MeqTrees at 1,000,000:1 & Other Tales

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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.

The Project Formerly Known As "Beat NEWSTAR"

- 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!
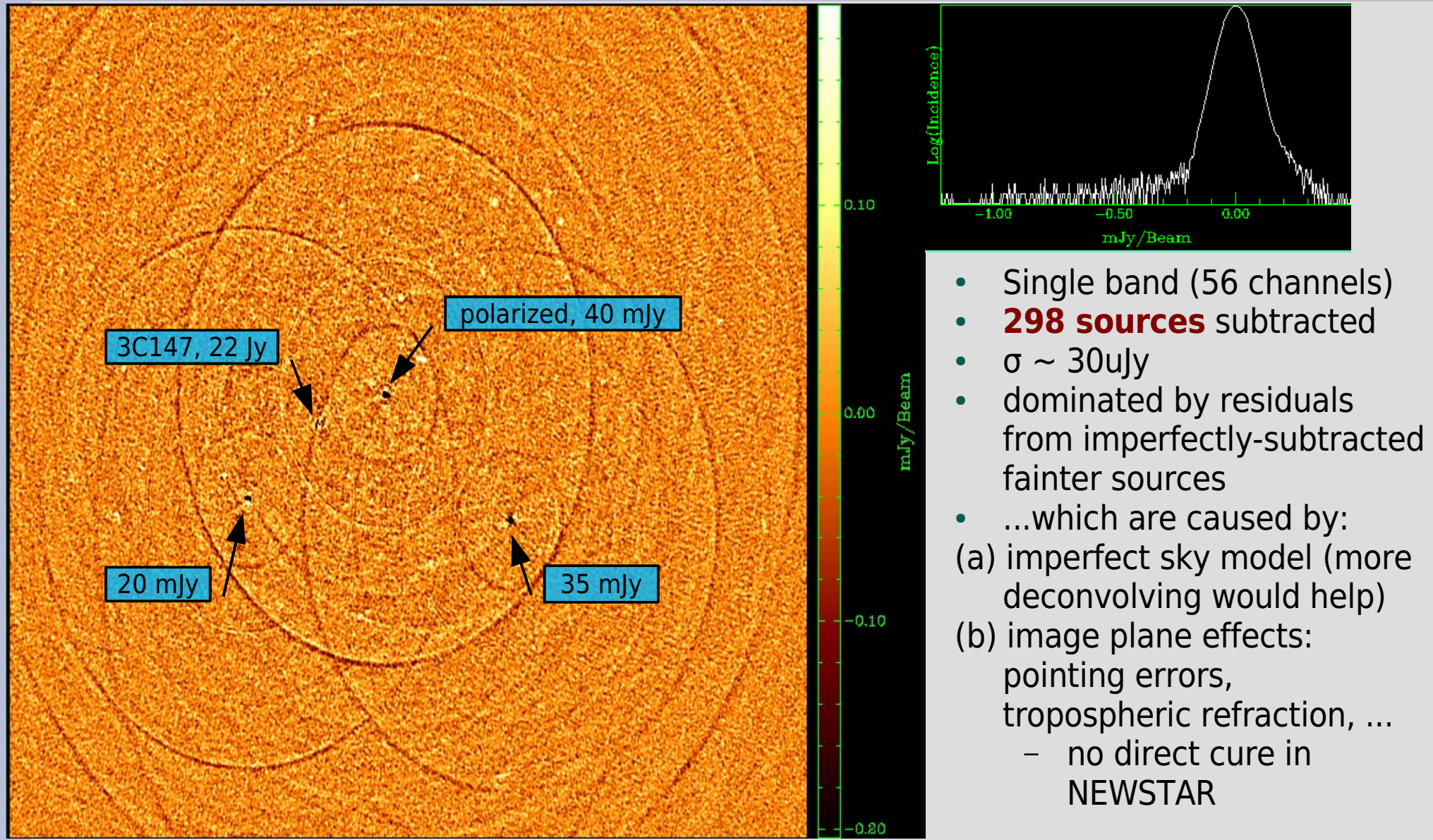 - WR holder in dynamic range (→2 million)

The 3C147 Field
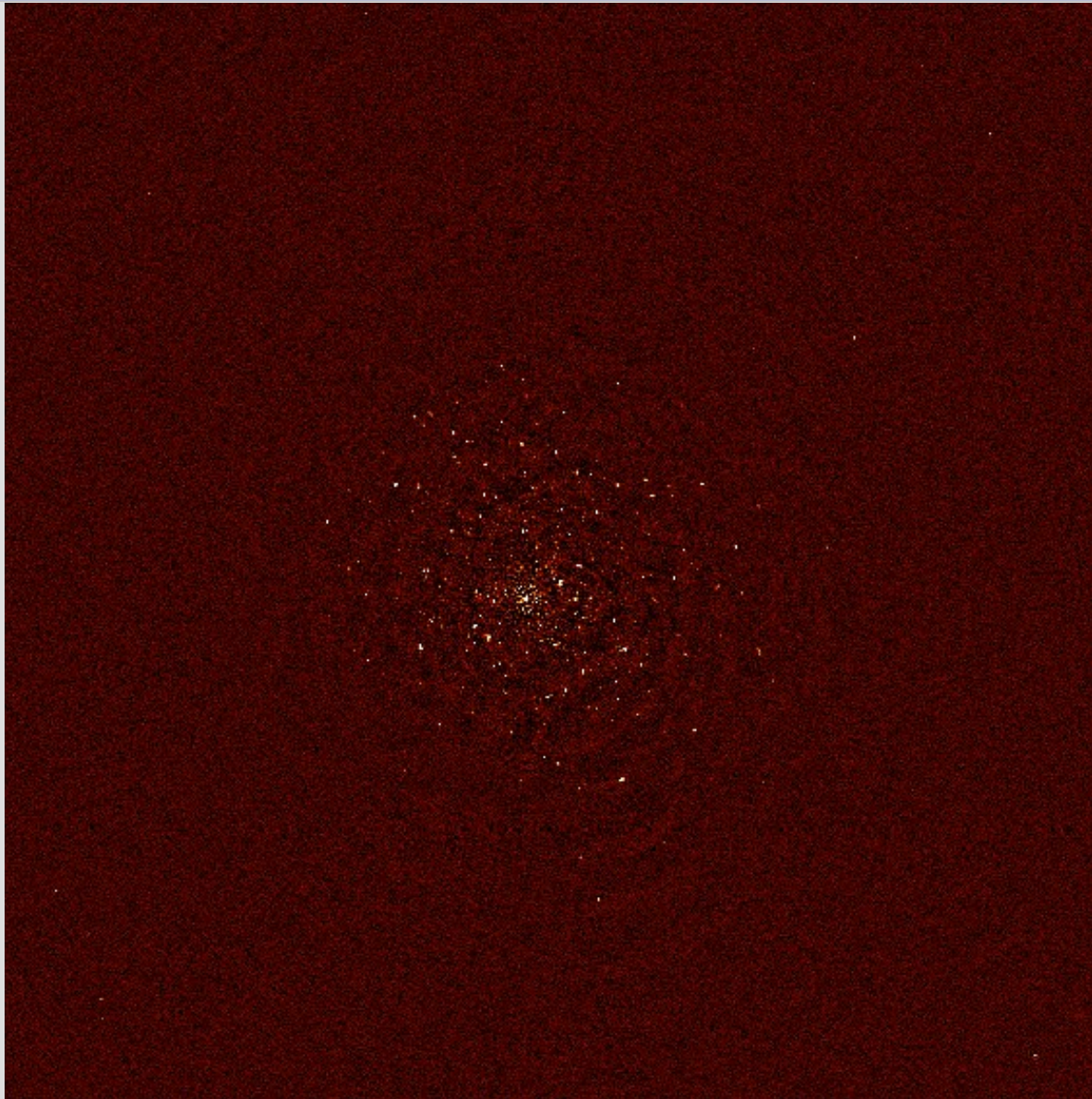
- 1x12 hr WSRT 21cm observation
- 30sec. integration
- 8x64 channels 21cm B=160 MHz
- 3C147 is 22Jy

- 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
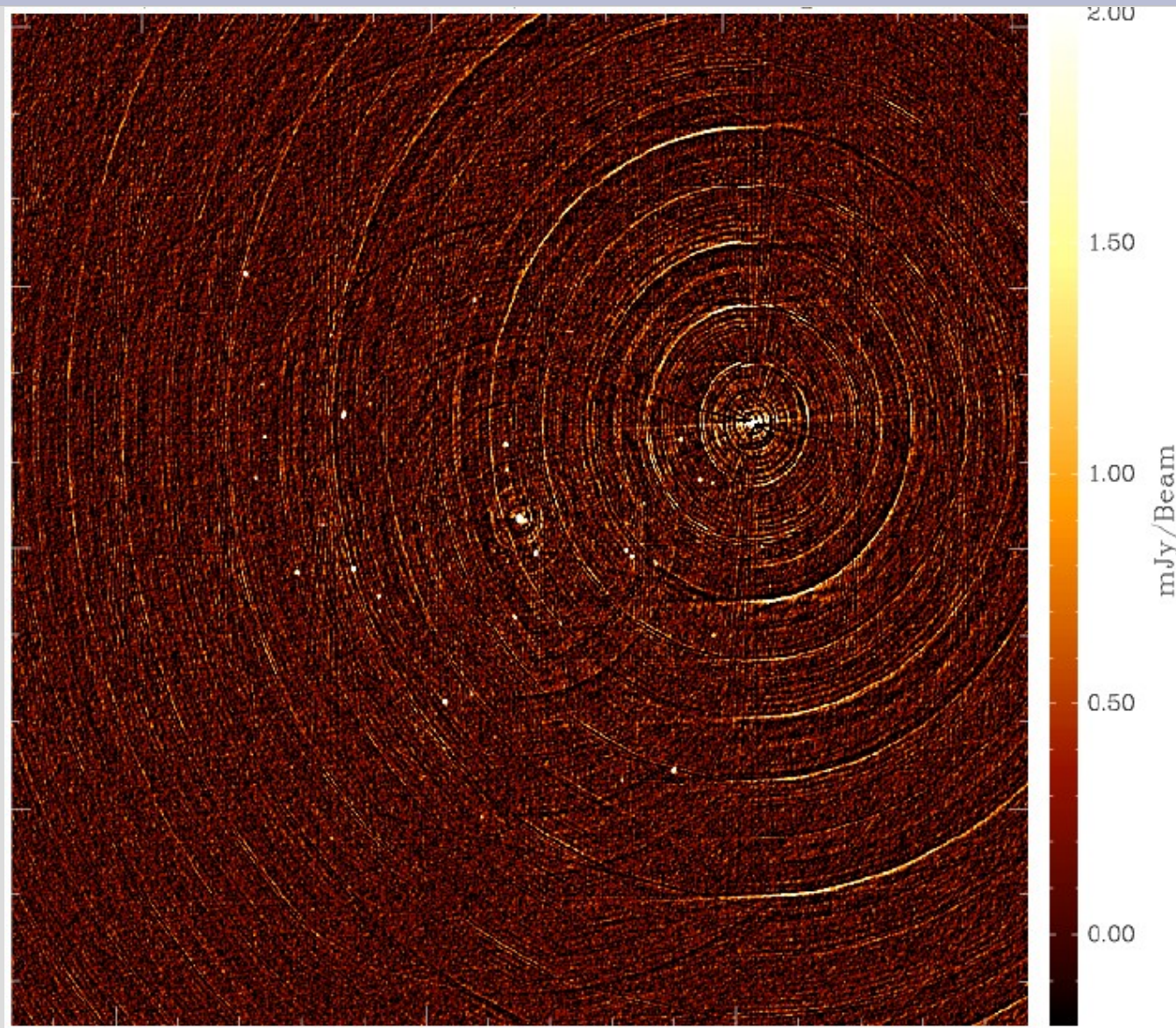
Calibrating For
Image-Plane Effects II

- 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

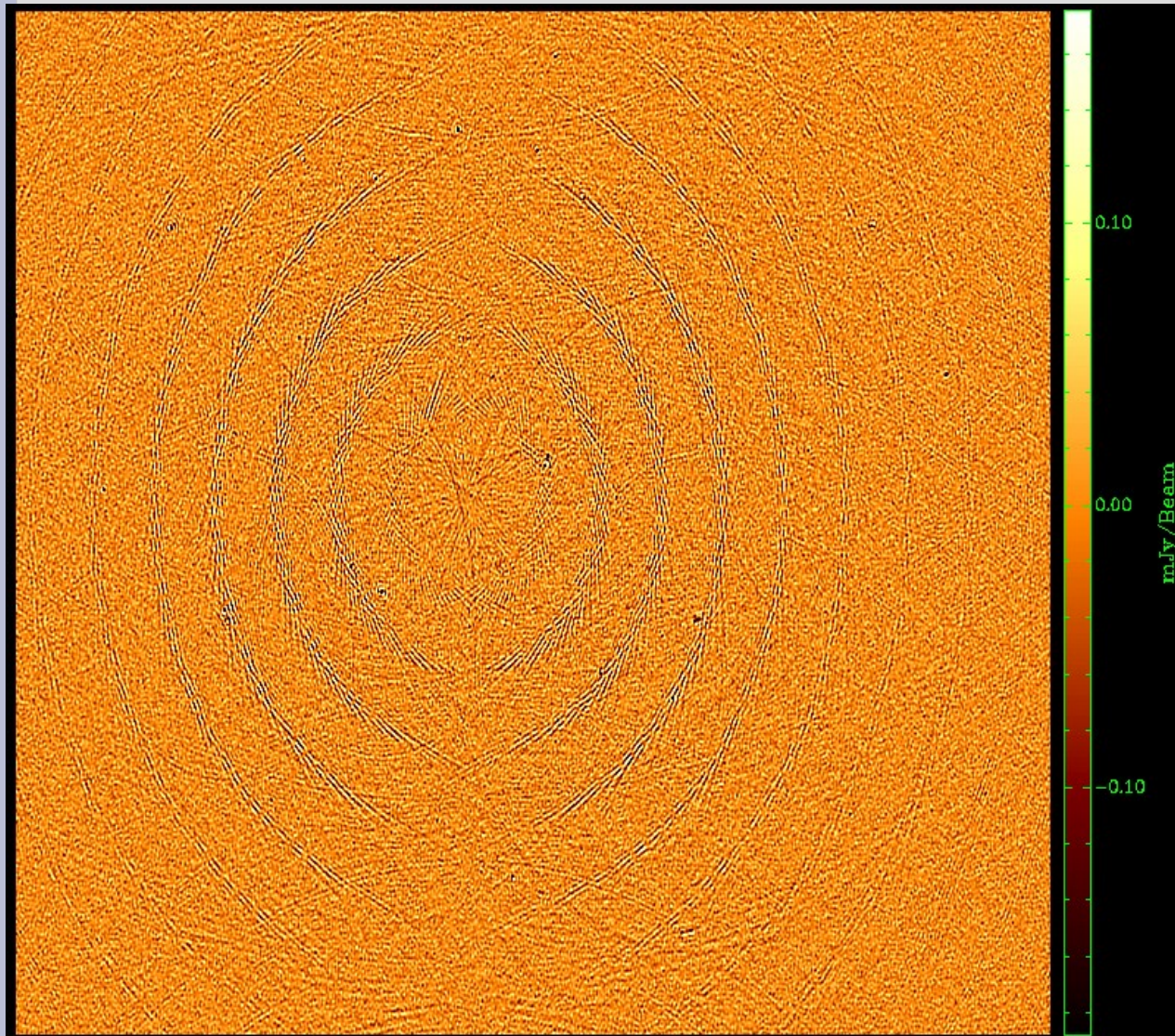- All sorts of ME's can be implemented. Let's start with this one:

$$V_{pq} = \overbrace{B_p}^{\text{bandpass}} \overbrace{G_p}^{\text{gain}} \underbrace{\left(\sum_s \overbrace{E_p^{(s)}}^{\text{beam}} \overbrace{X_{pq}}^{\substack{\text{source} \\ \text{coherency}}} E_q^{(s)\dagger} \right)}_{\text{sum over sources}} G_q^\dagger B_q^\dagger$$

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

$G_p(t)$ is a solvable

$B_p(\nu)$ 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
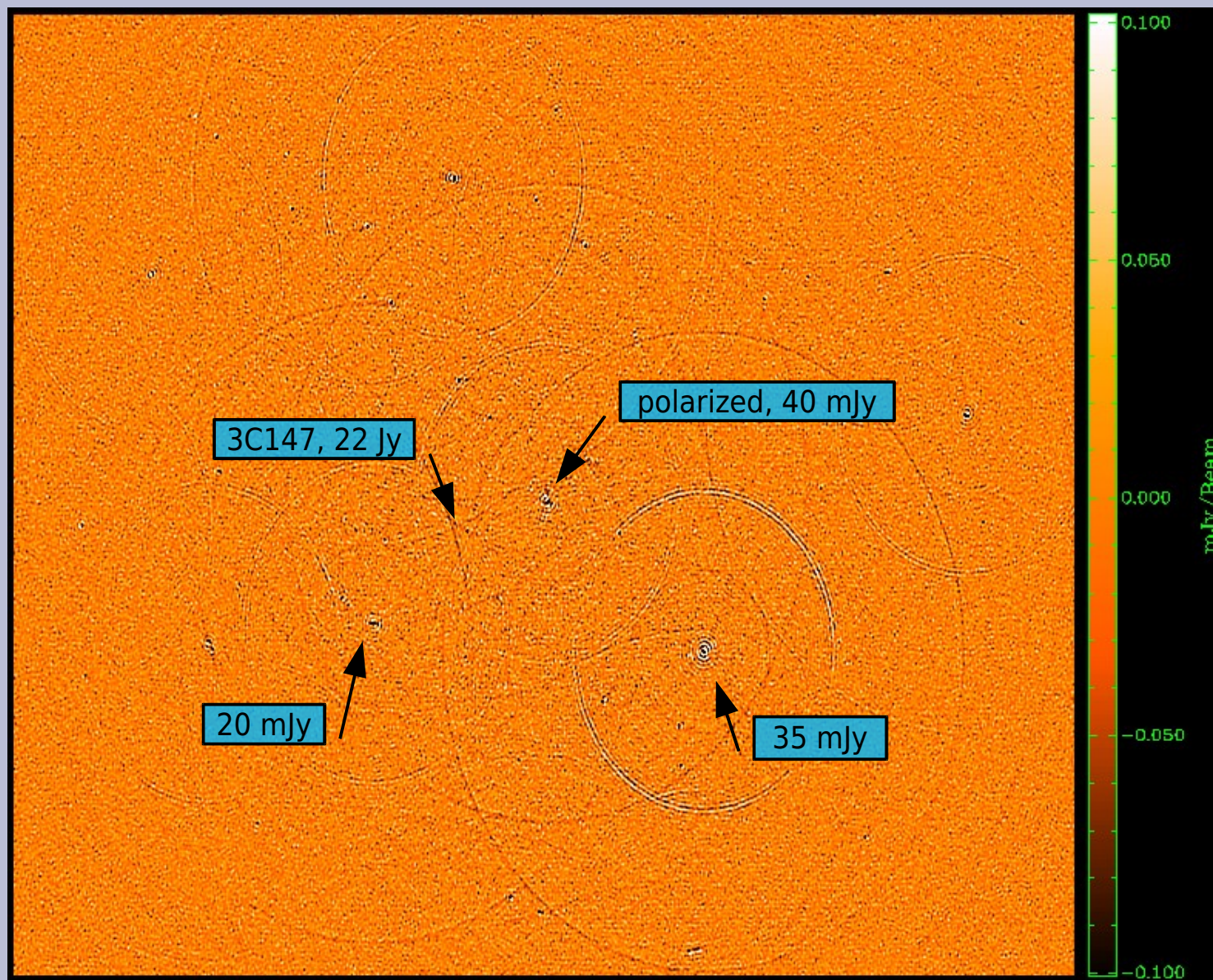- Further increase polynomial degree?
  – or spline?

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:

$$
V_{pq} = \overbrace{G_p}^{\text{gain \& bandpass}} \underbrace{\left(\sum_s \overbrace{E_p^{(s)}}^{\text{beam}} \overbrace{X_{pq}}^{\substack{\text{source} \\ \text{coherency}}} E_q^{(s)\dagger} \right)}_{\text{sum over sources}} G_q^{\dagger}
$$

$G_p(\nu, t)$ 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:

$$V_{pq} = \overbrace{G_p}^{\text{gain \& bandpass}} \underbrace{\left(\sum_s \overbrace{E_p^{(s)}}^{\text{beam}} \overbrace{X_{pq}}^{\substack{\text{source} \\ \text{coherency}}} E_q^{(s)\dagger} \right)}_{\text{sum over sources}} G_q^{\dagger}$$

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

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

$$E_p(l, m, \nu) = E(l + \Delta l_p, m + \Delta m_p, \nu)$$

...and solve for the offsets.

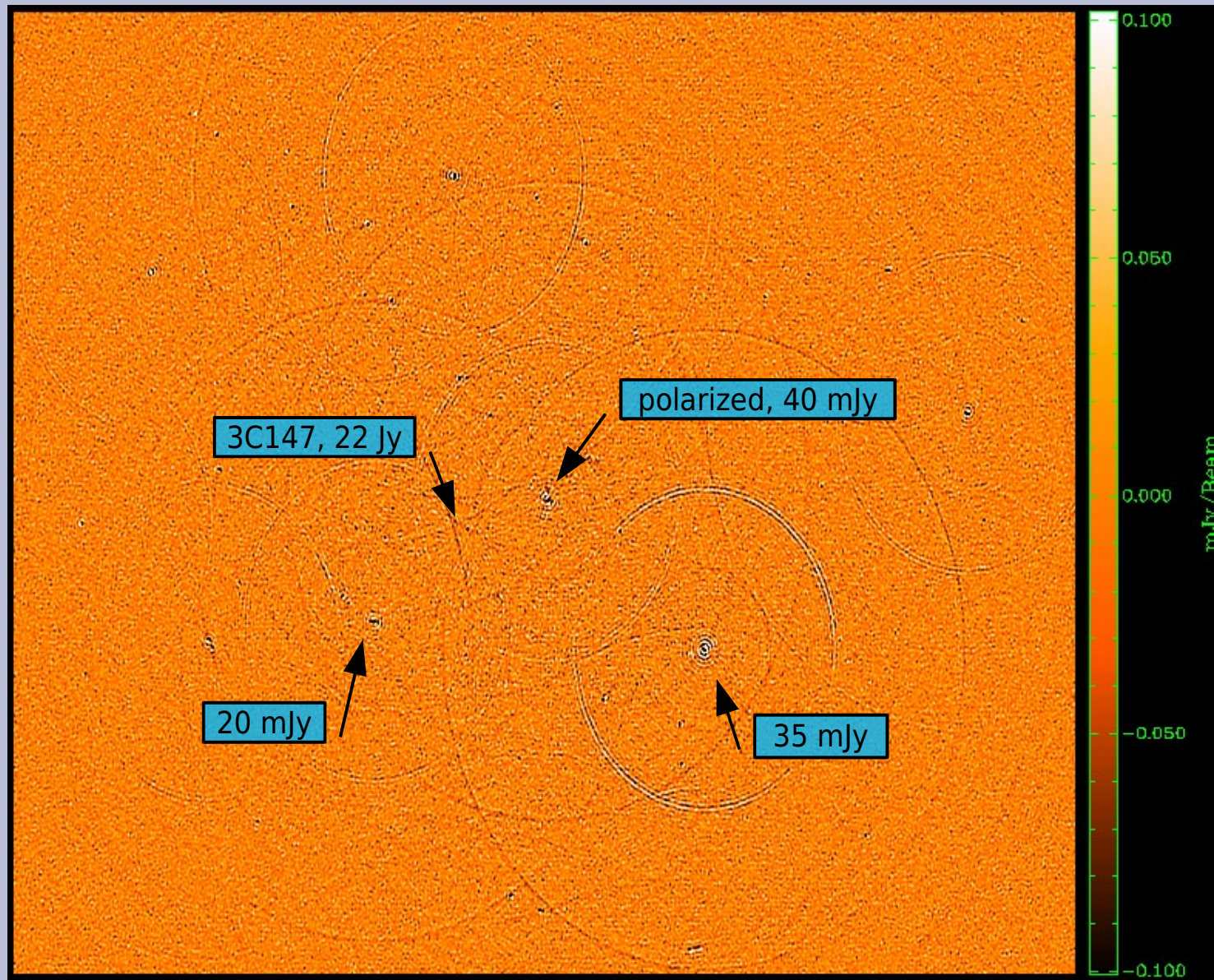# Differential Gains

- Or we can introduce differential gains:

$$V_{pq} = \overbrace{G_p}^{\text{gain \& bandpass}} \underbrace{\left(\sum_s \overbrace{\Delta E_p^{(s)}}^{\substack{\text{differential} \\ \text{gain}}} \overbrace{E_p^{(s)}}^{\text{beam}} \overbrace{X_{pq}}^{\substack{\text{source} \\ \text{coherency}}} E_q^{(s)\dagger} \Delta E_q^{(s)\dagger} \right)}_{\text{sum over sources}} G_q^{\dagger}$$
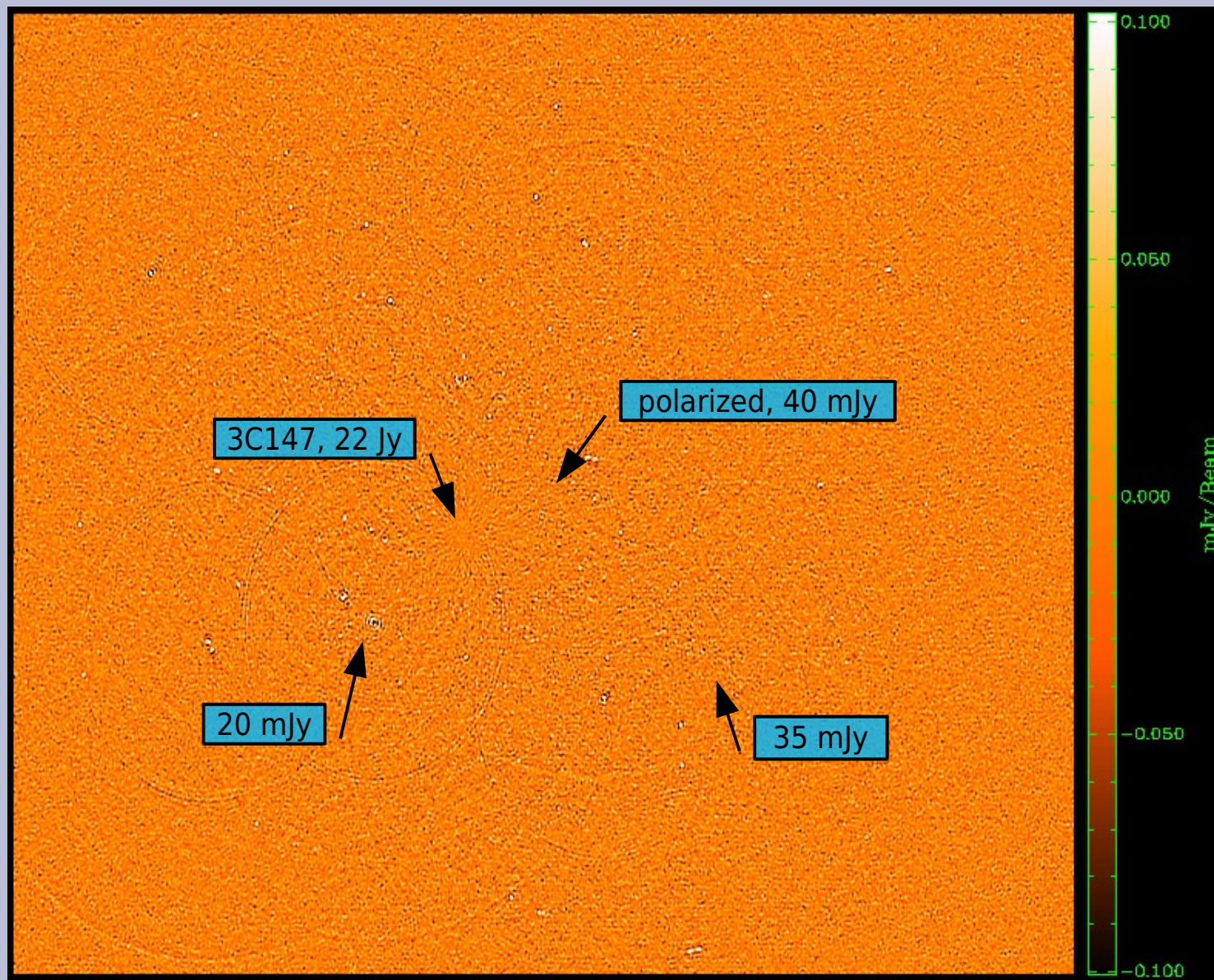
$\Delta E_p^{(s)}$ is frequency-independent, slowly varying in time.

Solvable for a handful of "troublesome" sources,

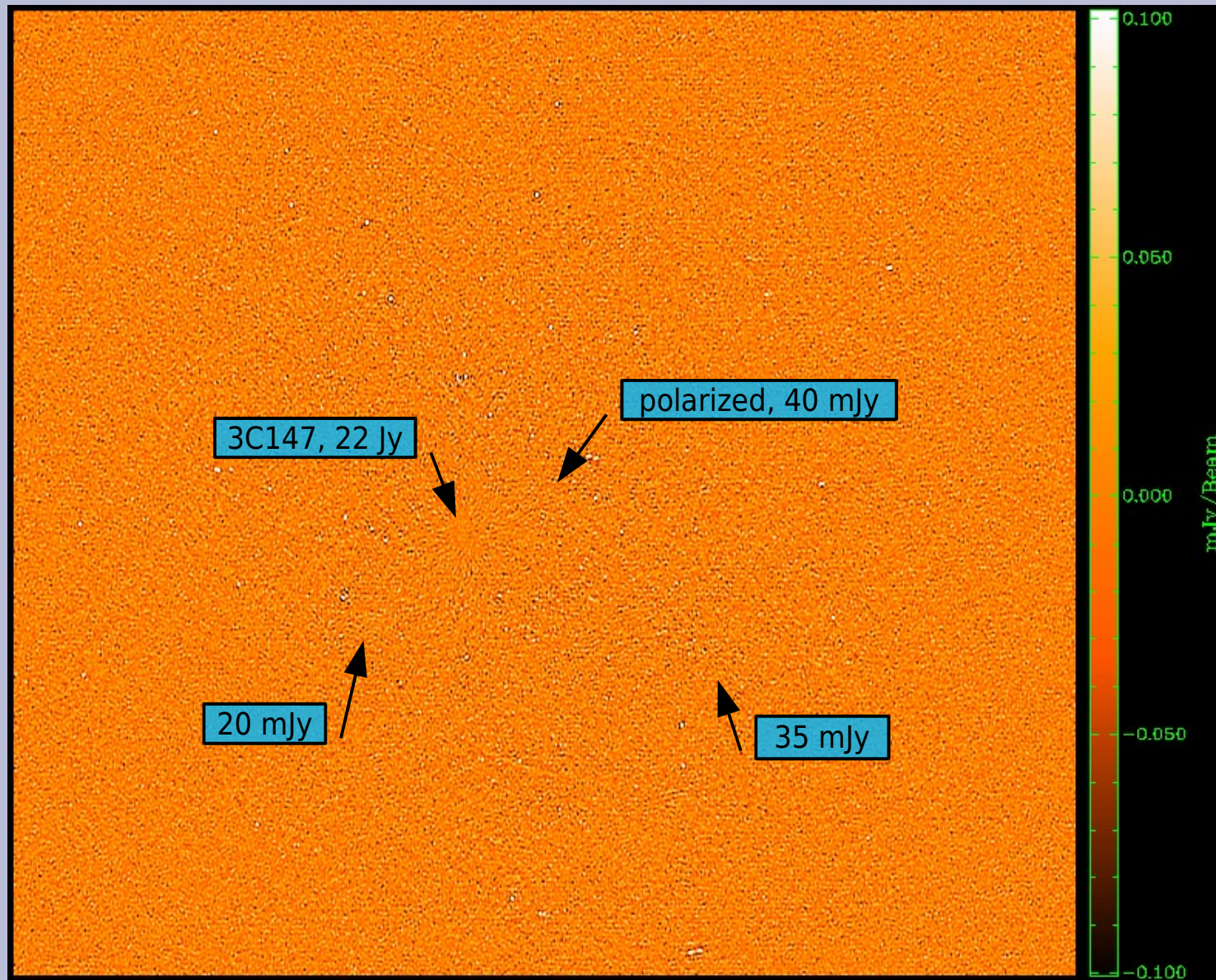and set to unity for the rest.

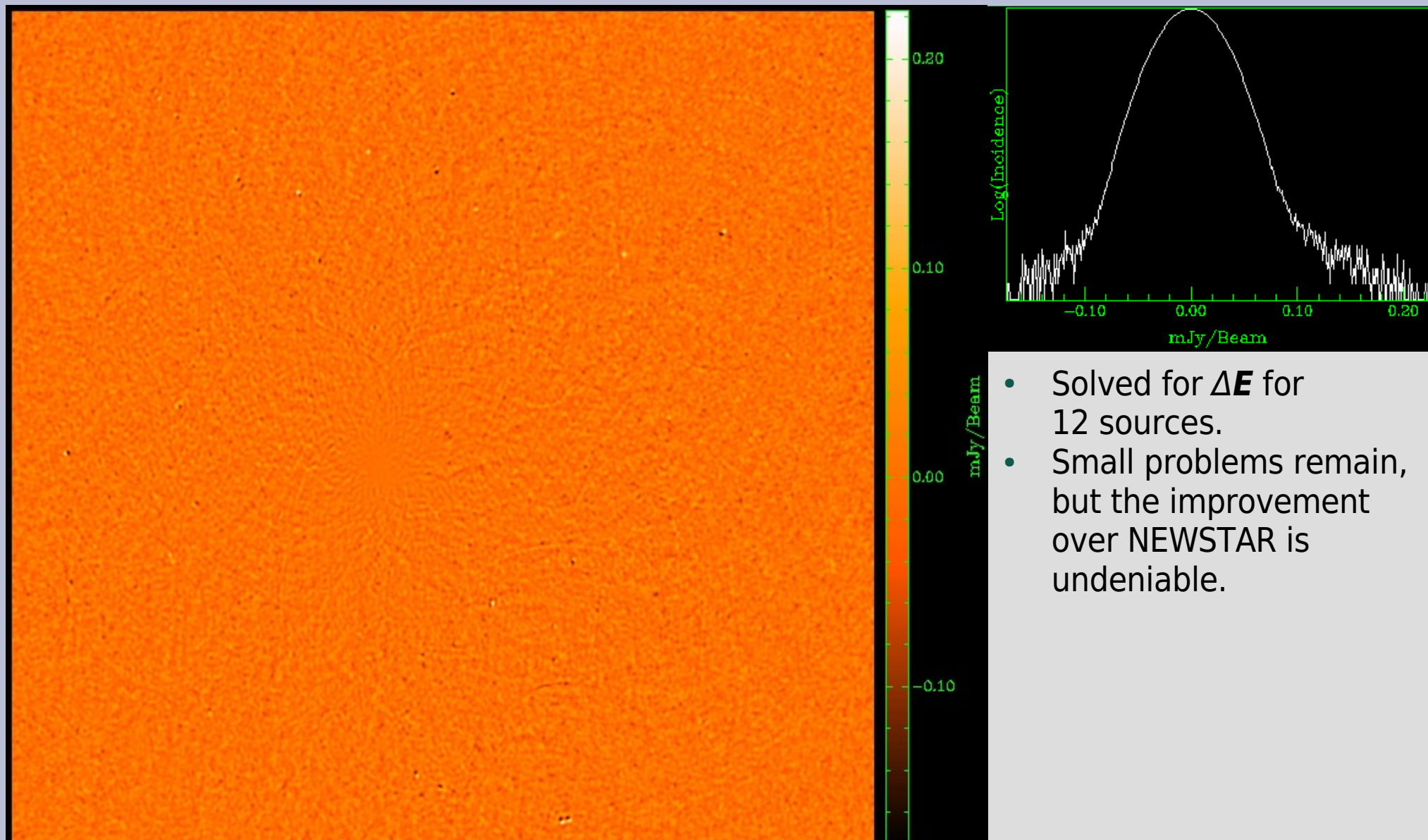# Flyswatter I

- The "before" image.

Flyswatter II

- Solved for ΔE for 5 sources.

Flyswatter III

- Solved for ΔE for 10 sources.

The Best Map So Far

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

Some Parameter Counts

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

MeqTrees Status
http://www.astron.nl/meqwiki

- Binary release 1.0: March 5 (4 days early!)
  - Chris Williams, Stef Salvini (OeRC)
  - .deb packages for Ubuntu 8.04, 8.10 32/64 bit
  - other distros to be added according to demand
- Can be checked out & built from source
  - Debian, RH & derivatives, SuSE, Gentoo
- OSX port done by Mike Sipior
  - see wiki for details
  - dependency libraries & toolchain currently THE major roadblock
 - will be added to binary release eventually...

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

PURR

- "PURR is Useful for Remembering Reductions"
- Disciplined people keep notes.
- Undisciplined people write software to keep notes for them.
- For a typical Purr product, see the "3C147 Calibration Tutorial" on **http://www.astron.nl/meqwiki**

Group 1: Developers
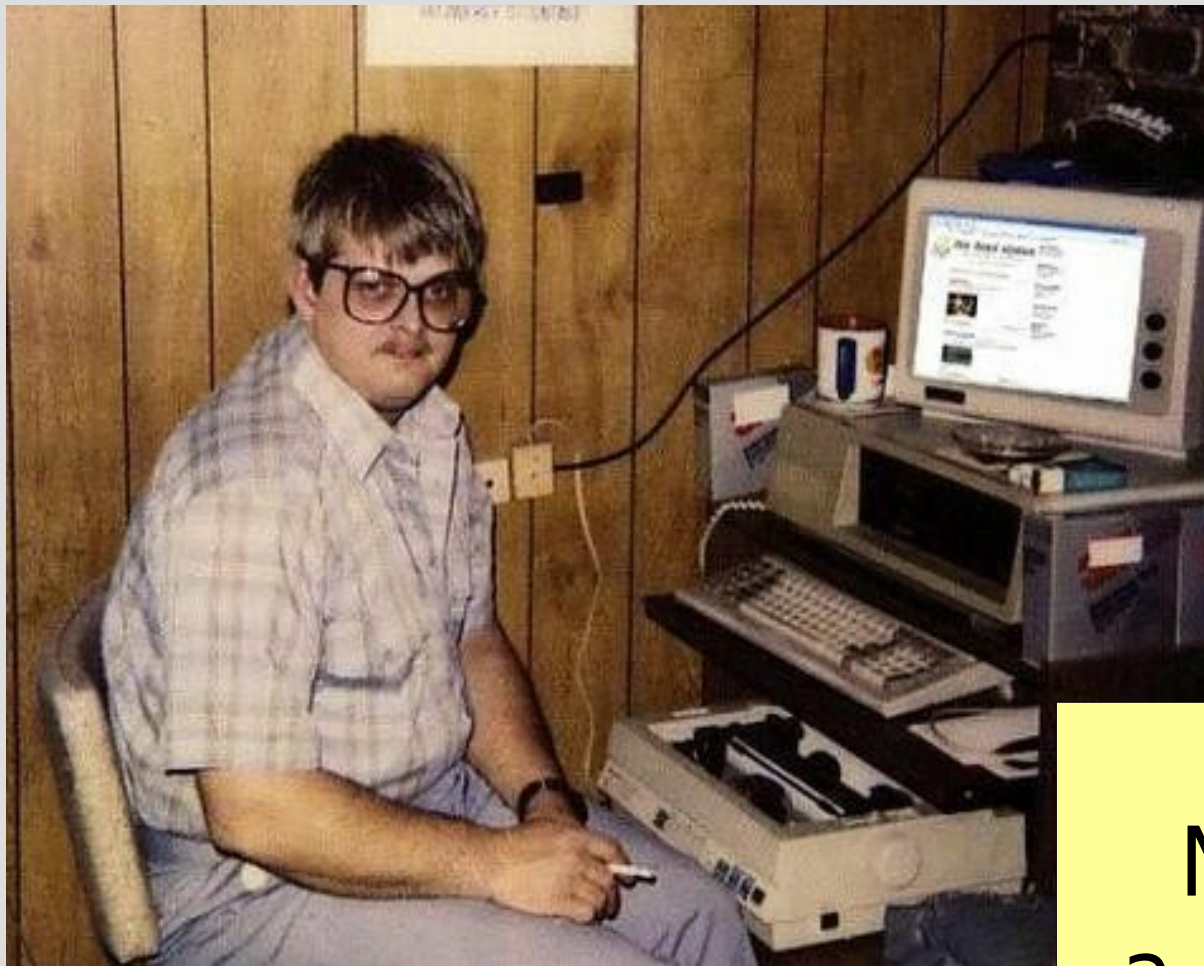
Developers:
- overworked
- underpaid
- grouchy
- ...but covered in reflected glory

NB: this is not
a picture of Oleg

Group 2: Power Users

Power Users:

- have more fun
- steal glory from developers

NB: this is also not a picture of Oleg

Group 3: Button-Pushing Astronomers

The ideal astronomer UI (Tony Willis):

GO

GO FASTER

DO WHAT I MEAN!

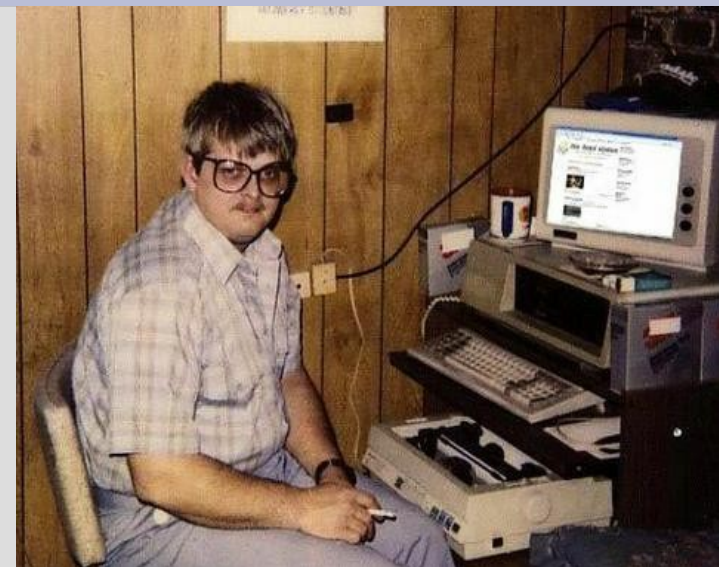NB: this picture is meant to be purely representative

Who Is Going To Solve The SKA Calibration Problem?

a million astronomers at a million keyboards?

or power users who come up with clever new algorithms?

a few developers in smoke-filled cubicles?

Powering The Power Users

- How do we turn button-pushers into power users?

- The TTU: really rapid experimentation
  - and no emotional attachment
- Purr
  - effortless log-keeping
  - ...and sharing!

Conclusions

- MeqTrees is installable.
- We can do better than NEWSTAR.
- 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.