Error recognition and self-calibration

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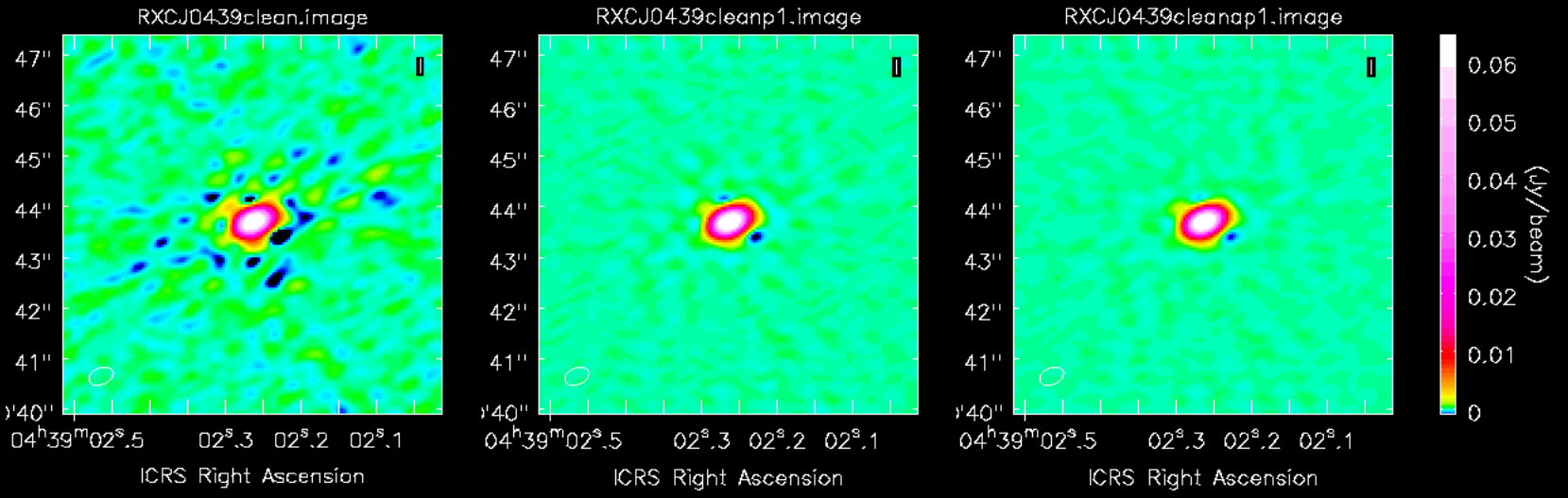

- 'Principles' and practice
  - Effects of ϕ & amp errors
- Whento self-calibrate
  - Strategies for setting params

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Image inspection

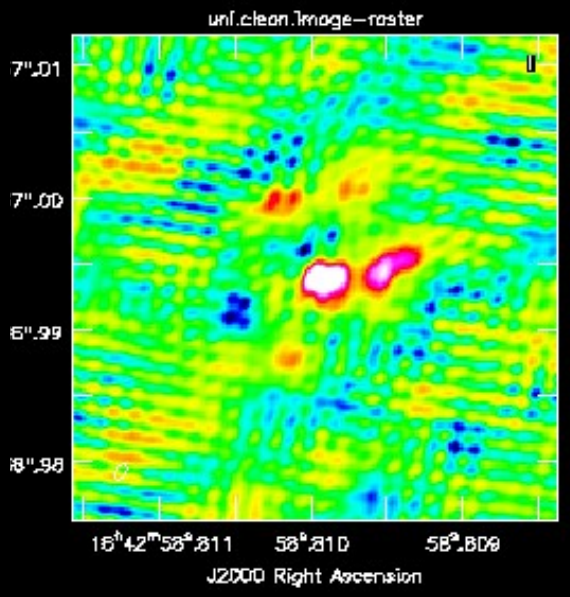
- Look at the off-source rms noise
  - Use on-line calculators (e.g. JVLA, ALMA) or formulae
  - Measure rms with (e.g.) casa viewer or imstat
  - Does the image rms increase near bright sources?
  - Is the noise random or are there ripples?
- Are there obvious artefacts?
  - Coherent I features <-4σ
  - Rings, streaks etc.
- Properties of artefacts
  - Additive (constant over the field) or multiplicative (scales with brightness)?
  - Symmetric or antisymmetric around bright sources?

$$S_{rms} = \frac{2kT_{sys}}{A_{eff}\sqrt{N_A(N_A-1)t_{\mathrm{int}}\Delta\nu}}$$

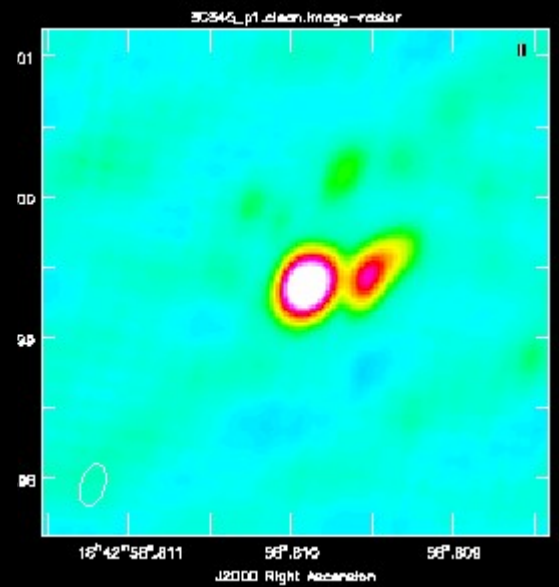
Image artefacts

- Unnatural small-scale on-source structure
  - Diffuse structure looks spotty
  - Short-wavelength sinusoidal ripples
- Deconvolution errors
  - Often associated with poor long baseline *uv* coverage
    - Give these lower weight (high value 'robust', uvtaper)
    - Take care with masking, don't over-clean

Uniform weighting Unsuitable for sparse uv sampling, partly-calibrated data



Natural weighting Coarser resolution but far fewer artefacts, better S/N

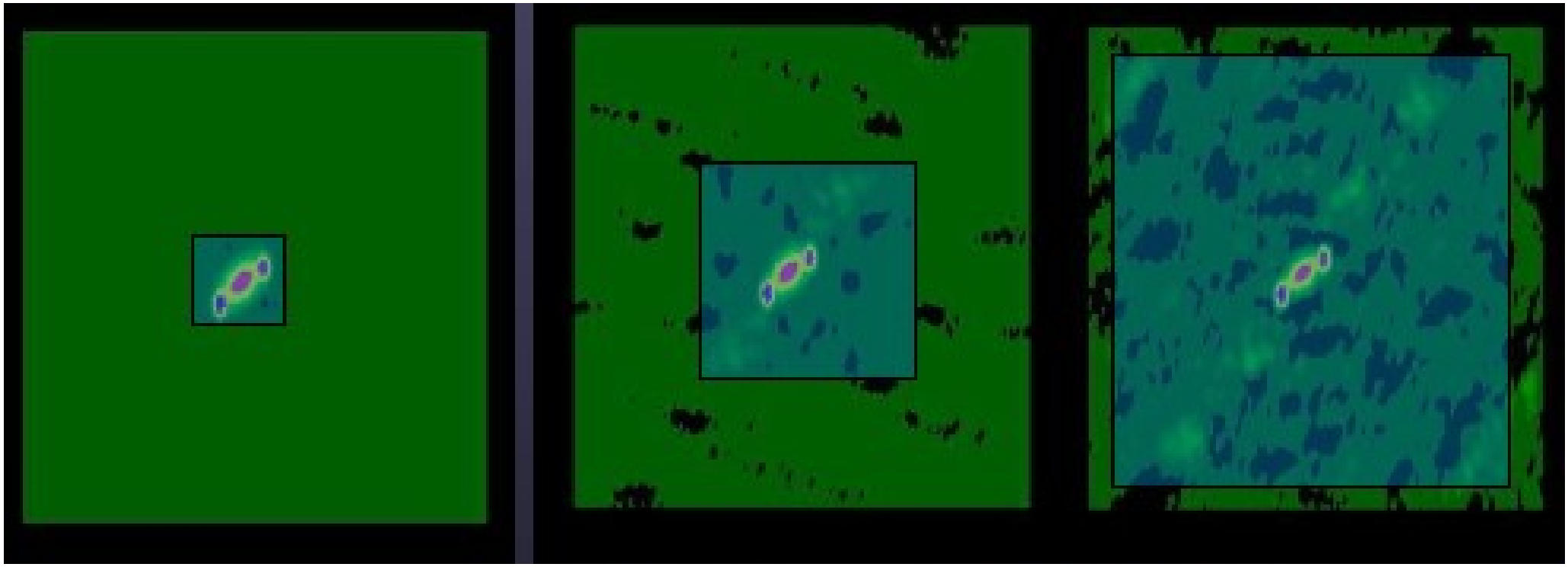


Possible causes: image scales

- Is the image big enough?
  - Confusing sources outside the image
  - Make a wider-field, tapered image and look
  - Look in standard catalogues for cm-wave (NVSS)
- Are the pixels small enough to sample the beam?
  - Are bright point sources accurately located on pixels?
- Wide-field issues (calculate expected effects)
  - Averaging time too long? (Azimuthal smearing ∝ radius)
  - Spectral channels too wide? (Radial smearing ∝ radius)
  - *w*-term (non-coplanar baselines)?
  - Ionosphere (single field > isoplanatic patch at long λ)?
  - Pointing/antenna position errors (see calibration talk)?

Probably not an ALMA problem

CLEAN boxes too big

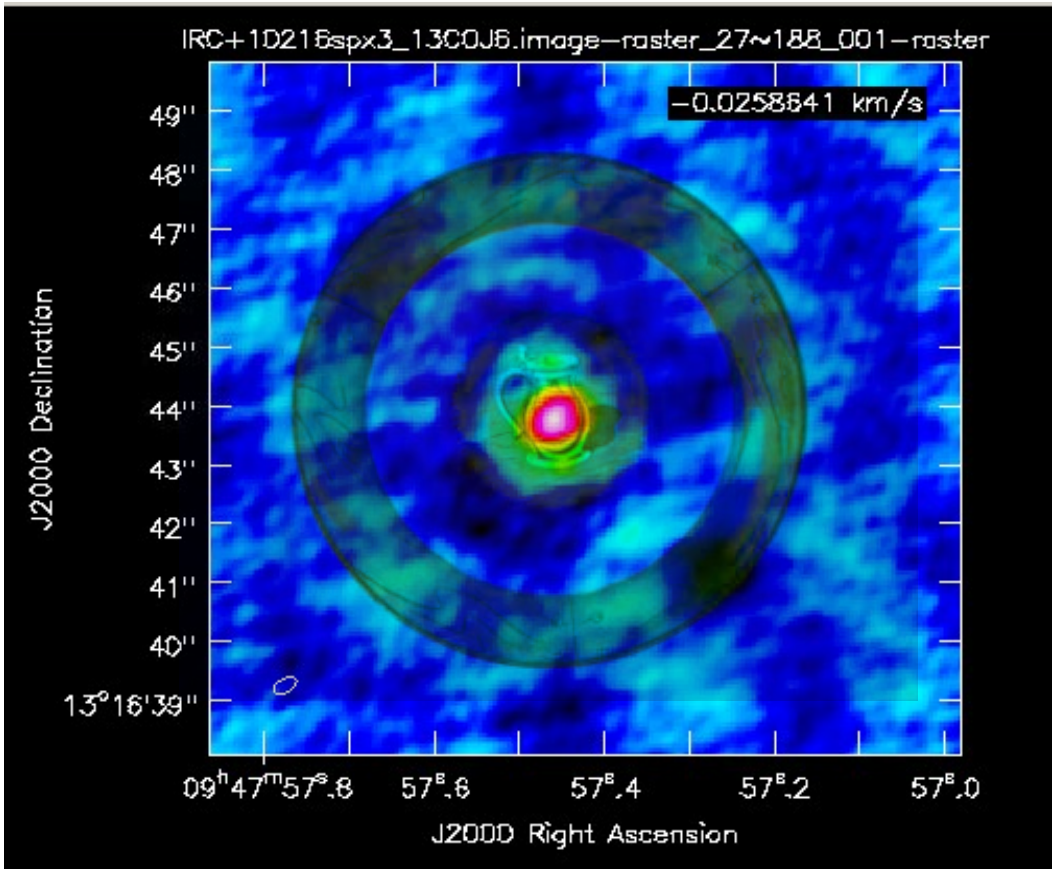


Correct Too big Far too big

It is hard to make real emission go away, but possible to 'freeze' artefacts, especially into self-calibration. If unsure, do a small number of iterations per cycle and increase mask size if needed.

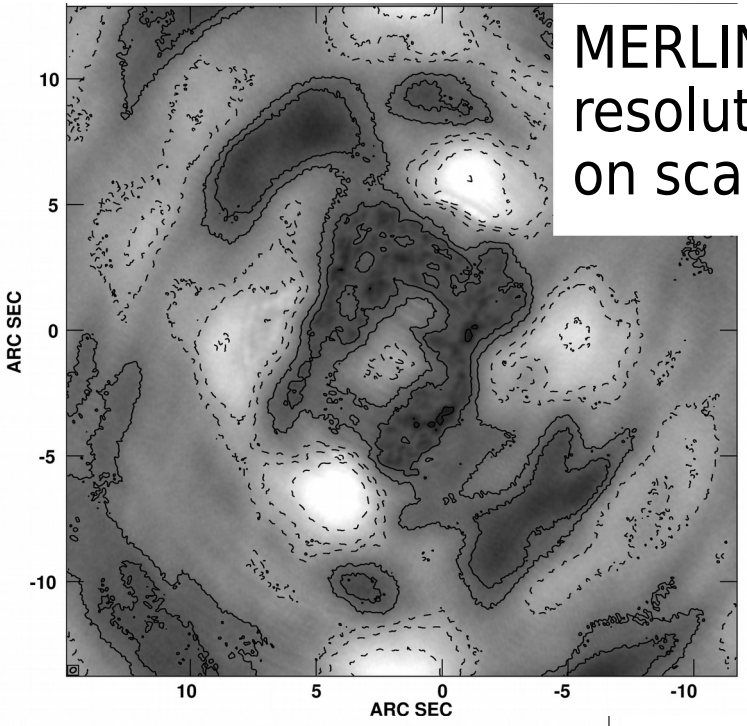
Image artefacts: Cereal Bowl

- Large-scale negative structures
  - Negative “bowl' around source structure
  - Large-scale sinusoidal ripples
  - 'Cereal bowl' effect
- **Missing short spacings**



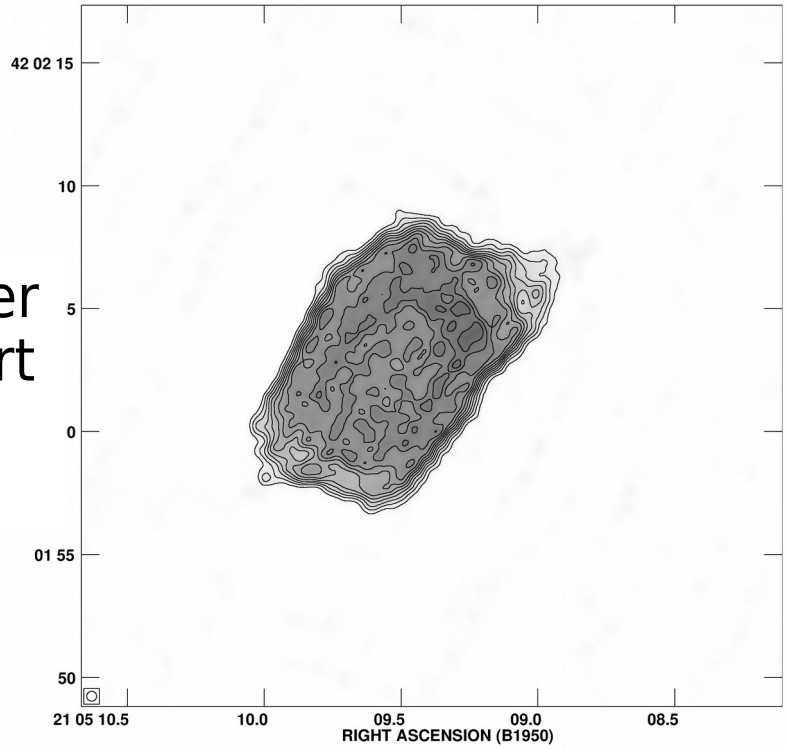
Missing spacings

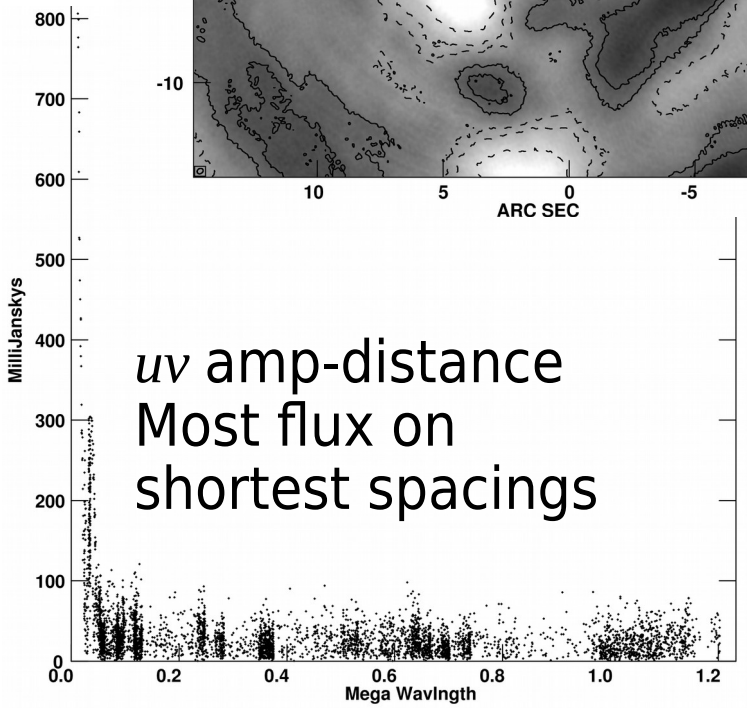
extreme example: PNE NGC 7027



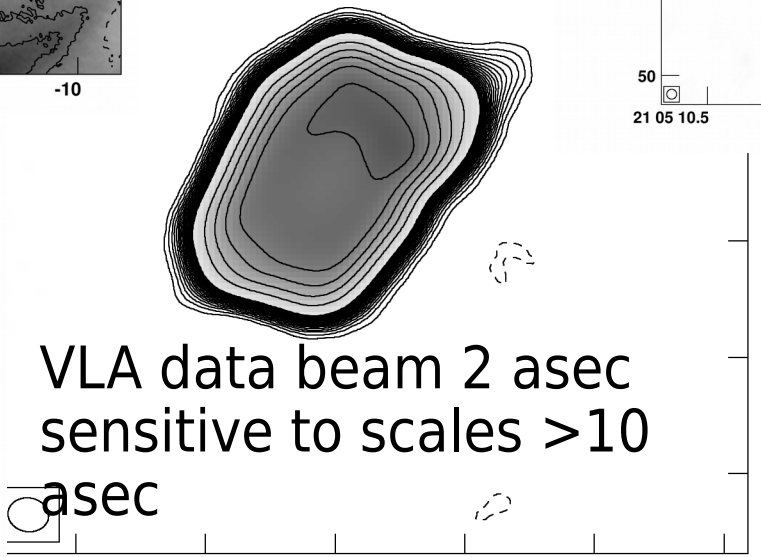
MERLIN ~200 mas resolution, sensitive on scales ≤ 2 asec

Could try uvtaper (more wt to short baselines) but better to add





uv amp-distance
Most flux on shortest spacings



VLA data beam 2 asec sensitive to scales >10 asec

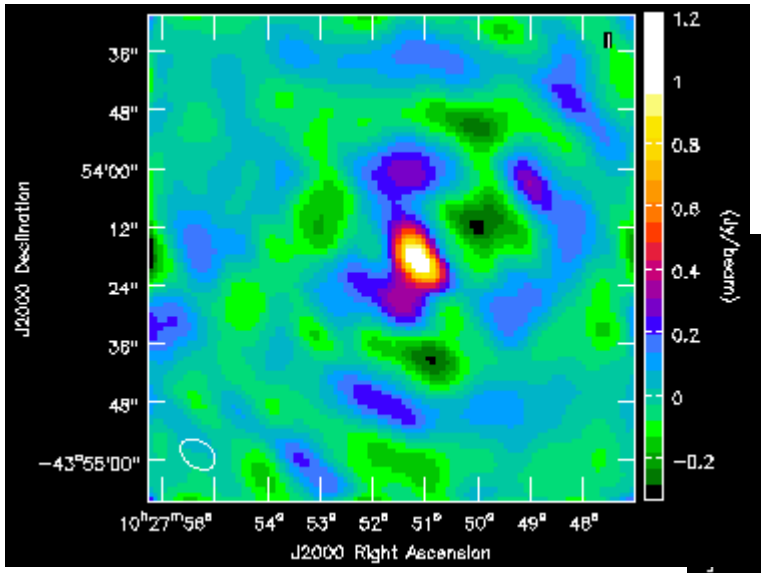
Tweak weights in concat to get lovely combined image!

Bains 1998

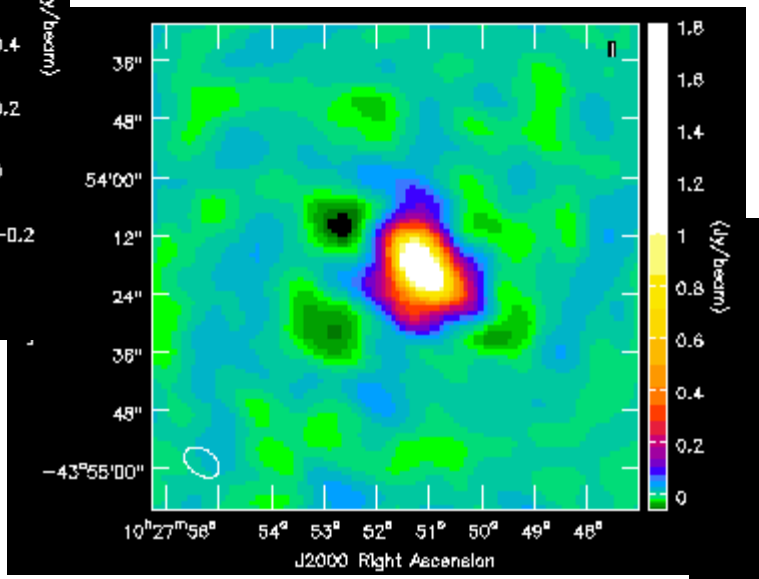
Errors arising in the (u, v) plane

- Fourier relations between (u, v) and image planes
  - e.g. single very high (δ) visibility: sinusoidal fringe
- Visibility definition: $V_\nu(u,v)=\iint I_\nu(x,y)e^{-2\pi i(ux+vy)}dxdy$
  - e.g. $V(u)=\delta(u-u_0)e^{-i\phi_\epsilon}$
  - for phase error ϕ_ϵ on baseline u_0
    - leading to (for k good baselines) $I(x)=2\phi_\epsilon\sin(2\pi u_0 x)+2\sum_{k=1}^{N(N-1)/2}\cos(2\pi u_k x)$
- **phase** errors are odd (sin) functions in image plane
- By a similar argument, **amplitude** errors are even (cos) functions
  - Also find (small) ϕ^o phase error ≡ (2ϕ)% amp error
    - (Ch 13, Synthesis Imaging *Taylor, Carilli & Perley 1999*)

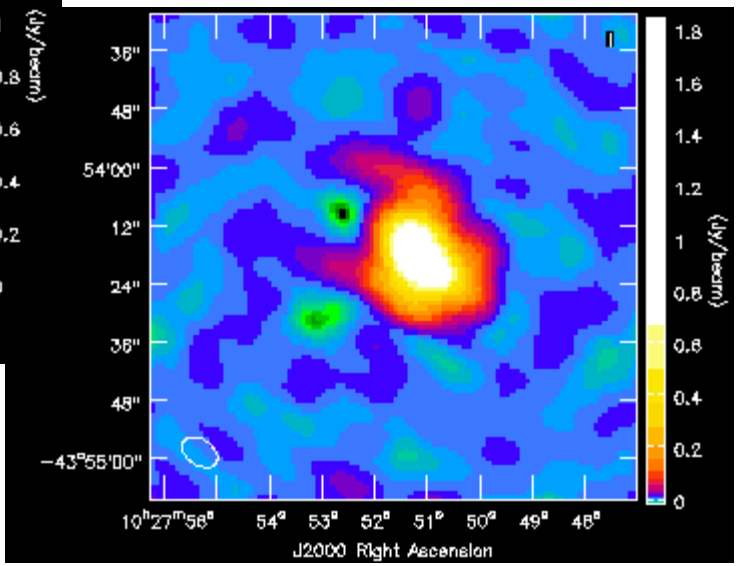
Examples of phase & amp errors

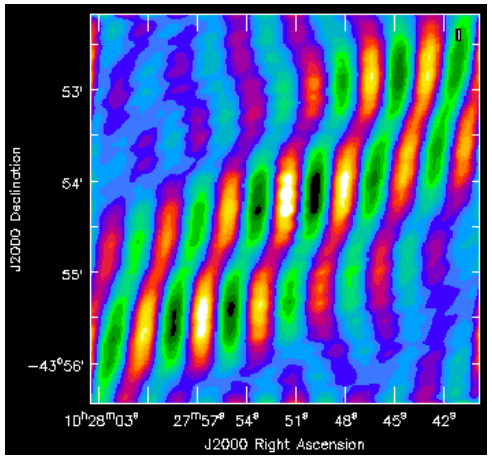


Phase-ref solutions only
Anti-symmetric (phase) errors dominate



Phase self-cal only
Symmetric (amp) errors dominate





Phase and amp self-cal
Residual errors (model deficiencies?)

A few high amps (easily flagged) cause symmetric stripes
Asymmetric stripes are usually delay errors

Summary of error recognition

- (u,v) plane
  - Stripy map? Look for outliers (high or low)
    - Check bandpass, T_{sys} plots and band shape
- Image plane
  - Do the defects look like the dirty beam?
    - Deconvolution errors for sparse uv coverage?
      - Too-uniform weighting (too small robust value)
  - Symmetric or antisymmetric?
    - Large spacing - short baselines and v.v.
      - Self-calibrate? Identify in uv plane, flag? (check phase ref)
  - Inadequate model / bad masking?
  - Missing spacings? Try uvtaper
- Last resort: image DAs v. DVs or per spw, half time...
  - Isolate antenna(s) causing problems

Why self-calibration?

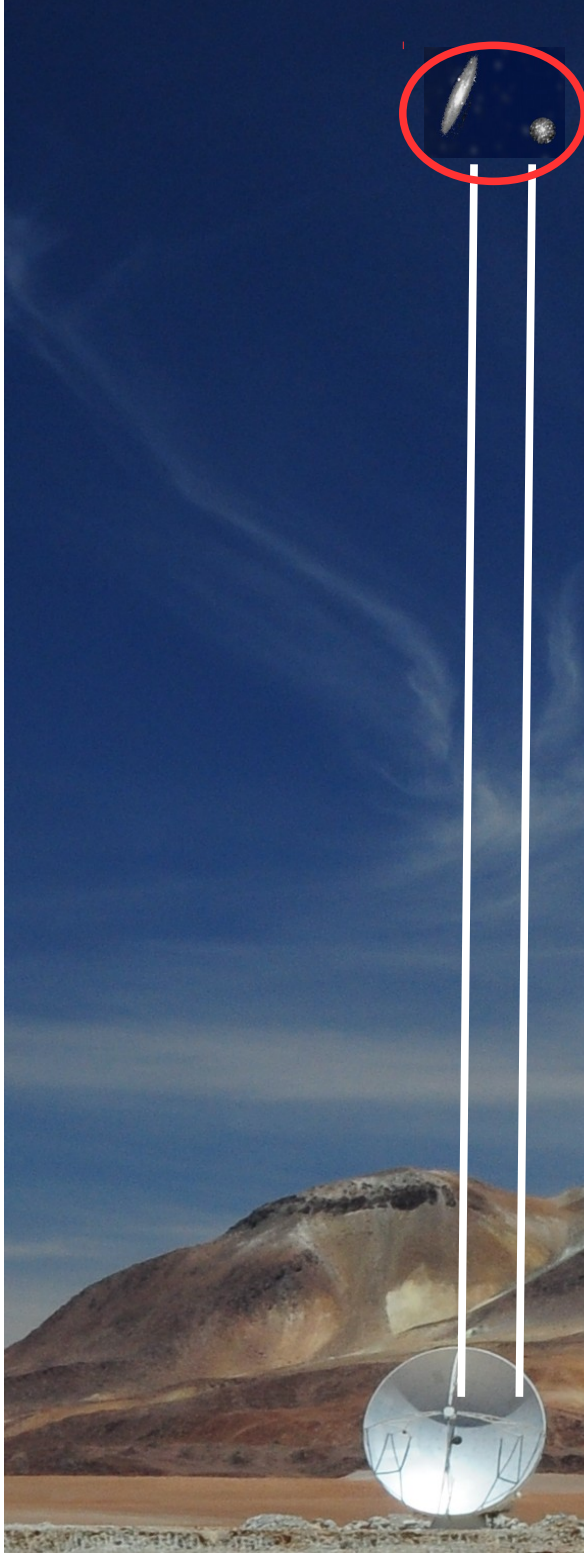
- Improve the image signal-to-noise ratio and fidelity (response to extended/faint structure)
  - Overcome dynamic range limitations
- The atmosphere is similar, not identical, above the target and above the phase-ref
  - Offsets in distance and time
    - 1^{o} angular separation ≡ 4 min time (4^{m} RA at low Dec)
- The phase-ref model may not be perfect
- The phase-ref may be fainter than the target, so solutions are less accurate
- There may be no phase-reference at all!
- Maybe aligning data sets taken at different times
  - Position, flux scale (subtract variable components!)

When to self-calibrate

- What noise expected for actual duration & conditions?
  - Should you self-calibrate even if you have reached it?
  - Maybe!
    - Aligning astrometry/photometry
    - Low-level phase errors may add negligible noise but distort flux distribution, obscurring detail
      - ALMA LB 'basket-weave' background
  - What dynamic range is possible?
    - VLA, WSRT, (e-)MERLIN >1 000 000 (*Perley, Smirnov, Laing, Muxlow*)
    - ALMA ~100 000 (*Fenech*)? Anyone got better?
- More usually, expect e.g. 500, start from 100...
  - The fewer antennas, the more potential improvement

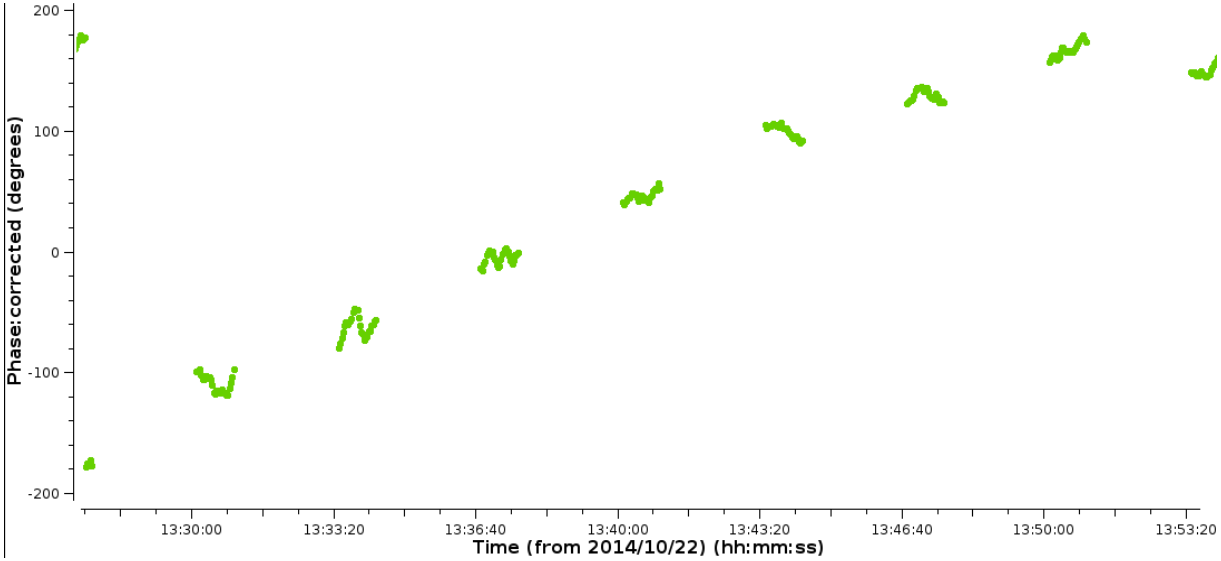
Prior calibration

- Apply instrumental corrections
  - T_{sys}, WVR etc.
- Edit obvious bad data
- Derive and apply frequency- and time-dependent corrections from astrophysical sources
  - Bandpass, flux scale
  - Phase-ref. phase and amp. corrections
    - Phase-ref close to target
      - Sky ***almost*** the same
        - But not quite!



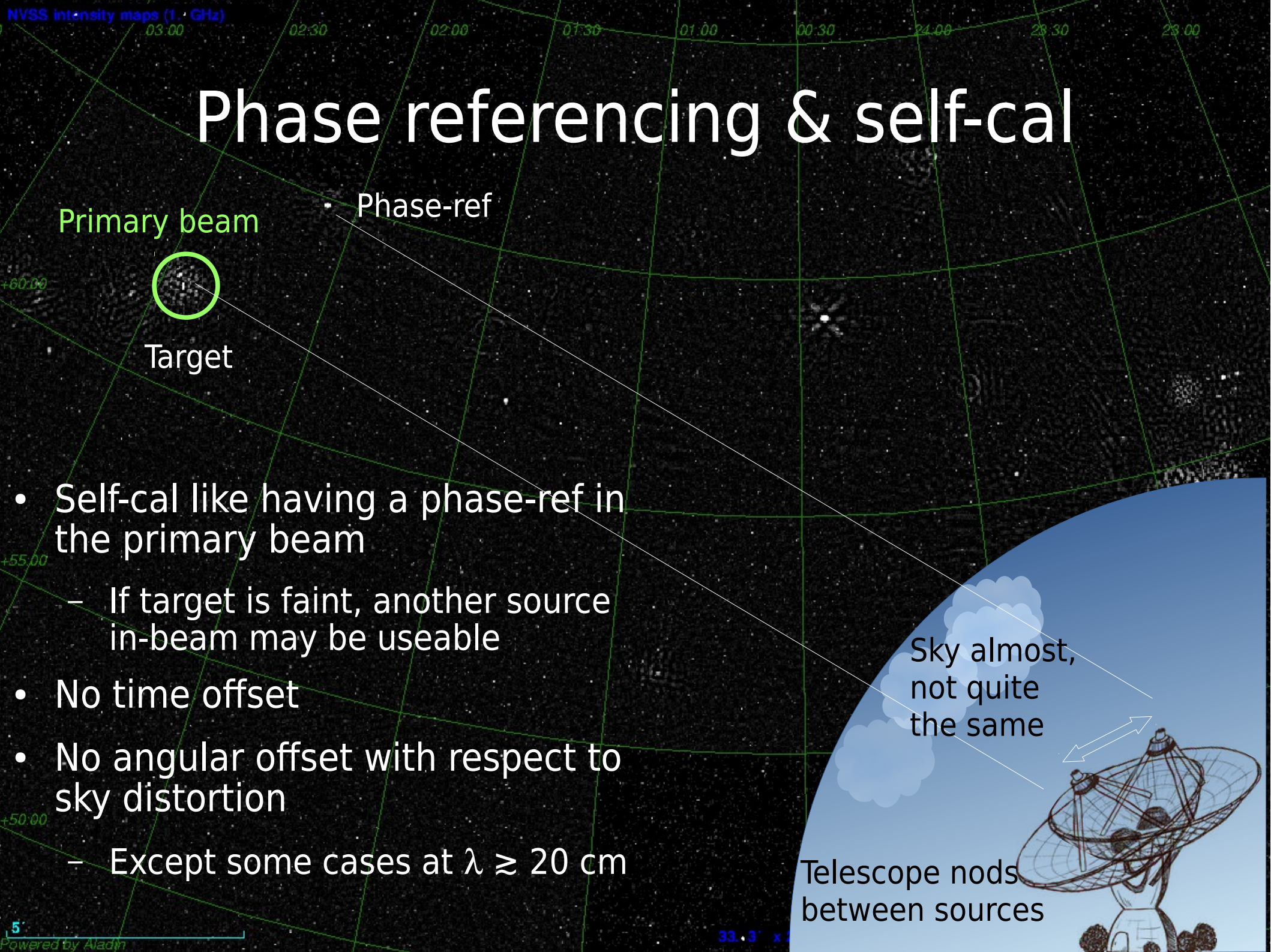
Phase transfer accuracy

- Sky separation
  - Raw calibrator phase change $d\phi_{atm}$ ~π per ~20 min
- Assume Dec 0^o



- Phase-ref: target separation, say $d\theta$ = 2^o = 120 arcmin
  - Convert θ in degrees to 'R.A.-like' units of time
    - ($d\theta$/360^o) x cos(Dec.)x 24hr ~7.5 min at Dec. 20^o
- In 7.5 min, $d\phi_{atm}$ gives π/8 ~65^o phase change
  - Phase corrections from the phase-ref may have up to ~65^o error when applied to the target

Phase referencing & self-cal



- Self-cal like having a phase-ref in the primary beam
  - If target is faint, another source in-beam may be useable
- No time offset
- No angular offset with respect to sky distortion
  - Except some cases at $\lambda \gtrsim 20$ cm

Calibration errors and dynamic range

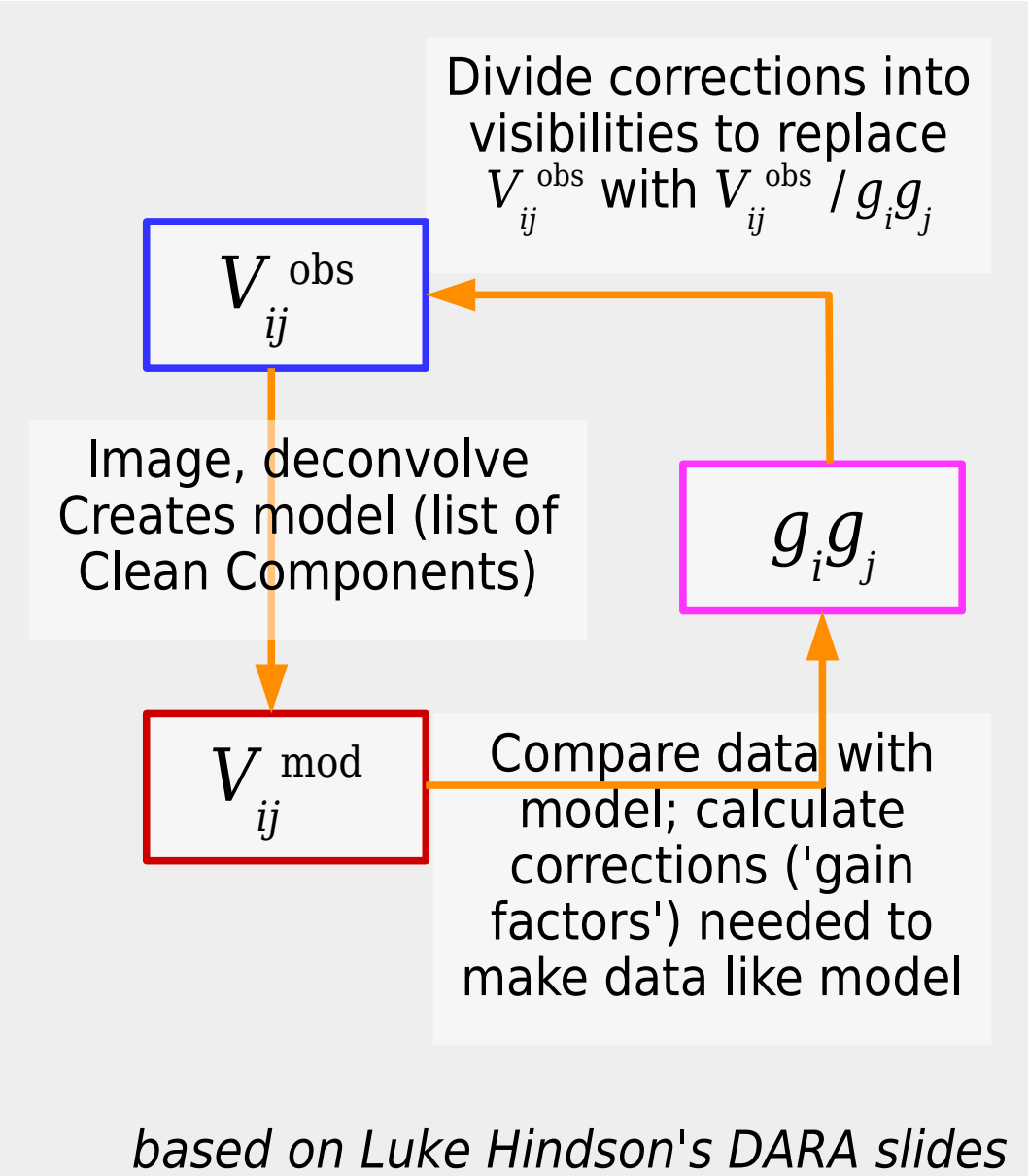
- Max. Dynamic range $D_{\mathrm{B}}(\phi_\varepsilon)$ due to phase errors ϕ_ε (in radians) on all baselines, per scan for N antennas ~ N / ϕ_ε
  - e.g. ϕ_ε ~radians (5°)~0.09 on $N =$ 40 gives $D_{\mathrm{B}}(\phi_\varepsilon)$~440
- Dynamic range $D_{\mathrm{B}}(\varepsilon)$ reduction due to fractional amplitude errors ε on all baselines, per scan ~ N/ε
  - $D_{\mathrm{B}}(\varepsilon)$~ 400 for ε ~0.1 i.e. 10% amp error
- **A phase error of 5° is as bad as a 10% amp error**
- **Phase errors are sin (odd), amp are cos (even)**
- Phase errors are asymmetric (mirror) function in image
- Amp errors are symmetric function in image
- See *Perley* Ch 13 in NRAO 'Synthesis Imaging'

Phase effects in many scans

- Averaging phase fluctuations causes amp decorrelation
  - Visibility $V = V_o e^{i\phi}$ so $\langle V \rangle = V_o \langle e^{i\phi} \rangle = V_o e^{-(\phi_{rms}^2)/2}$
- Δt is interval after which phase errors independent
  - Δt > scan (phase-ref:target cycle)
    - Δt ~ duration of EB, ~30 min? Shorter on long baselines
- Phase errors ϕ_ε affecting all baselines limit dynamic range of M intervals Δt to ~ $\sqrt{M}\, N / (\sqrt{2}\, \phi_\varepsilon)$
  - e.g. M=2, N=35
  - ϕ_ε = 20° = π/9 (~0.35) rad ~ 6% amp decorrelation
    - Dynamic range D_B(all)<few100 (typical ALMA limit pre-selfcal)

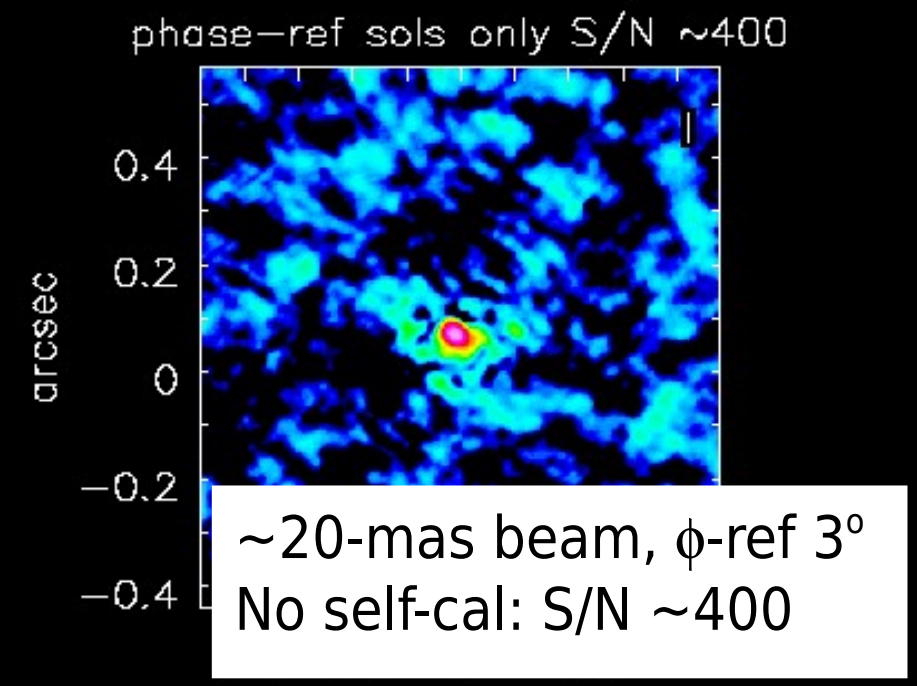
Self-calibration overview

- Visibility data, phase-ref etc. corrections applied
  - Initial model:
    - First image from V
- Compare data with model
  - Derive gain correction factors per antenna using χ^2 minimisation
- Apply gain corrections to data and image again
- Repeat cycle until image reaches noise/dynamic range limit and model matches data (allowing for noise)

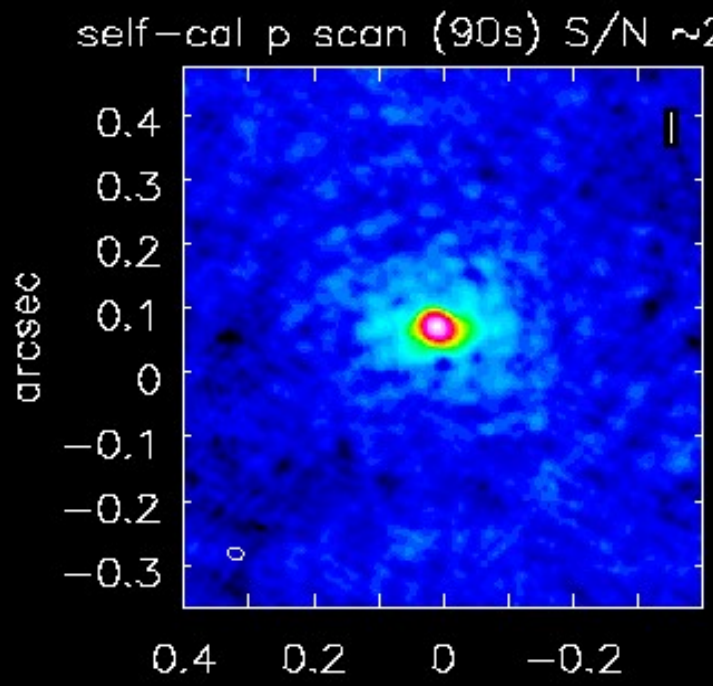


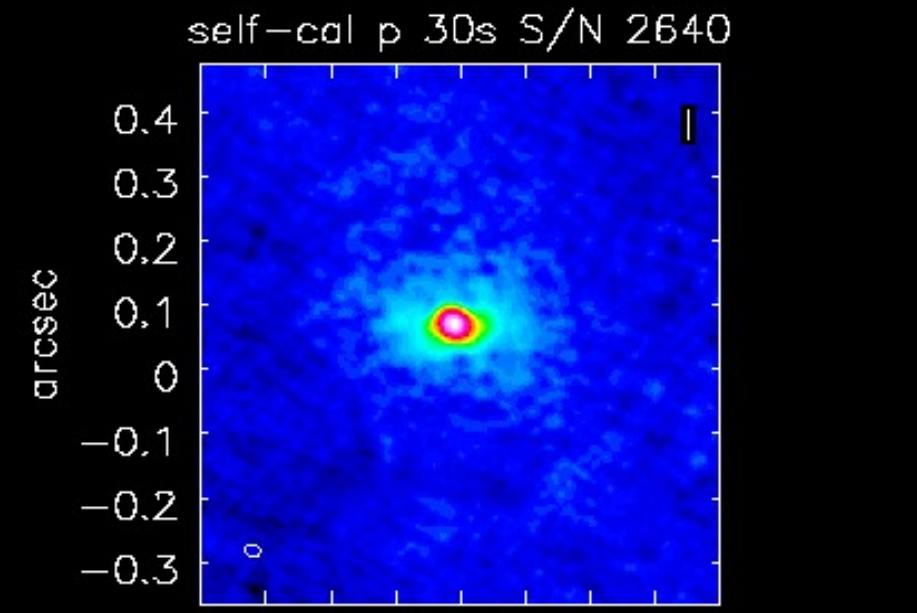
based on Luke Hindson's DARA slides

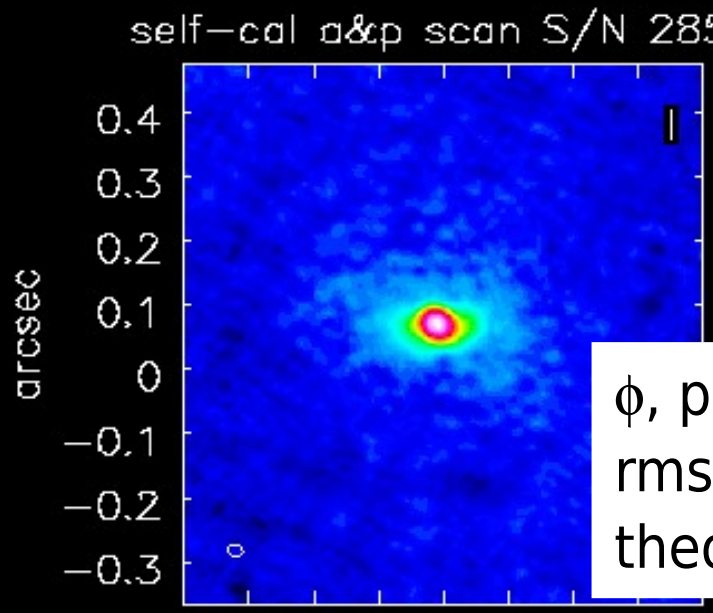
L2 Pup before & after self-cal

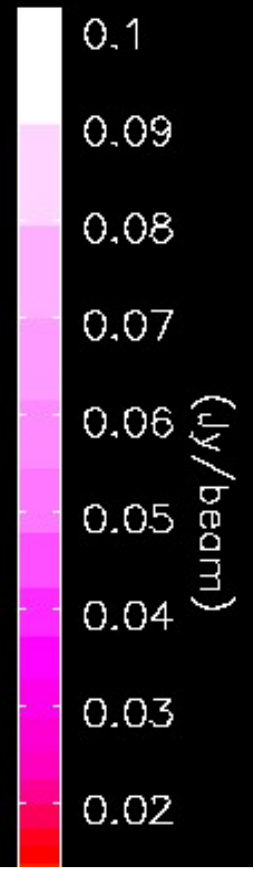


~20-mas beam, ϕ-ref 3°
No self-cal: S/N ~400





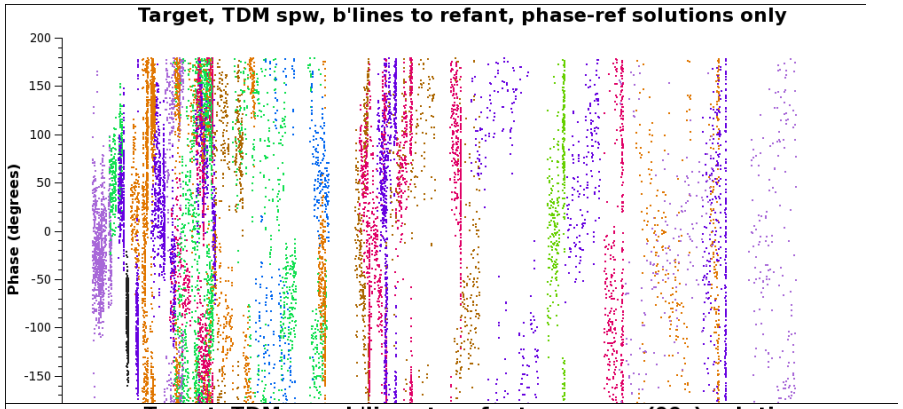


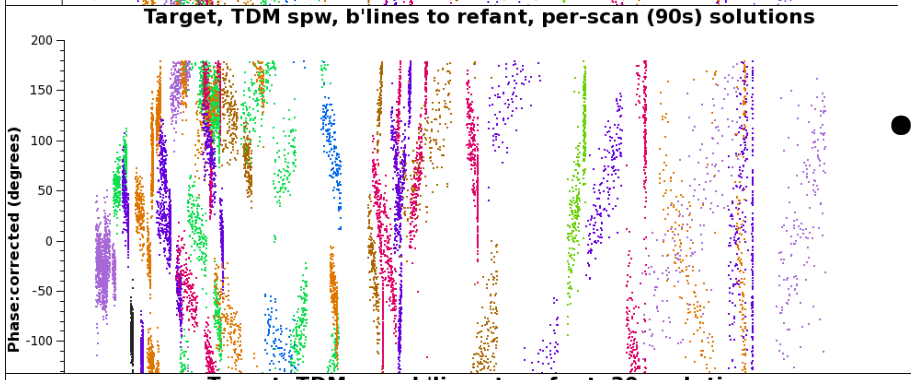


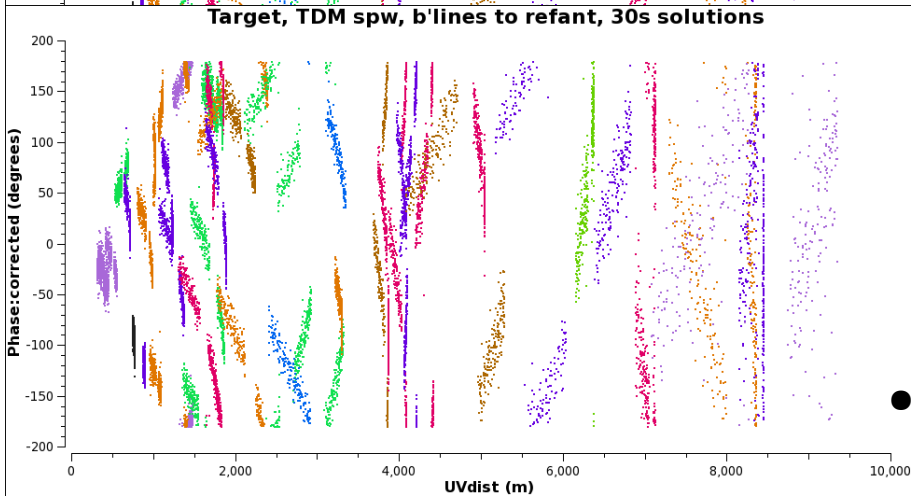
ϕ, p self-cal S/N 2850
rms 35 μJy
theoretical 22 μJy

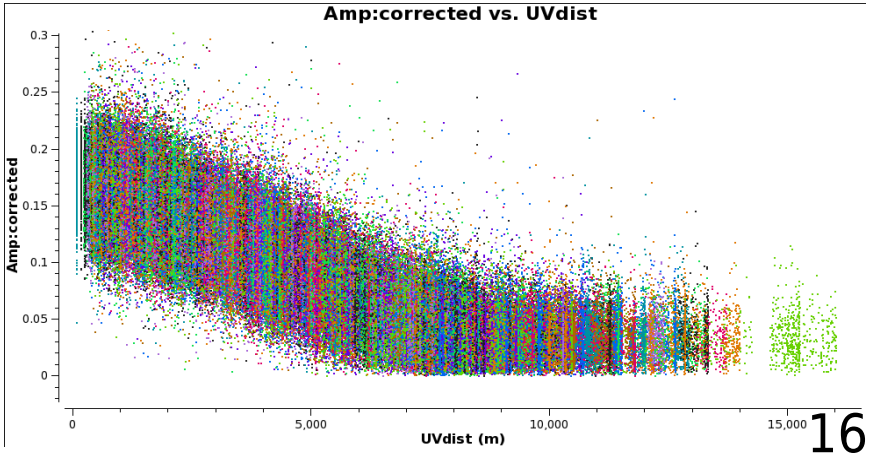
Target phases selfcal

TDM spw



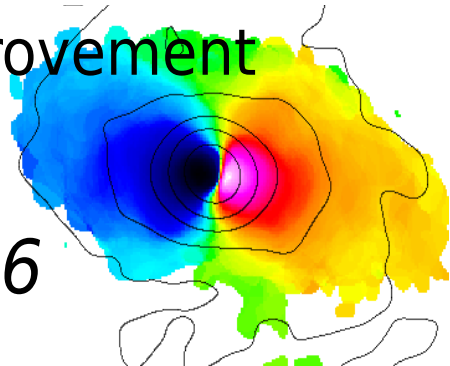






16 km

- Initial per-scan phase solution improves S/N 500%
  - 30s phase solutions
  - per-scan amp & phase
    - another 40% improvement
  - Lines benefitted
- L2 Pup B *Kervella+'16*



What solution interval? minimum

- Require S/N ≥3 per solint dt_{min} per antenna
  - $\sigma_{ant} \leqq P/3$ in dt_{min} where P is image peak
  - Image rms = $\sigma_{array} = \sigma_{baseline} / \sqrt{[N(N\text{-}1)/2]}$
    - Each antenna has (N-1) baselines
    - Two additional degrees of freedom:
      - phase (or amp) correction; origin of phase (or flux scale)
    - $\sigma_{ant} = \sigma_{baseline} / \sqrt{[(N\text{-}3)]}$
  - $\sigma_{ant}(dt_{min}) \leqq \sigma_{array}(t_{tot}) \sqrt{[t_{tot} / dt_{min}]} \sqrt{[(N(N\text{-}1)/(2(N\text{-}3))]}$
- $dt_{min} \geq [3(\sigma_{array}(t_{tot})/P)]^2 \; t_{tot} \;\; [N(N\text{-}1)/(2(N\text{-}3))]$
  - To solve separately for each of 2 pols, 4 spw, use 8 x dt_{min}
  - NB S/N ($P/\sigma_{array}(t_{tot})$) improves with calibration

What solution interval? maximum

- Solint $\mathrm{d}t_{\mathrm{max}}$ < timescale for significant changes
  - Amp & ϕ change due to source structure as well as errors ε
    - Fast phase rate if peaks far from centre
  - Usual 'upper limit' for phase rate is $\mathrm{d}\phi < \pi/4$ per $\mathrm{d}t$
    - Inspect visibility phases for rate and for scatter
  - S/N (amplitude/σ_{rms}) per antenna usually must be >3
    - Including longest baselines to refant (plot amp v. uvdist)
    - Noise σ_{rms} realist goal - estimate from sensitivity calculator
      - Can you reach S/N > 3 in $\mathrm{d}t_{\mathrm{max}}$?

In practice...

- Inspect phase (refant & *) you want to correct
  - What interval shows systematic drift?
    - Not just noise - that can't be calibrated away!
  - Average by channel as appropriate (see next slide)
    - Maybe average pols &/or spw?
      - Can be offsets
        - Phase-ref refant issues, atmospheric transmission differences
    - Try longer solint, per spw/pol first
      - Apply solutions, shorter solint, average in other dimensions
- Longer solint does not always improve solution accuracy
  - Shorter solint may fail less often
    - e.g. bright but offset target

Noise in initial choice of solint?

In practice...

- Inspect phase (refant & *) you want to correct
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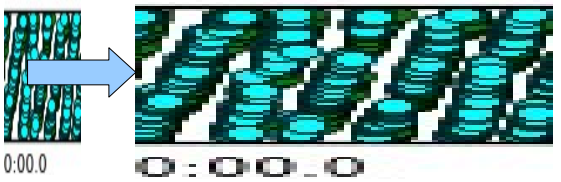
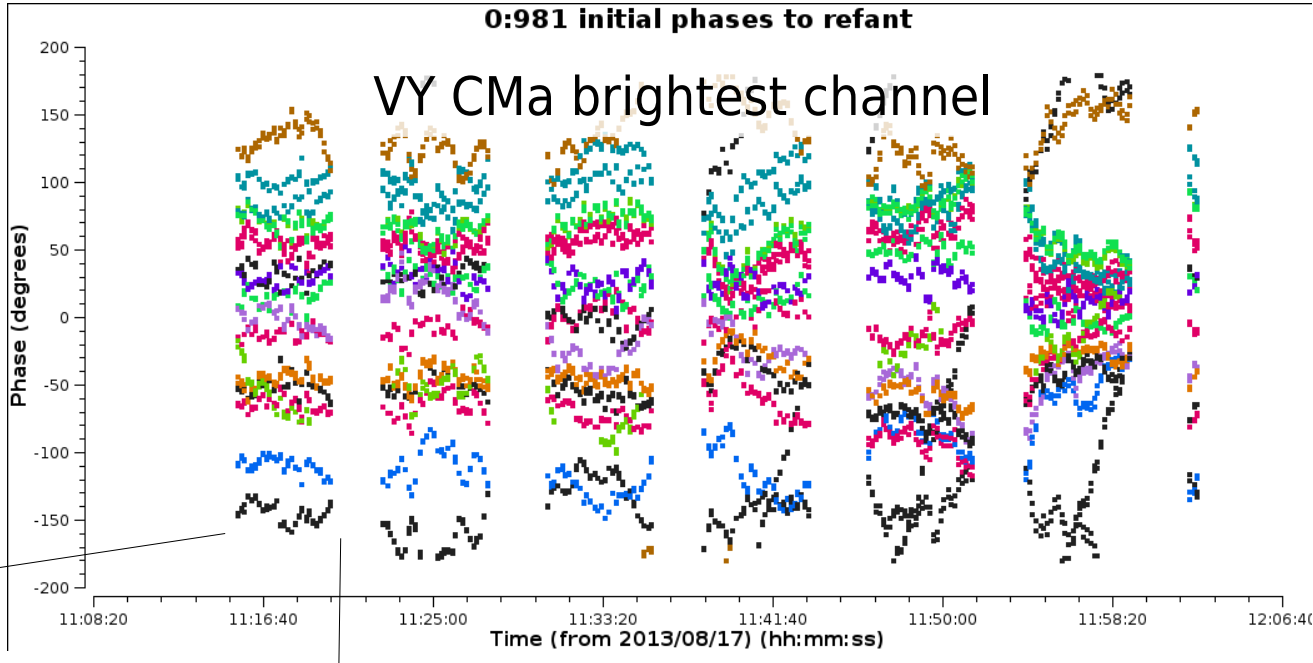
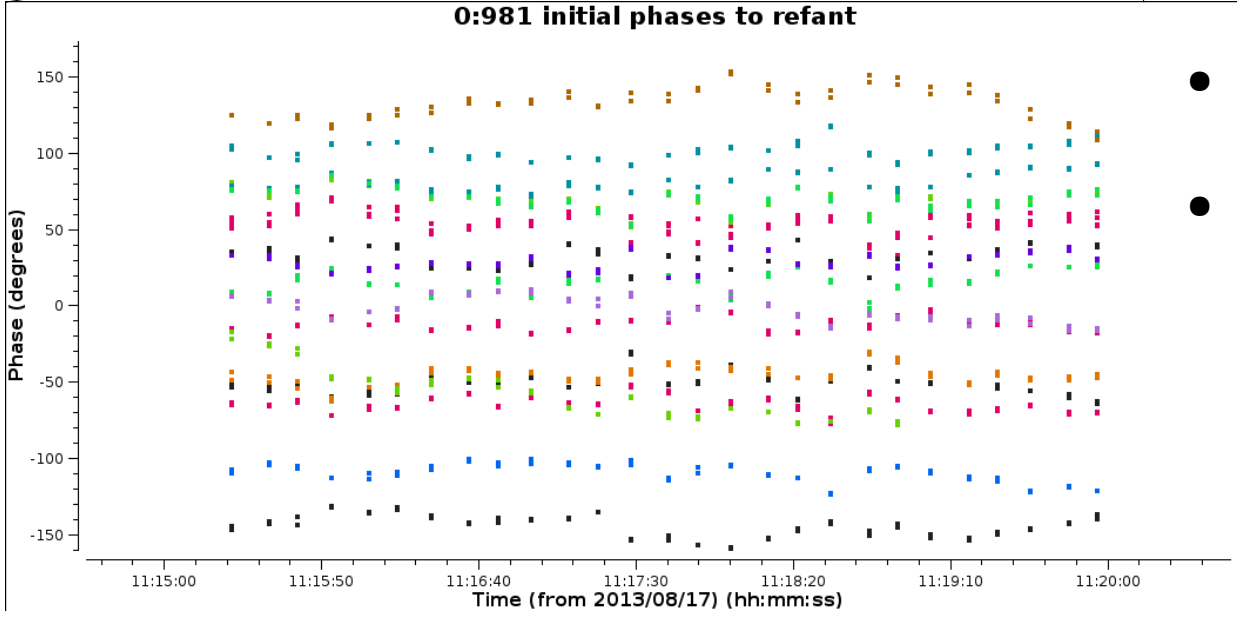


Inspect phase v. time

- Zoom in on one scan
  - 12-s averaging
- Mostly ~1 min drifts
  - Small scatter

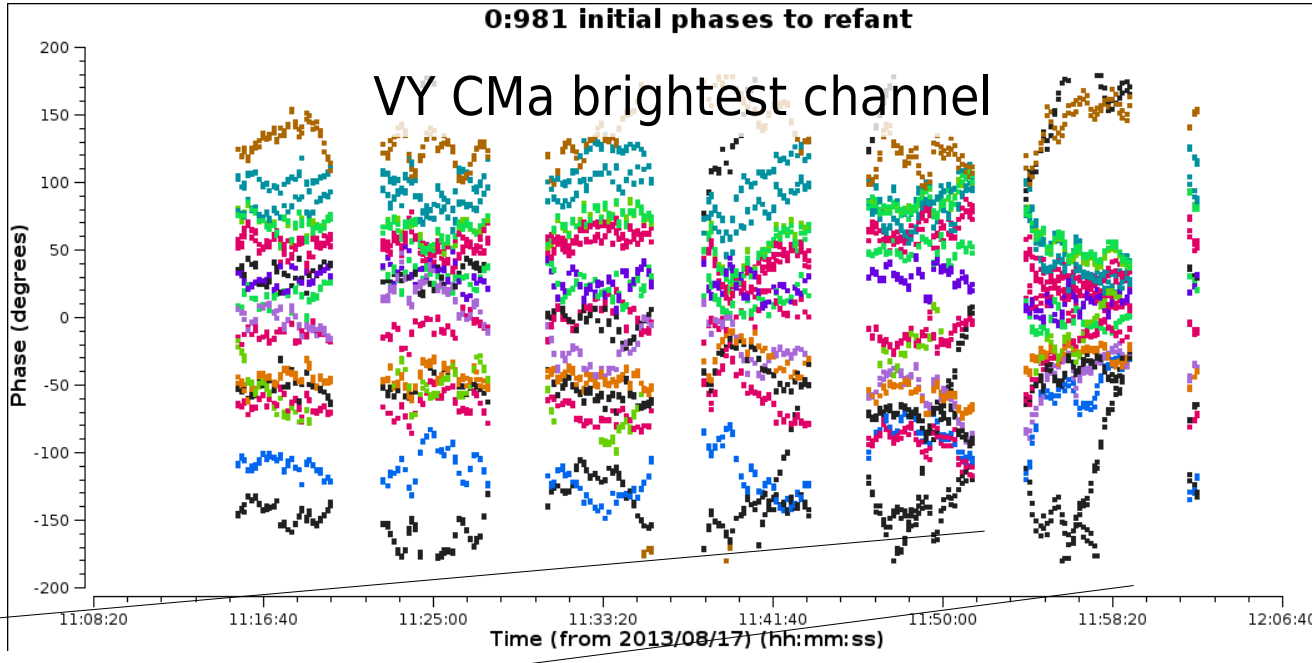


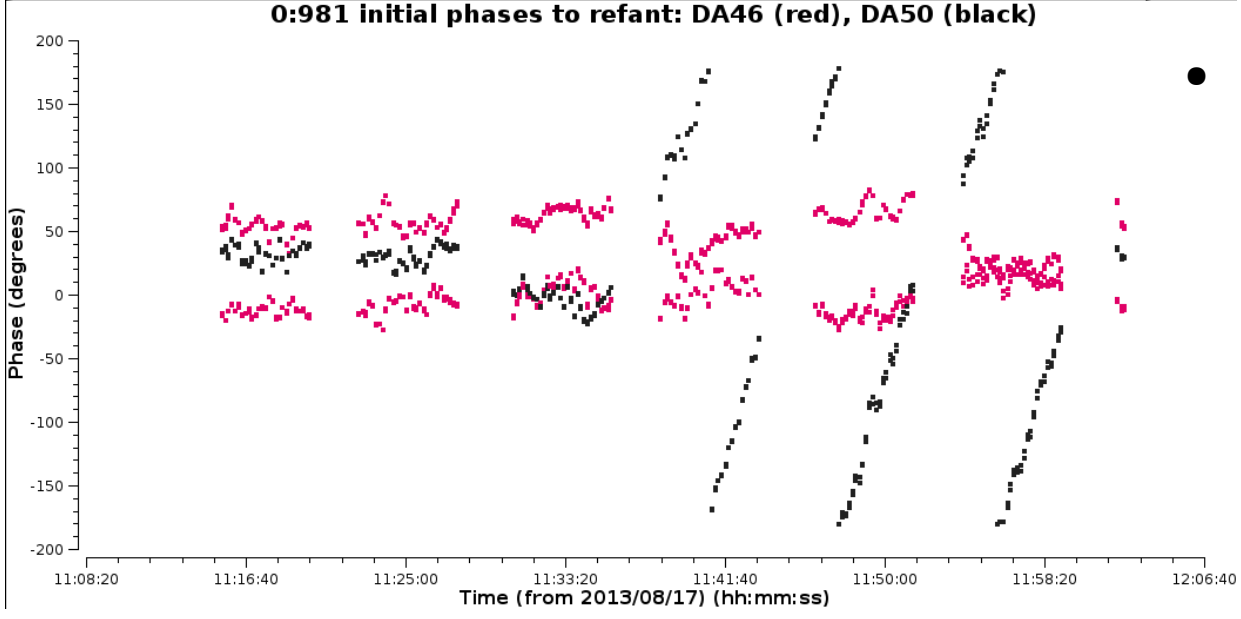


- Faster rate in last scans?
- Plenty of S/N

Inspect phase v. time

- Zoom in on one scan
  - 12-s averaging
- Mostly ~1 min drifts
  - Small scatter





- Faster rate in last scans?
  - Sudden change
    - One antenna
  - Exclude at first
    - Then calibrate
      - Shorter solint

Model constraints

- Parameterised model (FT in visibility plain)
  - Traditional (delta function) Clean Components
  - Multiscale Clean may work
    - Beware artefacts around elongated narrow features!
- Can self-calibrate in full polarization
  - Get total intensity phases right first
    - Also OK to calibrate total intensity amps first?
- Is target spectral index α significant?
  - Check correct phase-ref α (or normalisation) used
  - Generally, use nterms=1 for initial ϕ-only self-cal
    - Use nterms ≥2 for image *before* & during amp self-cal!

Starting self-calibration

- Usually, applycal calwt=False during self-cal
  - Noisiest antennas are most important to correct
    - Usually best to use natural weighting or robust ≥0.5
- If necessary start with low minsnr e.g. 2
  - applycal applymode='calonly' will pass failed solutions
    - Avoid flagging salvagable data due to poor model
  - Or, if failed solutions are really bad data, 'calflag'
- Usually, phase-only first
  - You may need to do a number of rounds of self-cal
    - Improve model and/or shorten solint
  - Aim is to get morphology right - total extent of source

Iterative self-calibration

- Include all significant flux in mask/model
  - but build up slowly, iteratively, if in doubt
    - Real source details will reappear if not included at first
    - Artefacts can become frozen in to model
      - less of a risk if *uv* coverage is good
- Don't apply primary beam correction until finished!
- If enough S/N, go on to amp (with spec. index?)
  - Start with a longer solint than for phase-only
    - Occasionally, an antenna is very mis-scaled (e.g. bad T_{sys})
      - Make model excluding bad antenna if possible
      - Try initial v. long-time, amp self-cal, normalise if necessary
- Iterate only if model improved or parameters changed
  - Stop when no improvement / ideal S/N reached

Calibration table consistency

Image_0
Gaincal caltable=p5min, gaintable=[]
Applycal gaintable=[p5min]

Discard this table after making better model

Image_p5min
Gaincal caltable=p0.5min, gaintable=[]
Applycal gaintable=[p0.5min]

Accumulate these tables

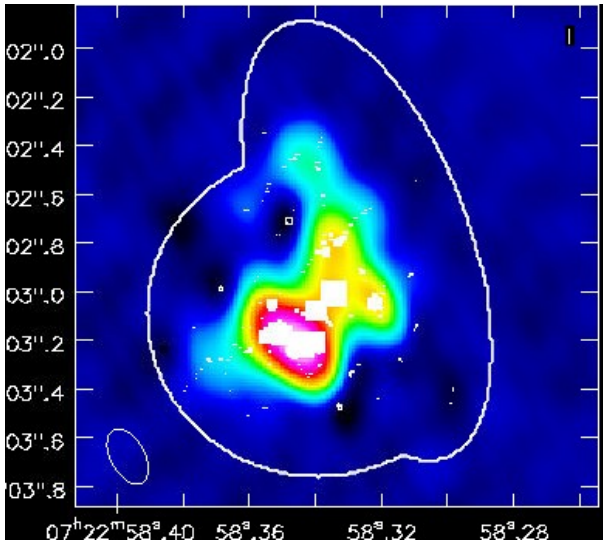
Image_p0.5min (nterms=2)
Gaincal caltable=a5min, gaintable=[p0.5min]
Applycal gaintable=[p0.5min, a5min]

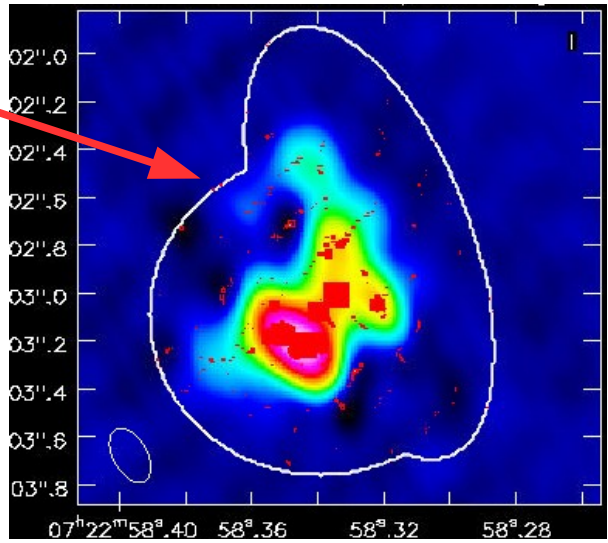
Image_p0.5min_ap5min (nterms=2)
Gaincal caltable=a1min, gaintable=[p0.5min, a5min]
Applycal gaintable=[p0.5min, a5min, a1min]

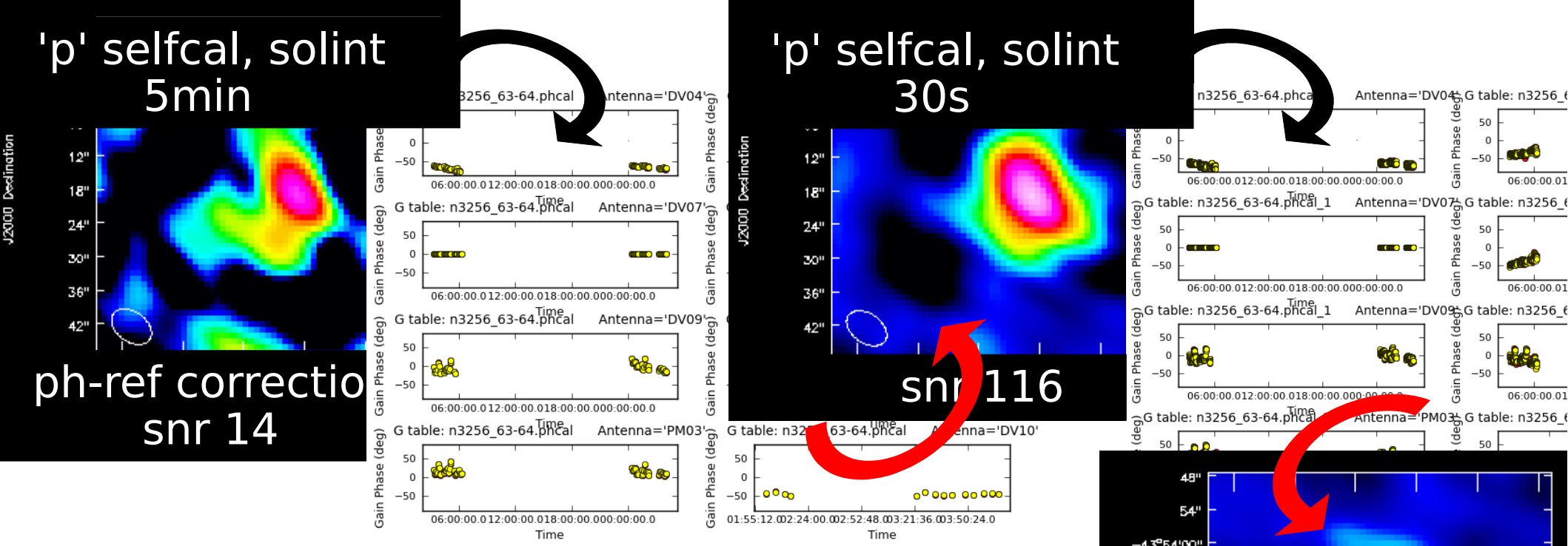
Final image (final applycal calibration all in **corrected** column)

Preparing model for self-cal

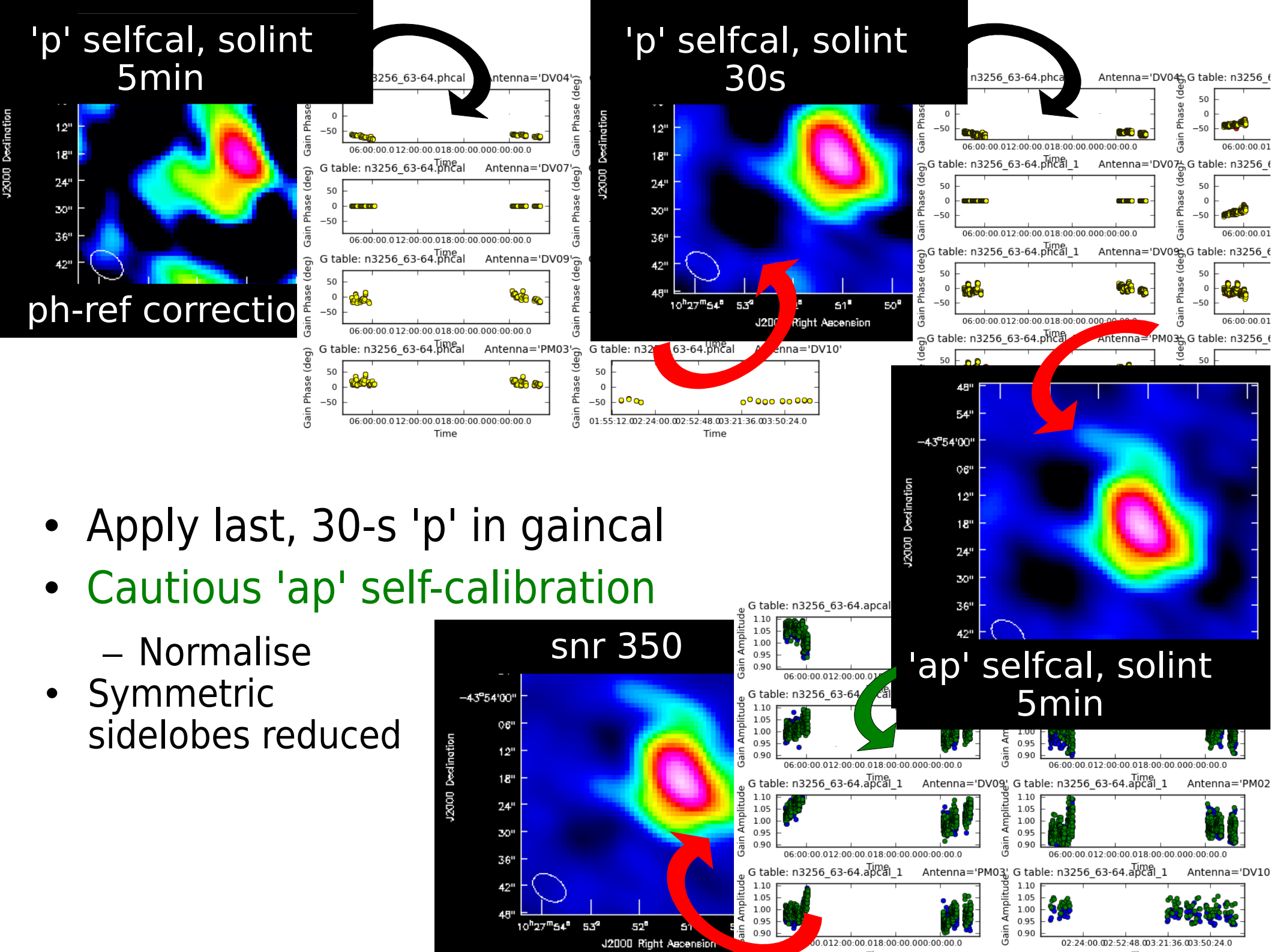
- Take care in setting mask (clean boxes)
  - Clean Components to be used as model
- Mask conservatively for initial models for phase self-cal
  - CC should trace emission
    - but -ives are part of data
      - Beware 'pile-ups' at mask edges
- Make sure all flux is in model for amplitude self-cal
  - If in doubt, normalise solutions
    - Flux might go up (~10% at most) as phase improves
      - Should never go down!



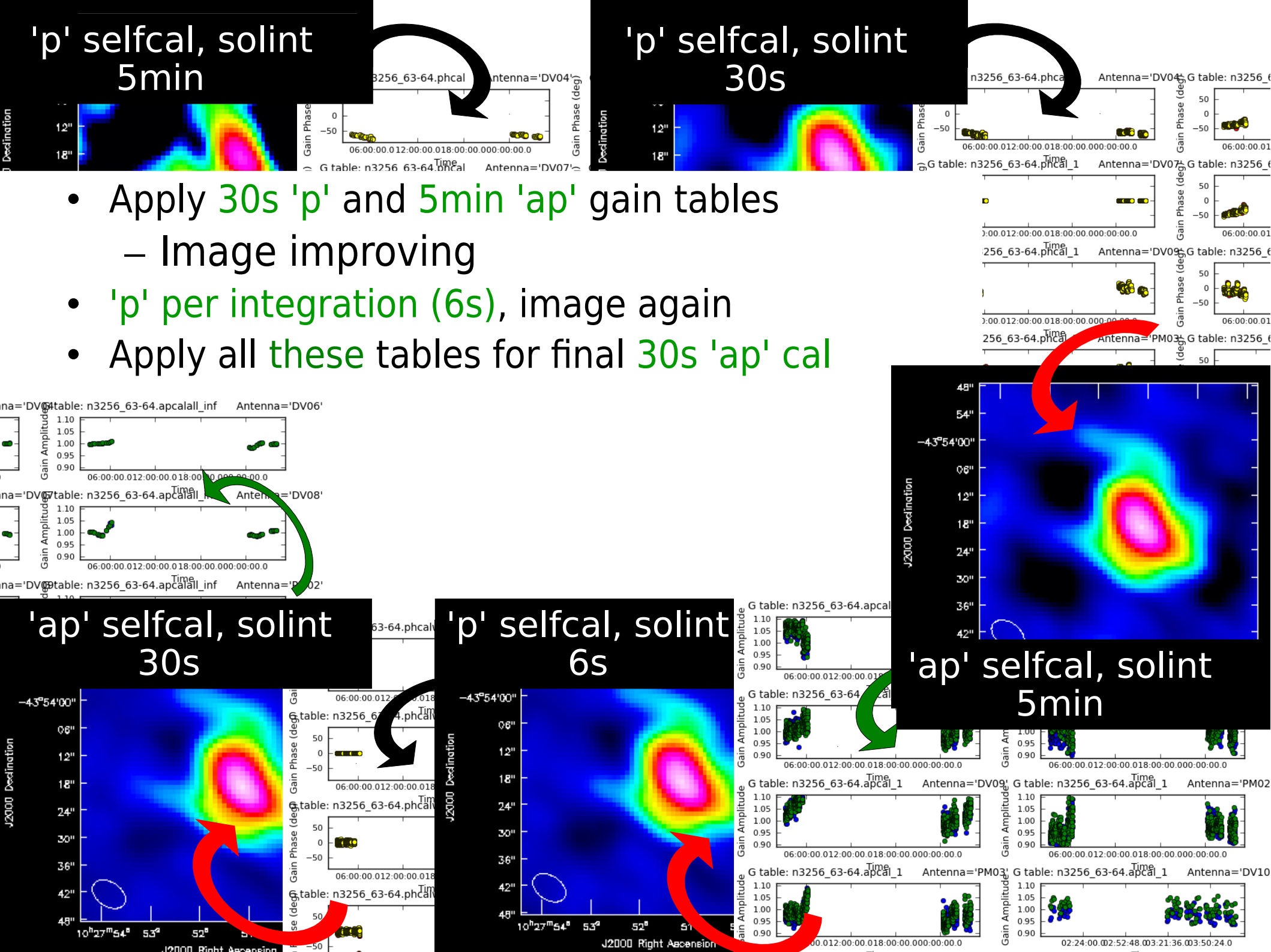




- Apply phase-ref etc. corrections, image
  - FT of image CC is left in MS
  - Model for 5-min phase-only self-cal
- Apply, image again
  - Better model so shorter solint next time
- Apply, image again
  - Symmetric errors
    - snr high enogh for amplitude self-cal

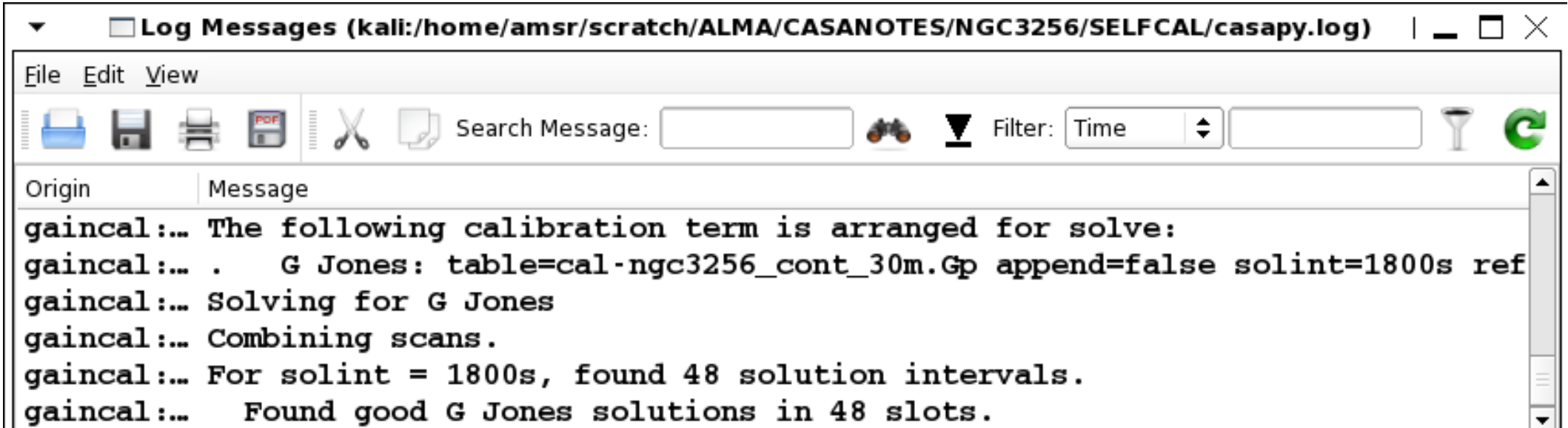


- Apply last, 30-s 'p' in gaincal
- Cautious 'ap' self-calibration
  - Normalise
- Symmetric sidelobes reduced


'p' selfcal, solint 5min
'p' selfcal, solint 30s
Apply 30s 'p' and 5min 'ap' gain tables
Image improving
'p' per integration (6s), image again
Apply all these tables for final 30s 'ap' cal
'ap' selfcal, solint 30s
'p' selfcal, solint 6s
'ap' selfcal, solint 5min
J2000 Declination
J2000 Right Ascension
Gain Phase (deg)
Gain Amplitude
Time

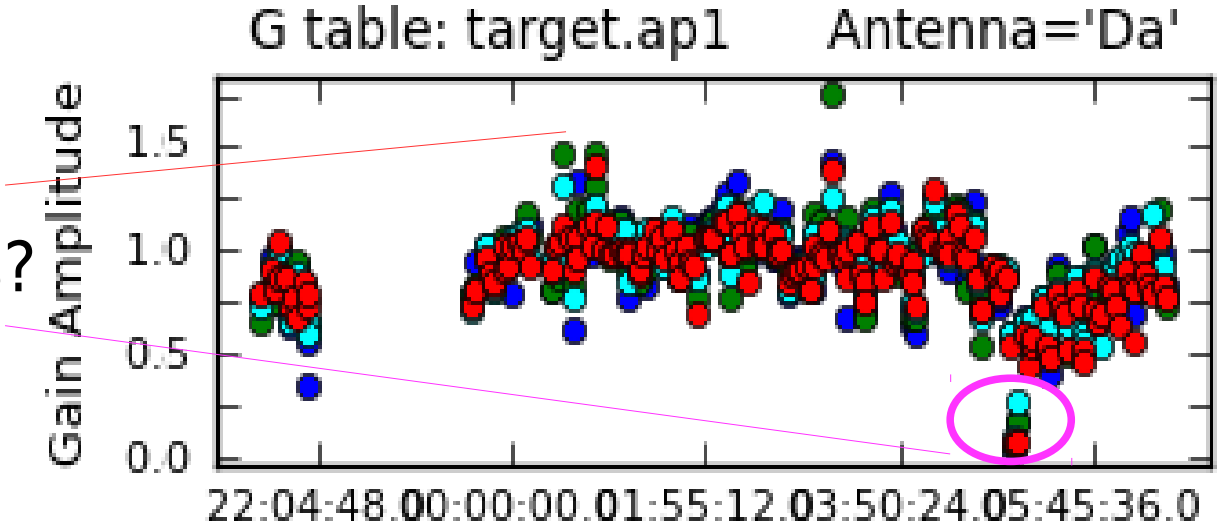
Has self-cal worked? 1

- >10% failed solutions?
  - Problem: check for bad data, wrong model/calibration
  - Change solint? Longer?
    - Or shorter if target is bright and phase changes rapidly
  - Faint source but can see structure? Try lower `minsnr`
    - If so, check solutions are not too noisy



Has self-cal worked? 2

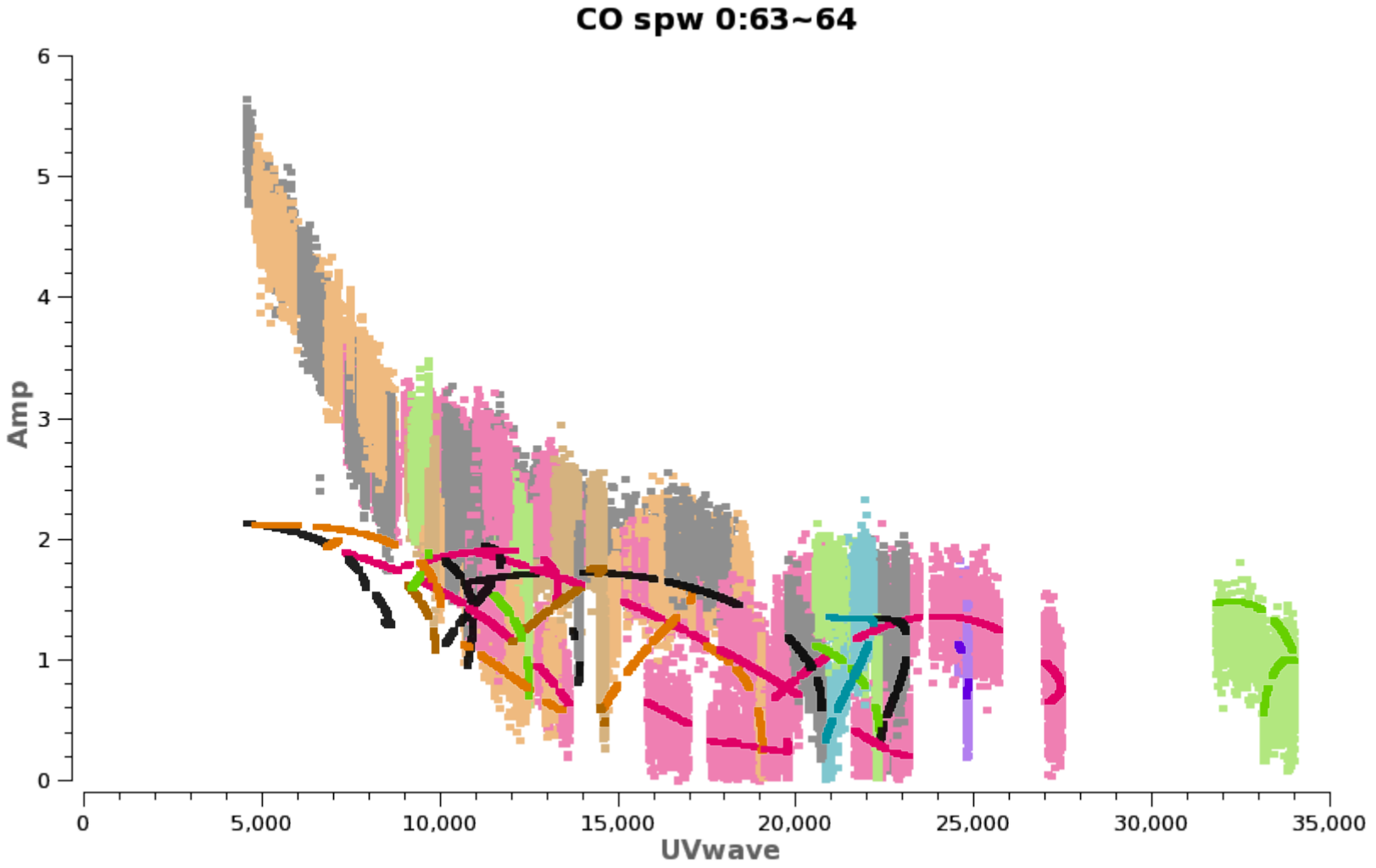
- Inspect solutions
  - Noisy? Longer solint
  - Low/high amp jumps?
    - Flag bad data
  - Phase jumps?



    - Check phase-ref solution discontinuities
      - If necessary starting model excludes a scan/antenna
- ***S/N in image should improve***
  - Image peak should stay same or *slightly* increase
    - Amplitude solutions within ~20% of 1
      - Unless one (or more) antennas are obviously mis-scaled
    - Big change in flux or position? Probably wrong model
      - Check masking in clean - beware sidelobes

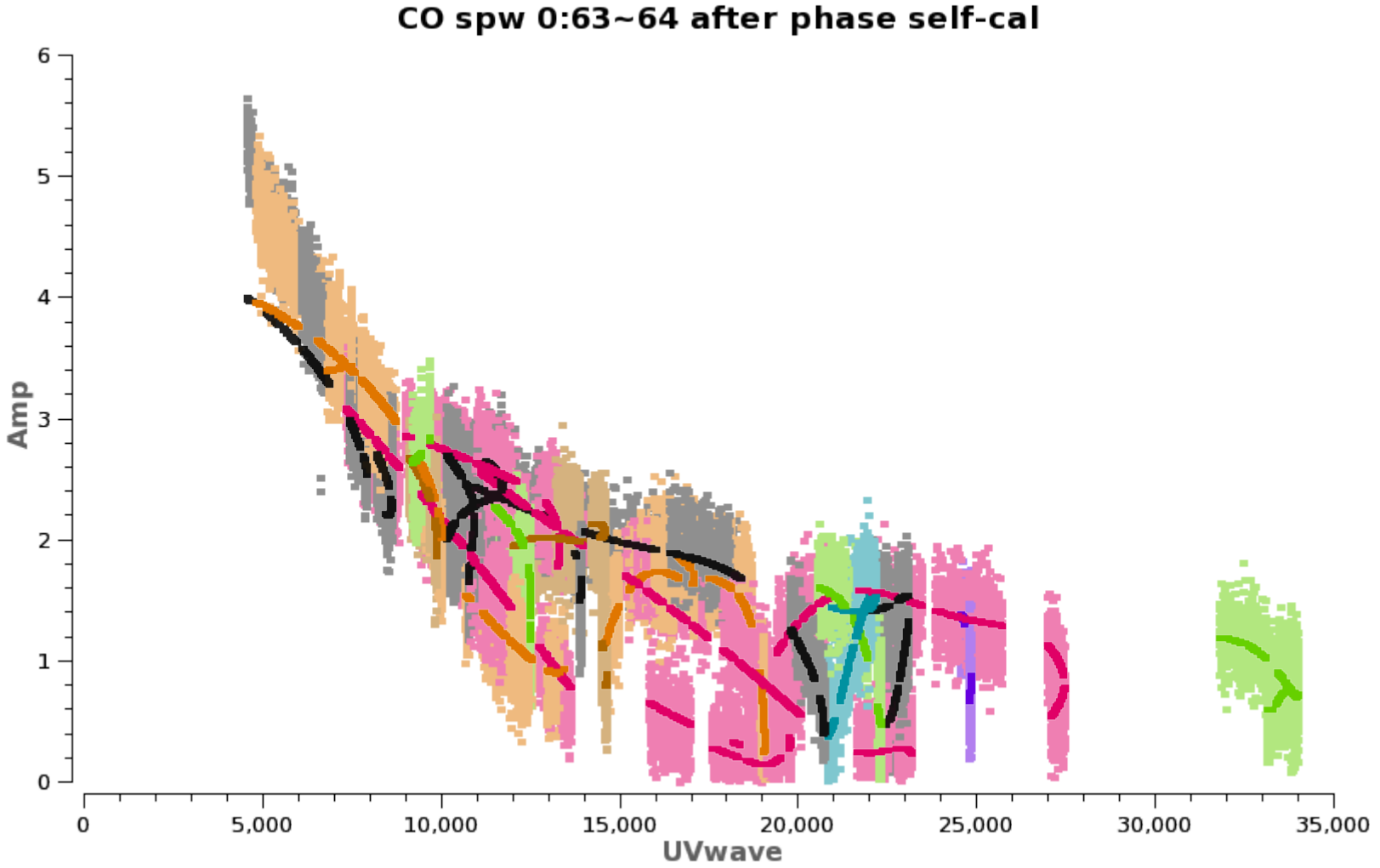
Compare model with data

- First model missing a lot of extended flux
  - Use for phase-only (not amp) selfcal



Compare model with data

- Vast improvement after just one round of self-cal

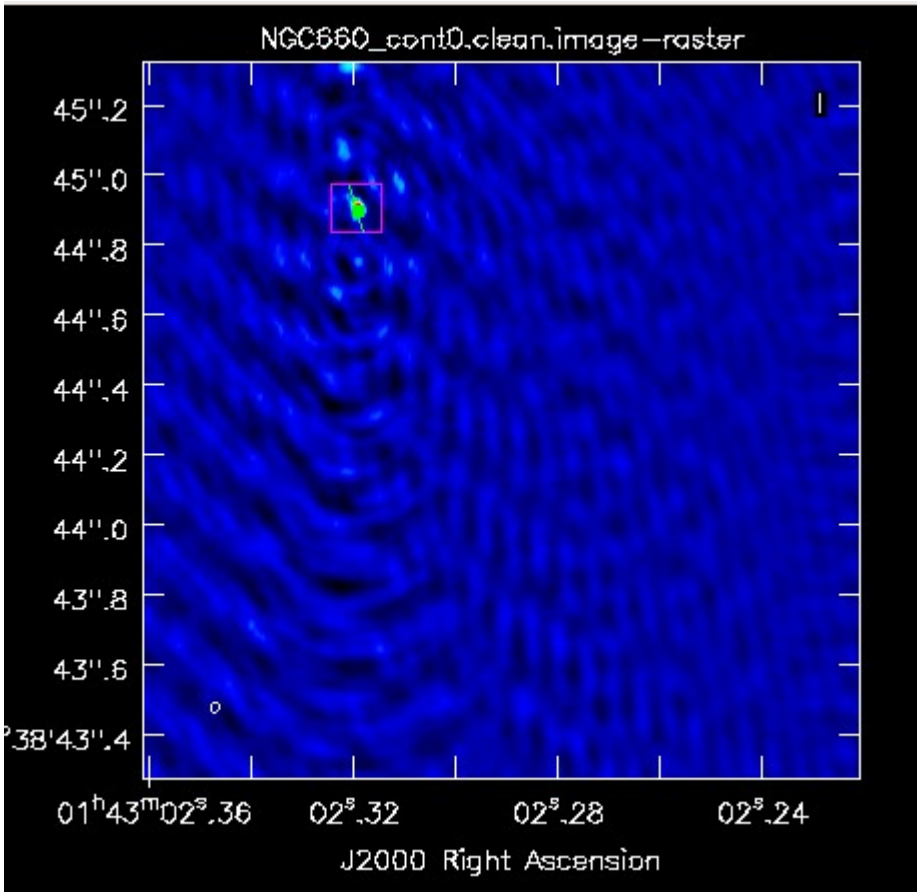


Self-calibration checks

- Plot solutions
  - If they look like noise, don't use!
    - Check you used the right model and any pre-applied cal
    - Edit data if only parts look really bad
    - Increase solint if less than a scan or so, source faint
      - But keep shorter than phase change of $\pi/4$, amp structure
- Succesive rounds of self-cal should improve
  - Phase/amp solutions should approach 0 / 1
- Image, check snr is increasing, position not shifted
- Compare model with data – is it converging?
  - Use plotms or overplot CC in viewer
- Check other spw's etc. also improved if relevant

Astrometry

- Target position is not known accurately?
  - Use **pre-self-cal** image to measure **astrometric** position
    - This is the most accurate position you can measure
  - Limited by ϕ-ref solution & antenna position accuracy, separation on sky, etc. (**Ed's the expert!**).
- Use this image as self-cal model for good astrometry



Frequency Dependence

- Continuum source spectral index α in amp self-cal
  - $S_1 = S_0\,(\nu_1/\nu_0)^{\alpha}$
    - $S_0/(S_1-S_0) = 1/[(\nu_1/\nu_0)^{\alpha} - 1]$
      = (flux density / flux density difference between spw)
  - e.g. spw0 @ ν_0 =100 GHz; spw2 @ ν_1 =102 GHz
    - $S_0/(S_1-S_0) = 1/[(102/100)^{\alpha} - 1]$
      - ~ 25 if $\alpha = 2$
  - If S/N > 25, use nterms = 2
- Atmospheric refraction is linear function of frequency
  - interp= 'nearestPD' etc. if extrapolating far in frequency

Aligning different observations

- Flux scale
  - Phase-ref variability
  - 5-10% uncertainty (more at higher bands)
    - Model uncertainty/short-term variability of flux standard
    - Transfer of solutions between cal sources
      - CASA optimisation tends to overestimate noisy spw flux
        - Select best spw if necessary in fluxscale
  - Spectral scans
    - If possible, self-calibrate on continuum
      - Check if spectral index and/or gain scaling for atmosperic refraction is required for very wide frequency ranges
    - Tools for alignment e.g. Nordic node `Specscan`
- If self-cal on line use mstransform first to shift to constant velocity
- Use freqtol and dirtol in concat as needed

Self-calibration on continuum

- mstransform to constant velocity after QA2 calibration
  - Multiple EBs combined?
    - Check concat tolerances have combined spw properly
- Select continuum
  - Hard to do accurately from uv spectrum
    - Make test cube first?
  - Err on side of rejecting too much for self-cal
    - Avoid lines contaminating flux scale
- Phase, then ap
    - Stop when no improvement in model/reduction in solint
- Make low-resolution cube to identify continuum
- Image continuum with multiscale
- uvcontsub, image lines

Summary/guidelines

- First image: Don't clean too deeply (avoid artefacts)
  - Use anything known about source structure as guidance
- Self-calibrate phase first
  - Scan length is often appropriate solint
    - Not too short - don't over-constrain phases with poor model
    - Re-image, possibly repeat phase self-cal
      - Better model so can possibly use shorter solint
- Amplitude self-cal needs better S/N
  - Clean deeply to ensure model contains all target flux
    - But errors usually change more slowly
  - Usually, correct phase first to allow longer solint
    - Occasionally, very mis-scaled amps need early correction