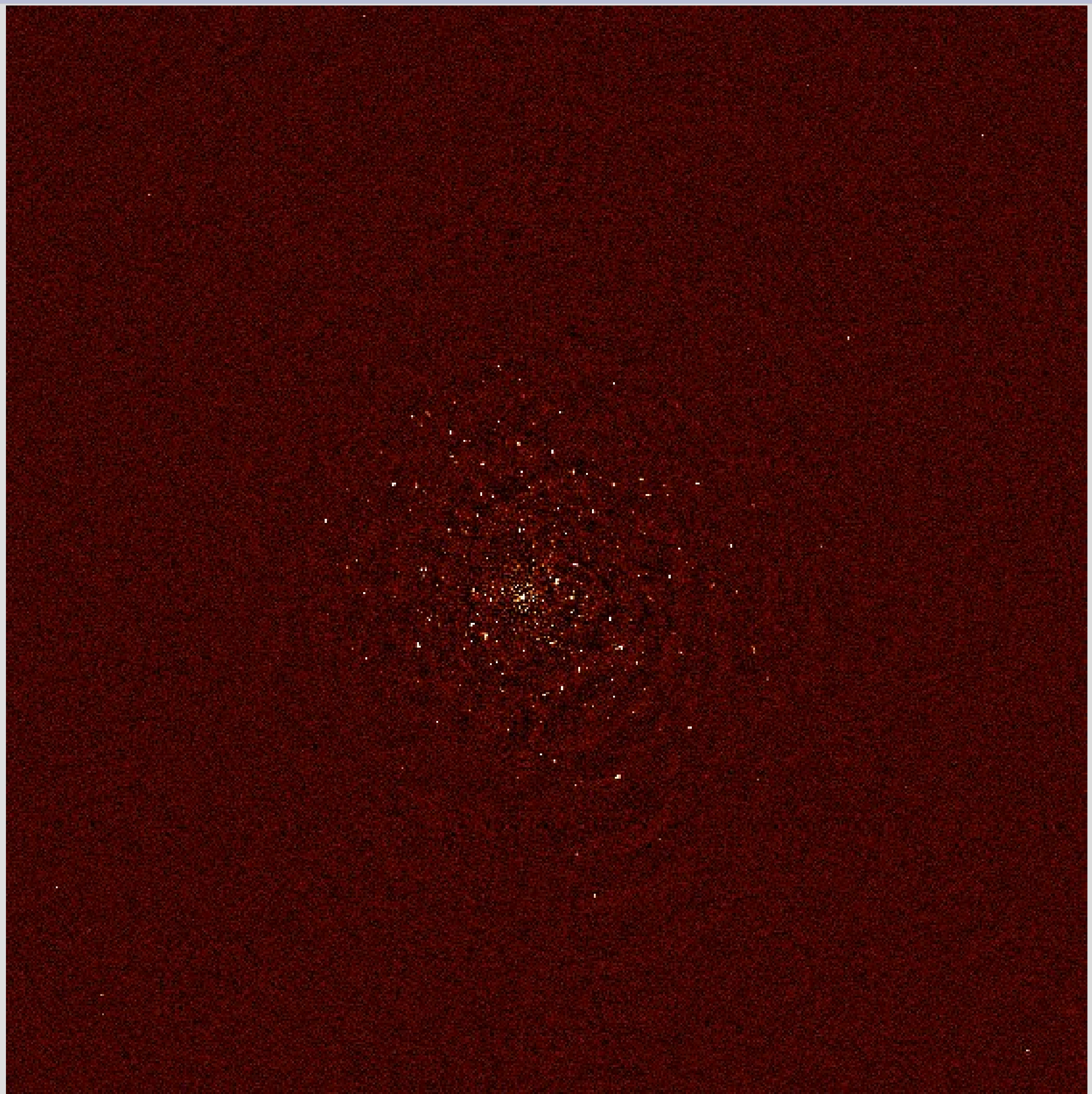
- An m.e. decomposes the observed visibility $\boldsymbol{V}_{pq}$ into intrinsic source properties and per-antenna *Jones terms*.
- Can describe an endless variety of (linear) physics.

“Beat NEWSTAR” Project

- Aim: demonstrate the advantages of ME-based calibration
  - by doing better than a legacy package
  - pick the right target...
- NEWSTAR (Netherlands East-West Synthesis Telescope Array Reduction)
  - not a terribly wide user base

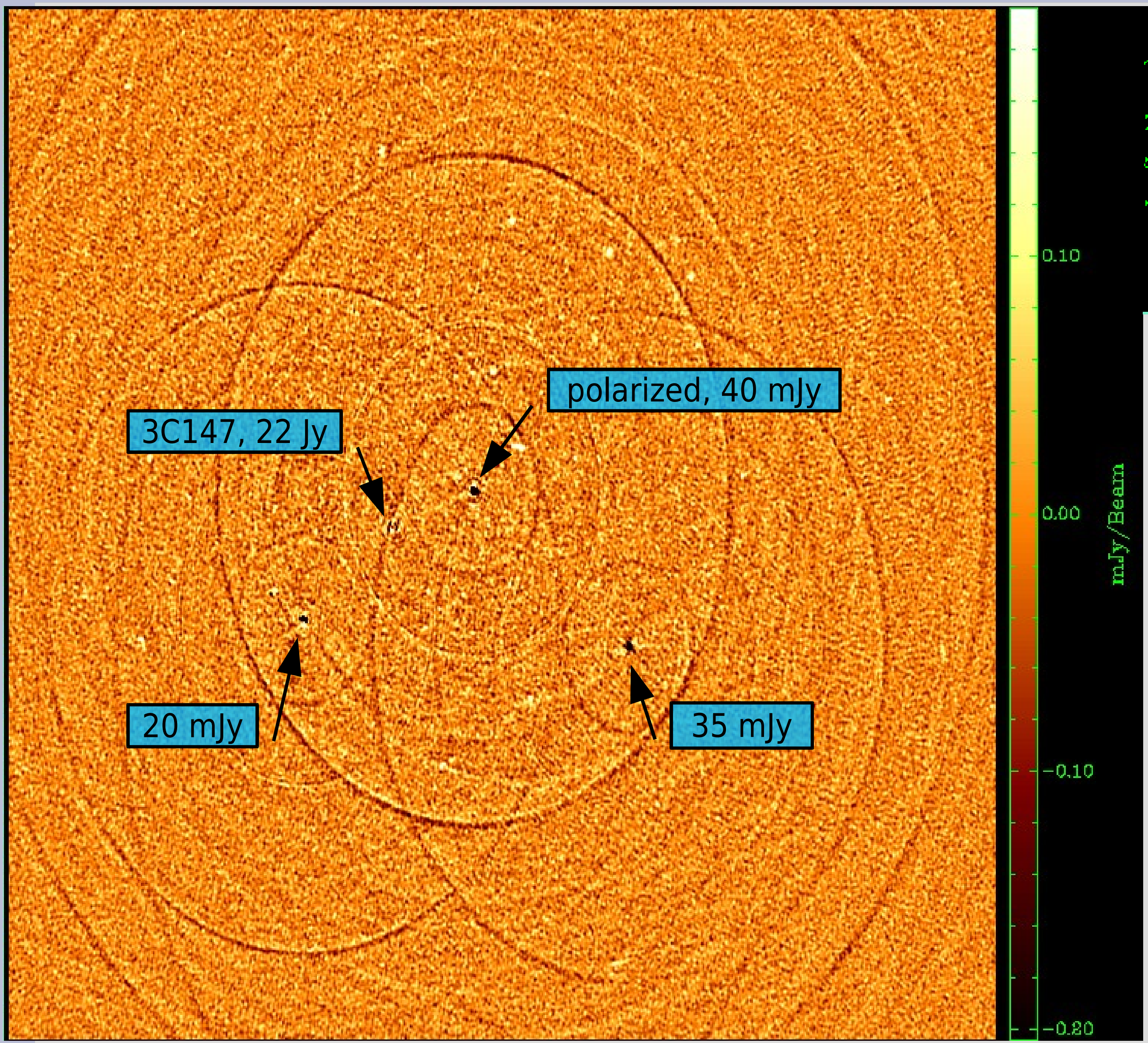
    ...but a very tall one!
  - WR holder in dynamic range ($\rightarrow$2 million)

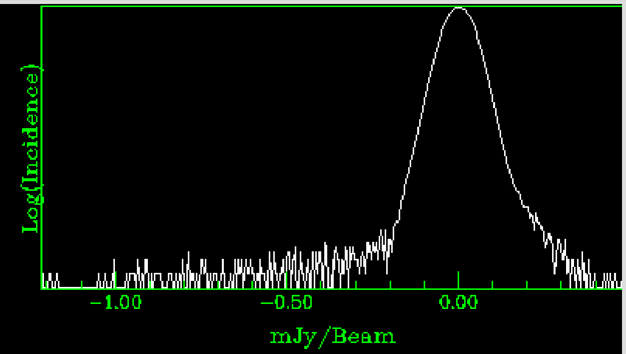
The 3C147 Field



- 1x12 hr WSRT 21cm observation
- 30sec. integration
- 8x64 channels 21cm B=160 MHz
- 3C147 is 22Jy
- NEWSTAR DR:
  - 1.5 million on-axis
  - 1000 off-axis

Best NEWSTAR Image





- Single band (56 channels)
- **298 sources** subtracted
- σ ~ 30uJy
- dominated by residuals from imperfectly-subtracted fainter sources
- ...which are caused by:

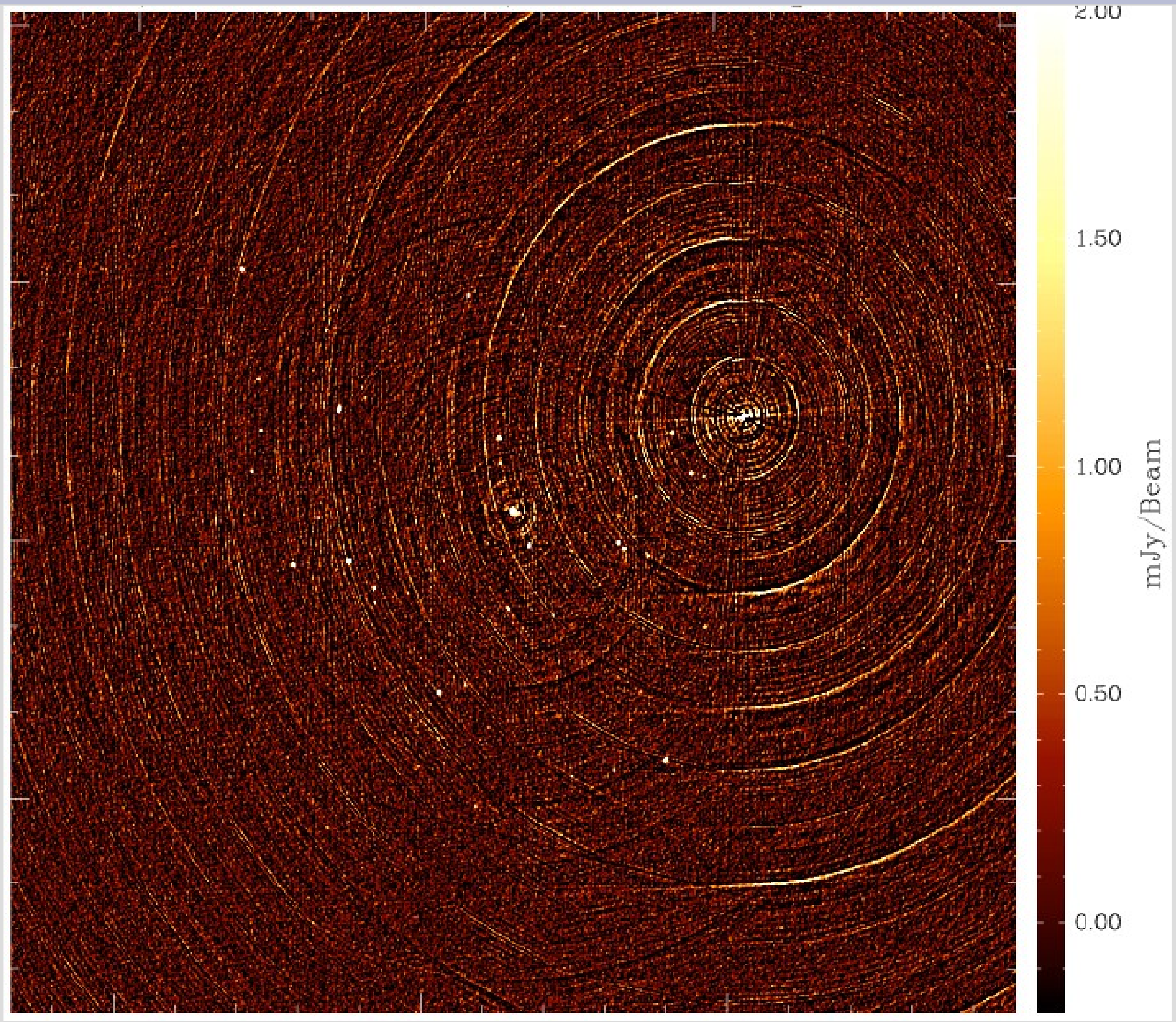
(a) imperfect sky model (more deconvolving would help)

(b) image plane effects: pointing errors, tropospheric refraction, ...
  - no direct cure in NEWSTAR

Calibrating For Image-Plane Effects I

- “Peeling” is different things to different people, but here we'll define it as:
  - selfcal on brightest source, subtract source
  - shift phase center to next source
  - selfcal, subtract, rinse & repeat
- Proven to work...
  - 3C343, 3C84, 3C196, etc. (Ger de Bruyn, Tom Oosterloo, Michiel Brentjens – NEWSTAR, Miriad)
- ...but cumbersome to use (miles of scripts)

3C343: A Typical Peeling Candidate



Calibrating For Image-Plane Effects II

- Weakness of peeling: interacting solutions when sources have comparable flux
  - need to iterate back and forth
- Alternative: simultaneous off-axis gain solutions (some call it “peeling” too.)
  - 3C343 (Michiel Brentjens -- MeqTrees)
- Alternative: solving for pointing errors
  - Sanjay Bhatnagar – CASA?
  - EVLA Memo 84, and this conference

The MeqTree Approach

- All sorts of ME's can be implemented. Let's start with this one:

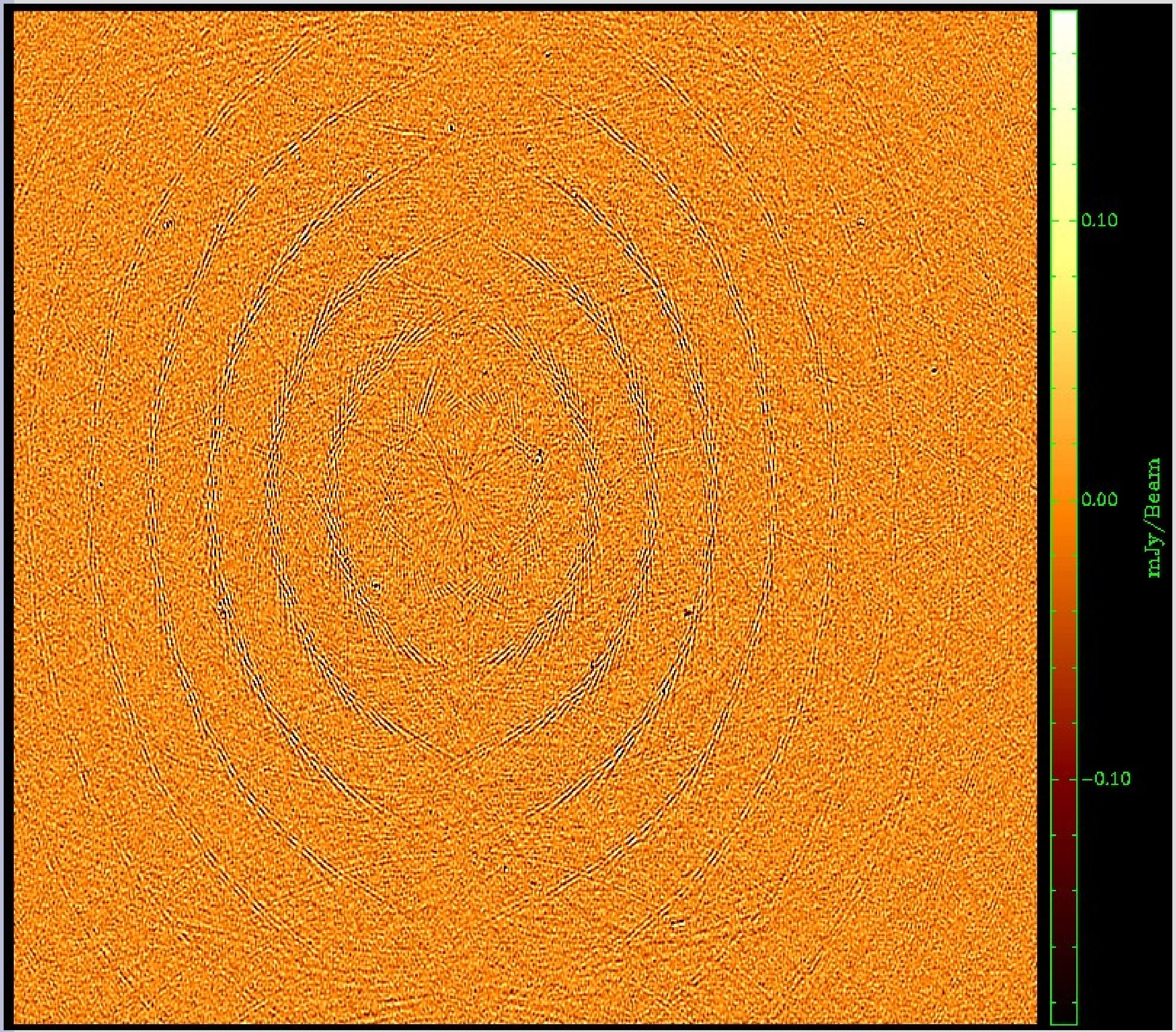
$$\mathbf{V}_{pq} = \underbrace{\mathbf{B}_p}_{\text{bandpass}} \underbrace{\mathbf{G}_p}_{\text{gain}} \underbrace{\left(\sum_s \underbrace{\mathbf{E}_p^{(s)}}_{\text{beam}} \underbrace{\mathbf{X}_{pq}}_{\text{source coherency}} \mathbf{E}_q^{(s)\dagger} \right)}_{\text{sum over sources}} \mathbf{G}_q^\dagger \mathbf{B}_q^\dagger$$

$\mathbf{E}_p^{(s)}$ is an analytic expression, $E(l, m, \nu) = \cos^3(C\nu\sqrt{l^2+m^2})$

$\mathbf{G}_p(t)$ is a solvable

$\mathbf{B}_p(\nu)$ is a solvable (with a long-scale time variation)

Bandpass Artifacts



- Residual pattern from 3C147 due to *bandpass instability.*
- We do a separate **B** solution every 30 min.
- Error pattern caused by variations in actual bandpass over the solution interval
  - error ~ 1/10,000
- We can mitigate this by making ***B*** a 1st-degree polynomial in time
  - error ~ 1/500,000
  - close to noise level but plainly visible
- Further increase polynomial degree?
  - or spline?

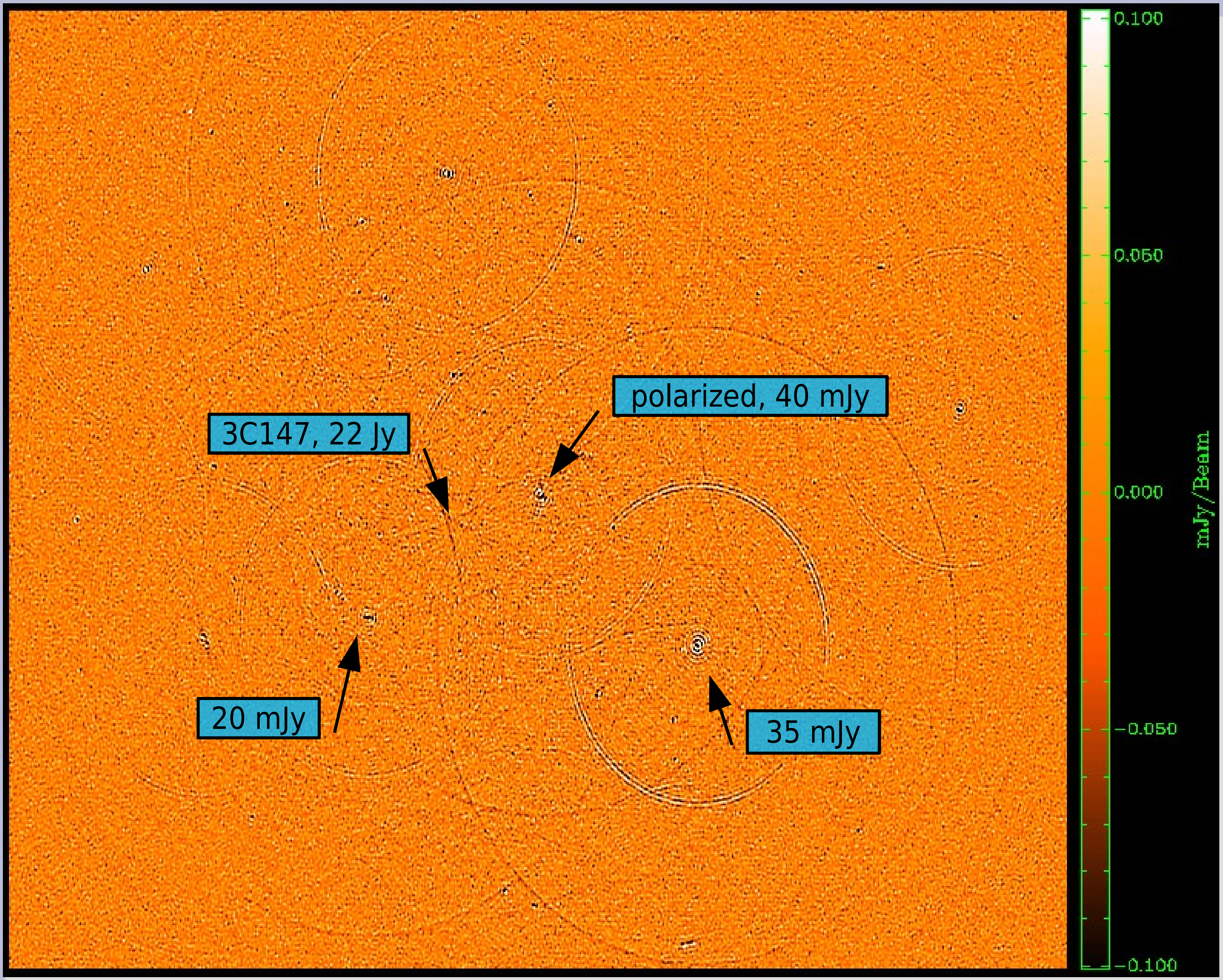
Dropping The Bandpass

- Do a per-channel selfcal
  - with sufficient S/N, why not?
  - this is what Ger does in NEWSTAR
- In M.E. terms:

$$\boldsymbol{V}_{pq} = \overbrace{\boldsymbol{G}_p}^{\text{gain \& bandpass}} \underbrace{\left(\sum_s \overbrace{\boldsymbol{E}_p^{(s)}}^{\text{beam}} \overbrace{\boldsymbol{X}_{pq}}^{\text{source coherency}} \boldsymbol{E}_q^{(s)\dagger} \right)}_{\text{sum over sources}} \boldsymbol{G}_q^{\dagger}$$

$\boldsymbol{G}_p(\nu, t)$ solved separately at each ν, t point.

Seeing The Pointing Errors



- Residual image, 298 sources subtracted
- Per-channel selfcal + closure errors
- Qualitatively similar to NEWSTAR map (uniform vs. radial weighting was used)
- Dominant feature is residuals from off-axis sources

Solving For Pointing Errors

- Bhatnagar's approach, in terms of our ME:

$$\boldsymbol{V}_{pq} = \underbrace{\overbrace{\boldsymbol{G}_p}^{\text{gain \& bandpass}} \left(\sum_s \overbrace{\boldsymbol{E}_p^{(s)}}^{\text{beam}} \overbrace{\boldsymbol{X}_{pq}}^{\text{source coherency}} \boldsymbol{E}_q^{(s)\dagger} \right)}_{\text{sum over sources}} \boldsymbol{G}_q^\dagger$$

Instead of using $\boldsymbol{E}_p^{(s)} \equiv E(l, m, \nu)$ for all p,

offset the beam pattern at each antenna p by $\Delta l_p, \Delta m_p$:

$$\boldsymbol{E}_p(l, m, \nu) = E(l + \Delta l_p, m + \Delta m_p, \nu)$$

...and solve for the offsets.

Differential Gains

- Or we can introduce differential gains:

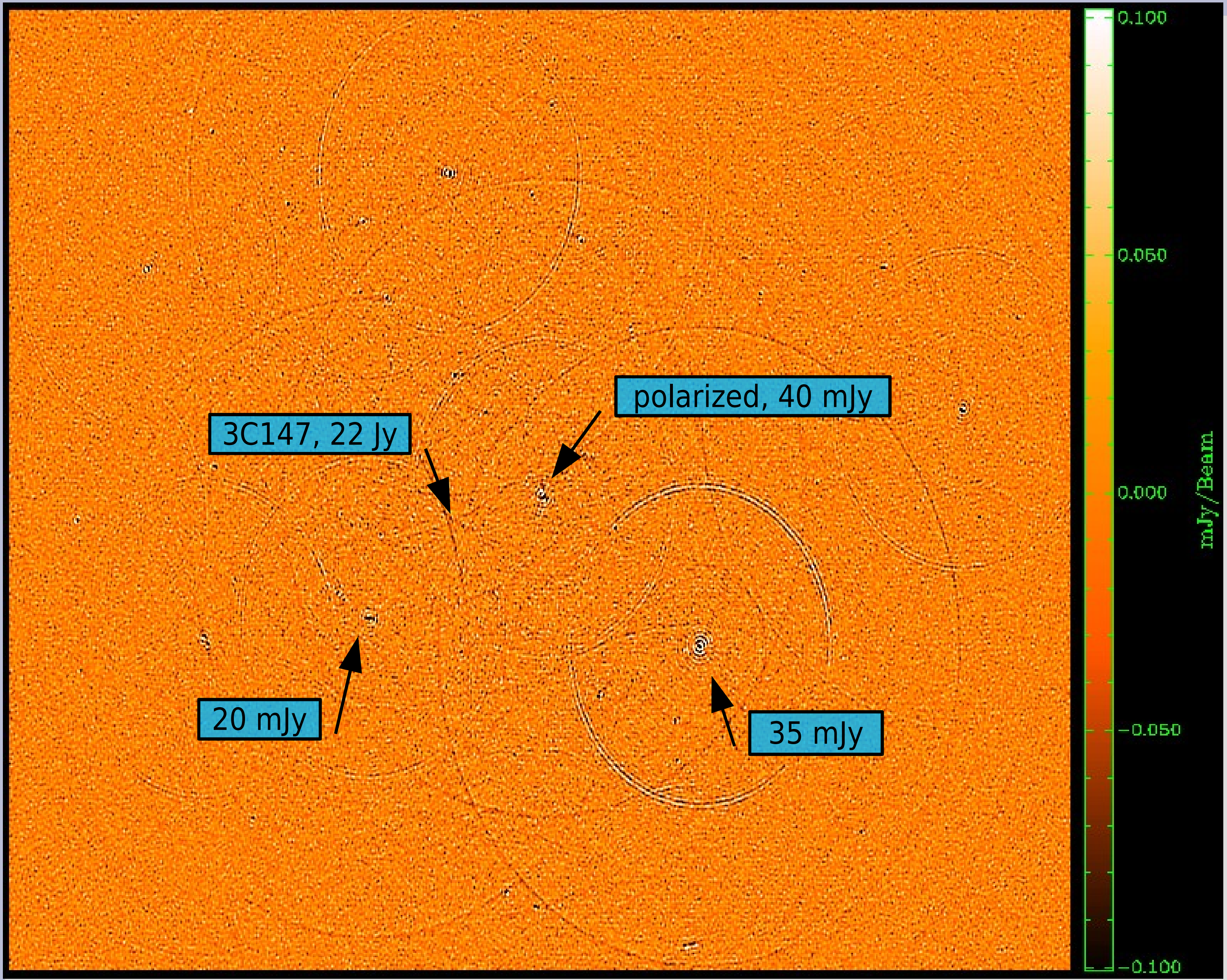
$$\boldsymbol{V}_{pq} = \overbrace{\boldsymbol{G}_p}^{\text{gain \& bandpass}} \underbrace{\left(\sum_s \overbrace{\Delta \boldsymbol{E}_p^{(s)}}^{\text{differential gain}} \overbrace{\boldsymbol{E}_p^{(s)}}^{\text{beam}} \overbrace{\boldsymbol{X}_{pq}}^{\text{source coherency}} \boldsymbol{E}_q^{(s)\dagger} \Delta \boldsymbol{E}_q^{(s)\dagger} \right)}_{\text{sum over sources}} \boldsymbol{G}_q^{\dagger}$$

$\Delta \boldsymbol{E}_p^{(s)}$ is frequency-independent, slowly varying in time.

Solvable for a handful of "troublesome" sources,

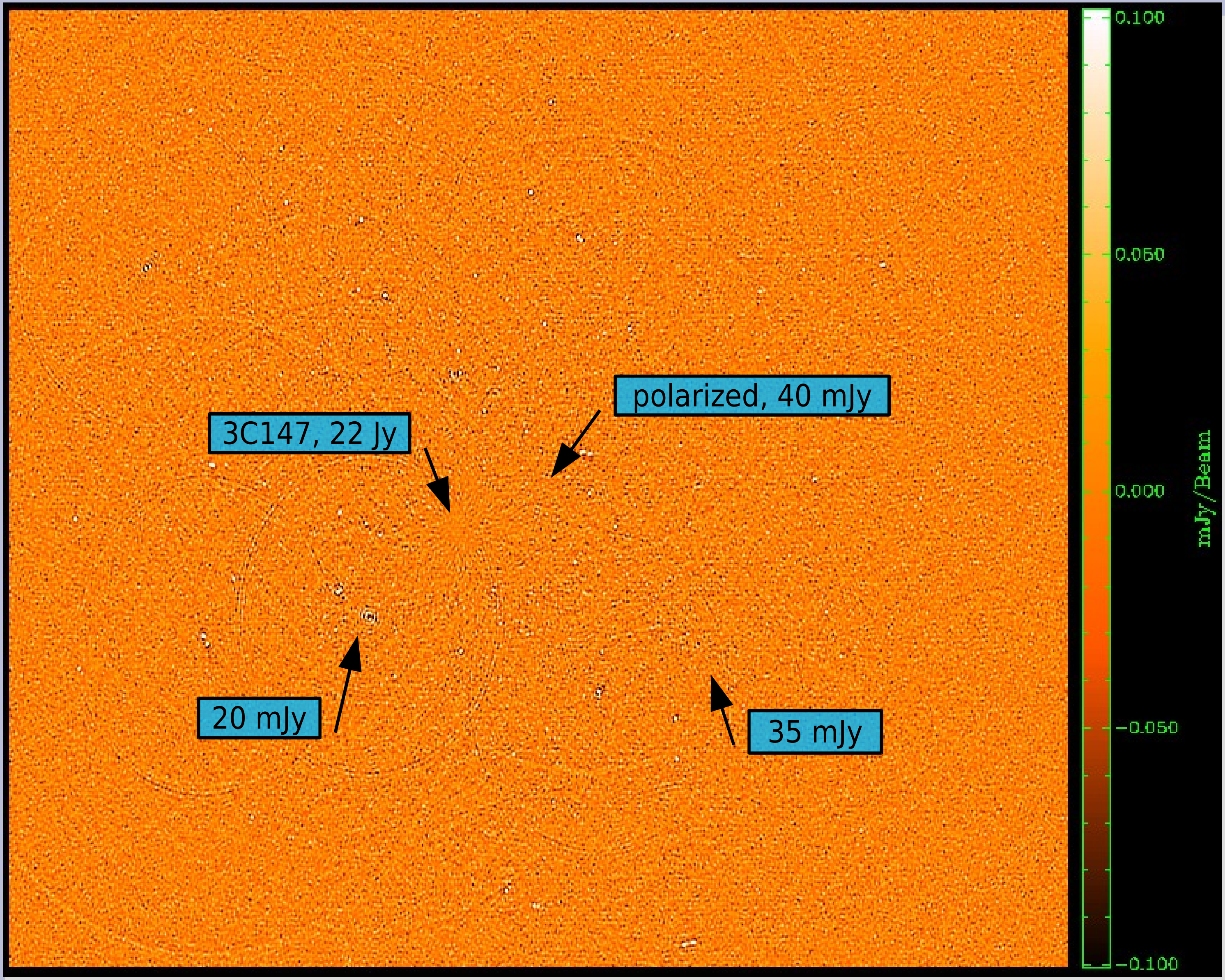
and set to unity for the rest.

Flyswatter I



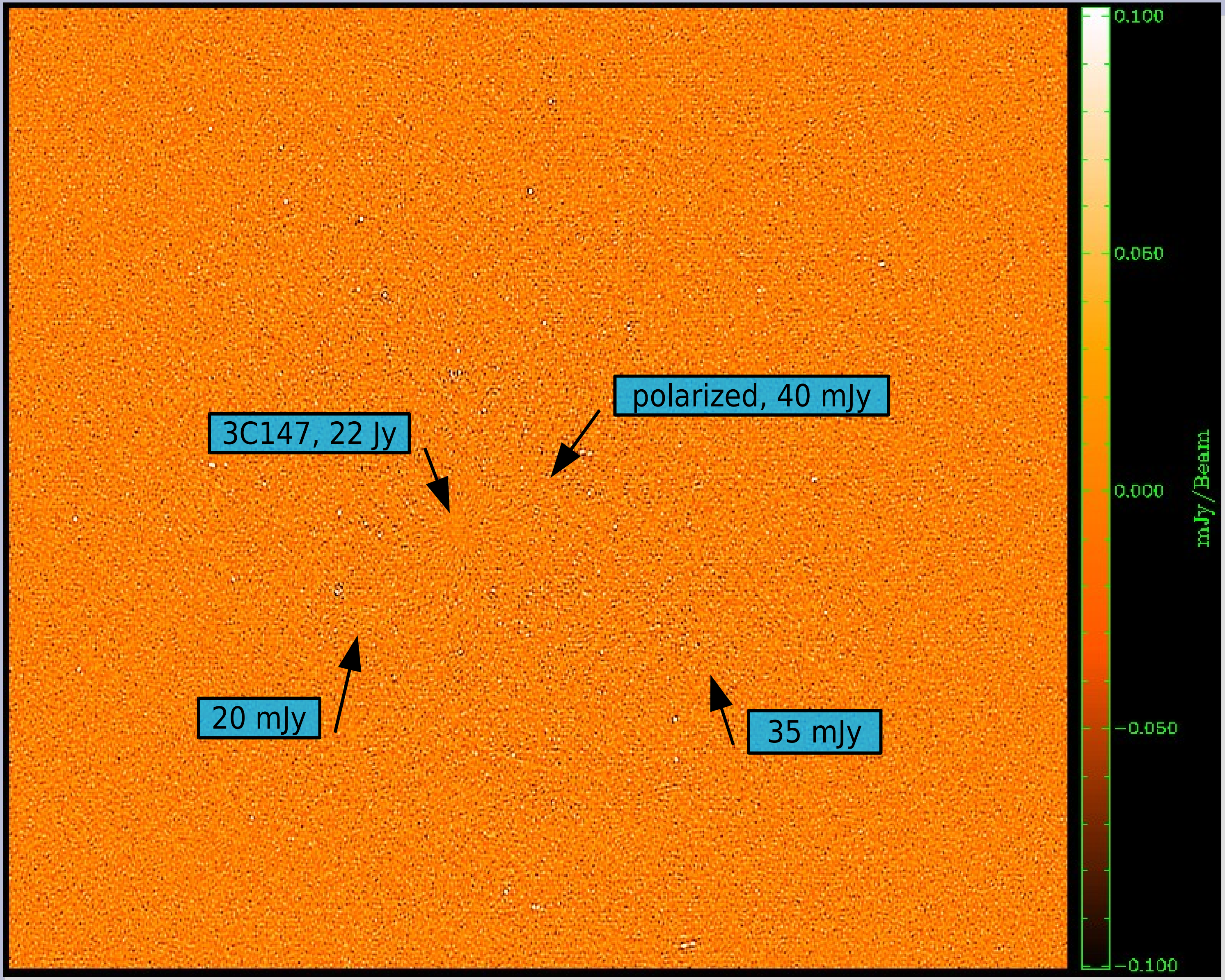
- The "before" image.

Flyswatter II



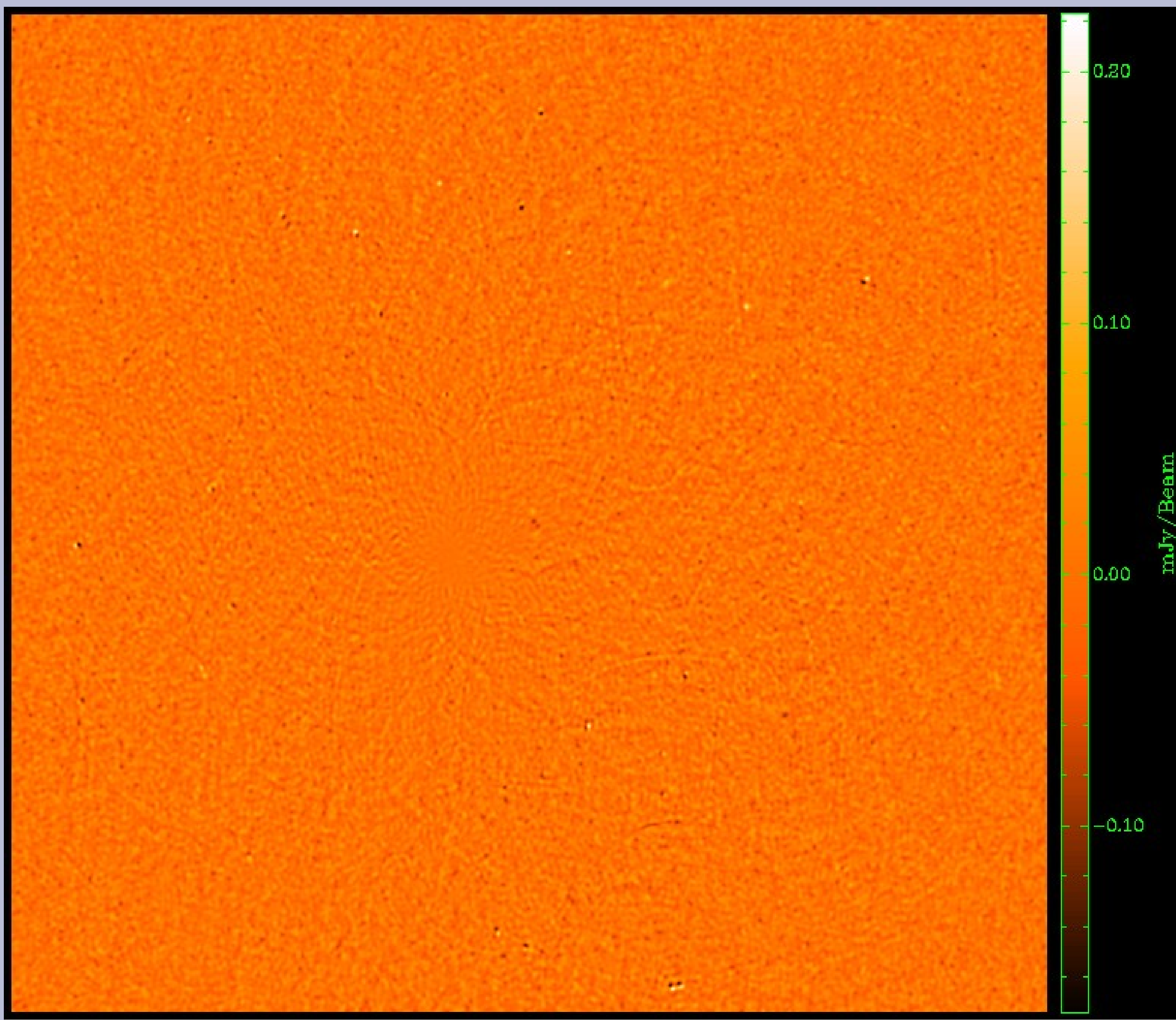
- Solved for *Δ**E*** for 5 sources.

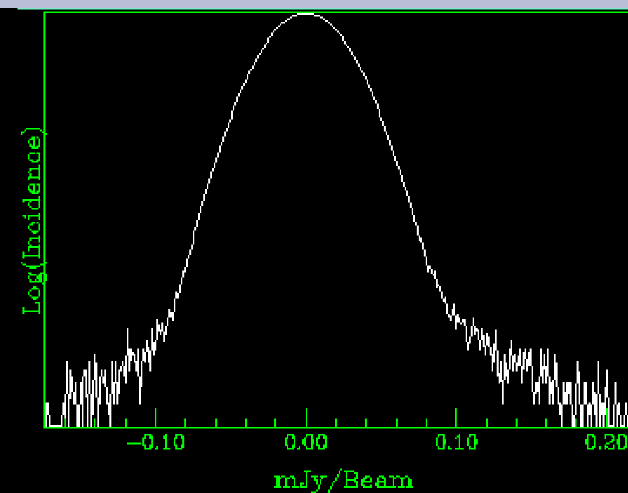
Flyswatter III



- Solved for $\Delta \boldsymbol{E}$ for 10 sources.

The Best Map So Far





- Solved for *Δ**E*** for 12 sources.
- Small problems remain, but the improvement over NEWSTAR is undeniable.

Some Parameter Counts

- We're throwing extra degrees of freedom (the ***ΔE***'s) at the model, how bad is this?
- Per-channel selfcal (14 antennas, 70 baselines, 30 frequency channels):
  2*14 complex gains per *t/ν* point,
  2*70 complex measurements per *t/ν* point
- One extra ***ΔE*** term:
  2*14 complex gains **per 30*60 *t/ν* points**,
  ~.015 of a parameter per *t/ν* point!
- But with bandpass calibration:
  2*14 ***G***-gains per 30 *t/ν* points ~ 1 per *t/ν* point
  2*30 ***B***-gains per 60 *t/ν* points ~ 1 per *t/ν* point

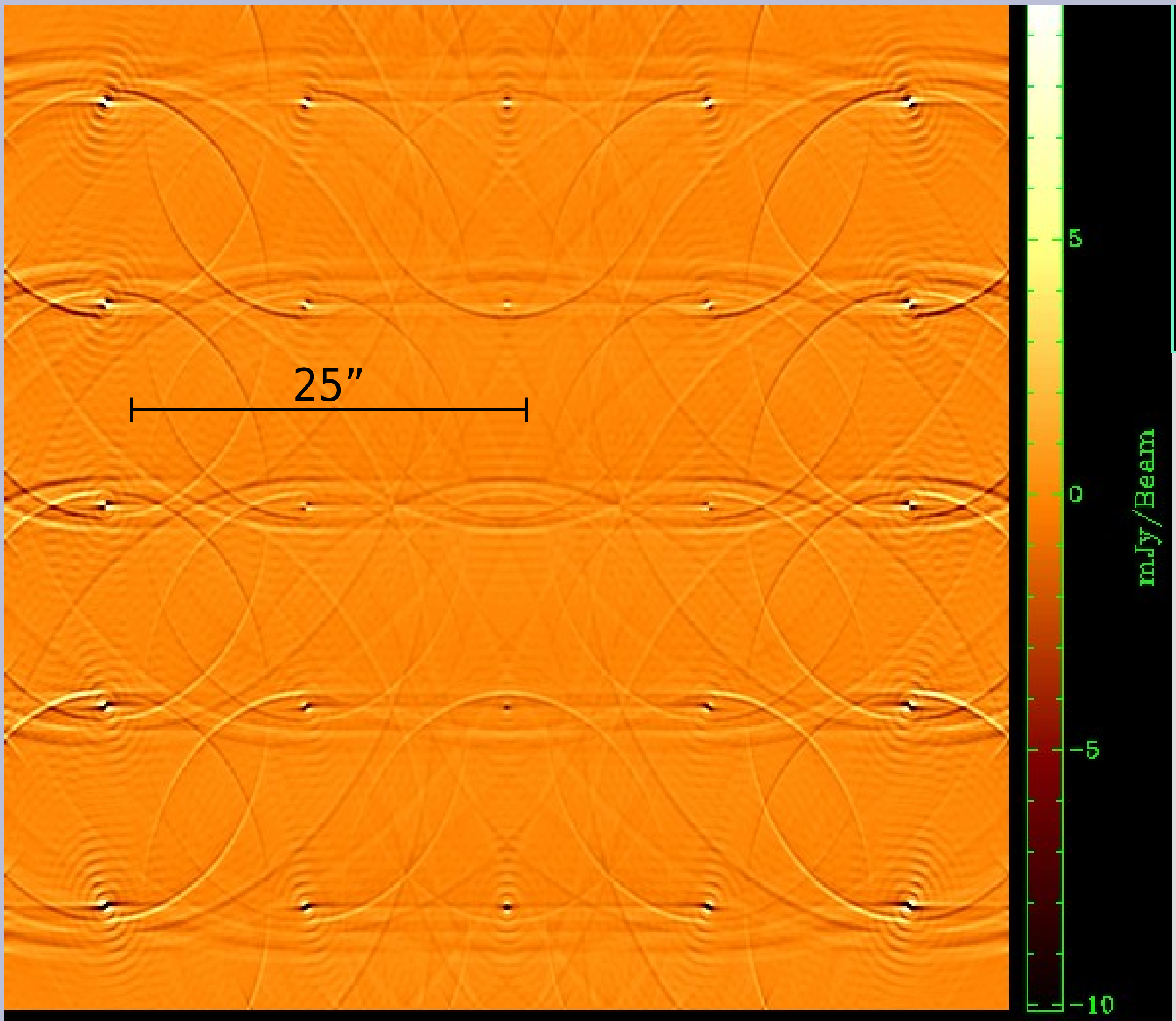
PURR

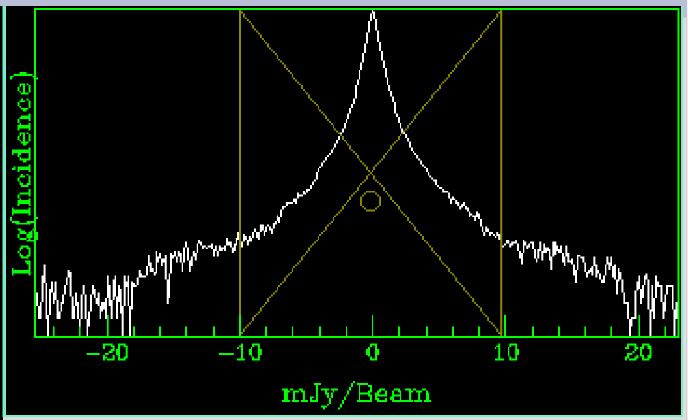
- “PURR is Useful for Remembering Reductions”
- Disciplined people keep notes.
- Undisciplined people write software to keep notes for them.

The TTU

- Inspired by the BTU – The Brouw Time Unit (≈ ½ quiet afternoon)
- 1 Tree Time Unit ≈ 45 minutes
  - which is how long a Sony extended capacity laptop battery lasts under decent CPU load.
- ...by a fortunate coincidence, is also how long it takes (me) to try something out in MeqTrees, from idea to image.
  - differential gains
  - tropospheric refraction

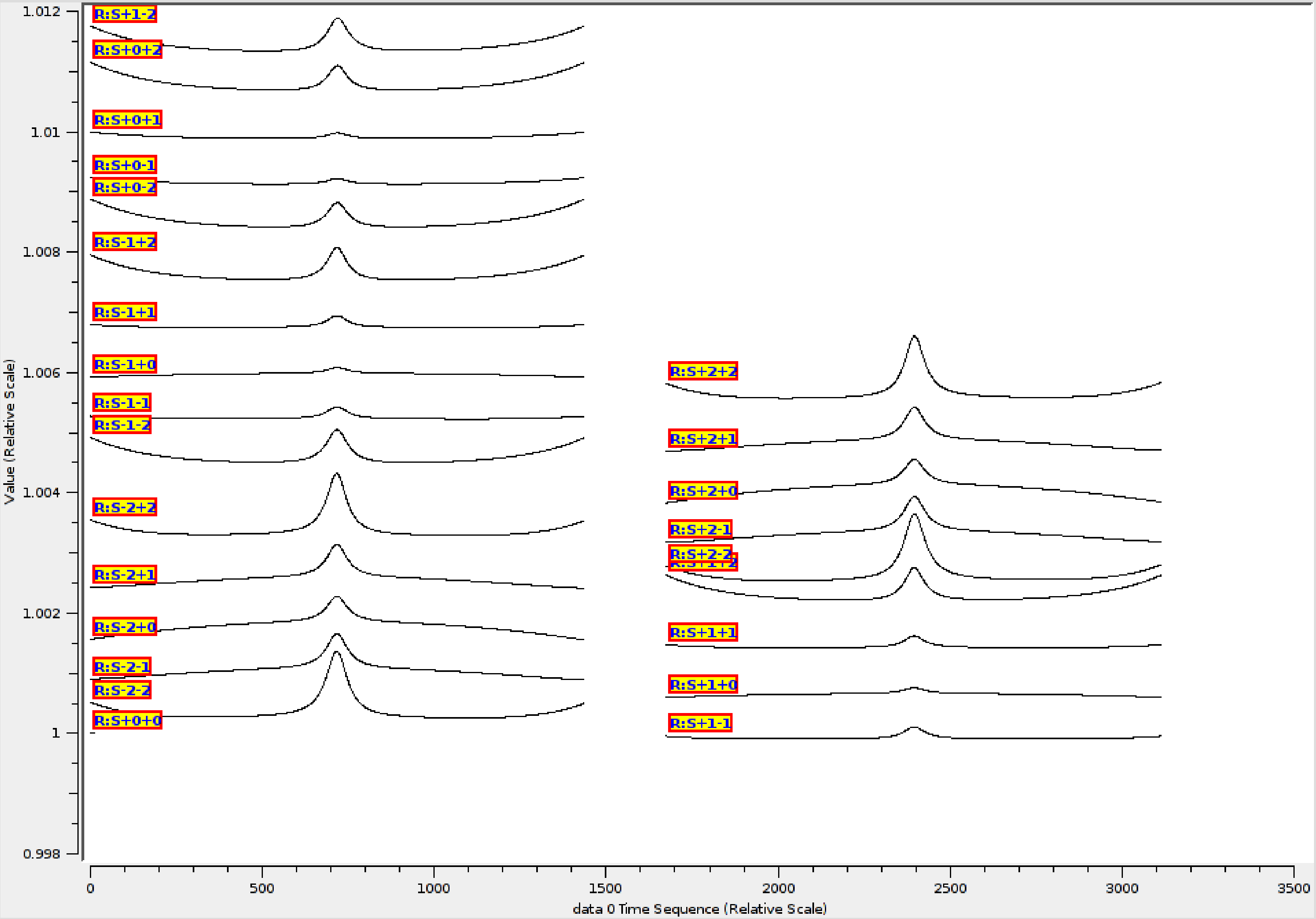
Tropospheric Refraction (A 1 TTU Simulation)



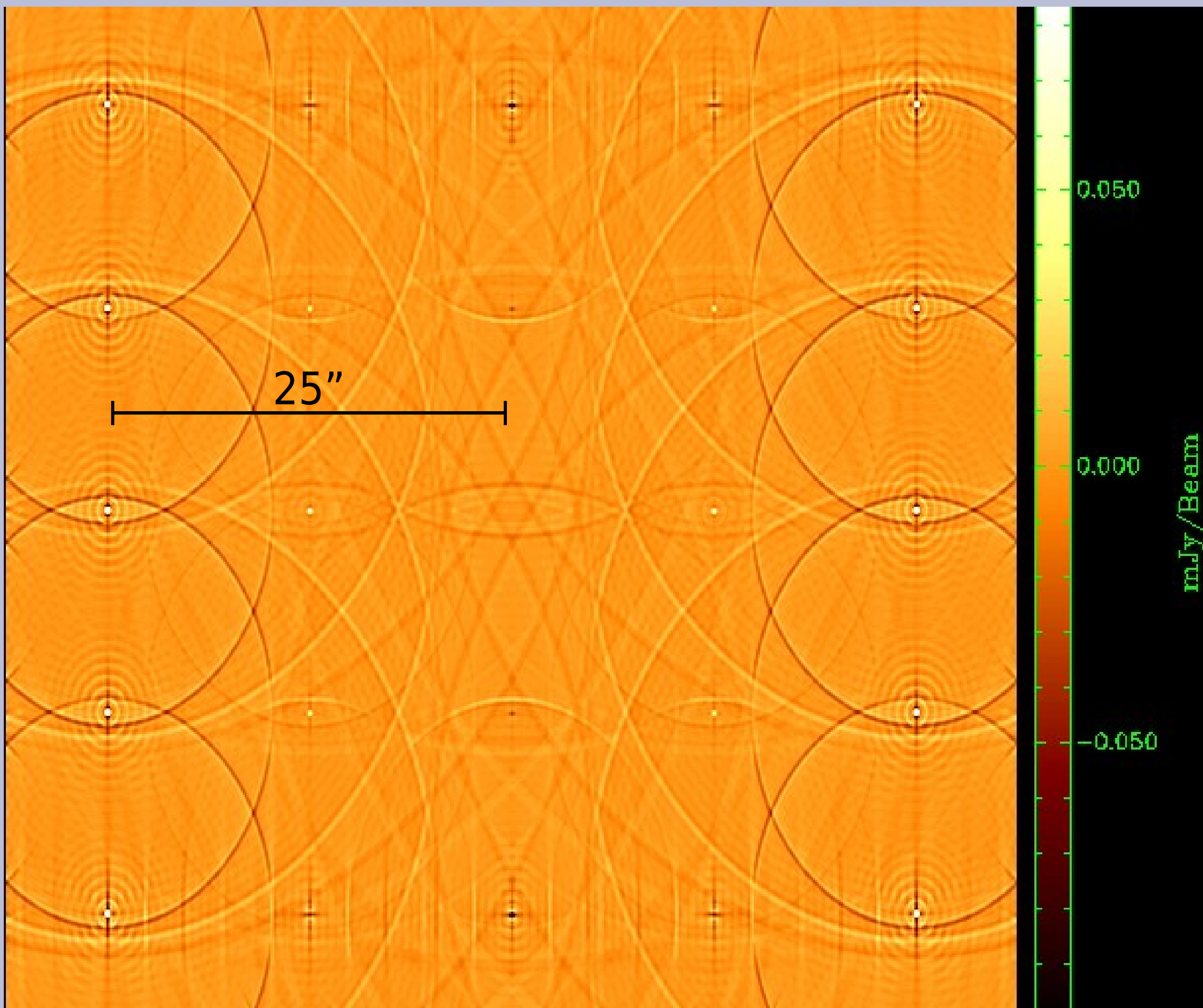


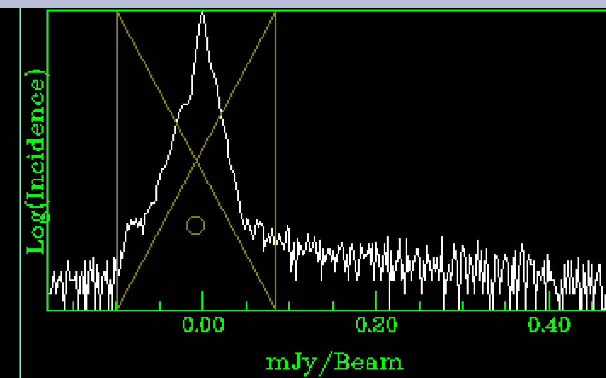
- Tropospheric refraction increases at low elevation
- Sources wobble around within the primary beam
- Time-variable effect

Beam Gain
As a Function Of Time



Differential Refraction





- Effect is variable across the FOV (FOV is “compressed”.)
- Adjusting pointing only corrects the central source
- Simulated residual error is ~10^{-4} at 30” off-axis.
- A bright source will ruin your day.

Conclusions

- NEWSTAR beaten.
- Differential gains boldly go where no peeling has gone before:
  - cleans up sources 1000 fainter than 3C147,
  - ...whose discernible effects are close to noise,
  - with very few extra parameters.
- Noordam Conjecture: “If it's bright enough to cause trouble, it's bright enough to be solved for.”
- Smirnov Corollary: usually within 1 TTU.