Measuring The Beam

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DDEs Westerbork-Style
(Luxury Problems?)

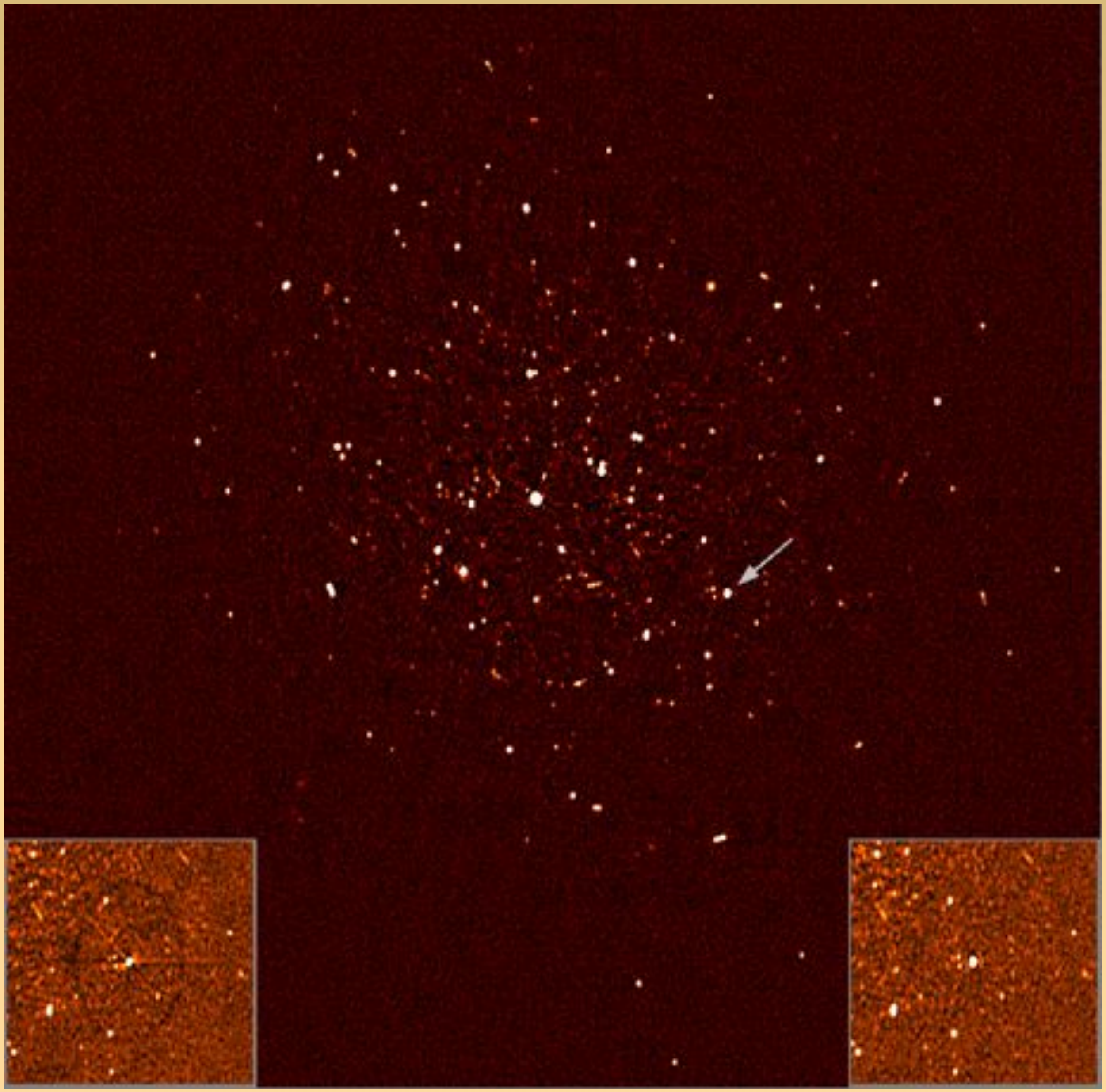
3C147 @21cm
Single 12h
WSRT synthesis

1,600,000:1 DR

Such DR made possible by WSRT's extremely stable design (equatorial mounts ⇒stationary beams, etc.)

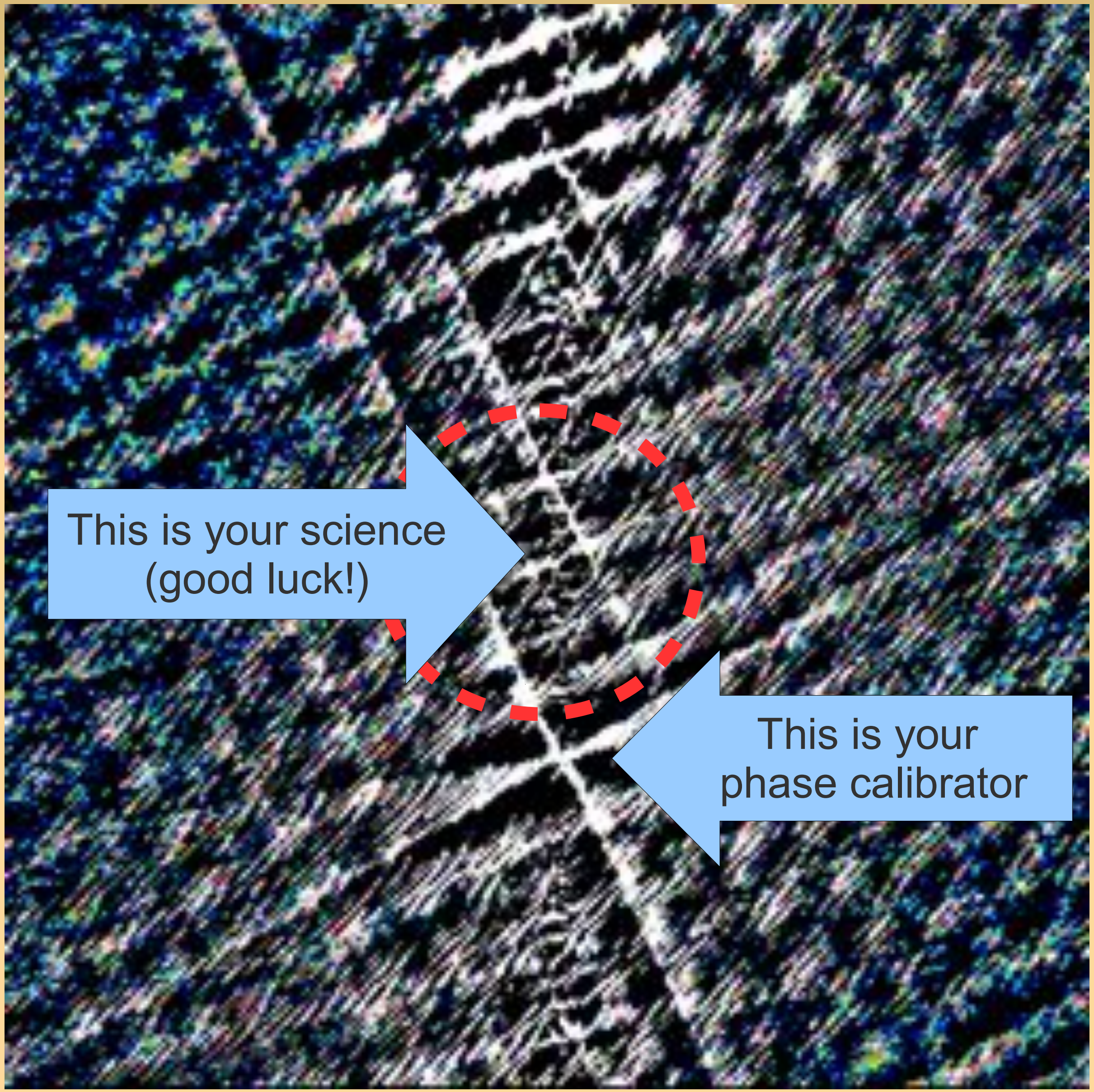
Nonetheless, this map is deep enough to show DDEs.

Cleaned up via application of *differential gains*.



Just a Luxury Problem?

DDEs: Not Always a Luxury Problem
(Courtesy of Ian Heywood)



EVLA 8 GHz: Looking for sub-mm galaxies and QSOs in the WHDF.

Dominant effect: bright calibrator source rotating through first sidelobe of the primary beam.

(This also has a horrible PSF, being an equatorial field.)

Brightness scale 0~50μJy

Direction-Dependent Gains (and subtraction in the *uv*-plane)

- Given a model for the dominant source components, solve for direction-dependent gain terms:

$$\overbrace{\boldsymbol{V}_{pq}}^{\text{model visibilities}} = \underbrace{\sum_s \overbrace{\boldsymbol{J}_p^{(s)}}^{\text{gain, source } s \text{ station } p} \overbrace{\boldsymbol{X}_{pq}^{(s)}}^{\text{source model } s} \overbrace{\boldsymbol{J}_q^{(s)\dagger}}^{\text{gain, source } s \text{ station } q}}_{\text{sum over sources}} \rightarrow \overbrace{\boldsymbol{D}_{pq}}^{\text{observed visibilities}}$$

2×2
visibility matrix

2×2
Jones matrix

- Image the residual visibilities ***{R=V-D}***
  - These are still subject to the same *relative* level of DDEs, but the *absolute* error level is lower.
- The subtracted source components can always be “restored” back into the resulting image

Differential Gains

- DoFs proliferate quickly, so it is better to use e.g.:

$$\mathbf{V}_{pq} = \underbrace{\mathbf{G}_p}_{\text{overall gain}} \underbrace{\left(\sum_s \underbrace{\mathbf{dE}_p^{(s)}}_{\text{differential gain}} \underbrace{\mathbf{E}_p^{(s)}}_{\text{nominal beam}} \underbrace{\mathbf{X}_{pq}^{(s)}}_{\text{source model}} \mathbf{E}_q^{(s)\dagger} \mathbf{dE}_q^{(s)\dagger} \right)}_{\text{sum over sources}} \mathbf{G}_q^{\dagger}$$

- *Direction-independent* gains ***G*** vary on short time-frequency scales
- Nominal beam model ***E*** accounts for the bulk of the DDE
- ***dE*** accounts for the small and slow direction-dependent variations (… hopefully)

A.k.a. “The Flyswatter”

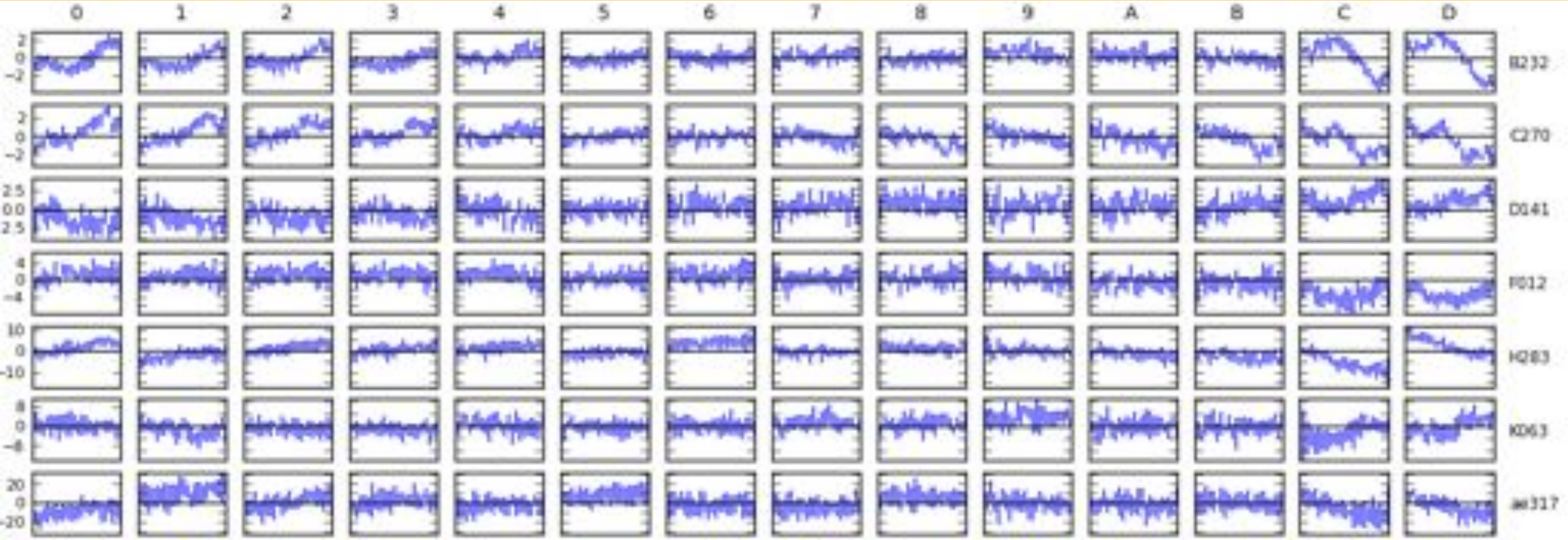
- **The Good: it swats sources**
  - Point-and-shoot: dE's can completely eliminate contaminating sources, making for great maps.
- **The Bad: it swats sources**
  - Mashes together all information on both the source and all DDEs towards it
- **The Ugly: it proliferates degrees of freedom**
  - Fundamental and computational limits on how many dE's you can have
  - LOFAR EoR project: up to 60 per antenna

A.k.a. “The Flyswatter”

- **The Good:**
  - dE's can completely eliminate contaminating sources, making for great maps!
  - See also talks by Ian Heywood, Panos Labropoulos
- **The Bad:**
  - Computationally feasible for a “handful” of sources at most
  - Proliferation of degrees of freedom
- **The Ugly:**
  - Mashes together all information on both the source and all instrumental effects towards it

The Ugly, continued...

- ...and makes no use of the fact that DDEs must have spatial continuity.
- Example: 3C147 field, dE-phase solutions as a function of time, per source, per antenna:



Alternatives: Fitting a "Global" DDE Model

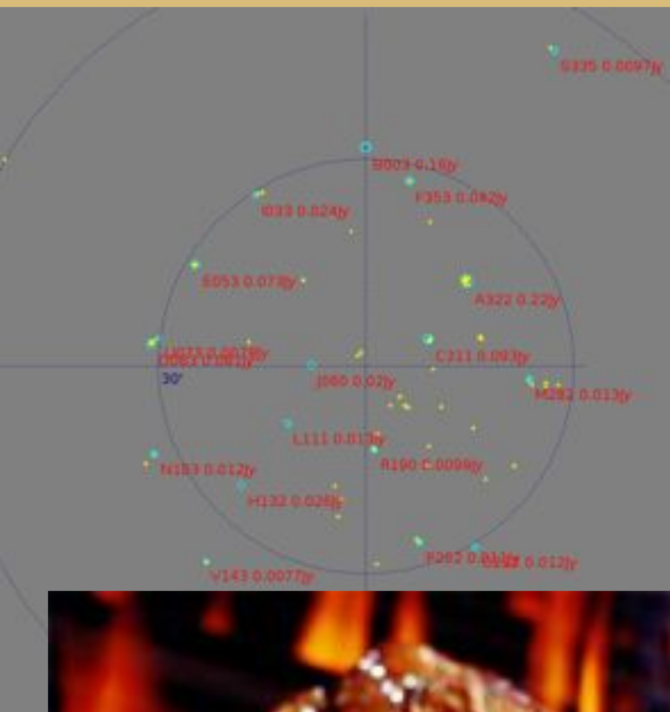
- Pointing selfcal (S. Bhatnagar)
  - Uses EVLA PB model, with a solvable pointing offset $\Delta l, \Delta m$
  - First-order approximation to $\partial\chi^2/\partial(\Delta l)$, $\partial\chi^2/\partial(\Delta m)$ using FFTs and convolutional functions
  - Uses entire sky model (image) as input
  - Results (so far): seems to improve pointing solutions, but little reduction in imaging artefacts
  - Possibly due to inadequate PB model?
- AW-projection can apply "global" correction during imaging

The QMC* Project

- Pick a field containing a cluster of reasonably bright off-axis sources
- Observe with WSRT @21cm
- Introduce deliberate (and secret!) pointing errors during observation
- Attempt to recover these during the reduction

*) Named in honour of the long-defunct WSRT Quality Monitoring Committee. Yes, the Dutch do love their committees. Fortunately, so do the Russians.

The QMC2 Field (01515+6736)
(a radio astronomer's worst nightmare)



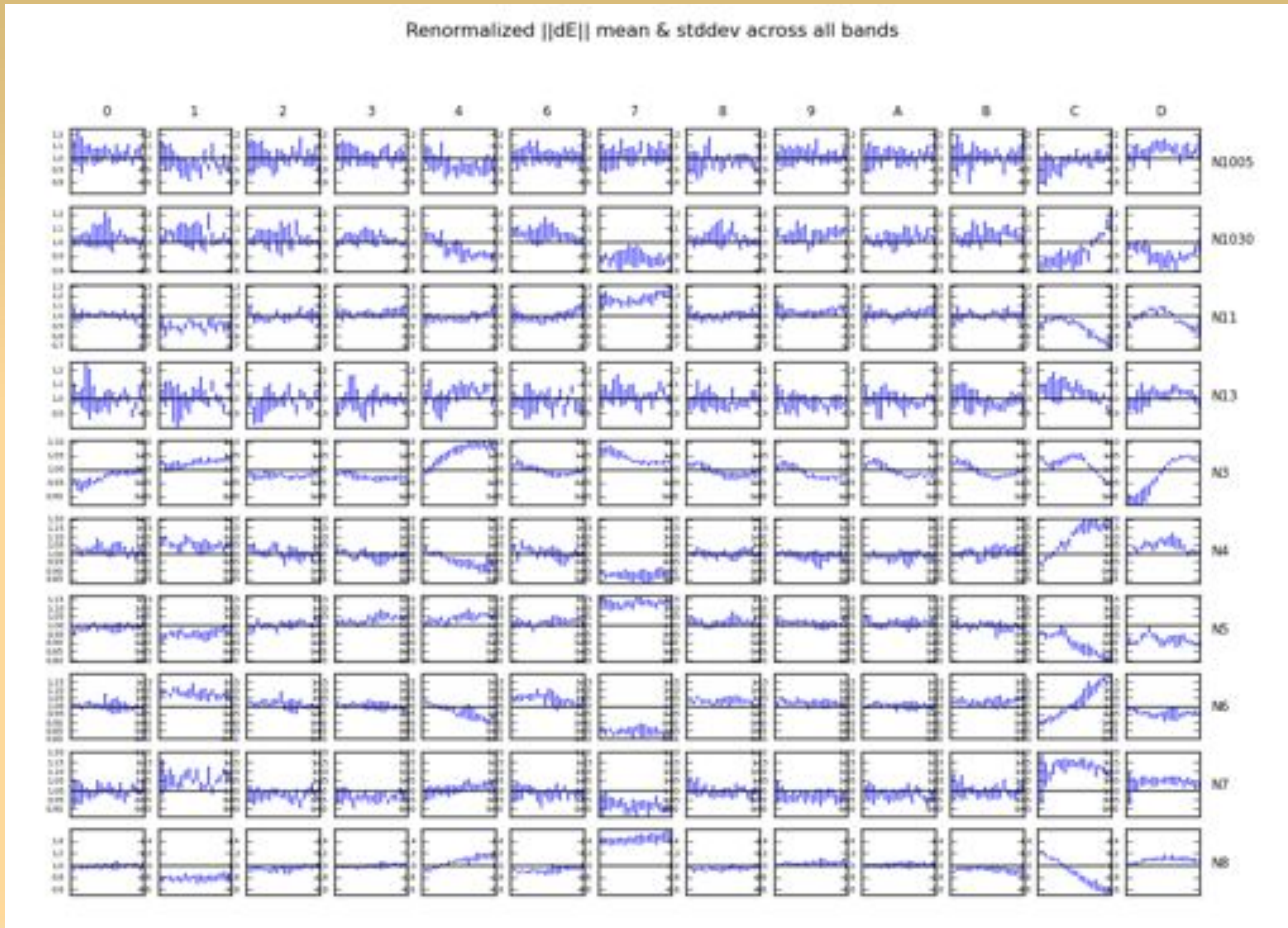
- >10 moderately bright off-center sources
- The type of field that usually has radio astronomers running away screaming...

- But perfect for our purposes!

DDEs vs. Source Structure

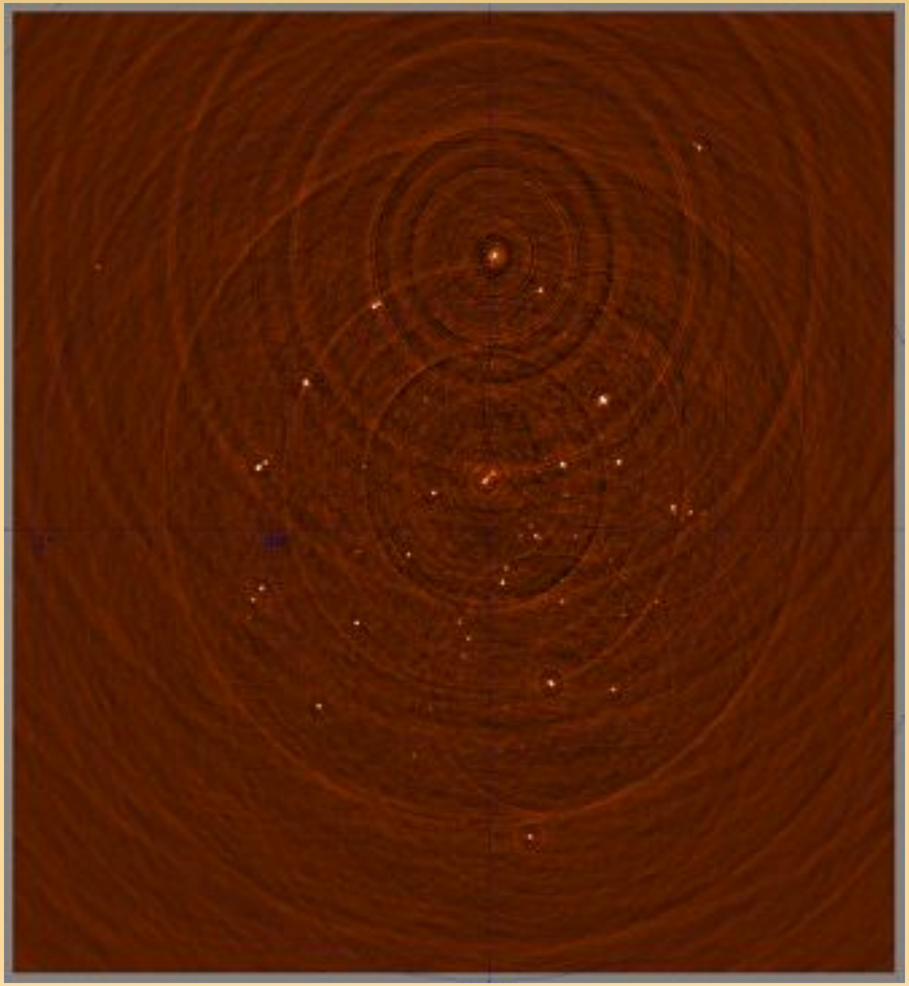
- We've been taking sky models for granted
- In real life, these need to be bootstrapped from the observations themselves.
- ...where it can be very difficult to decouple DDEs from spatial source structure.
  - Our QMC2 field has point-like sources only
  - Not so for QMC
- Unmodeled source structure...
  - ...is either partially absorbed into differential gain solutions
  - ...or else contaminates the “global” model fits

DDEs vs. Source Structure II:
(an example from a different observation)



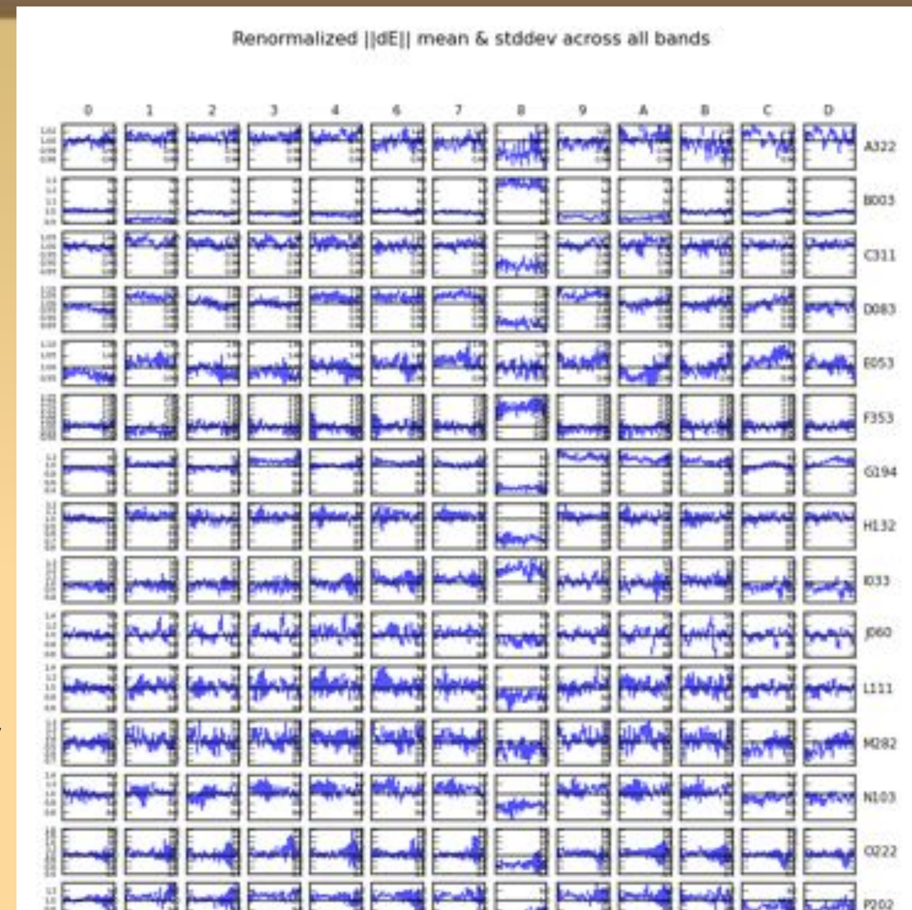
Gifts Of QMC2

- Initial observation (2010Jul3) was an “error-free” 12h synthesis, in order to build up a sky model
- *“I have never seen such a terrible WSRT map!”*
  – Ger de Bruyn
- Differential gains sorted out the issue as usual



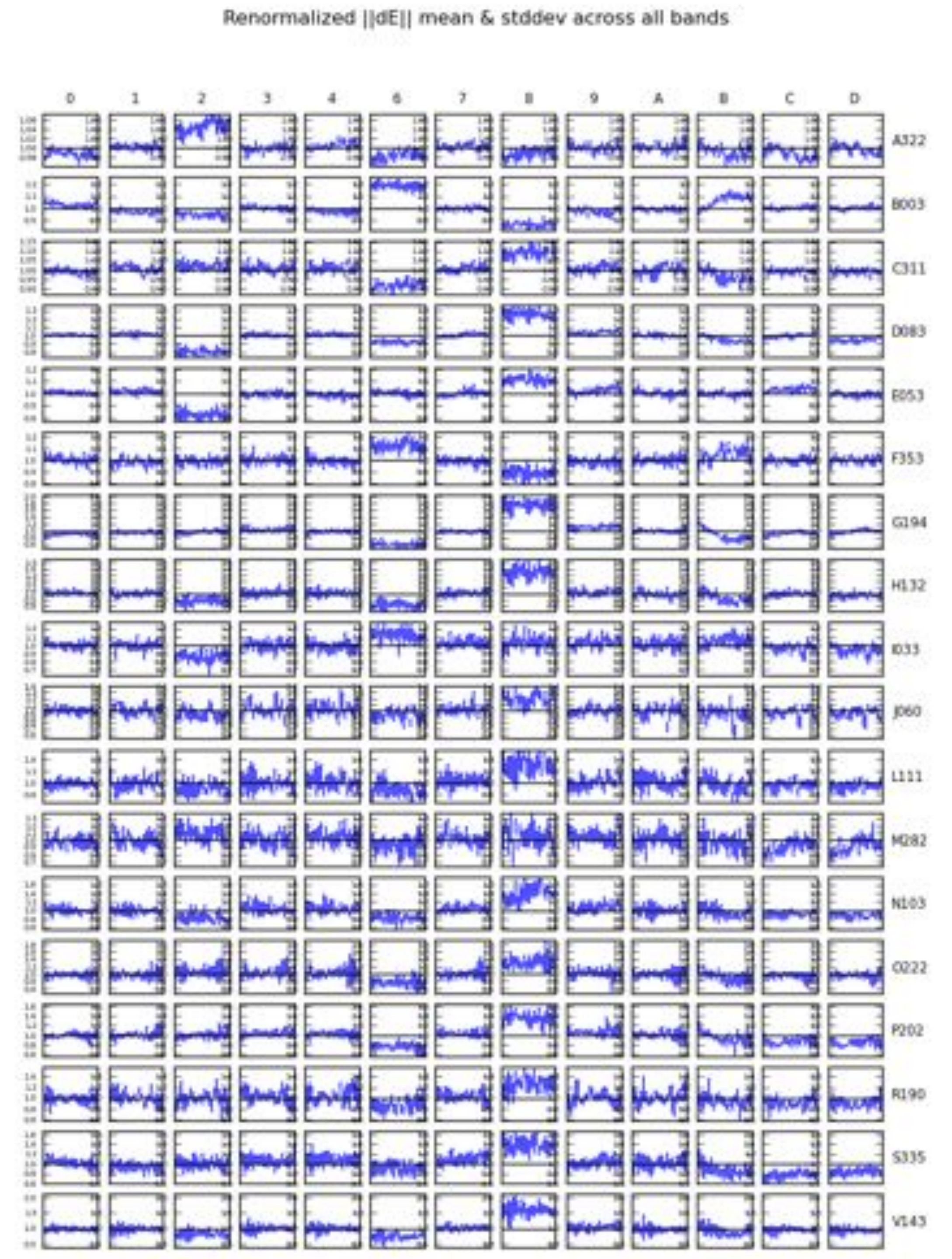
QMC2 2010Jul3 dE amplitudes

- ||dE|| solutions show large offsets on RT8, consistent with a significant mispointing to the North
- Problem was reported to the Observatory, and they discovered a faulty encoder on RT8's declination axis

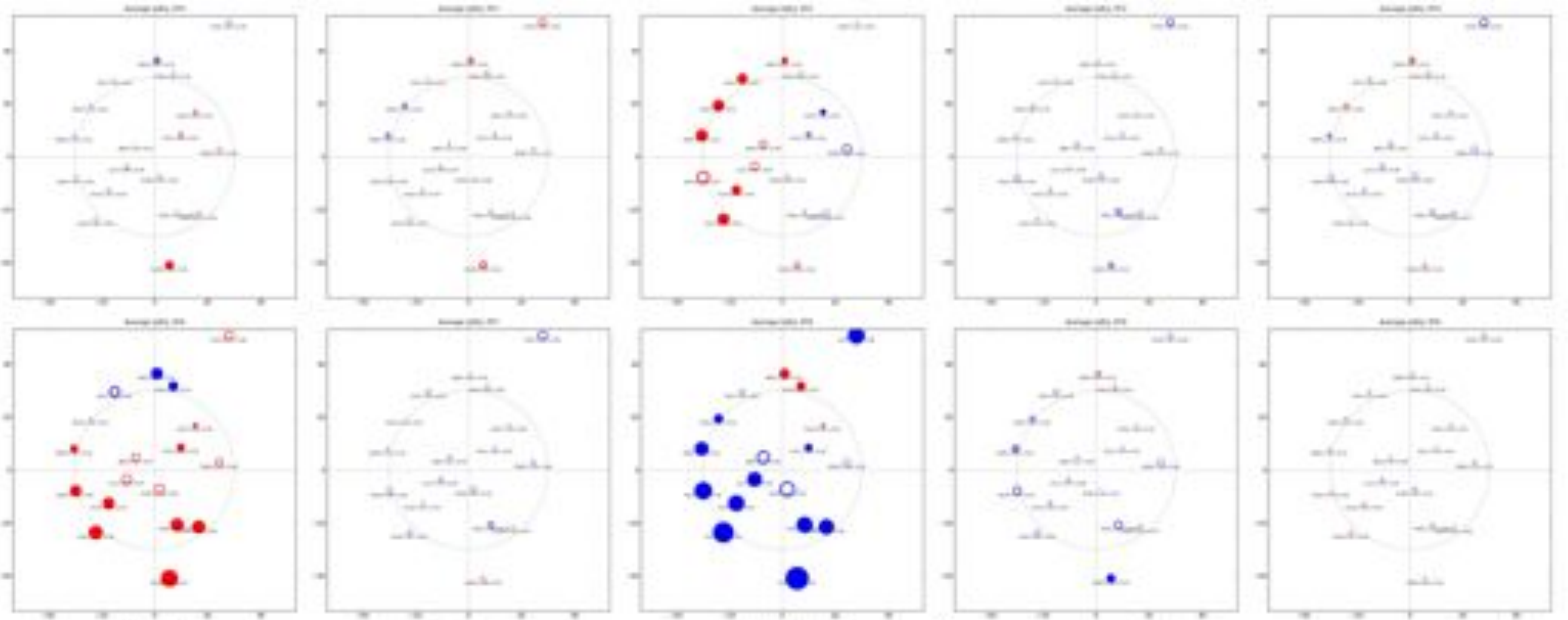


QMC2 2010Jul21: Now mispointed

- ||dE|| solutions suggest a static mispointing of RT2, RT6, RT8
- ...and a time-variable mispointing of RTB ("Hans's susprise")
- Hans confirmed that this was consistent with the mispointings he had put in.



“Rogues' Gallery” Plot



Plots of mean ||dE|| per antenna, at proper positions within the field.
Colour/size indicates
||dE||>1, <1.
(Note 3C source at NW!)

Phase II: Solving For Pointing Errors

- This was where things stood at the last CALIM
- ...where Sanjay suggested I should solve for pointing offsets on the same field
- A MeqTrees variation on pointing selfcal: DFT pointing solutions.
- MeqTrees can “solve for anything”: we need to construct a suitable model where the pointing offsets are parameters, then designate them as solvable and say “go”.

DFT Pointing Solutions

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

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

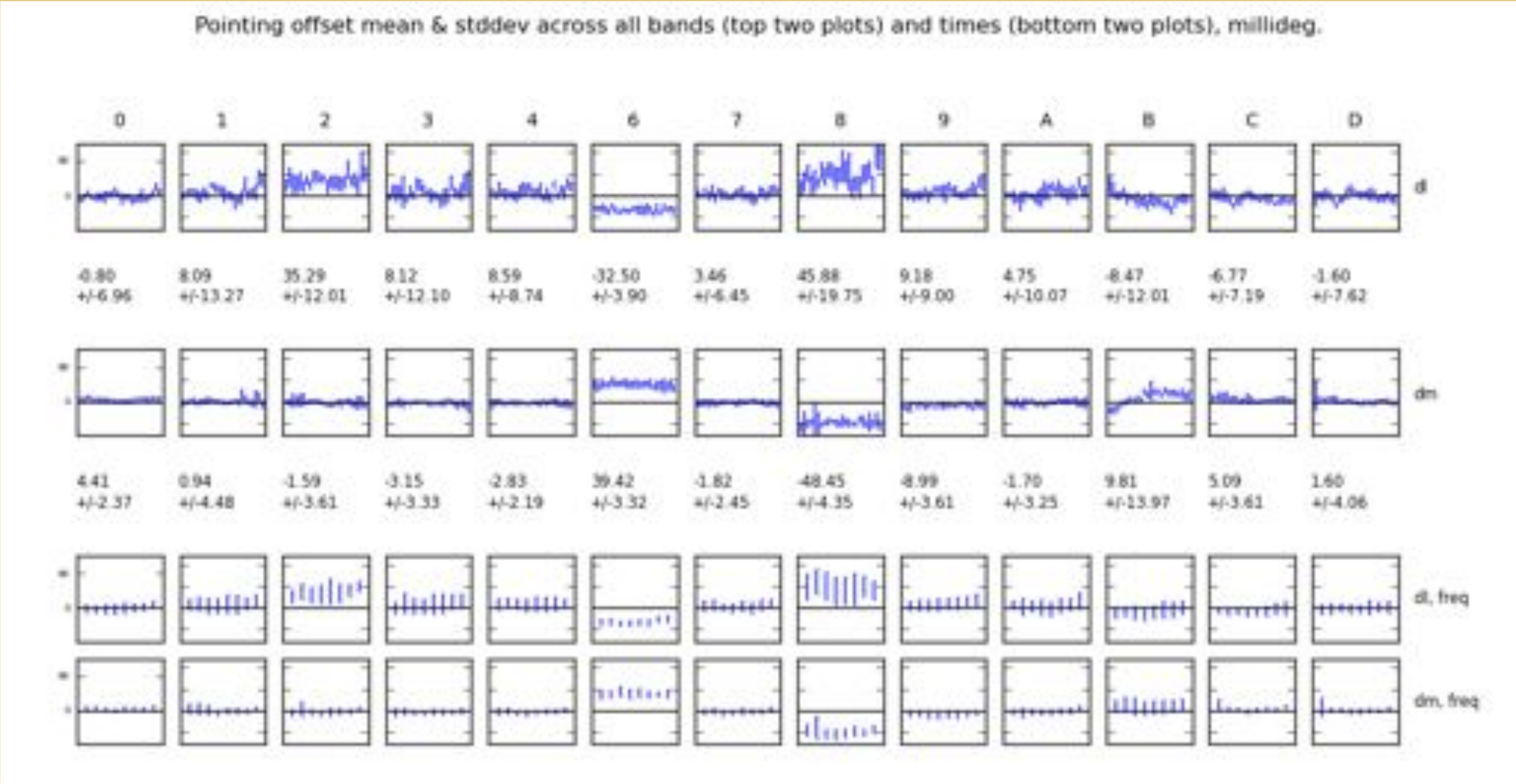
where $E(l,m,\nu)$ is a primary beam model.

...and solve for the offsets $\Delta l_p, \Delta m_p$.

Standard WSRT model: $E(l,m,\nu) = \cos^3(C\nu\sqrt{l^2+m^2})$

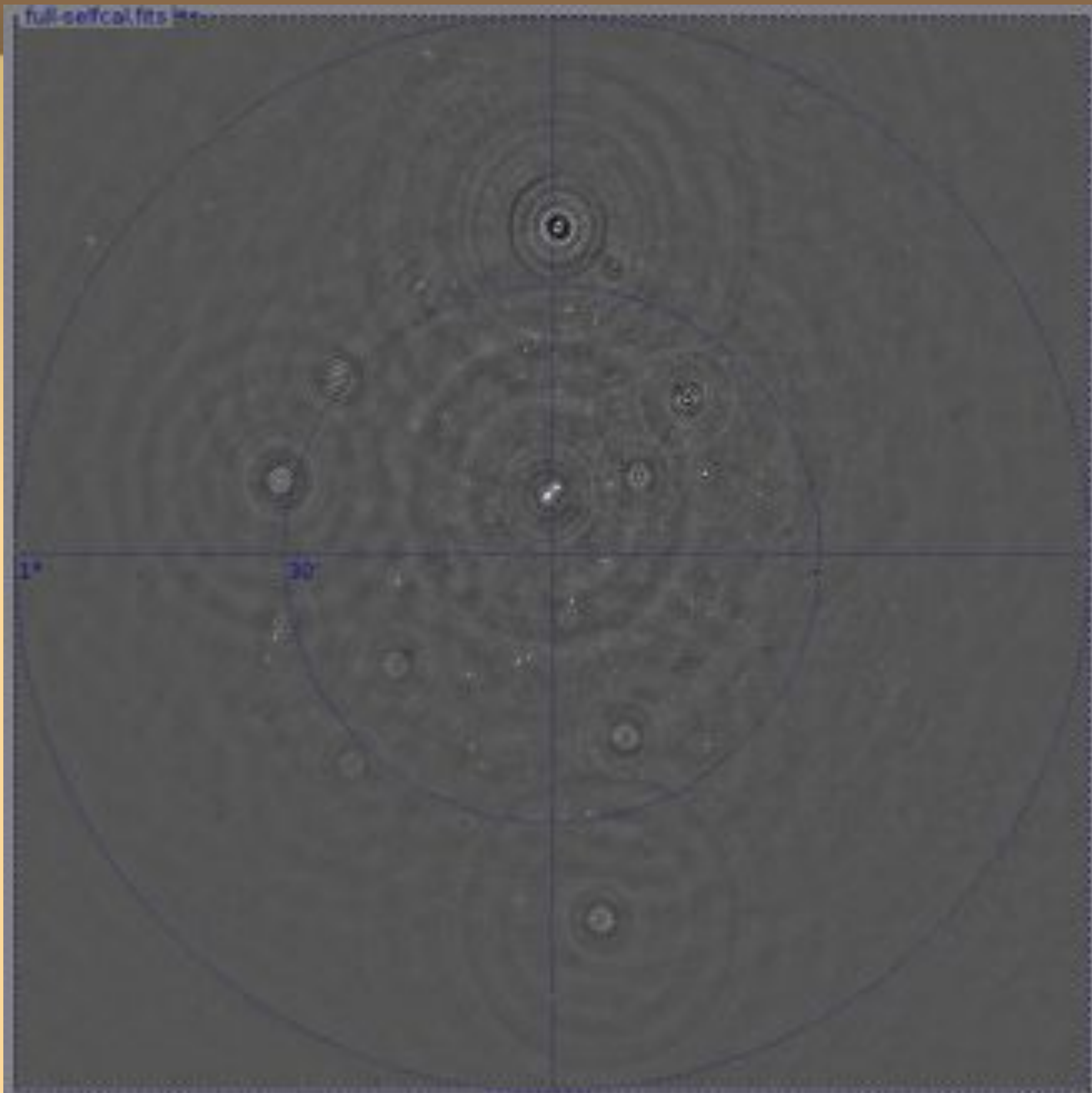
P.E. Solutions (QMC2 2011Jul21)

- Recovered solutions consistent with deliberate mispointings, but <u>underestimate</u> them:



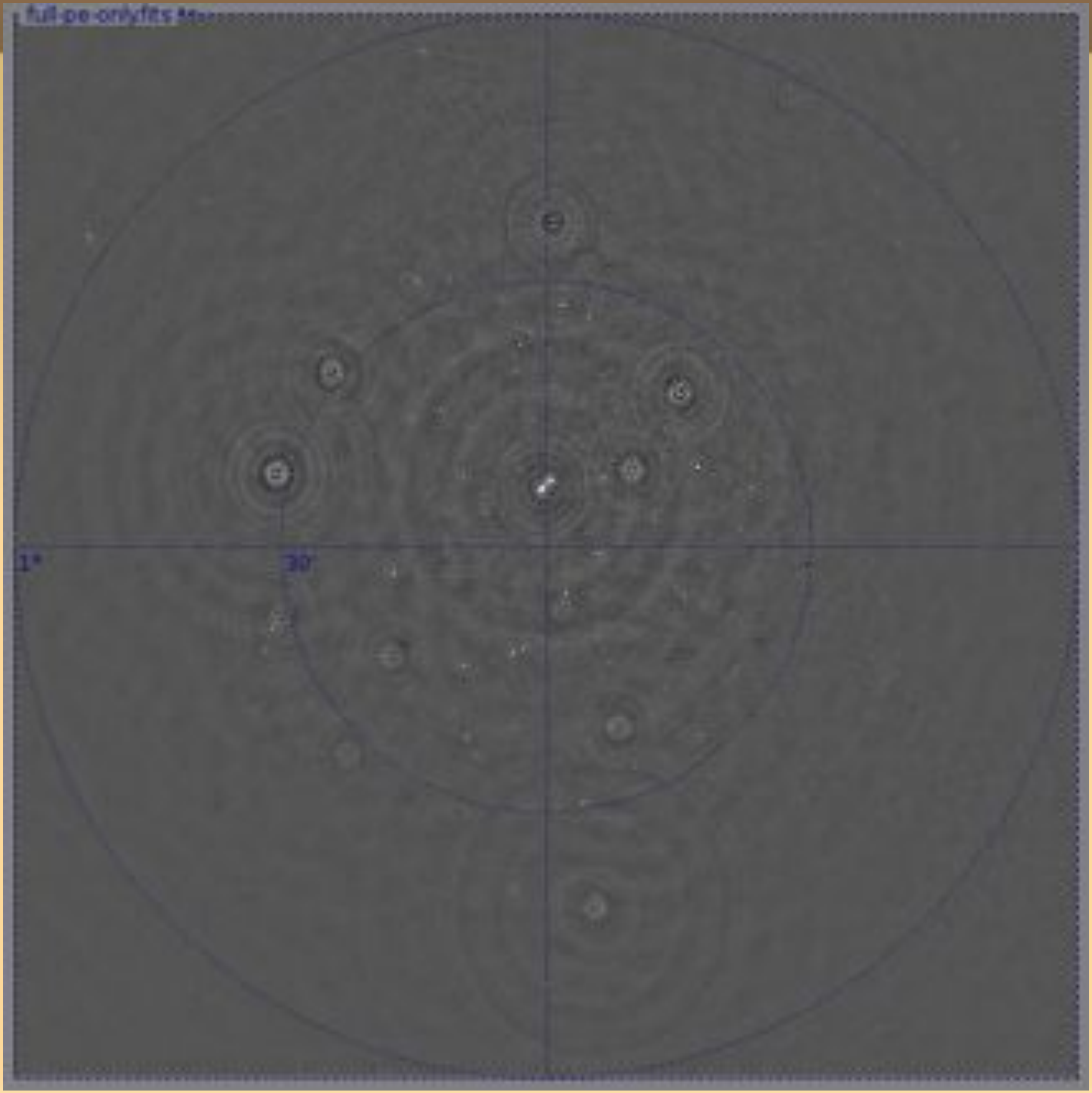
Fancy plots are all very nice, but...

Not so impressive...



Residual image, post-selfcal

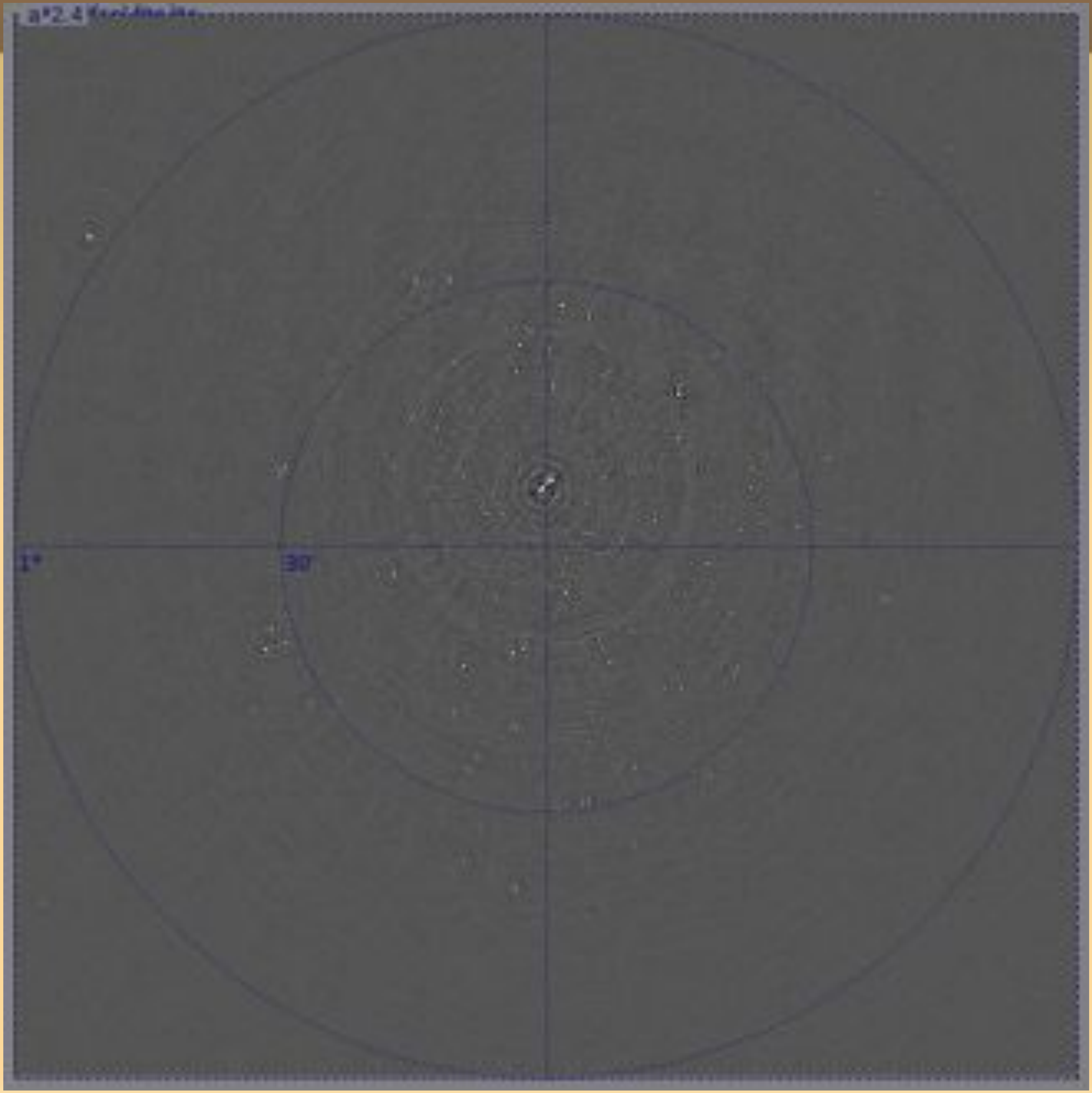
A Marginal Improvement



Residual image, post-selfcal, with pointing error solutions

(Note how this relative lack of improvement is consistent with Sanjay's pointing selfcal results.)

Nowhere Near The Flyswatter...



Residual image, post-selfcal, with differential gains.

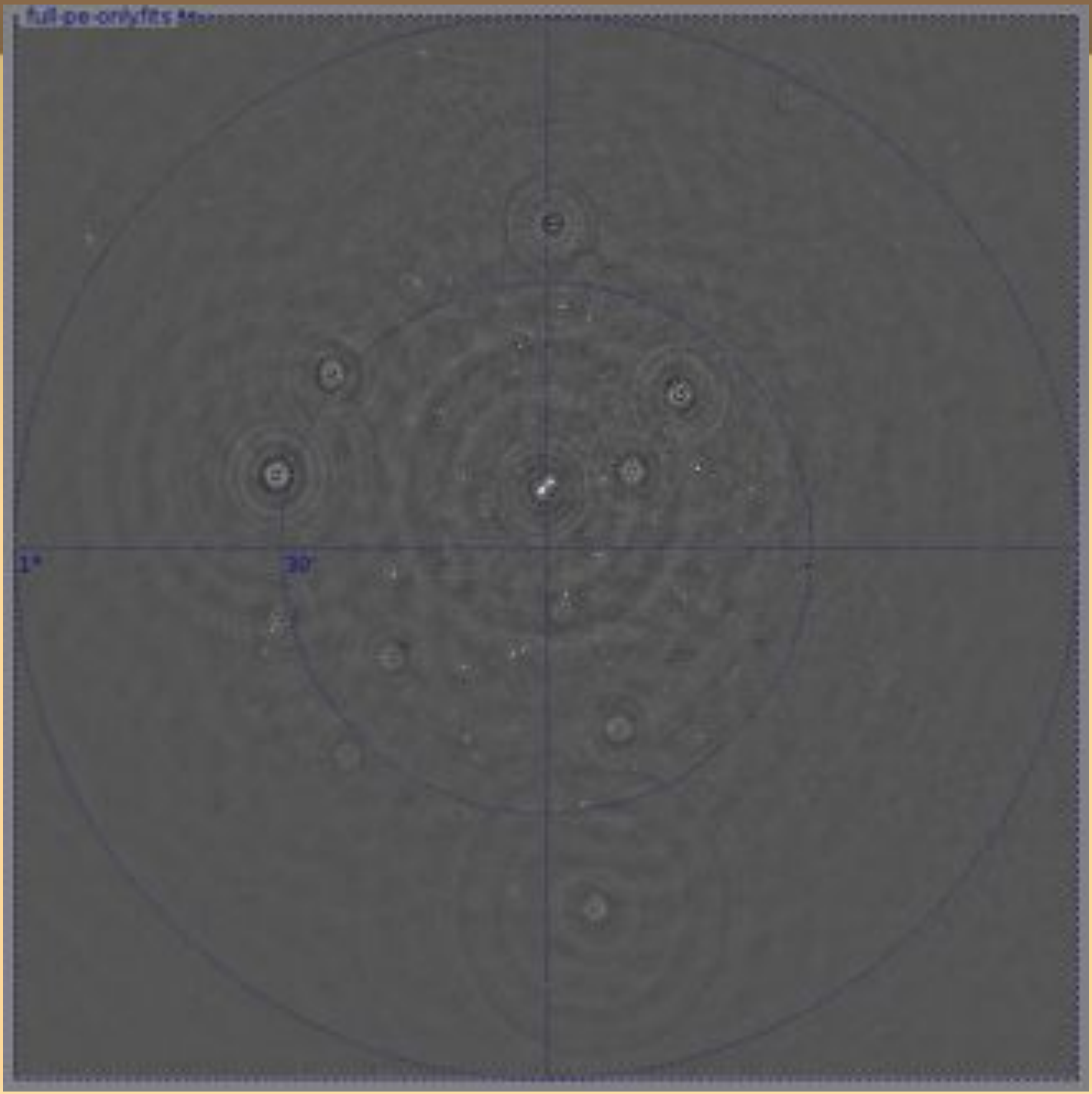
Parameterizing The Beam

- The advantage of the DFT approach is that we can introduce other parameters into the primary beam model.
- Just as a random example, we can introduce a per-antenna beam scale s_p:

$$\boldsymbol{E}_p(l,m,\nu)=E(l+\Delta l_p, m+\Delta m_p, s_p, \nu),$$
$$E(l,m,s,\nu)=\cos^3(C\nu s\sqrt{l^2+m^2})$$

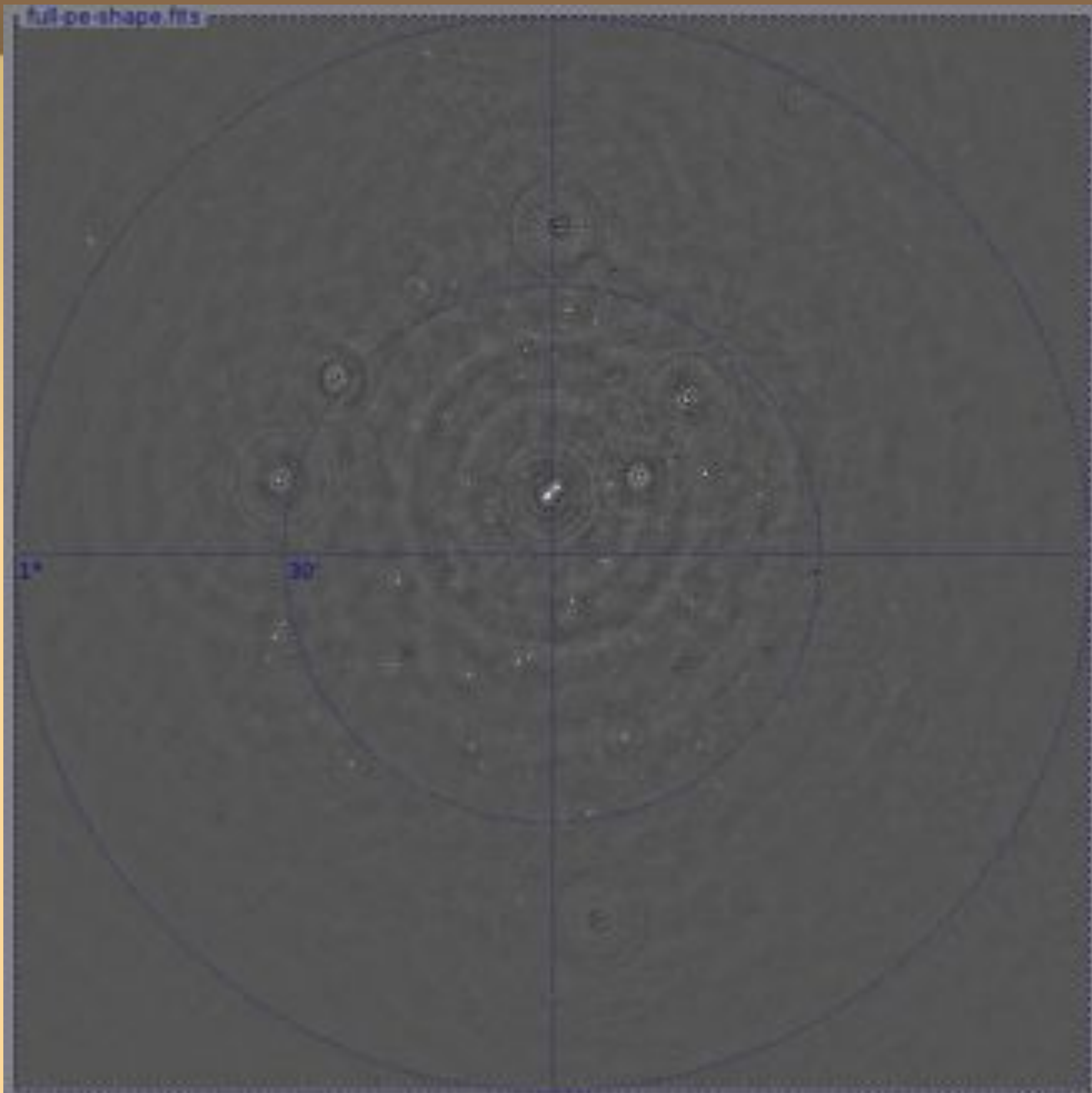
- And then treat s_p as a solvable.

P.E. Solution Only



Residual image, post-selfcal, with pointing error solutions

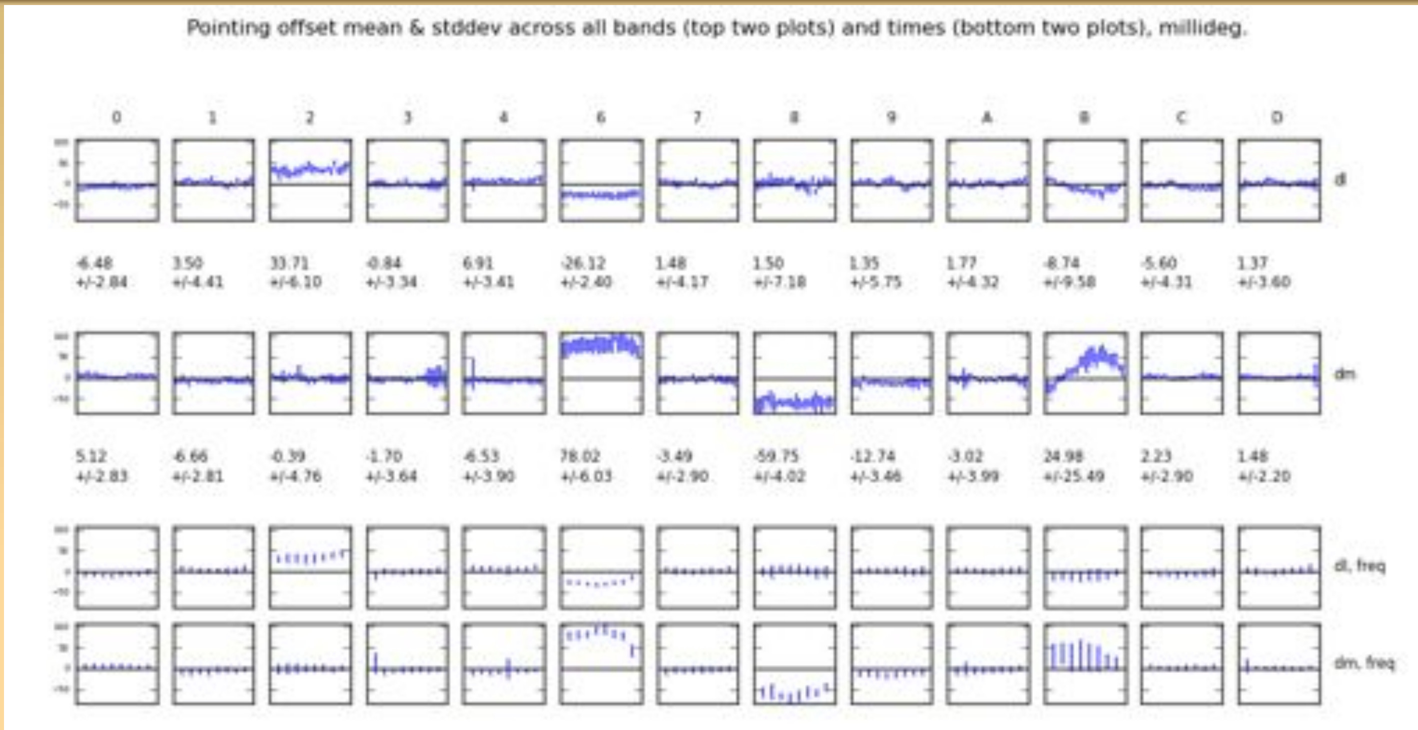
P.E. + Beam Extent

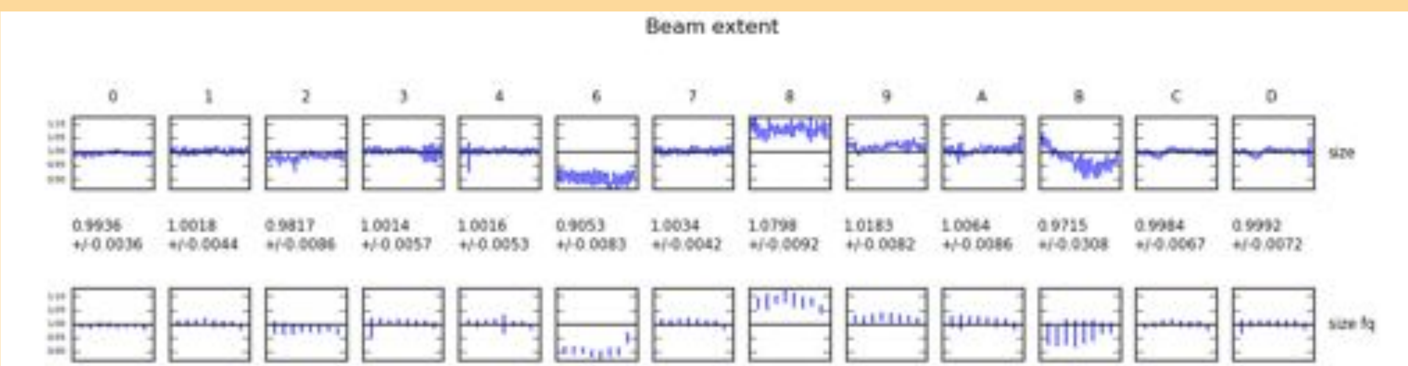


Residual image, post-selfcal, with pointing error and beam extent solutions

...not as good as differential gains, but an improvement!

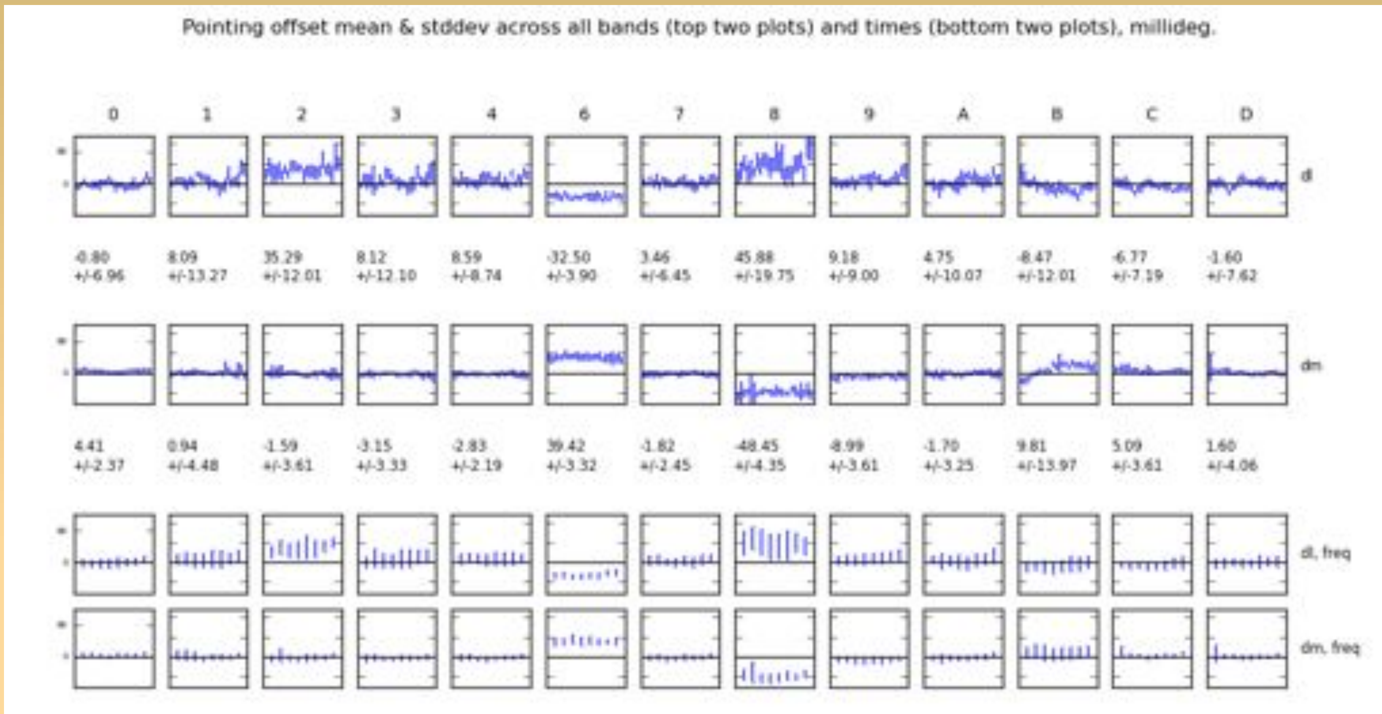
Now Back To The Pretty Plots





- Beam extent and pointing offset solutions are strongly coupled
- Beam extent solutions are non-physical (±10%!)
- More of the poitning
- Obviously the extra degree of freedom is compensating for something else, but what exactly?

Compare To The PE-Only Case



- P.E. solutions without a beam extent show more variance
- ...and underestimate the true mispointing to a larger degree

- Tentative conclusion: P.E. solutions are limited by the accuracy of the beam model
- ...as are the final maps
- There may also be a directional coupling determined by the configuration of sources in the field.

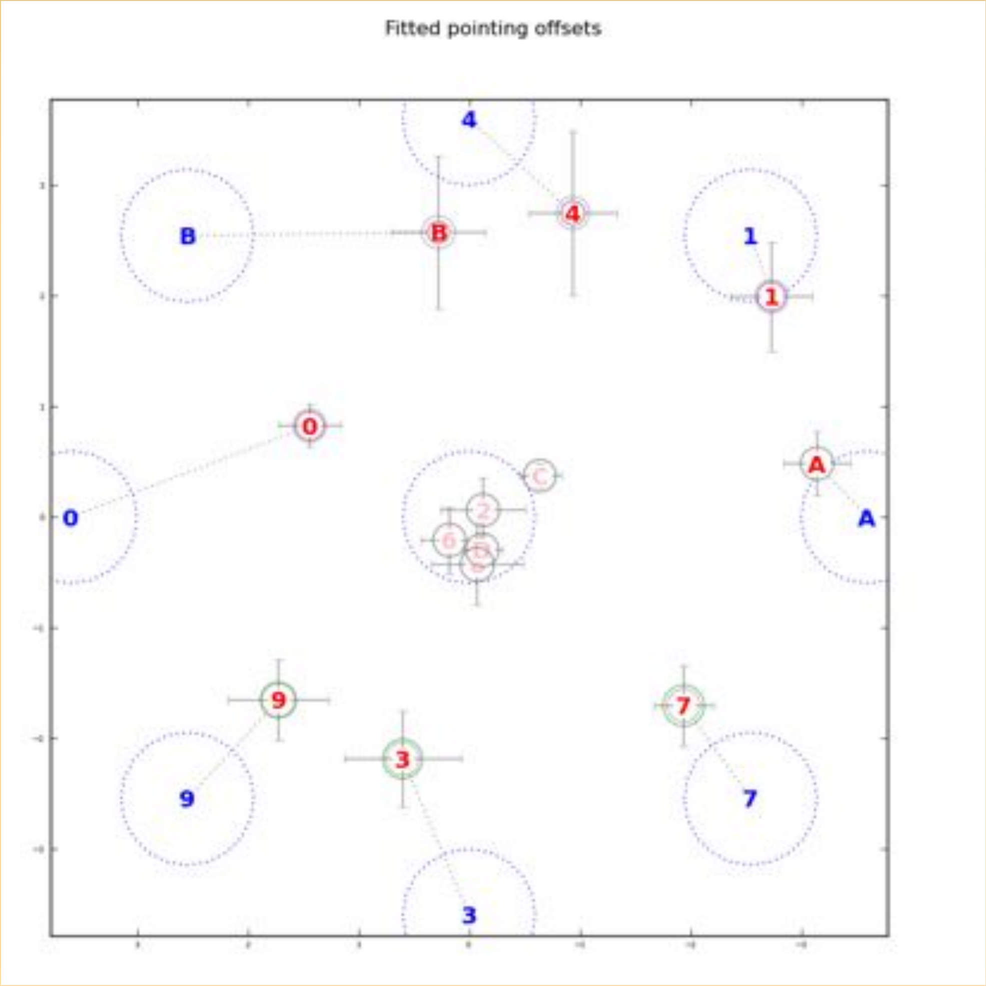
QMC2 “8-Way” Observations

- To check for directional coupling, we asked for another observation of QMC2 with 8 antennas mispointed to 8 points of the compass (by 60 mdeg each)
- This was done in March 2011, but due to some problems only 90 minutes of data were taken
- Thus no imaging was possible
- ...but we could still do P.E. solutions
  - (we'd been solving at 30-minute intervals before)

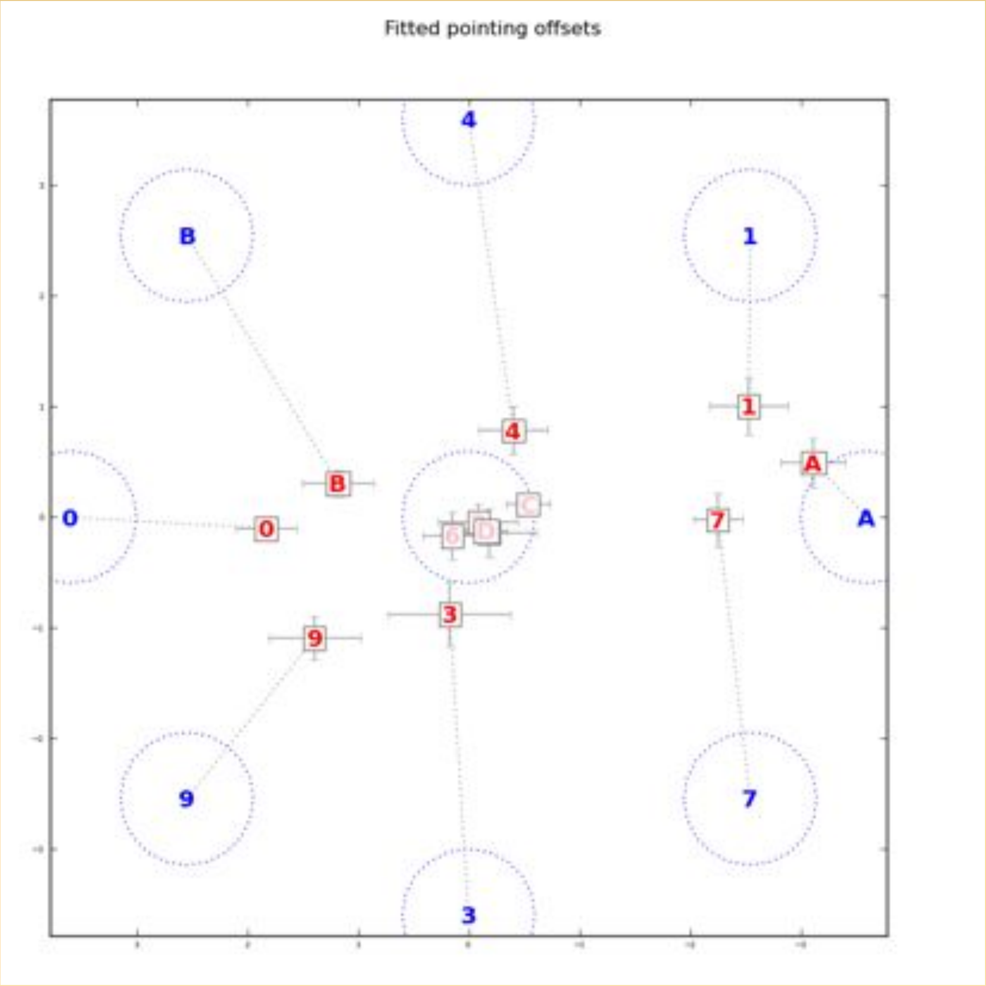
8-Way Pointing Solutions

- Expected vs. fitted pointing offsets

With a solvable beam extent



Without a solvable beam extent

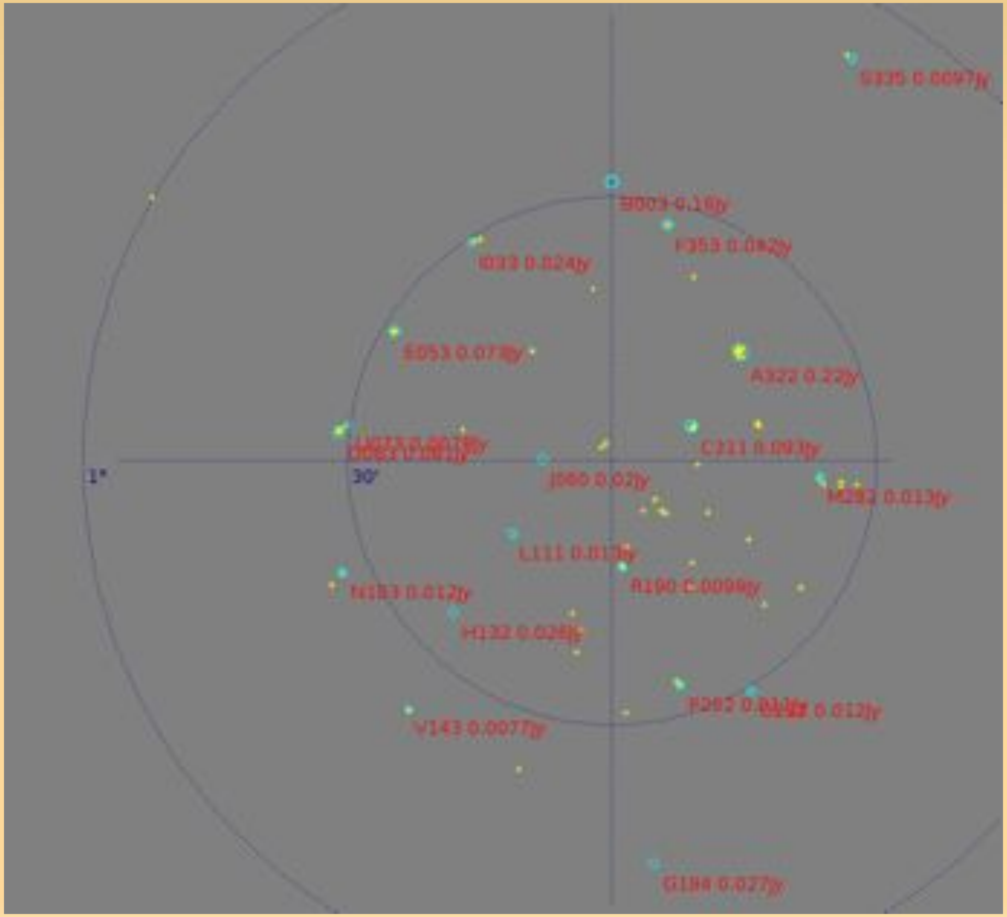


Know Thy Beams (and the incestousness of selfcal)

- Why not throw more parameters at the beam model?
- We do **NOT** have absolute, intrinsic source fluxes. Selfcal gives us fluxes attenuated by some *average* primary beam.
- Our solution is then only sensitive to *differences* between antennas (and timeslots).
- Given a perfectly-pointed observation and identical PBs, our method is *completely insensitive* to beamshape.
- Pointing errors give us a handle on the *gradient* of the beamshape.
  - (this also explains why the beam extent solutions above are non-physical!)

The Next Step: A QMC2 Mosaic

- Latest observation (2011Jul17): a 10-pointing mosaic, ~1 hour per pointing.
- 1 pointing to field centre, 9 pointings to off-axis sources around the half-power point.
- 8-way mispointed.
- Will use this to simultaneously constrain source fluxes and PB models.

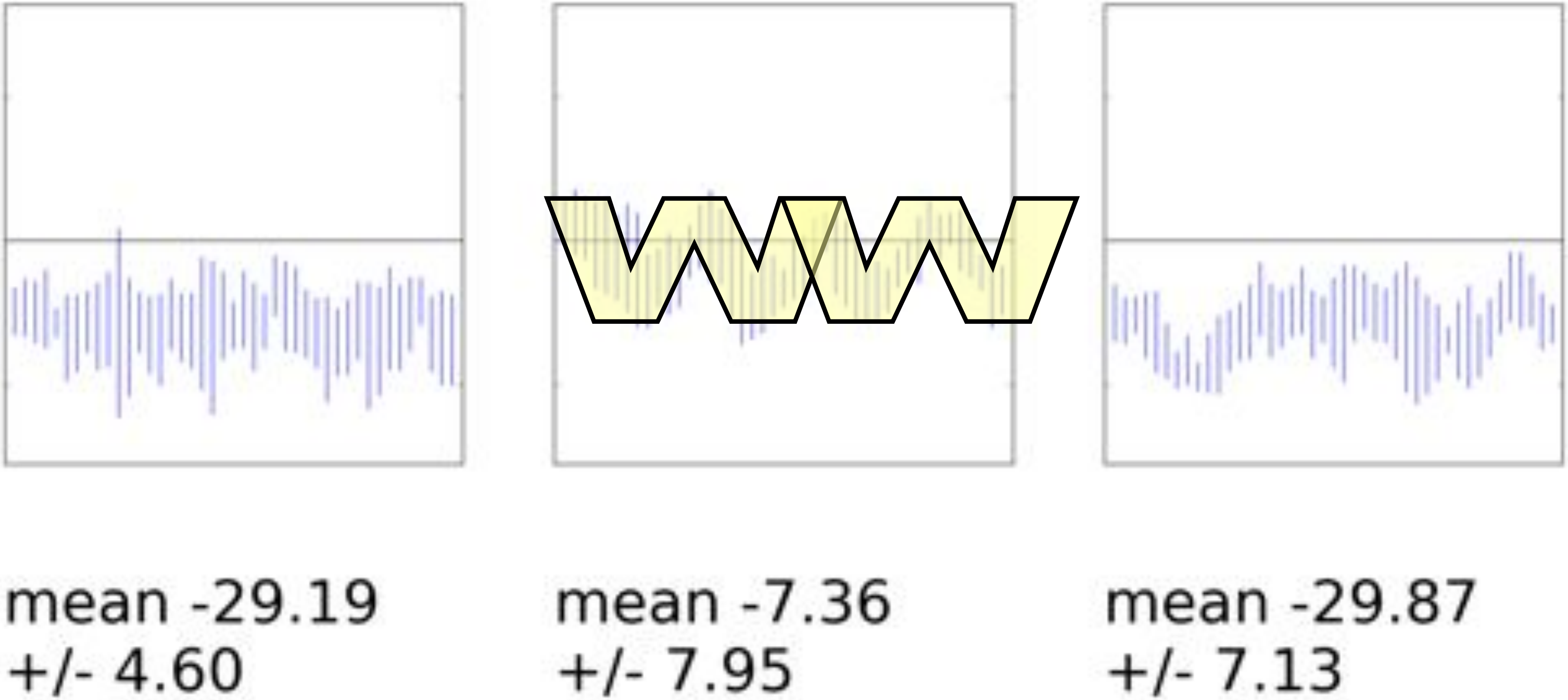


Yet Another Twist: Solving For P.E. On Shorter Time Scales

- Solutions every 30 sec, 2.5 min and 5 min.
- Longer time scales: decreased variance (higher SNR)
- Diminishing returns above 5 min.
- Show a striking feature unnoticed on the previous (30 min.) plots...

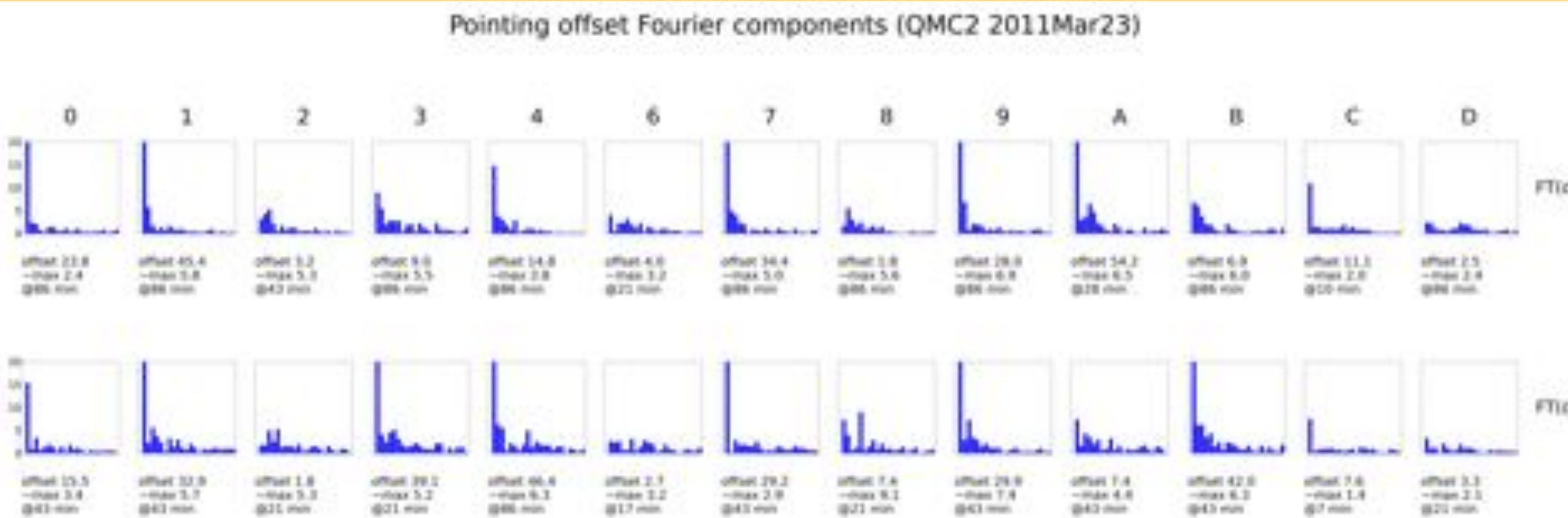
And Now, Applying Sophisticated Model Fitting Techniques...

Westerbork Wobble!

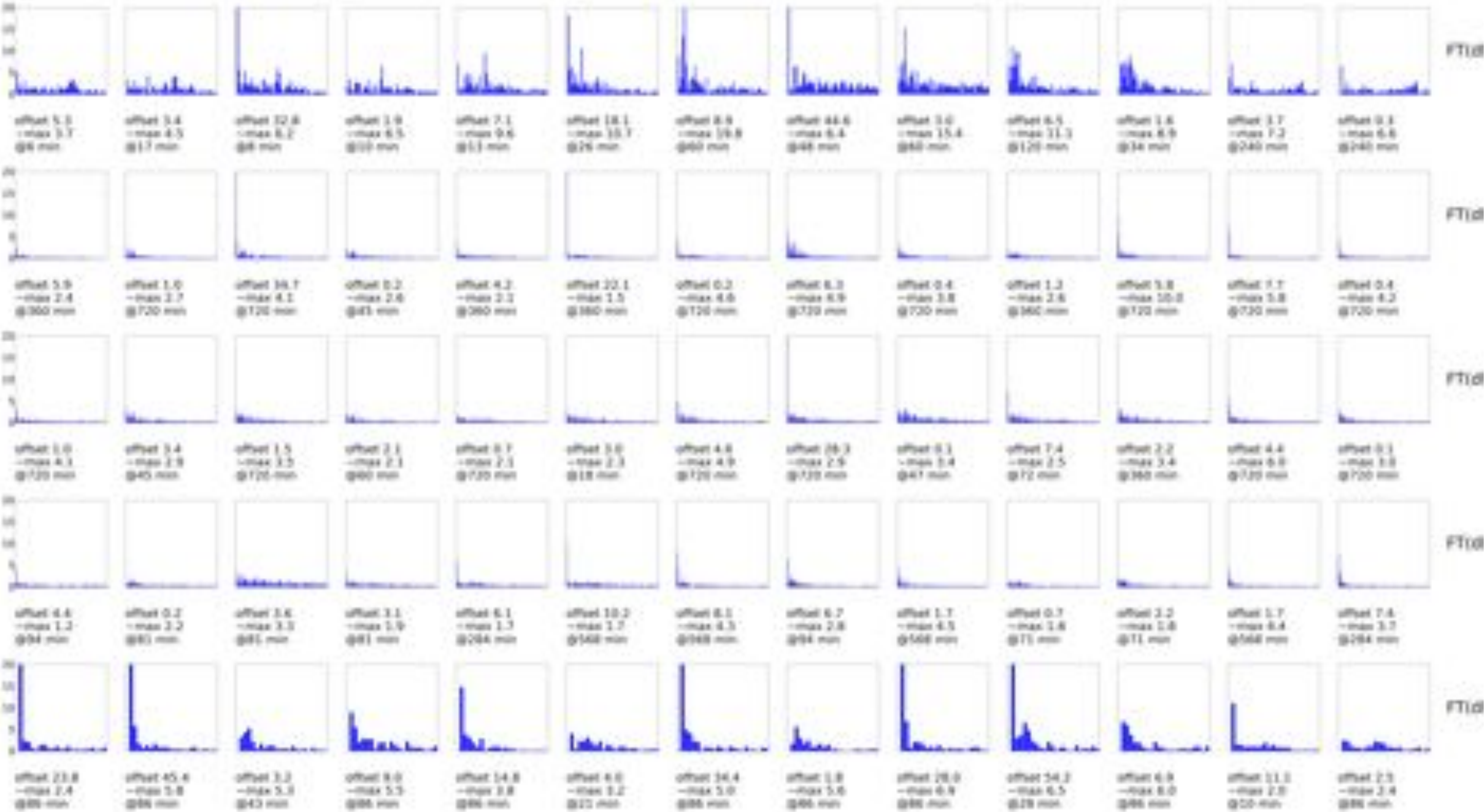


The Wobble

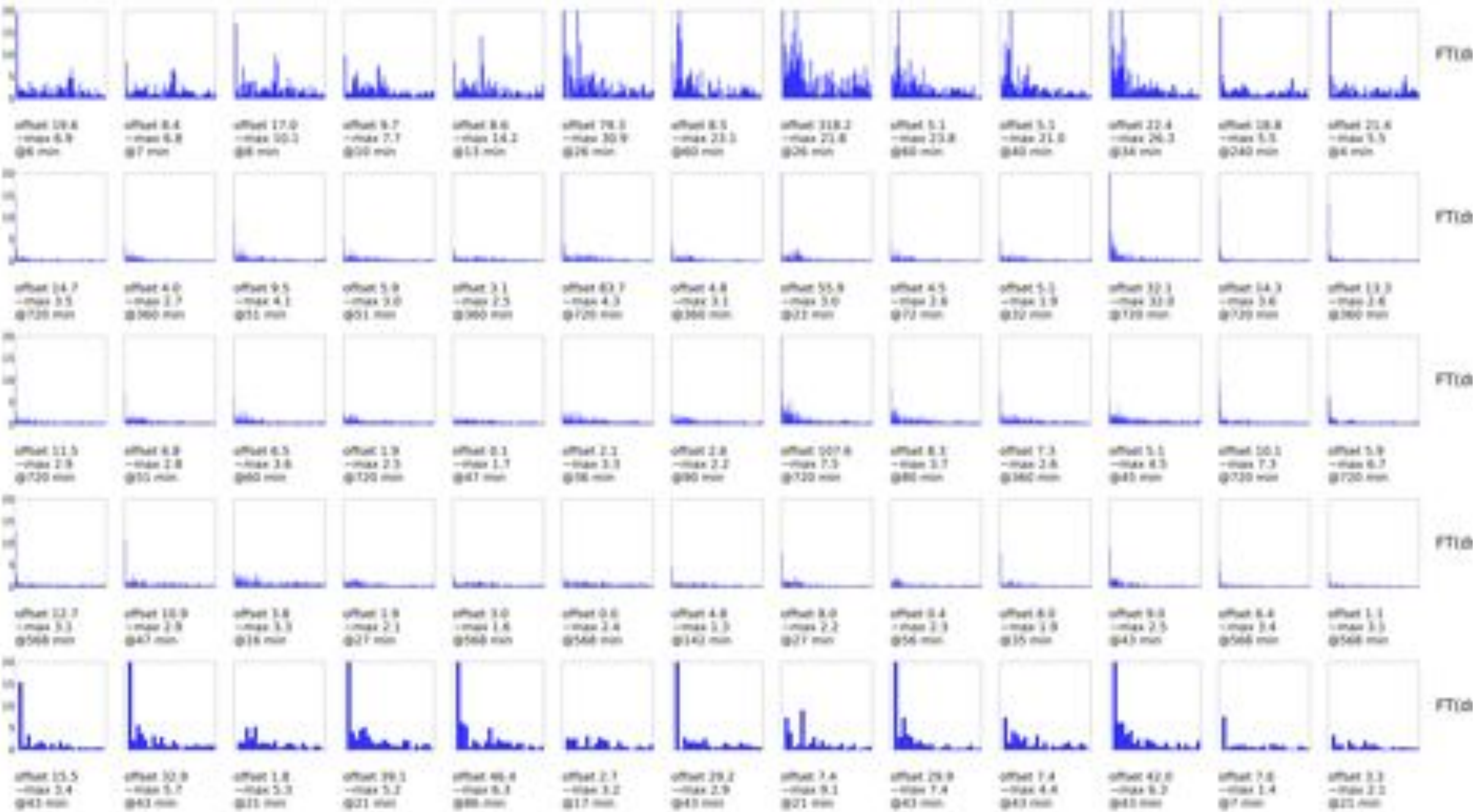
- A periodic (~20 min) variation in the pointing of 10-20 mdeg.
- Shows up in other observations, on **<u>other</u>** antennas (to varying extent)
- Fourier transform the pointing offsets, and plot the amplitudes of the Fourier components:



Wobbling Across 5 Epochs (RA)



Wobbling Across 5 Epochs (Dec)

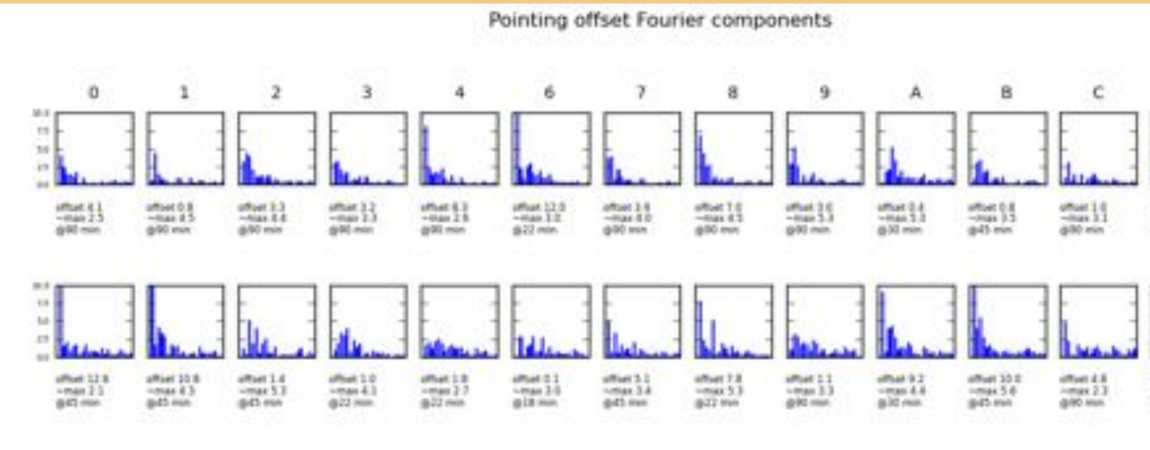


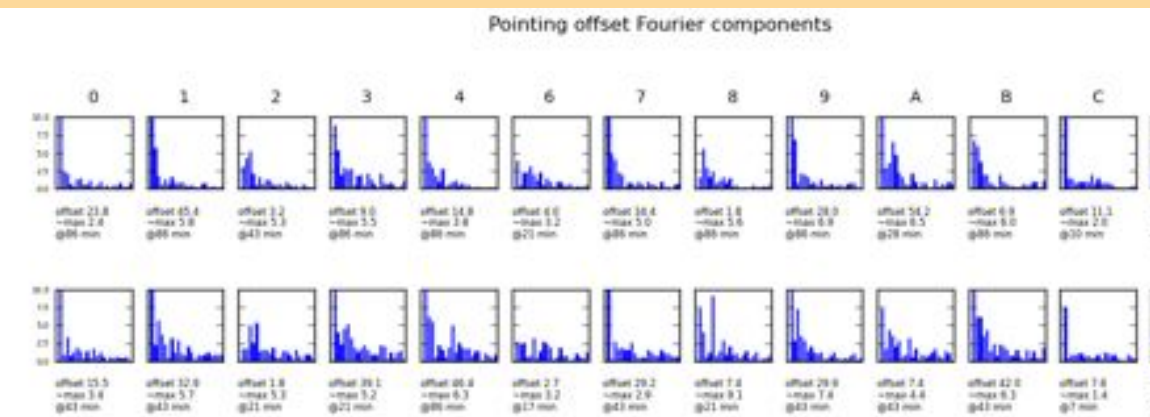
Wobbly Features

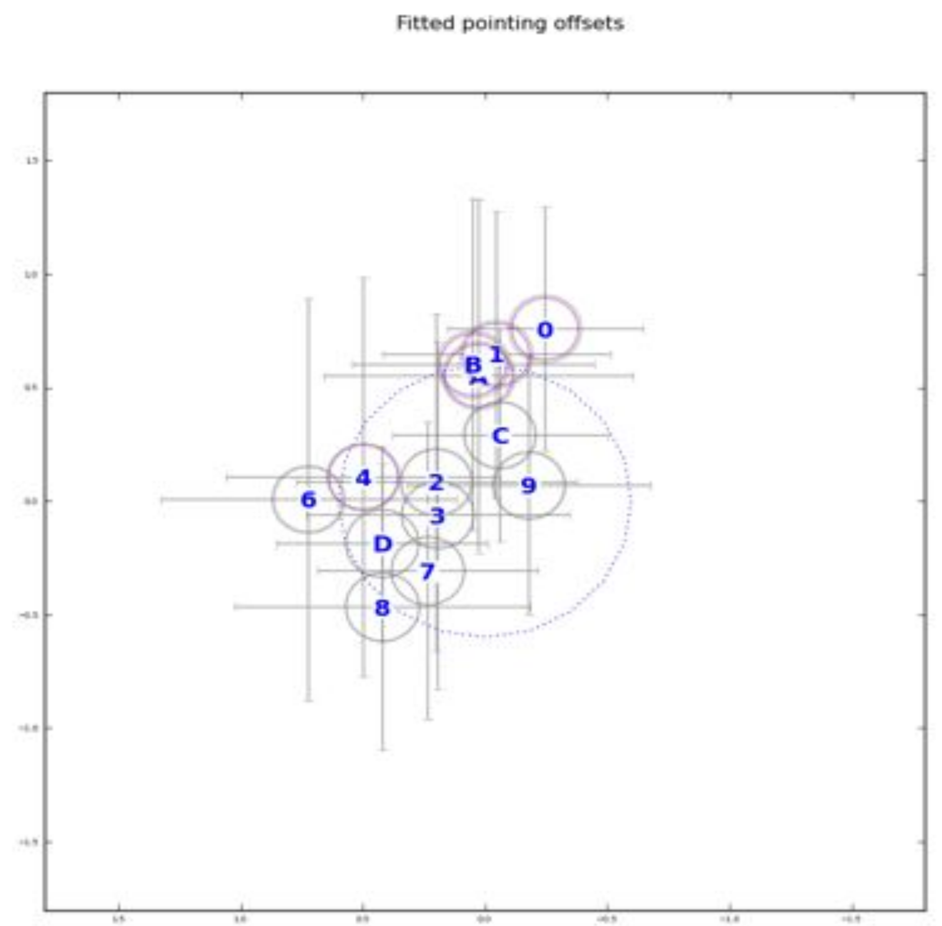
- RA & Dec coupled, Dec wobbles more
- Only some antennas wobble
  - But they differ epoch-to-epoch
- Wobble amplitude varies epoch-to-epoch
  - Can reach 20 mdeg (10 is nominal accuracy!)
  - Some epochs much worse than others, why? (waiting for wind data)
- Wobble period is 5 to 60 minutes
  - Quite stable (up to 4 hours)

The Promise of a QMC

- 60 ~ 90 minutes of data is enough to characterize both the static and the dynamic pointing quality.
- WSRT schedule always has suitable small gaps







Conclusions I

- Differential gains (dE's) can completely eliminate contaminating sources
  - ...but only feasible for a few (tens) of sources
- “Global model” DDE solutions (pointing selfcal, DFT pointing, etc.) are also feasible
  - ...but don't (yet) eliminate artefacts to the same extent
- The future is hybrid: high-DR imaging at SKA sensitivities will require:
  - dE's (or some variation thereof) on Cat I sources
  - “global model” DDE solutions on Cat II sources

Conclusions II

- Pointing error solutions are limited by the PB model
  - as are the remaining imaging artefacts
- **KNOW THY BEAMS!**
  - and we don't, really (so come to Portugal!)
- Westerbork Wobbles, and we ought to figure out why (APERTIF is coming)
- Would be nice to apply this to other observatories (Will the VLA Vaccilate? Must MeerKAT Meander?)
- I make really bad puns sometimes...