Experience from long baseline observations

Anita Richards (with thanks to ARC colleagues, Ed Fomalont, Robert Laing

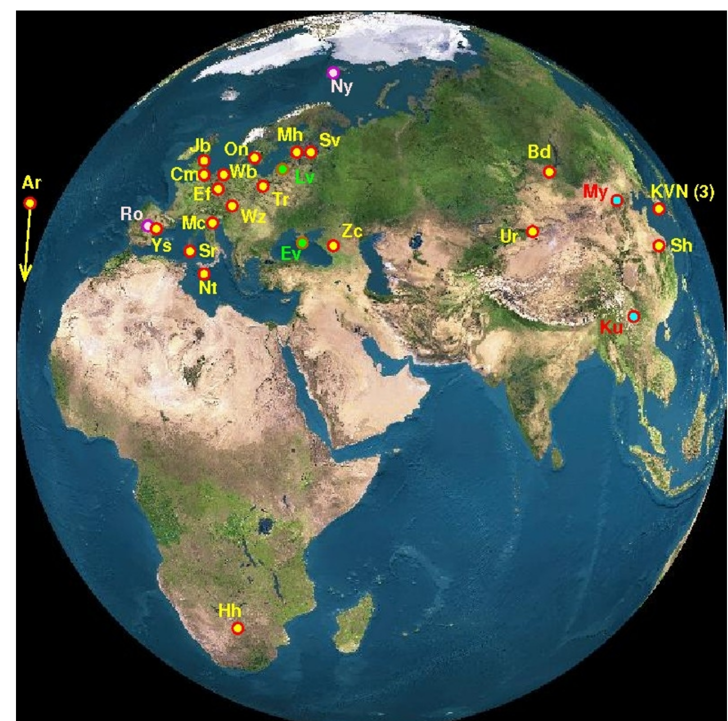
- **Prequel: VLBI data in CASA**
- **Cycle 3 long baseline phases**
  - **How well does the present system do in reality?**
- **What diagnostics, requirements?**
  - **Making use of what we've got**
- **Oxygen sounder**

ALMA
EUROPEAN ARC
ALMA Regional Centre || UK
The University of Manchester Jodrell Bank Observatory
MANCHESTER 1824
e-MERLIN
EUROPEAN VLBI NETWORK
IVOA

Prequel: EVN data in CASA

- Development in Africa with Radio Astronomy
  - Skills exchange for African VLBI Network (with SKA)
    - cm-wave focus, summer schools, want to teach in CASA
- Write EVN CASA script (much help from Mark Kettenis)
  - Well-behaved 5 GHz data
    - Target/phase-refs, BP cal
  - Max baseline ~12000 km
    - ~200 M$\lambda \equiv$ 200 km at λ 1mm
      - LLAMA-like but better atmosphere
  - No need for 'rate' calibration

http://jbcamail.jb.man.ac.uk/DARA_Newton_ro/EVN_Continuum

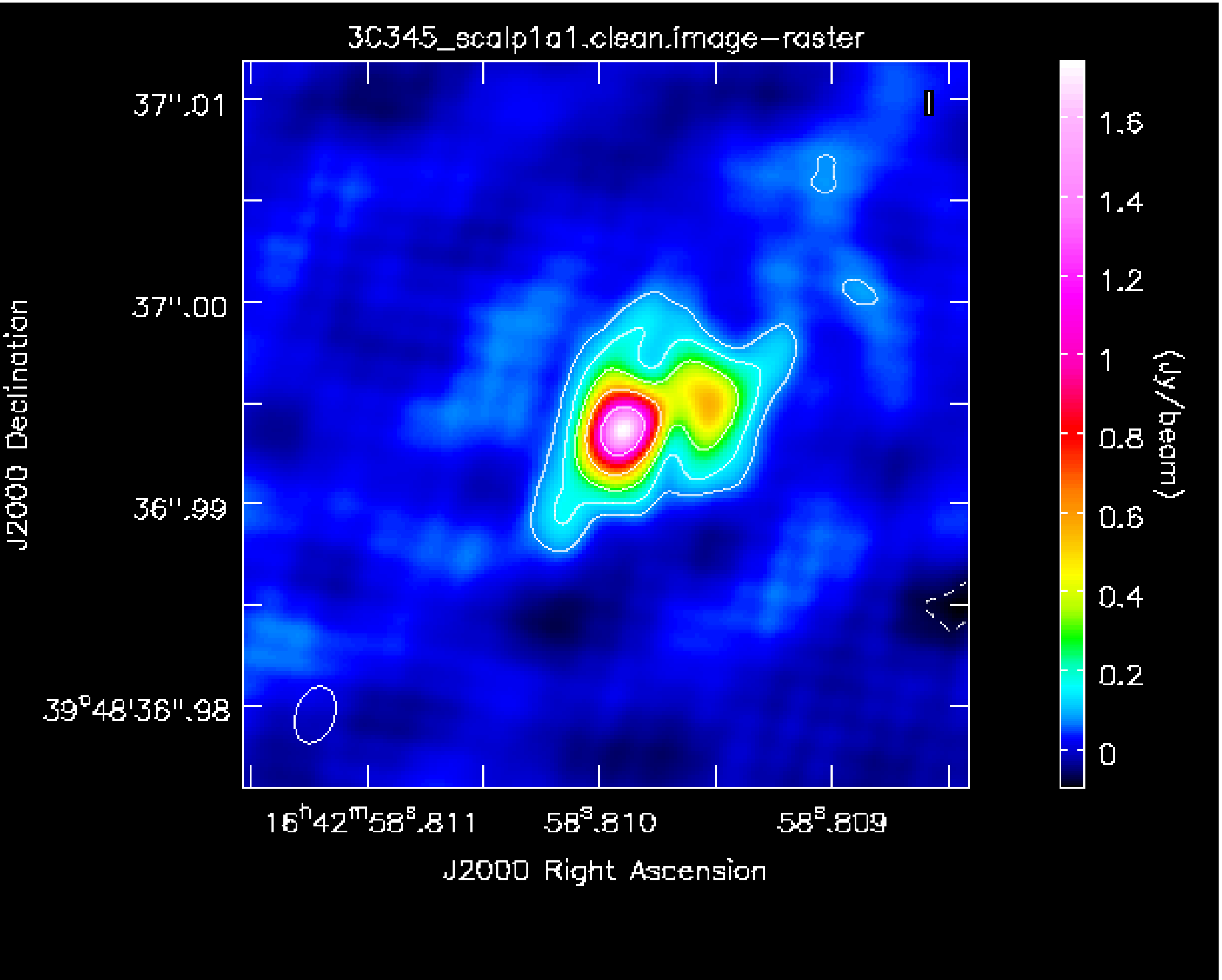


CASA EVN Script

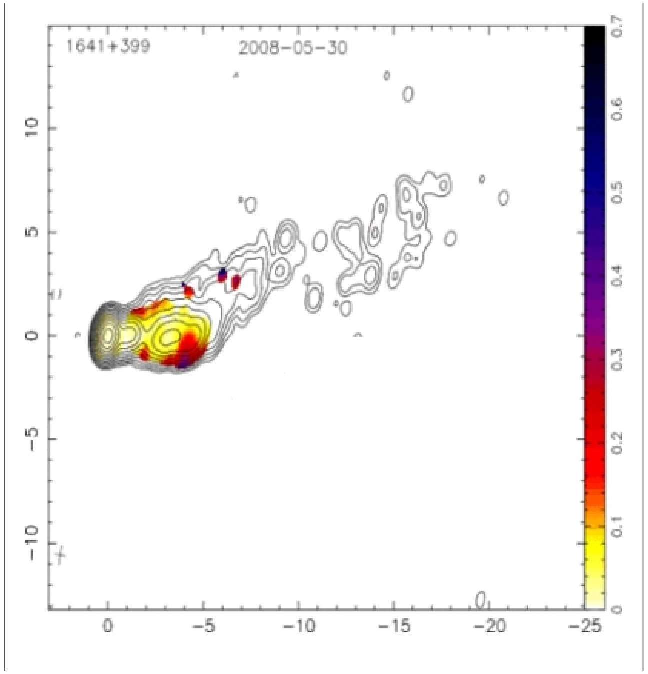
- Metadata issues converting EVN fitsIDI data format to MS
  - Antenna diameters, axis offsets have to be added
    - FITS non-standard? (OK in e-MERLIN data)
  - Tsys (incl. flux scale), gain-el tables via MK scripts
  - Glitch in interpolating across scans missing an antenna
- Otherwise normal CASA data reduction including delay
  - Need to apply parallactic angle correction for correct astrometry even for total intensity at >~1 Mλ
    - *Should we be doing this for ALMA at >1 km baselines?*
  - Many calibrators are resolved
    - Develop model iteratively if necessary

The result.... 3C345

Phase-referenced, self-calibrated

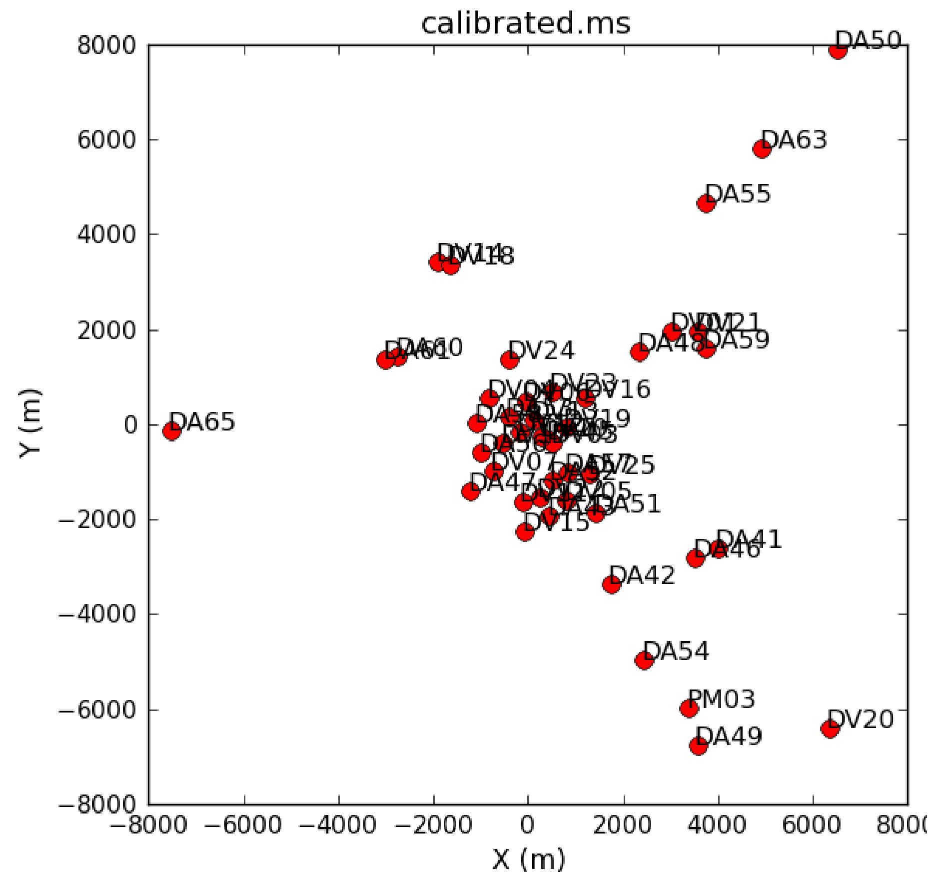


MOJAVE VLBA image of 3C345 at 15 GHz (different angle due to jet precession)



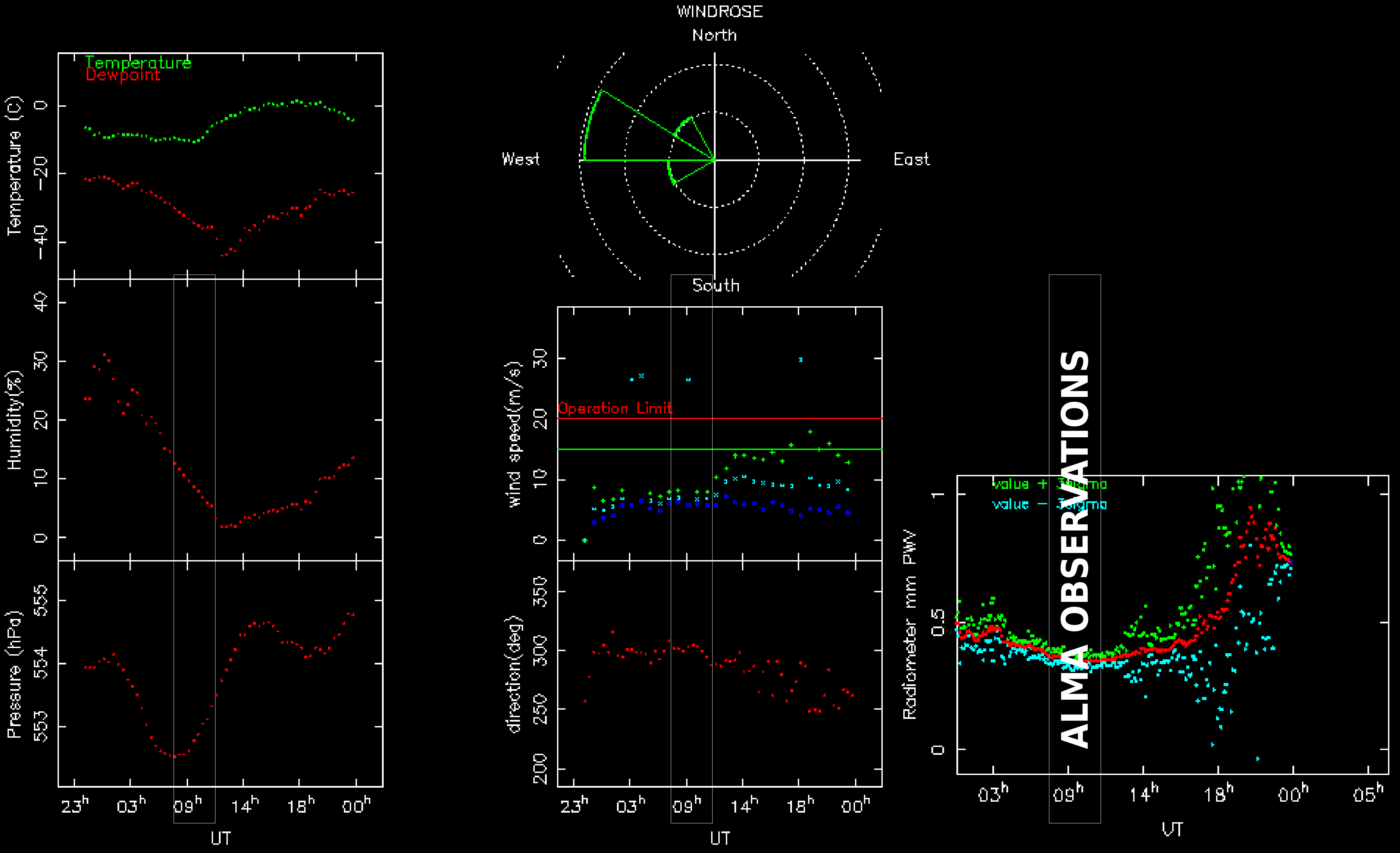
Cycle 3 long baseline science data

- Band 7, continuum+line, up to 16-km baselines
  - Phase-ref ~0.4 Jy, 2.8^{o} separation
  - ~2-3 min phase-ref : target cycles, 18:90 sec on-source
    - In 3 min (time), Earth rotation means a change in direction of atmospheric path of $1^{o}.5$ @ el 60^{o}
    - 5 m/s wind 6 km above telescope will cross $\sim 9^{o}$ in 3 min
  - PWV 0.41 mm, stable

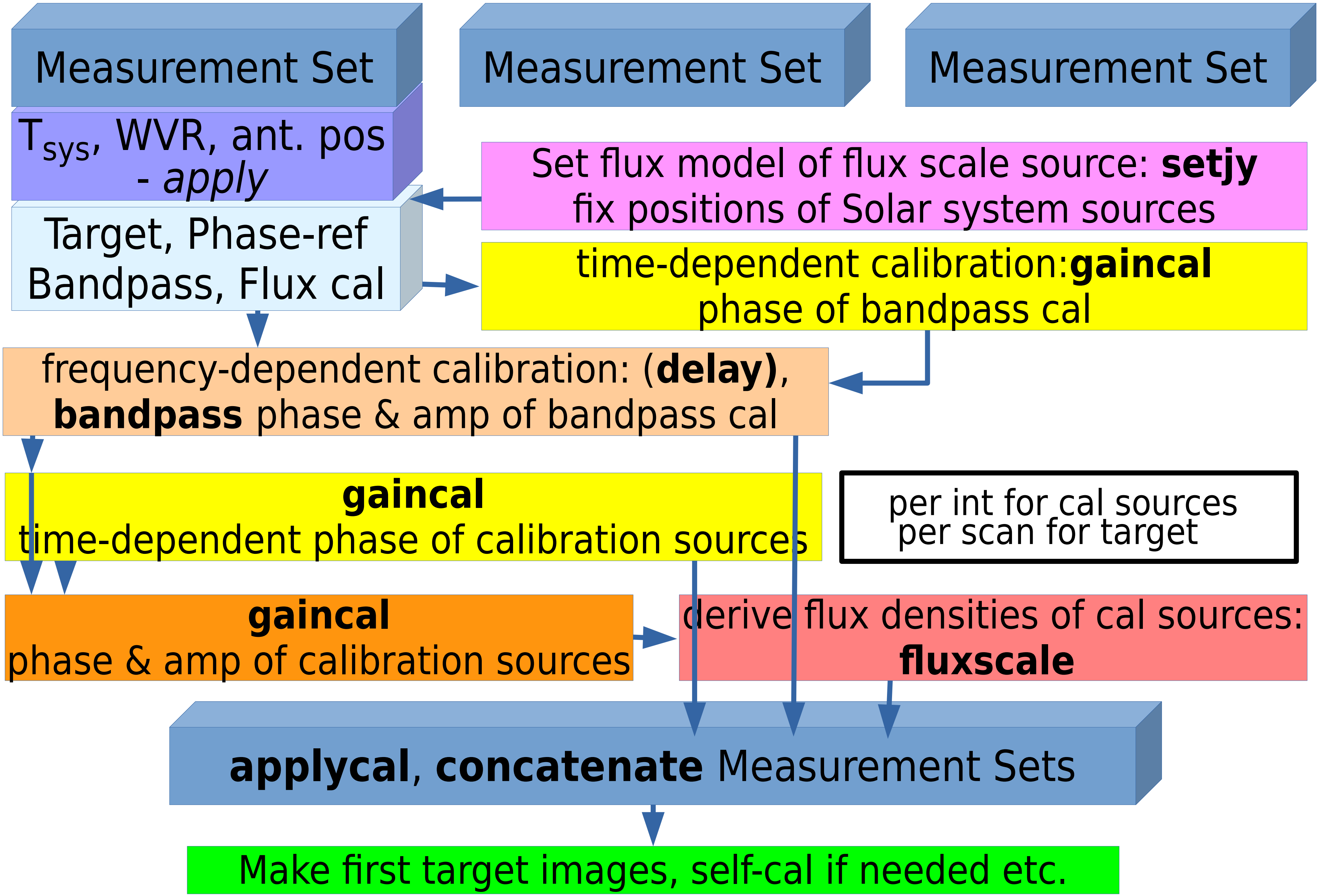


- Cycle 3 observations & data reduction techniques noticably smoother than 2014 – 15 LBC/SV!

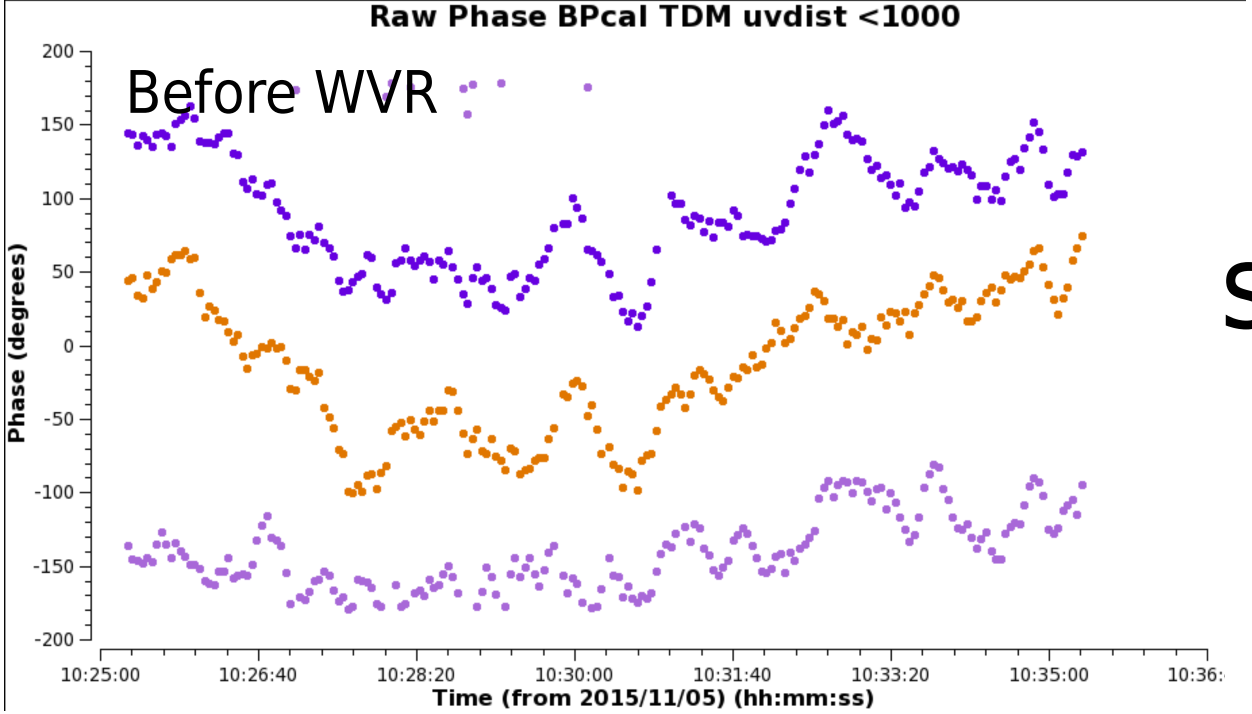
APEX monitoring on date of science obs

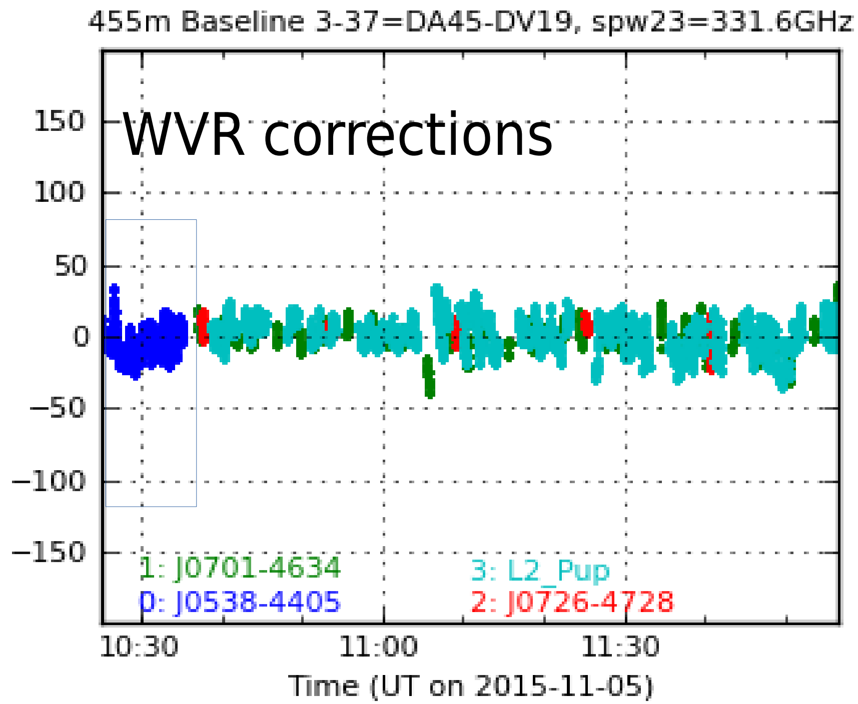


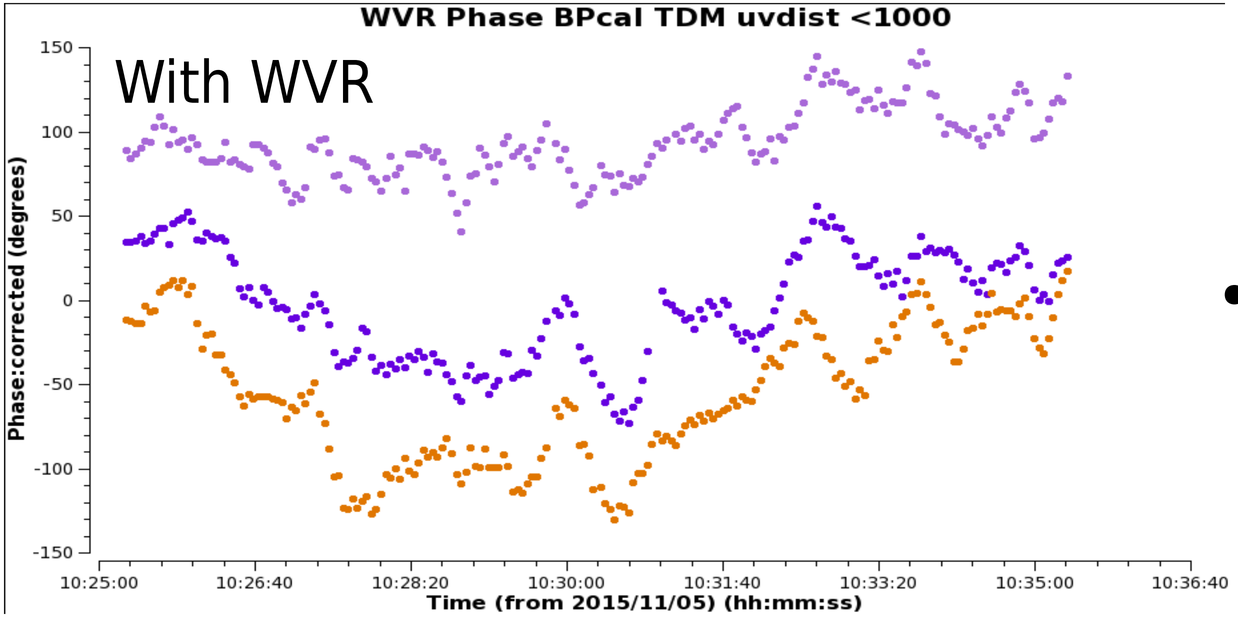
Science project 'QA2' flow



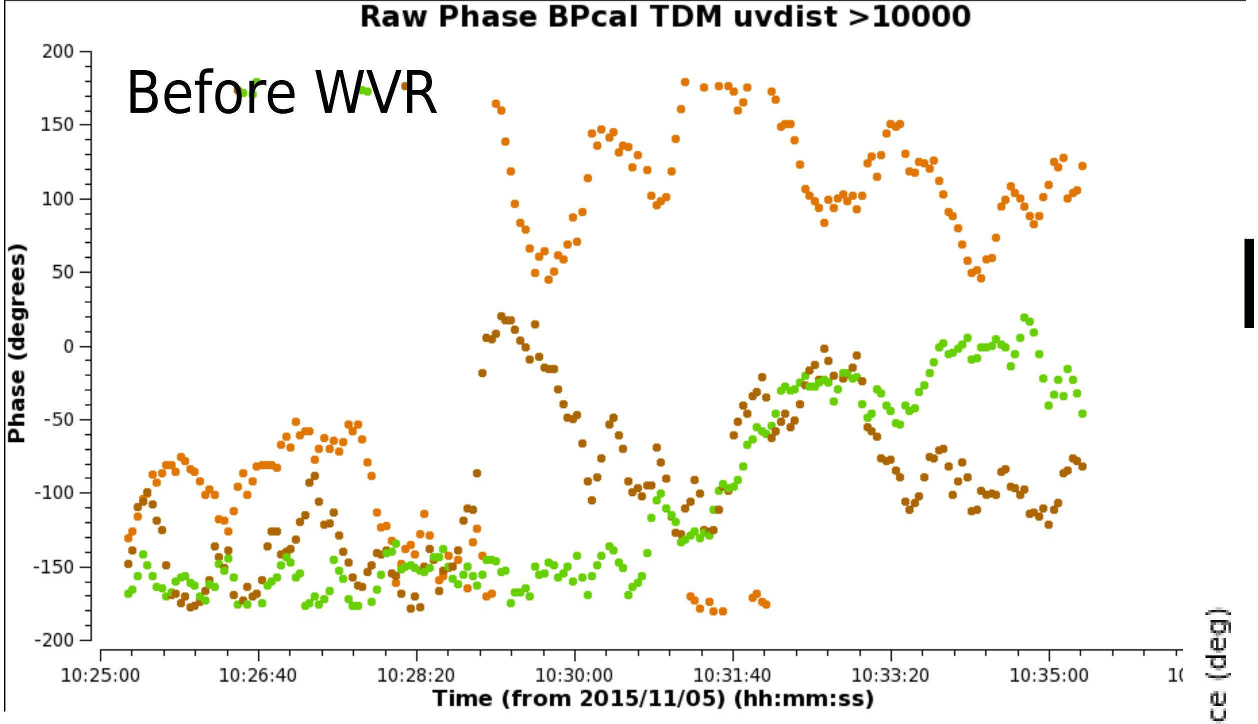
WVR short baselines



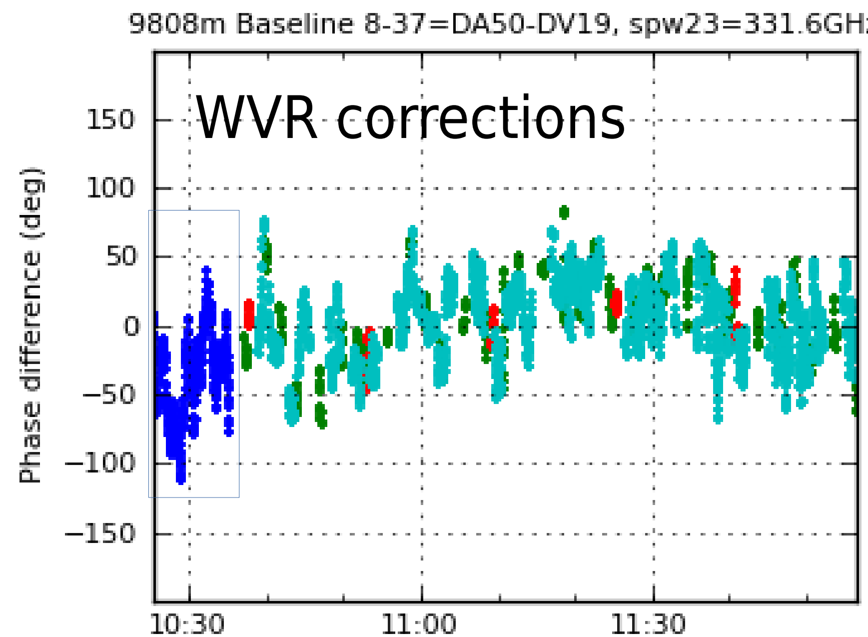


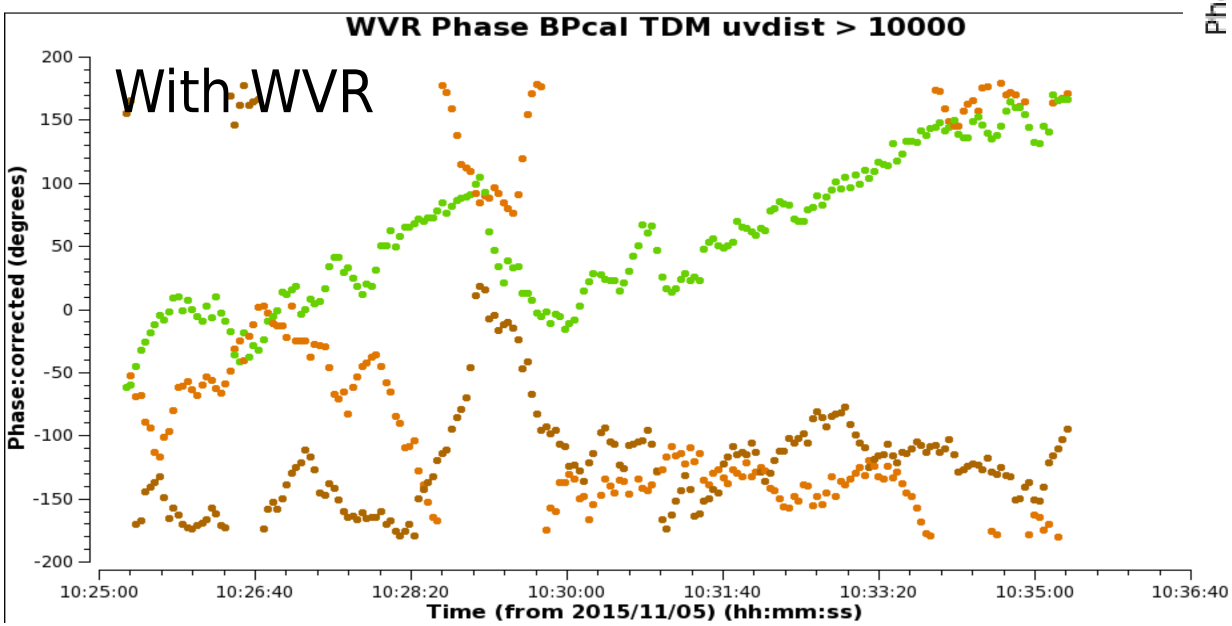


- Slight reduction in scatter
  - Pretty good anyway!

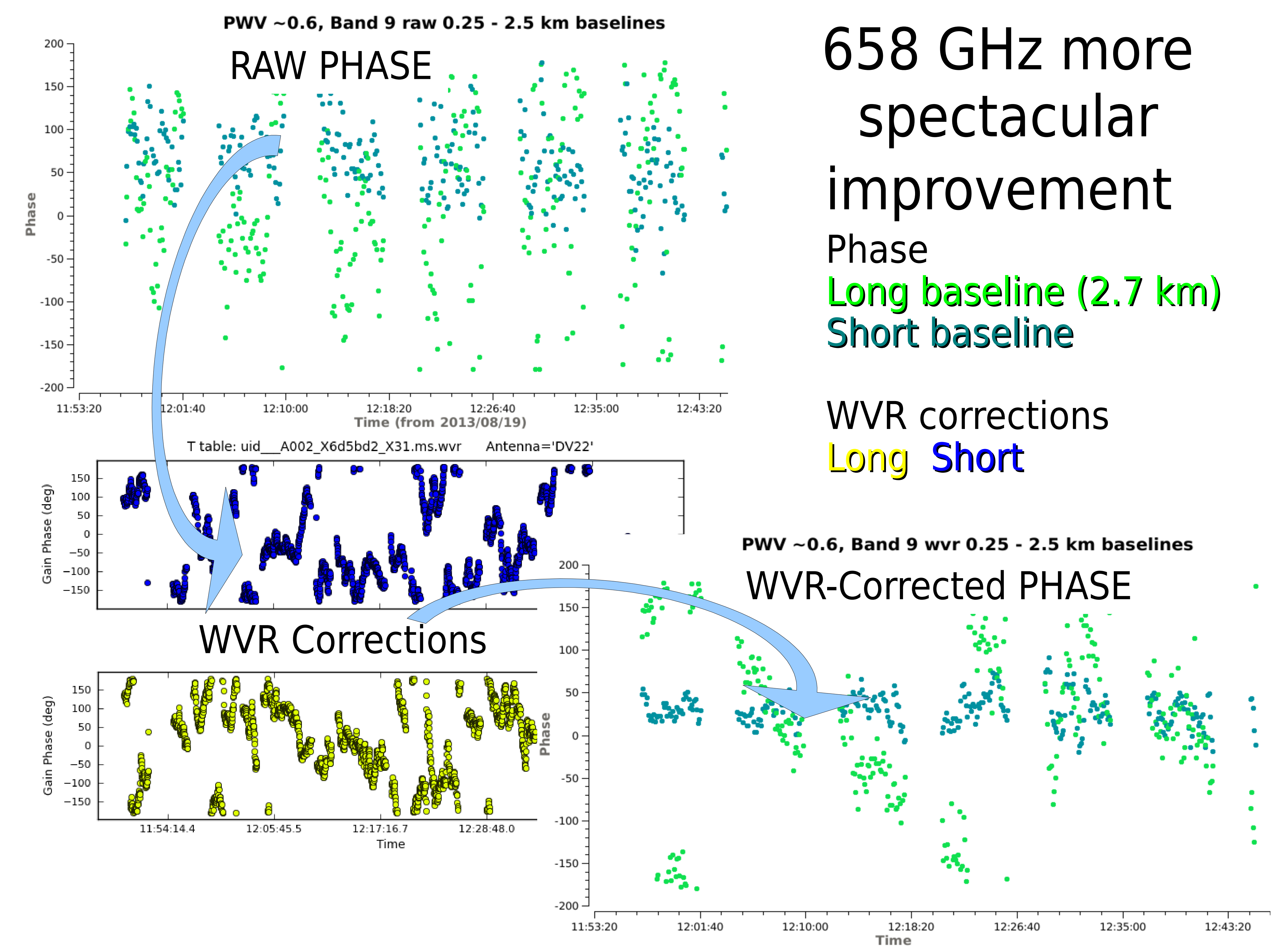


WVR
long baselines



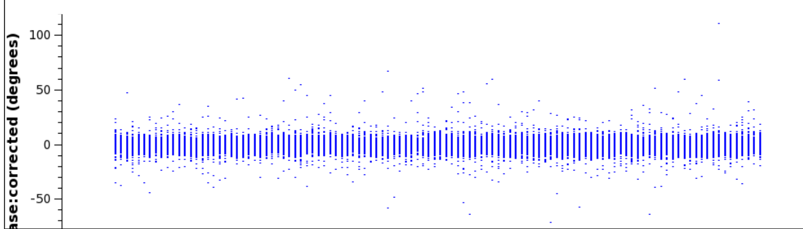


- Significant reduction in scatter
  - t_{int} 3 sec
  - WVR every 1 sec

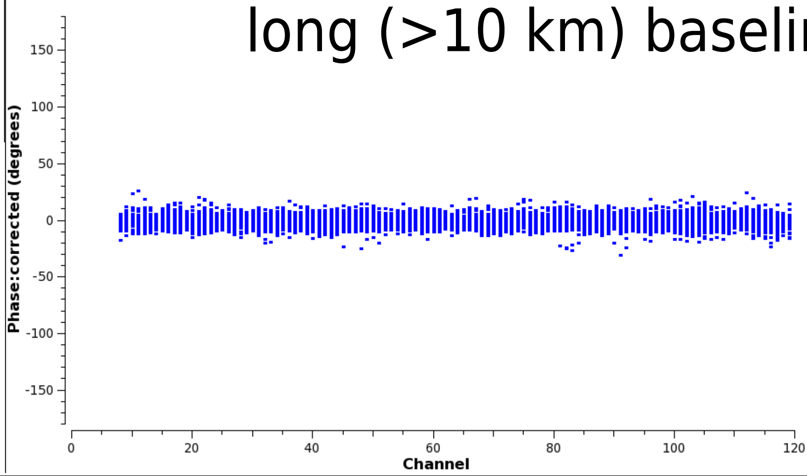

658 GHz more spectacular improvement
Phase
Long baseline (2.7 km)
Short baseline
WVR corrections
Long Short
PWV ~0.6, Band 9 raw 0.25 - 2.5 km baselines
RAW PHASE
Phase
Time (from 2013/08/19)
T table: uid___A002_X6d5bd2_X31.ms.wvr Antenna='DV22'
Gain Phase (deg)
WVR Corrections
Time
PWV ~0.6, Band 9 wvr 0.25 - 2.5 km baselines
WVR-Corrected PHASE
Time

Bandpass of calibrated phase ref

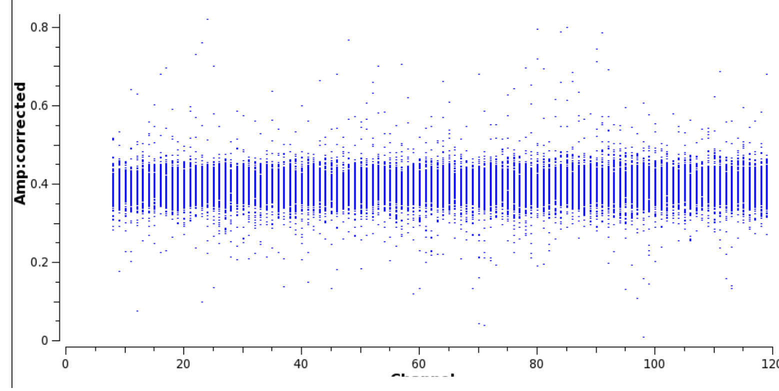
TDM phase short (<1 km) baselines



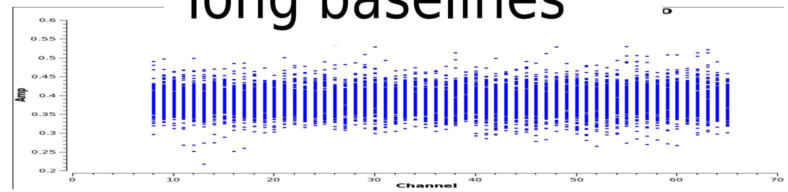
long (>10 km) baselines

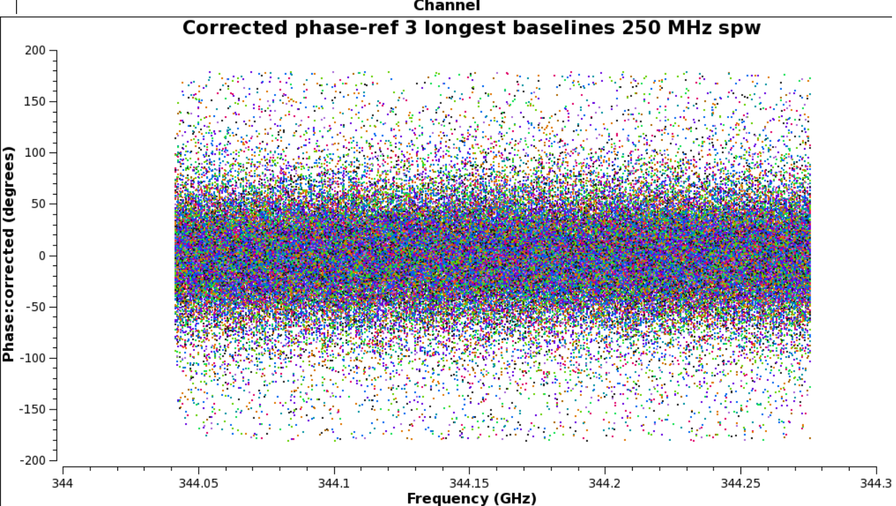


TDM amp short baselines



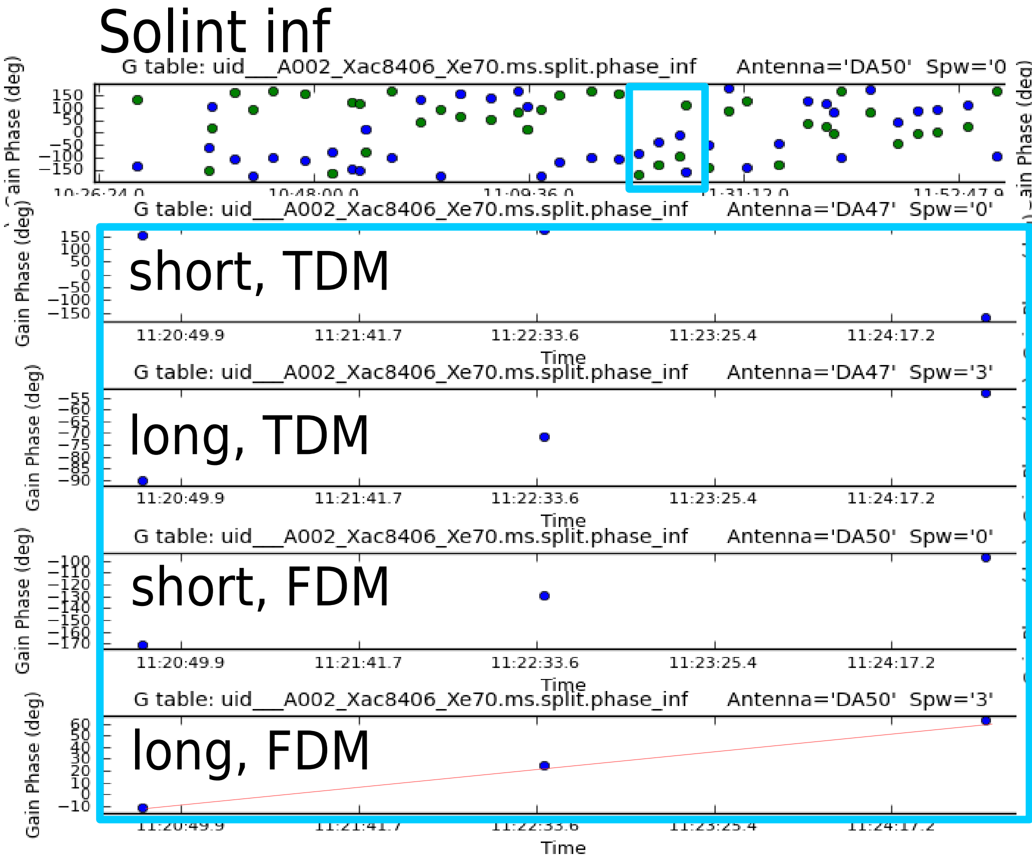
long baselines

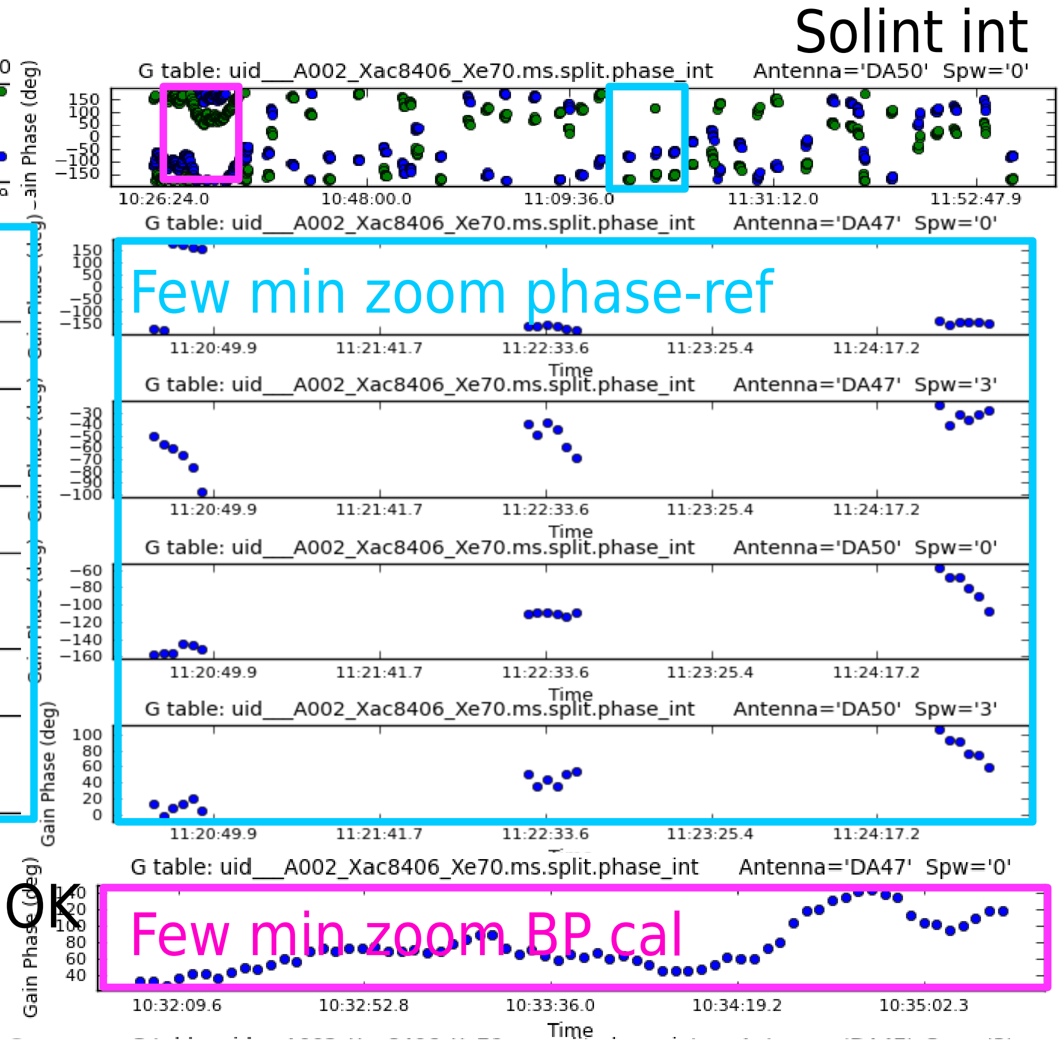




- Fully-calibrated phase-ref phase & amp good on all baselines
- Not too bad even in 122-kHz FDM channels, longest b'lines

Phase v. time cal tables

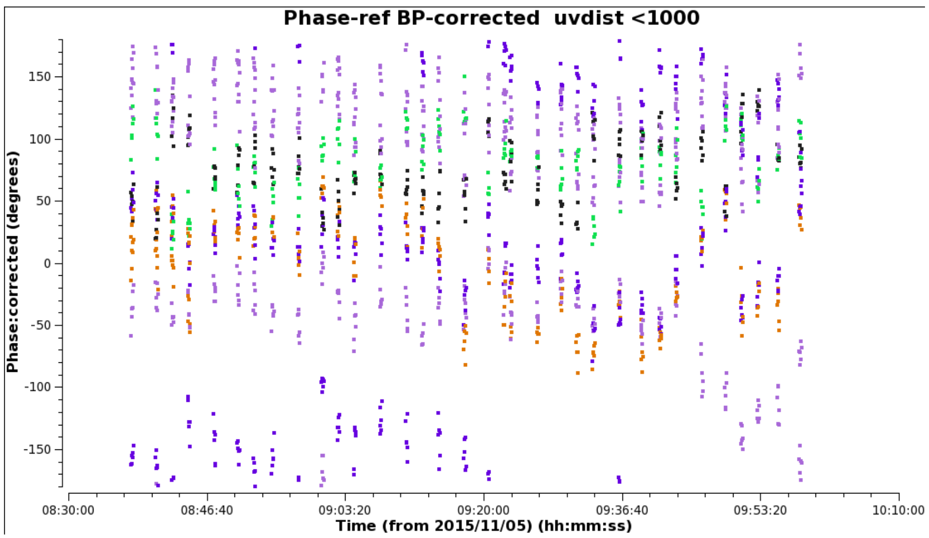


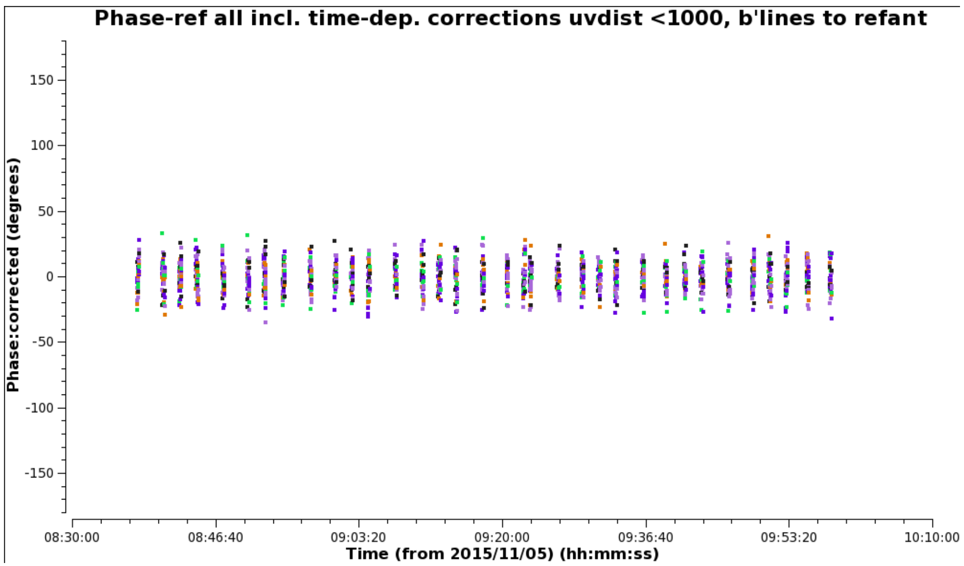


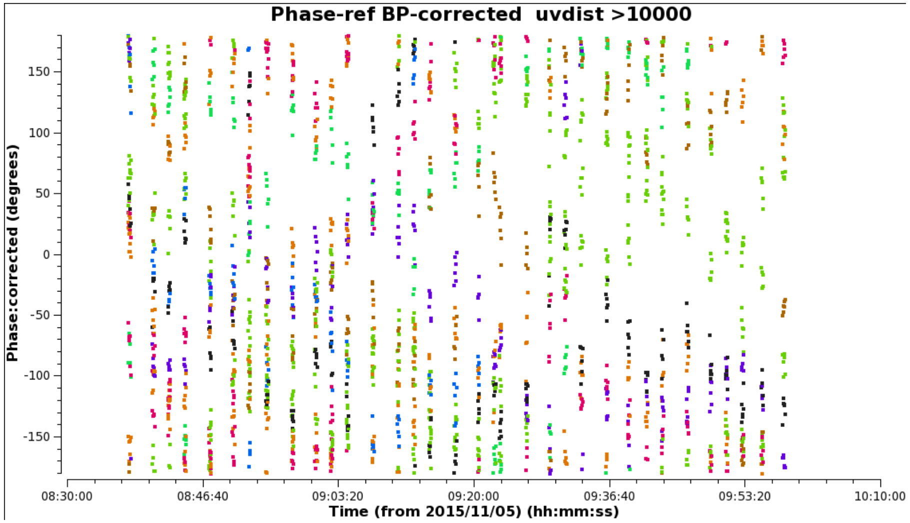
- Minute-scale linear interpolation OK
  - Small-scale ?non? random
    - ϕ~45 deg in 2 min typical
- M=66 scans, N= 44 ants (assuming errors per scan independent)
- Transfer of correction to target dynamic range limition ~ $\sqrt{M}\,N/\phi$ ~455

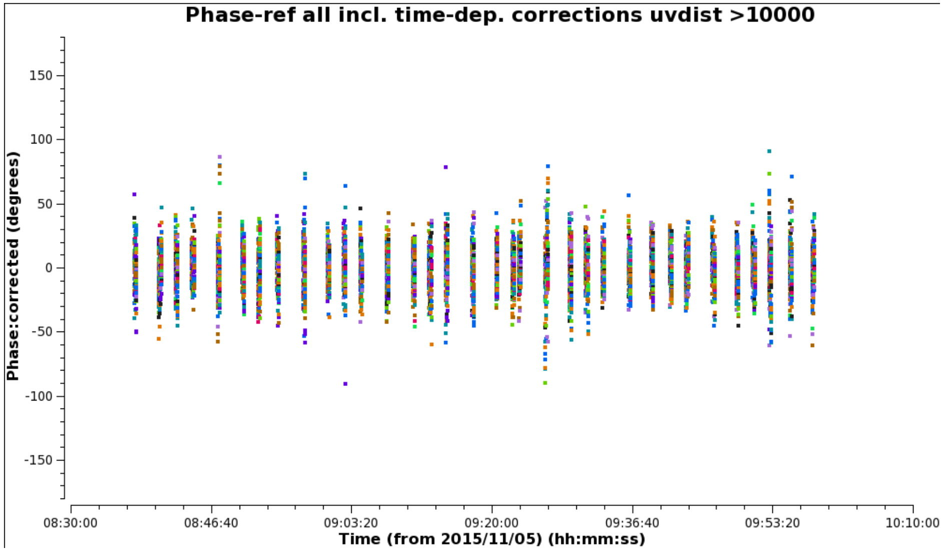
Pre- and post-phase-corrected phs ref

No time averaging, TDM spw

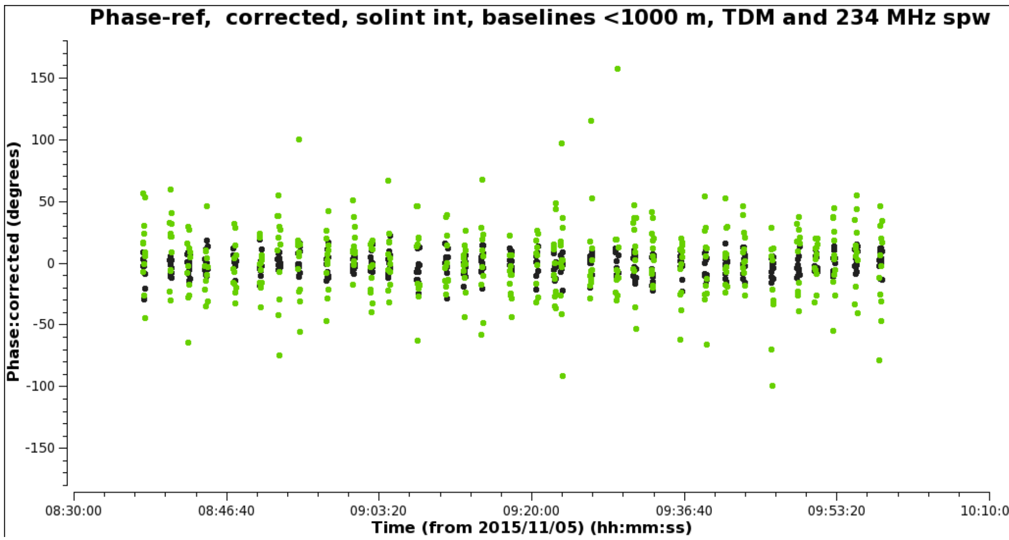


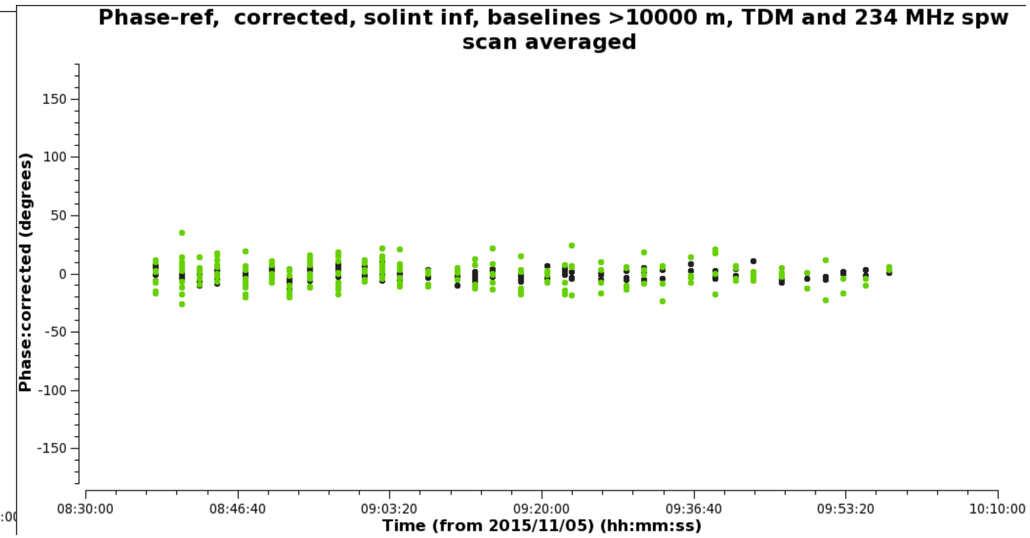


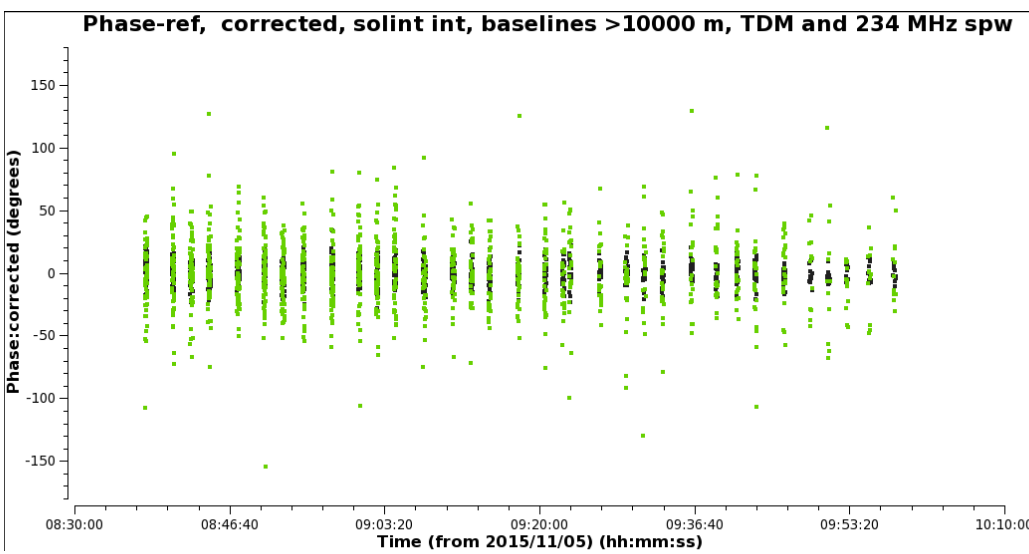


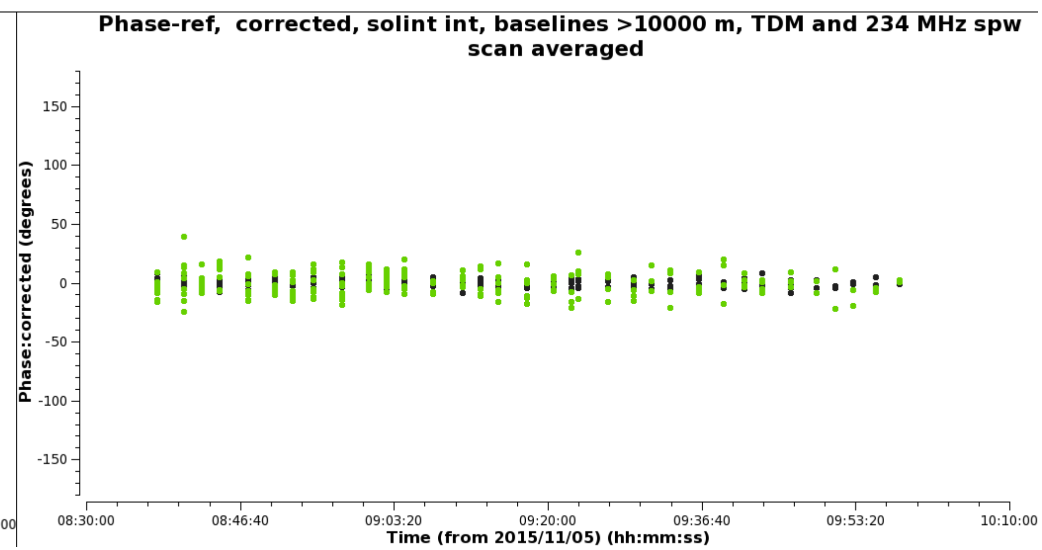


Corrected phase-ref 2 v. 0.25 GHz

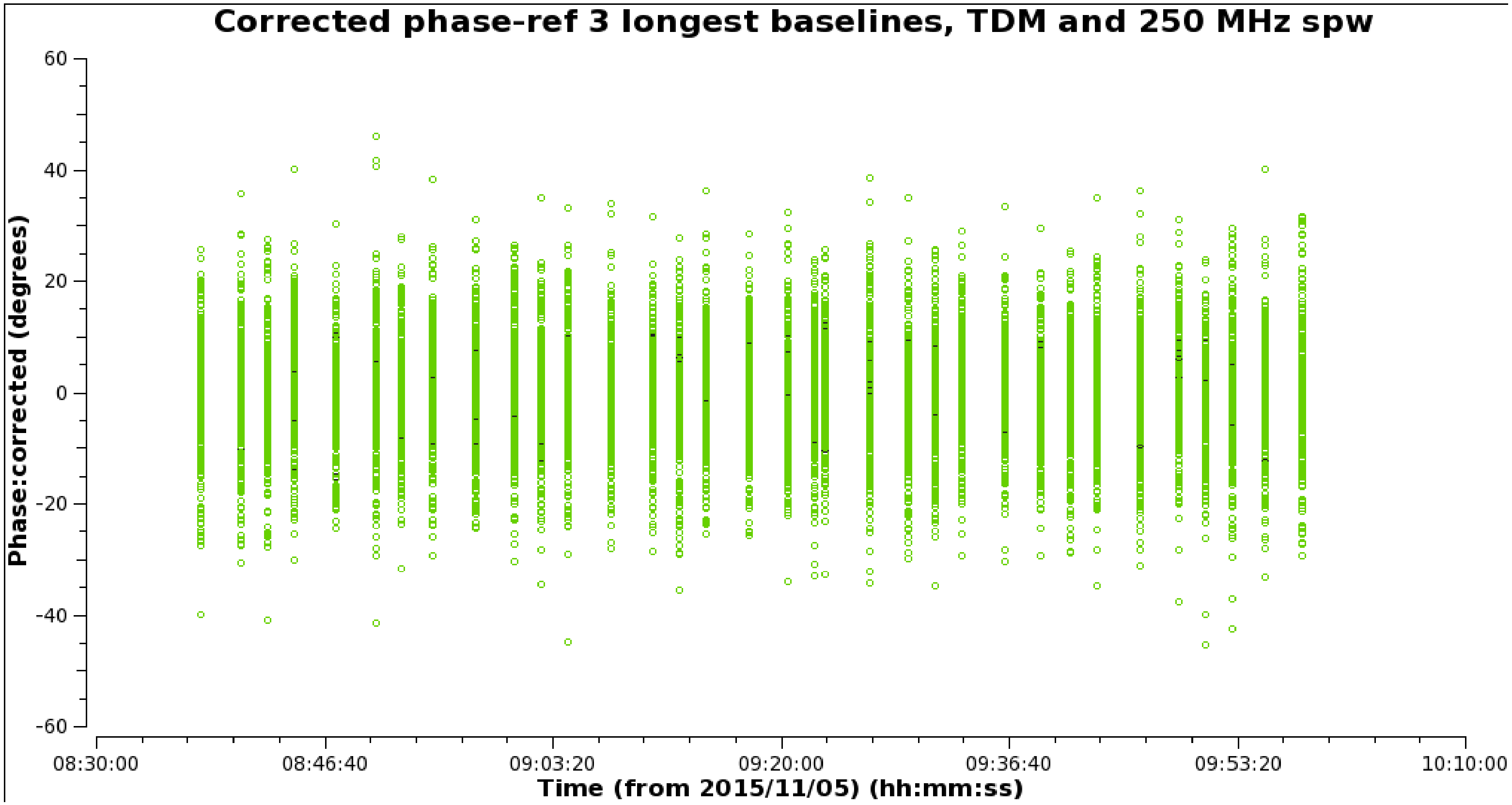






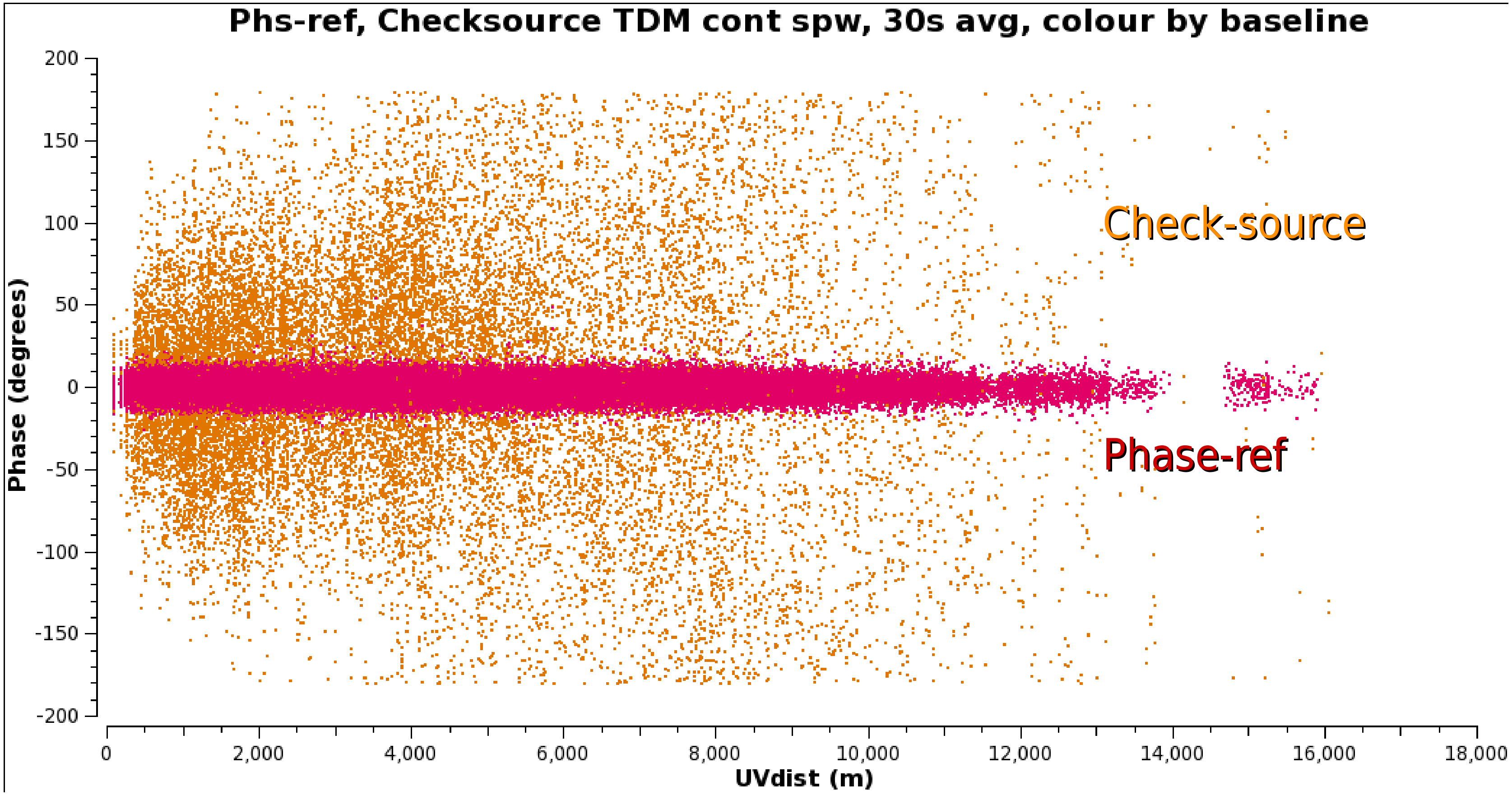


Longest baselines, 18-s avg



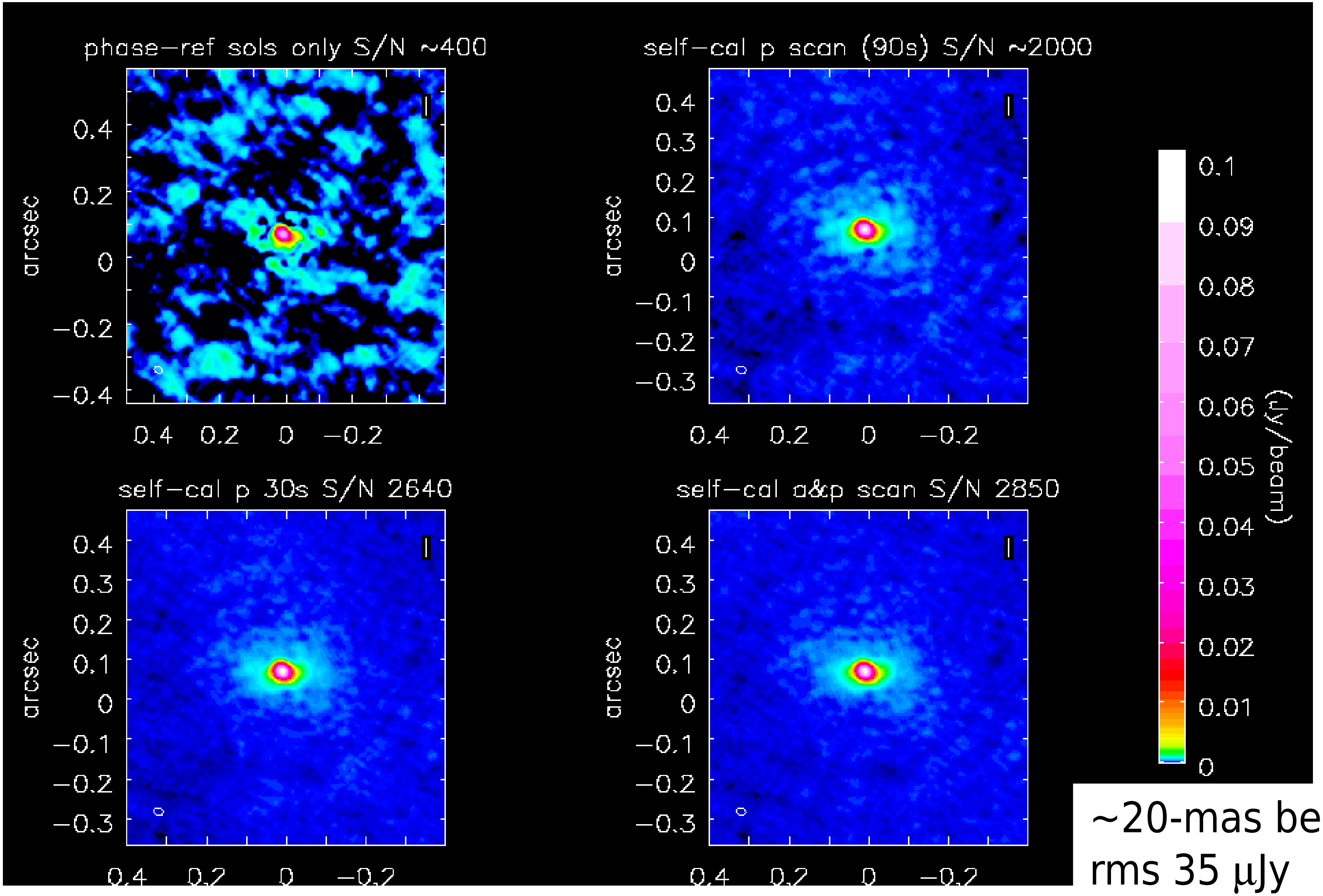
- Phase-ref ~400 mJy, phase OK in 250 MHz spw
  - ~140 mJy in 2 GHz or 70 mJy in 4 GHz, average pol.
- Need to test full averaging in phase referencing

Phase-ref v. checksource, corrected



- Checksource: 4.3° from phase-ref
- After applying phase-ref corrections:
  - Check-source offset from catalogue position 4.5 mas
  - Flux density in image only 43% of expected (145 mJy)

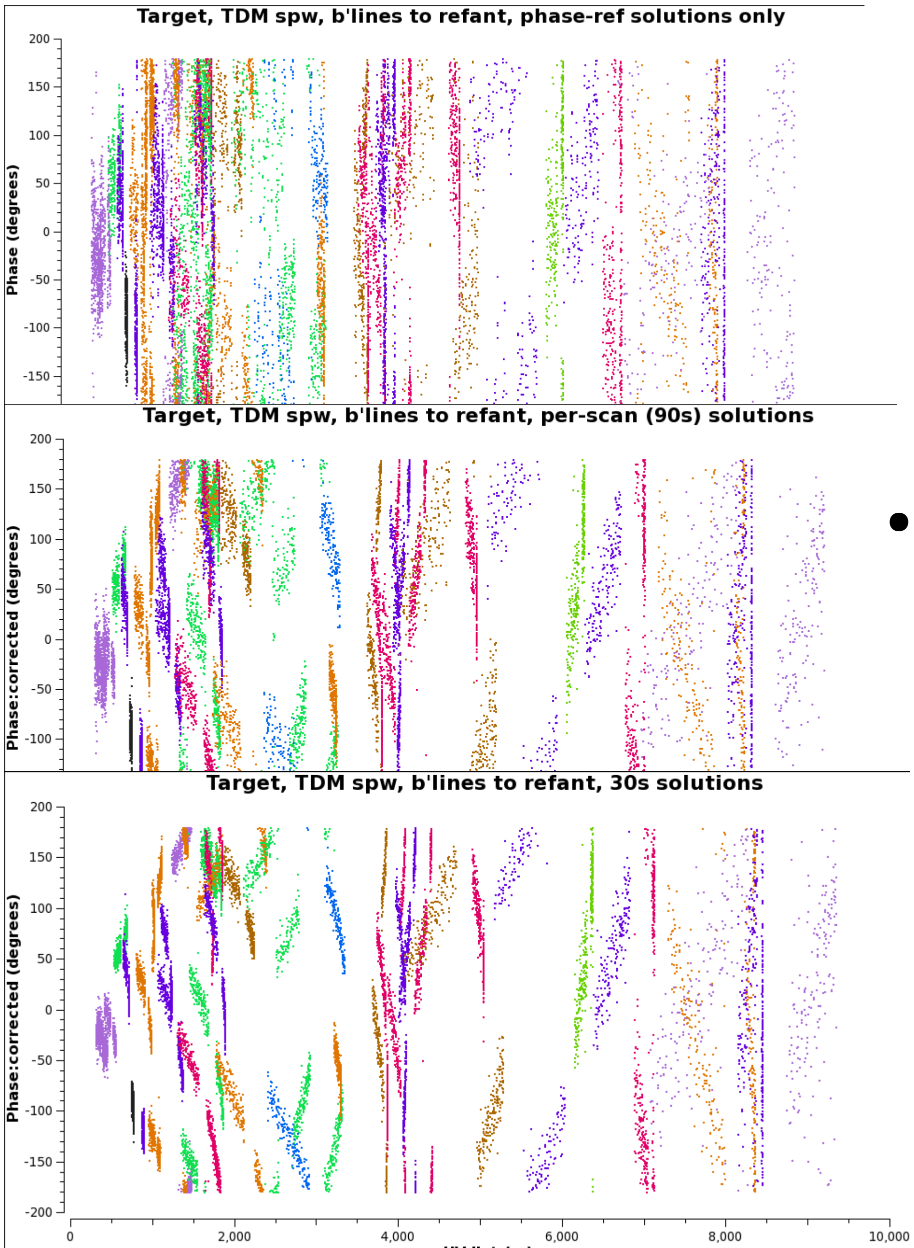
Target imaging

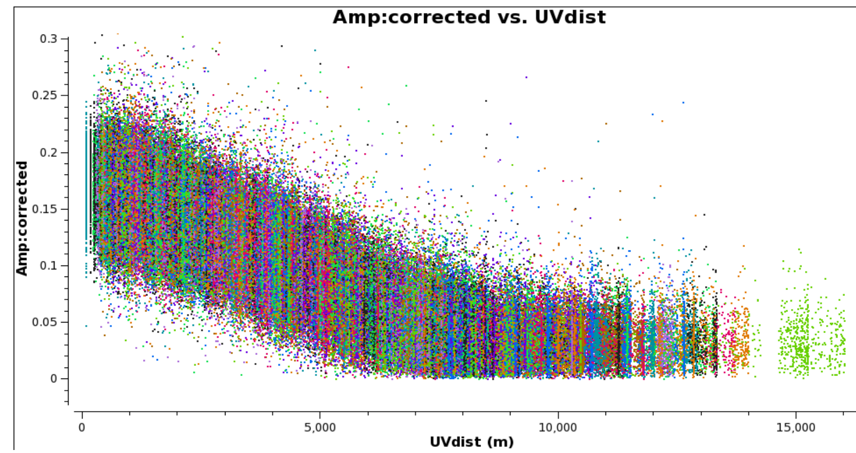


~20-mas beam
rms 35 μJy
theoretical 22 μJy

Target phases selfcal

TDM spw

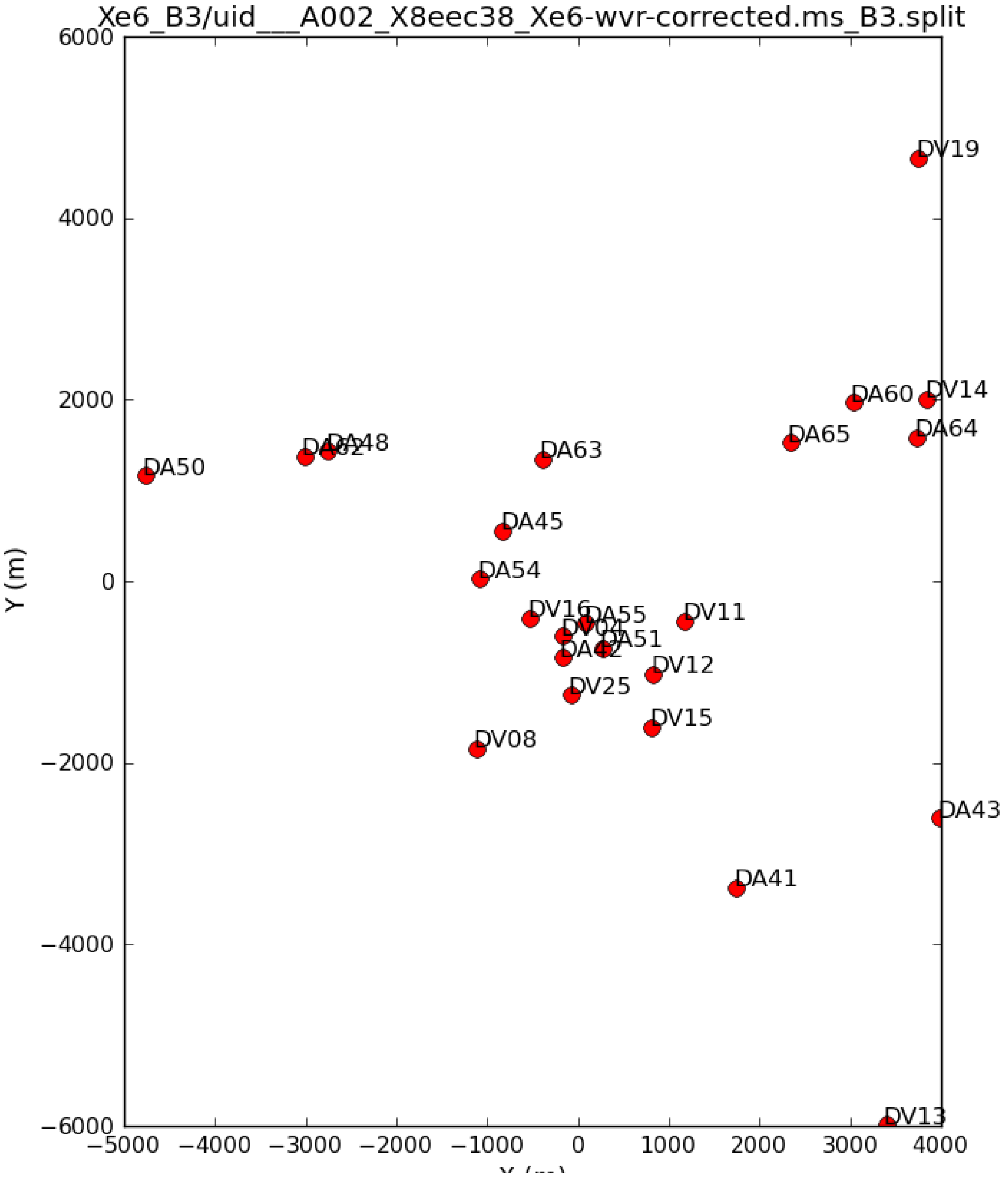




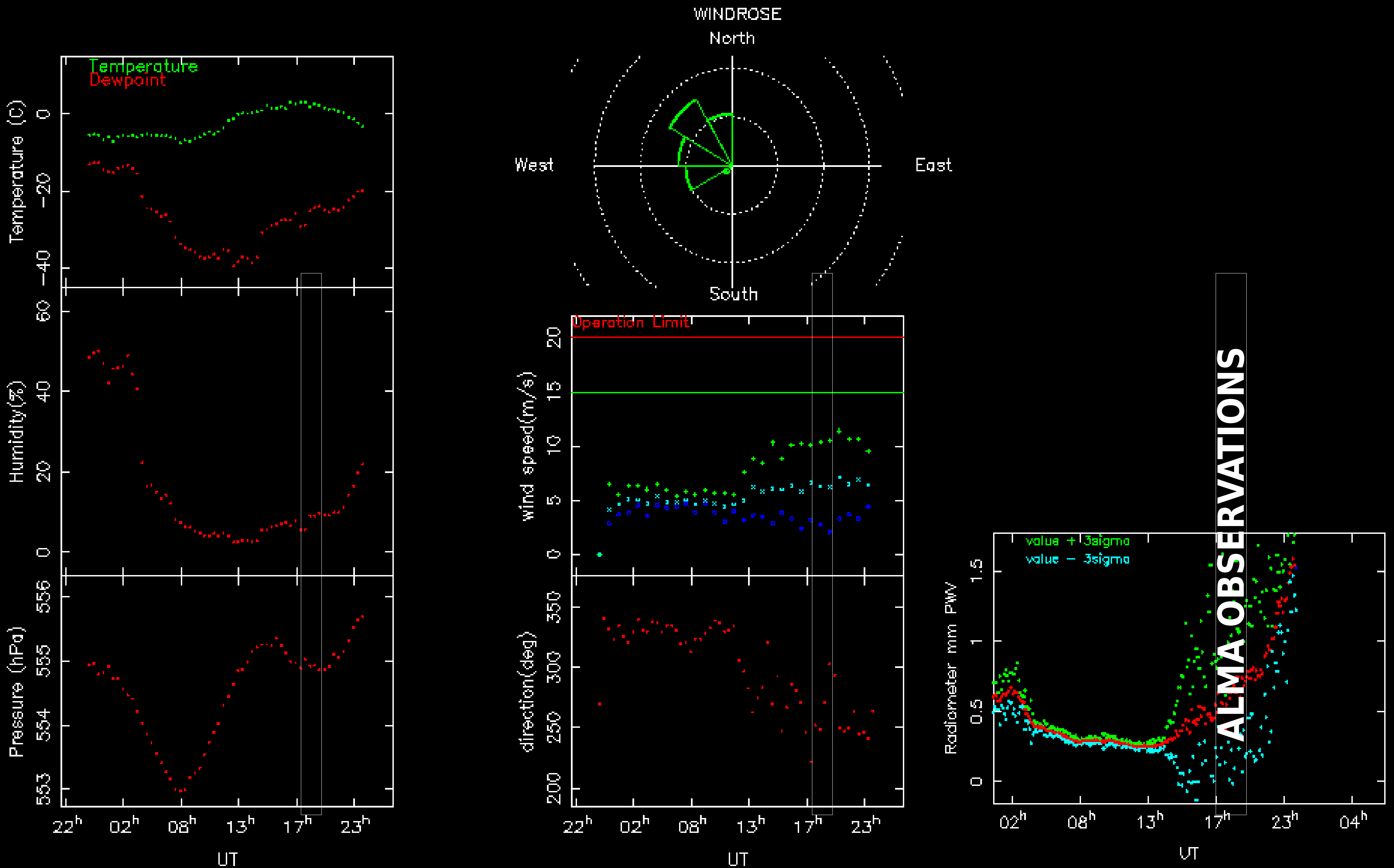
- Initial per-scan phase solution improves S/N 500%
  - 30s phase solutions
  - per-scan amp & phase
    - another 40% improvement
  - Longest baselines still noisy
    - Flux-limited/complex structure?
    - Calibration-limited?

Weak calibrator survey example

- TDM, all chans averaged
  - 20/40 s per scan B3/7
  - on-line WVR
- Observe phase-ref, targets within 15°
  - These, VLBI astrometry

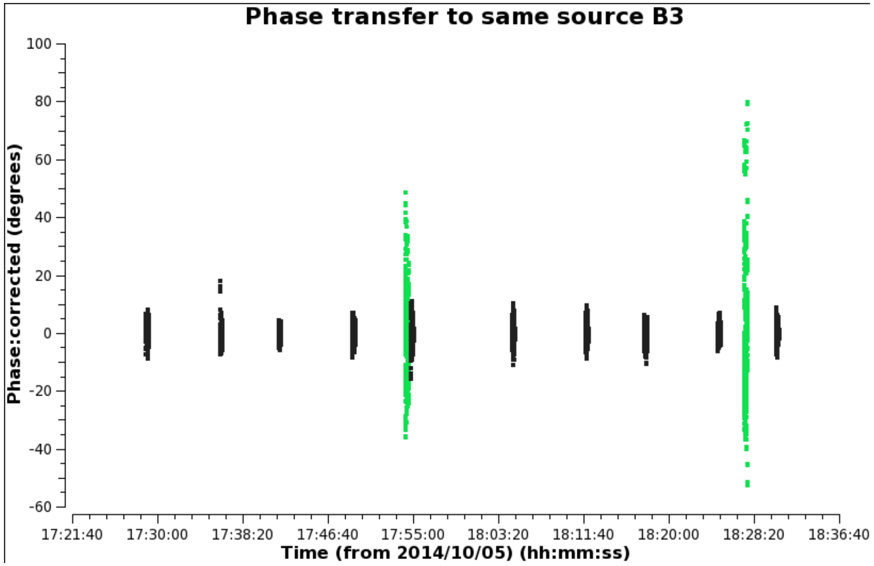


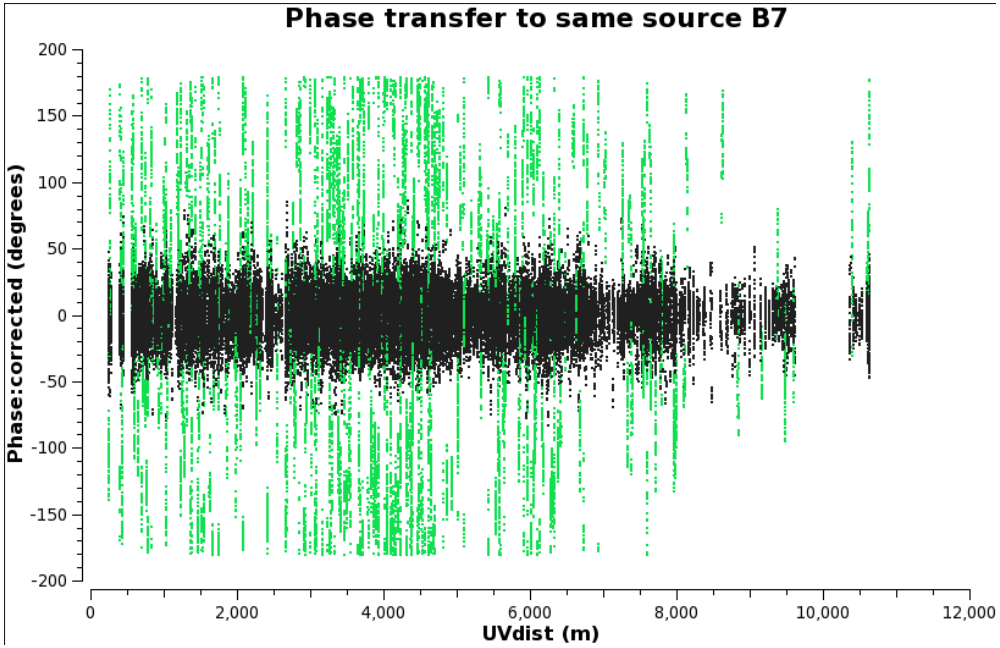
APEX monitoring – weak cals

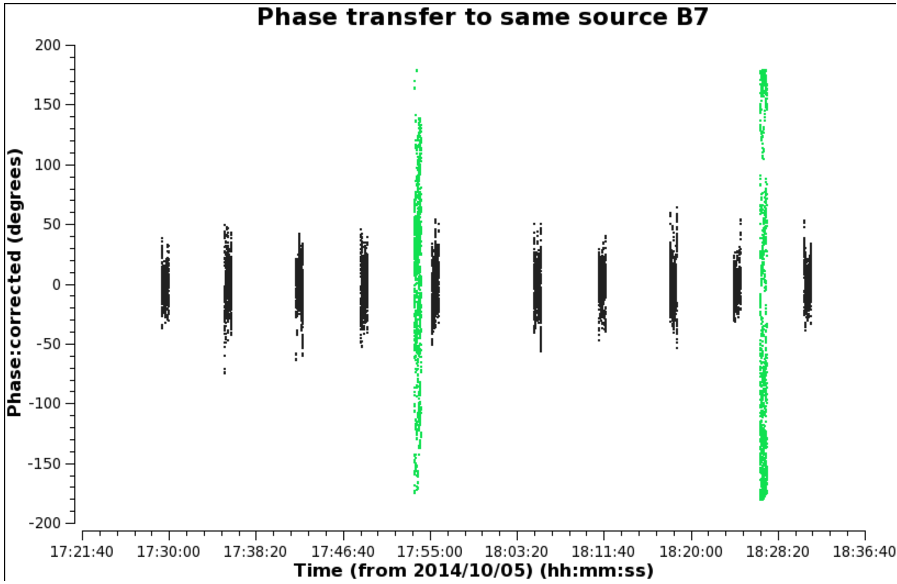


Weak cals

- Phase-ref itself observed as target
- Apply phs-ref solutions
- Divergence ∝ time gap
  - Not baseline length?

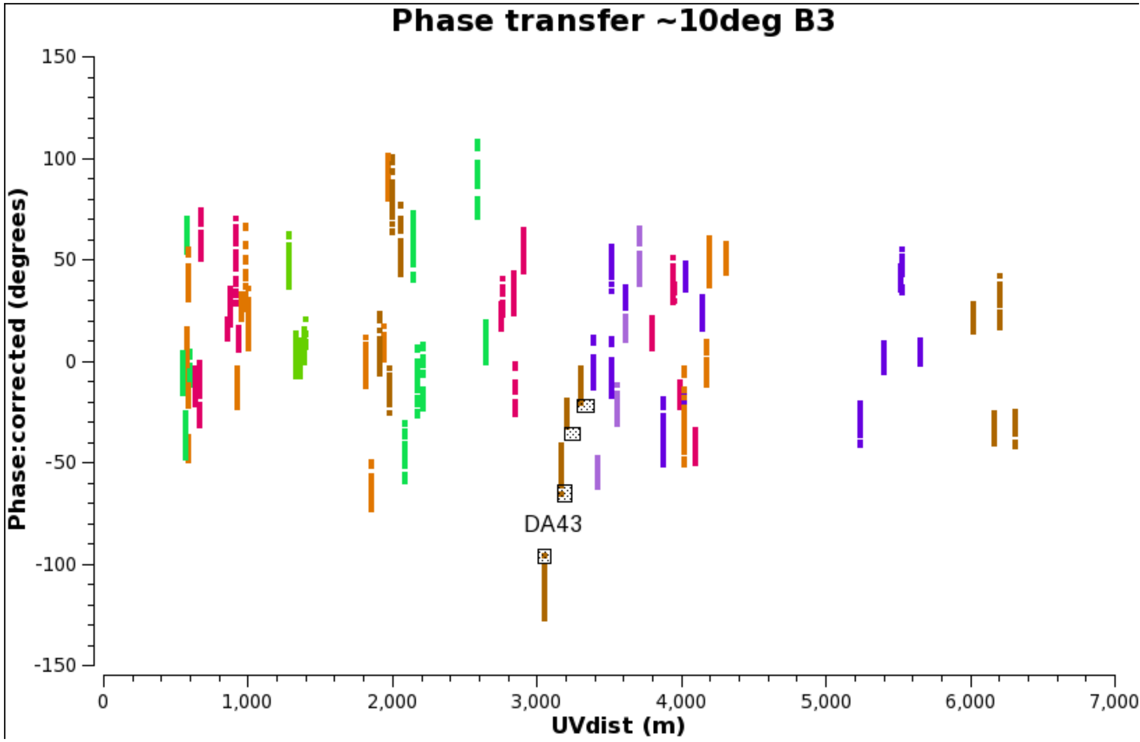


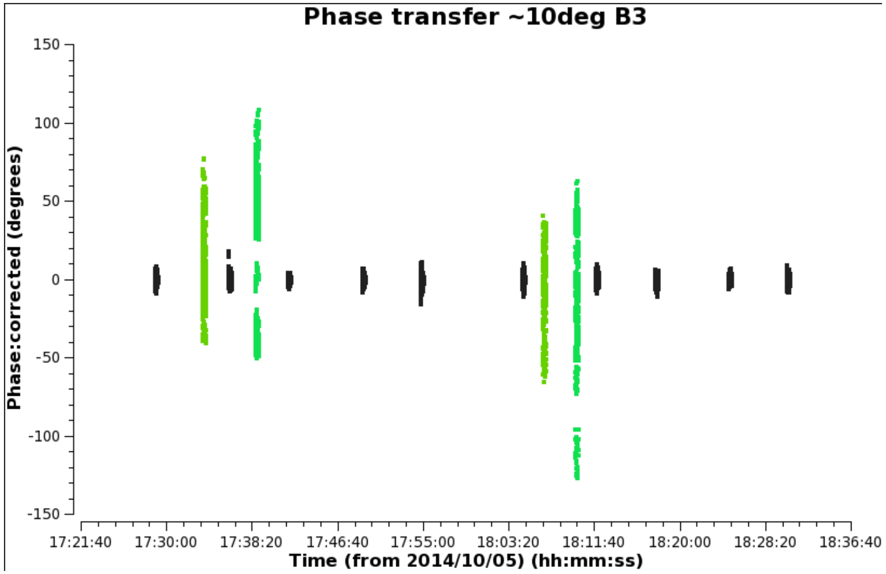


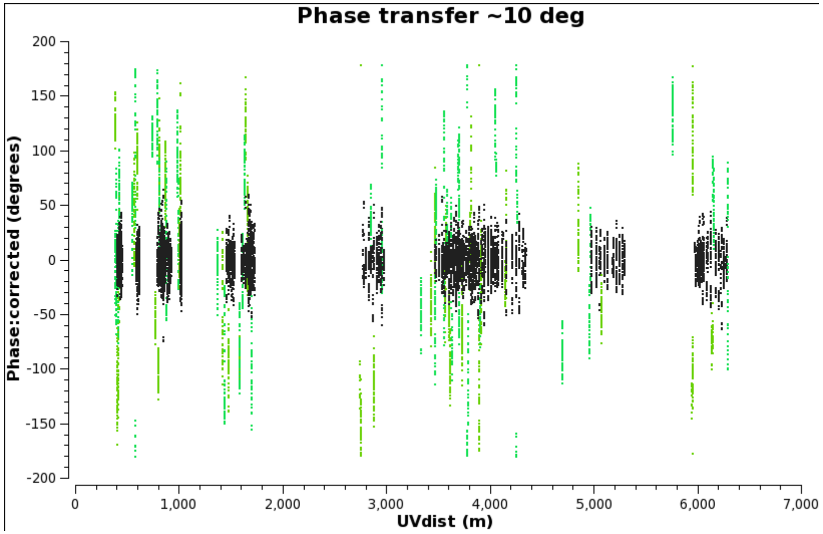


Phase transfer

- 2 bright targets ~10° from phase-ref
- Bad phase offsets
  - indep. of refant, baseline length
  - Not ant. pos errors

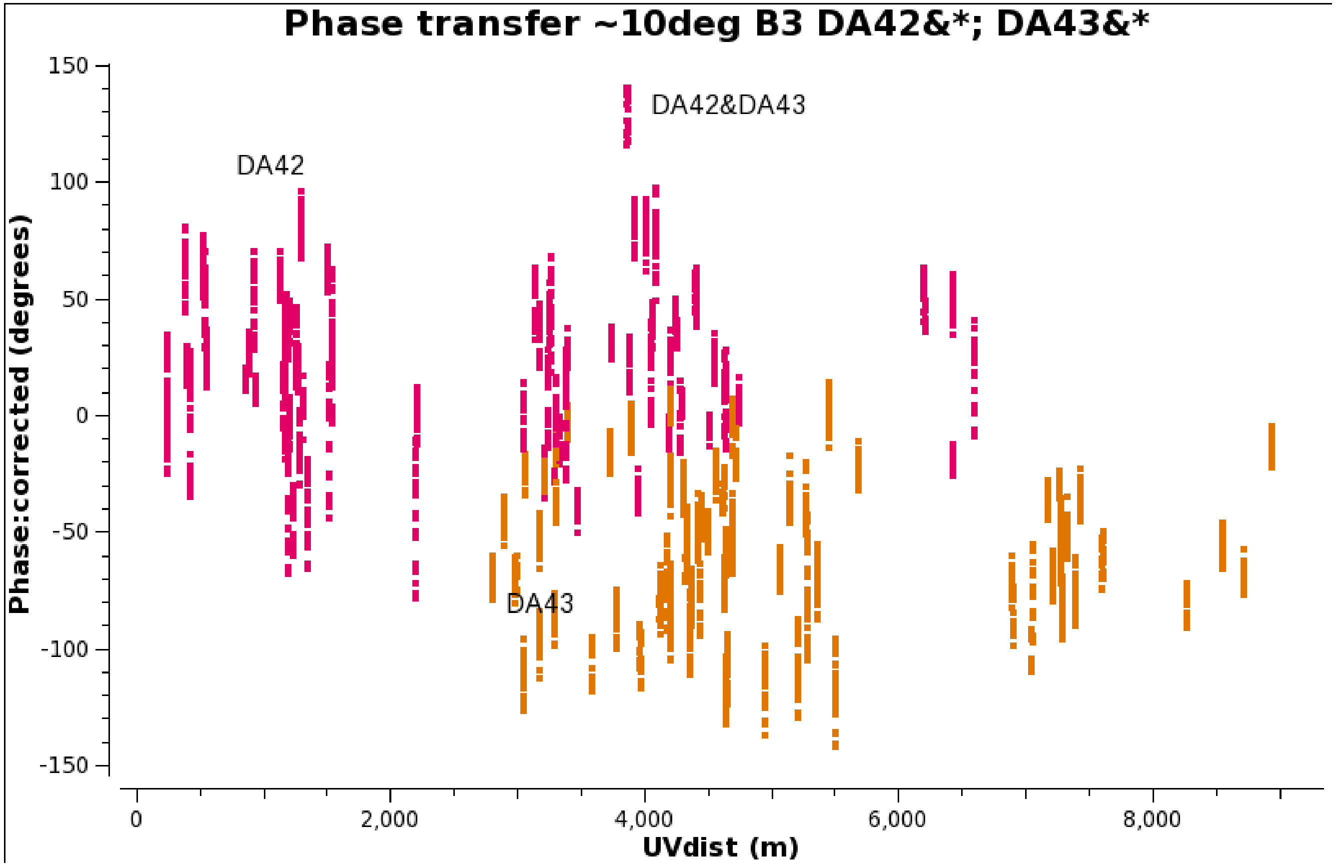






Some systematics?

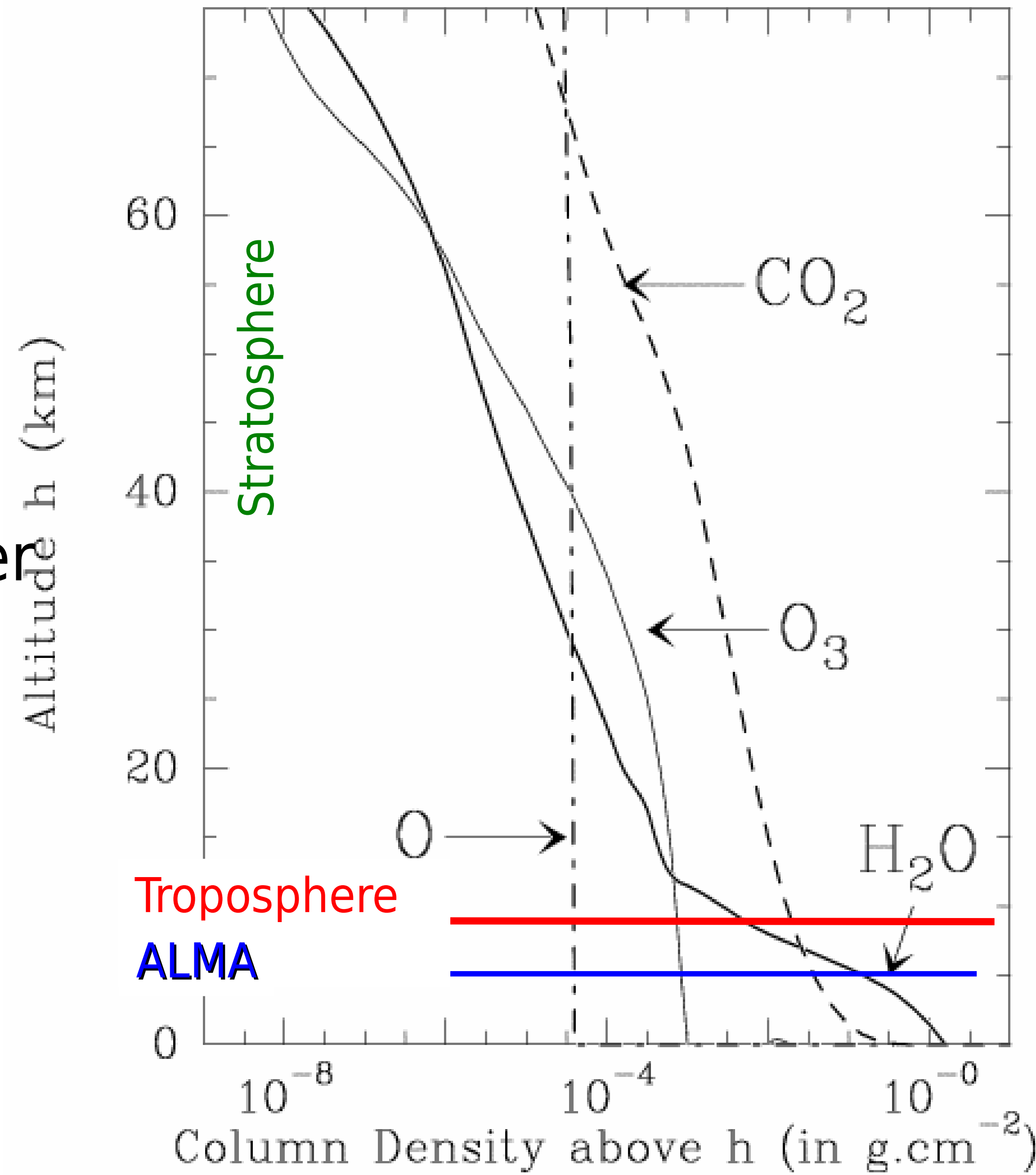
- Some phase offset directions depend on antenna
  - Outlying antennas e.g. DA43 see different dry component?
  - CSV-3146
- Systematic sec-min scale phase drifts
  - Not WV
- Direction-dependent or location dependent?



Atmosphere

- ALMA above much H_2O
  - Measures Vapour
  - Not clouds!
    - Empirical correction
- O_2 ubiquitous, O_3 higher
- Other species?
- Weather stations:
  - Pressure
  - Ground-level temp.
  - Wind speed etc.

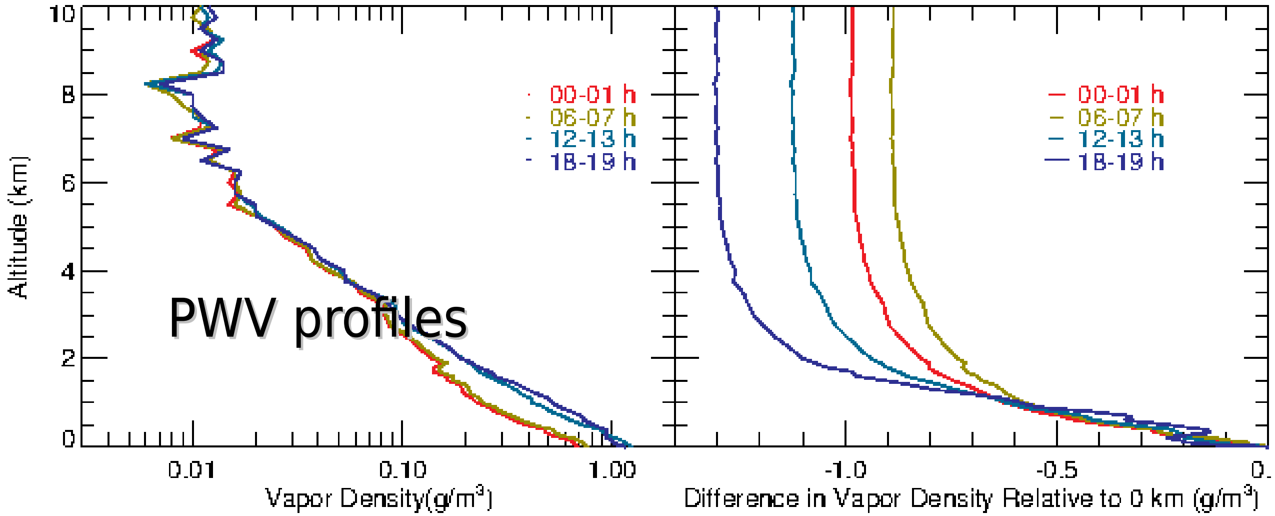
Column density as function of altitude

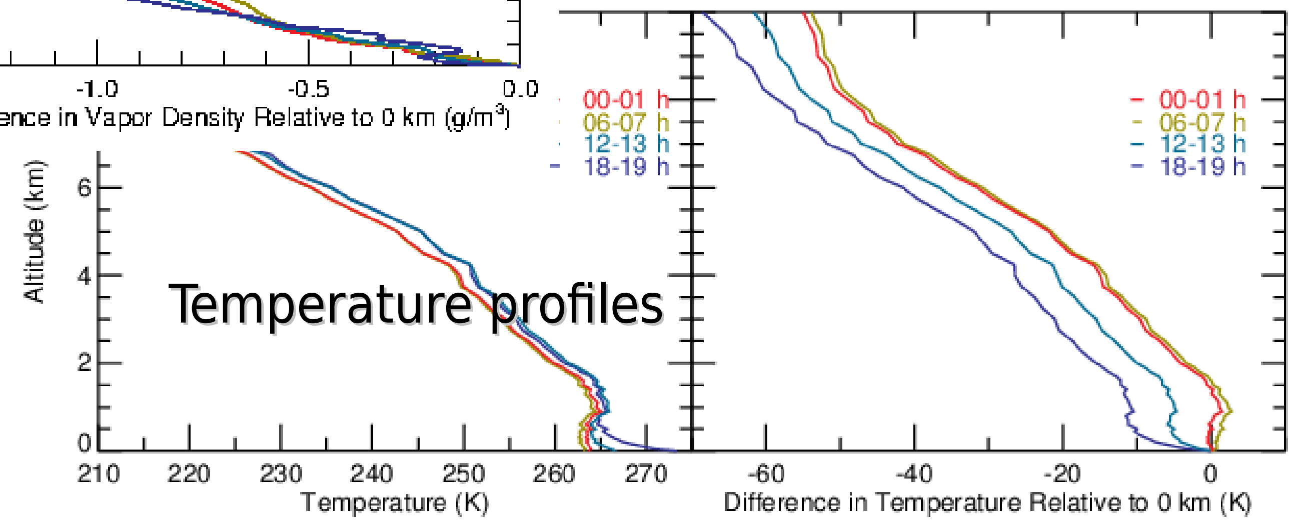


Oxygen sounder

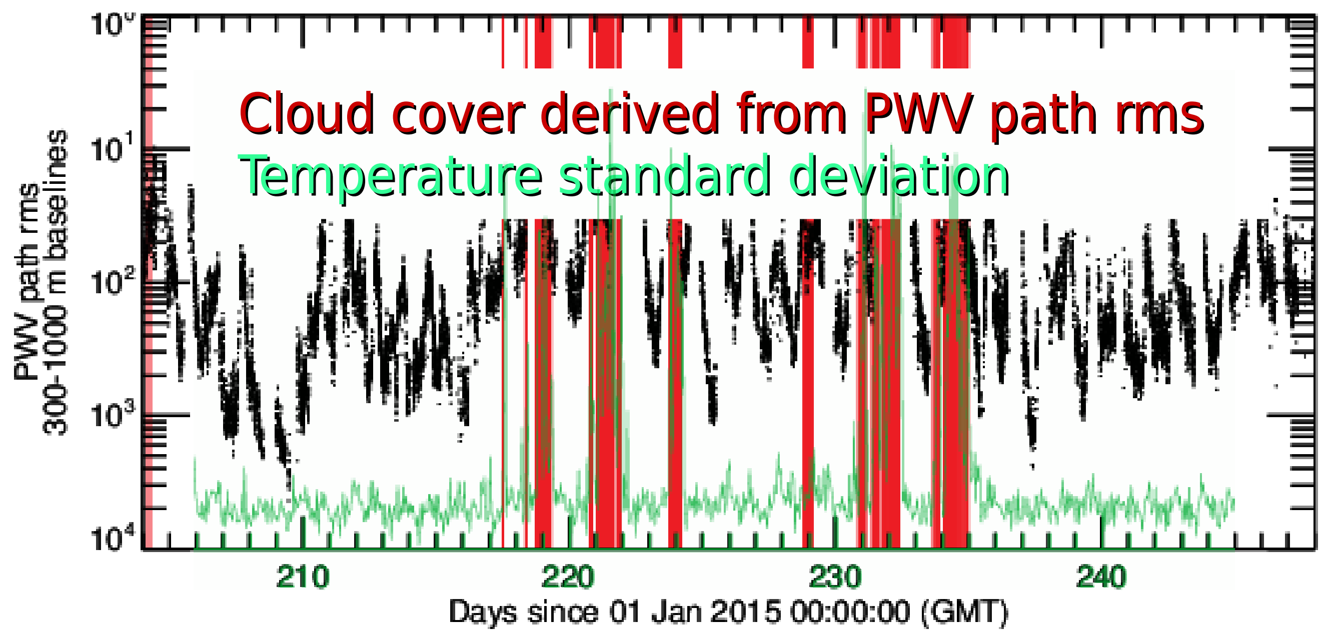
- Commissioned by Cavendish labs
  - Nikolic, Curtis
- Taking data at ALMA, not yet used
  - WV results agree with WVR
  - Dent (JAO), Bendo (Manc.) et al. exploring implementation
- Measures:
  - Cloud cover
  - Temperature profile
  - Variations in oxygen content
    - Model the elusive Dry Component!

Preliminary O-sounder results





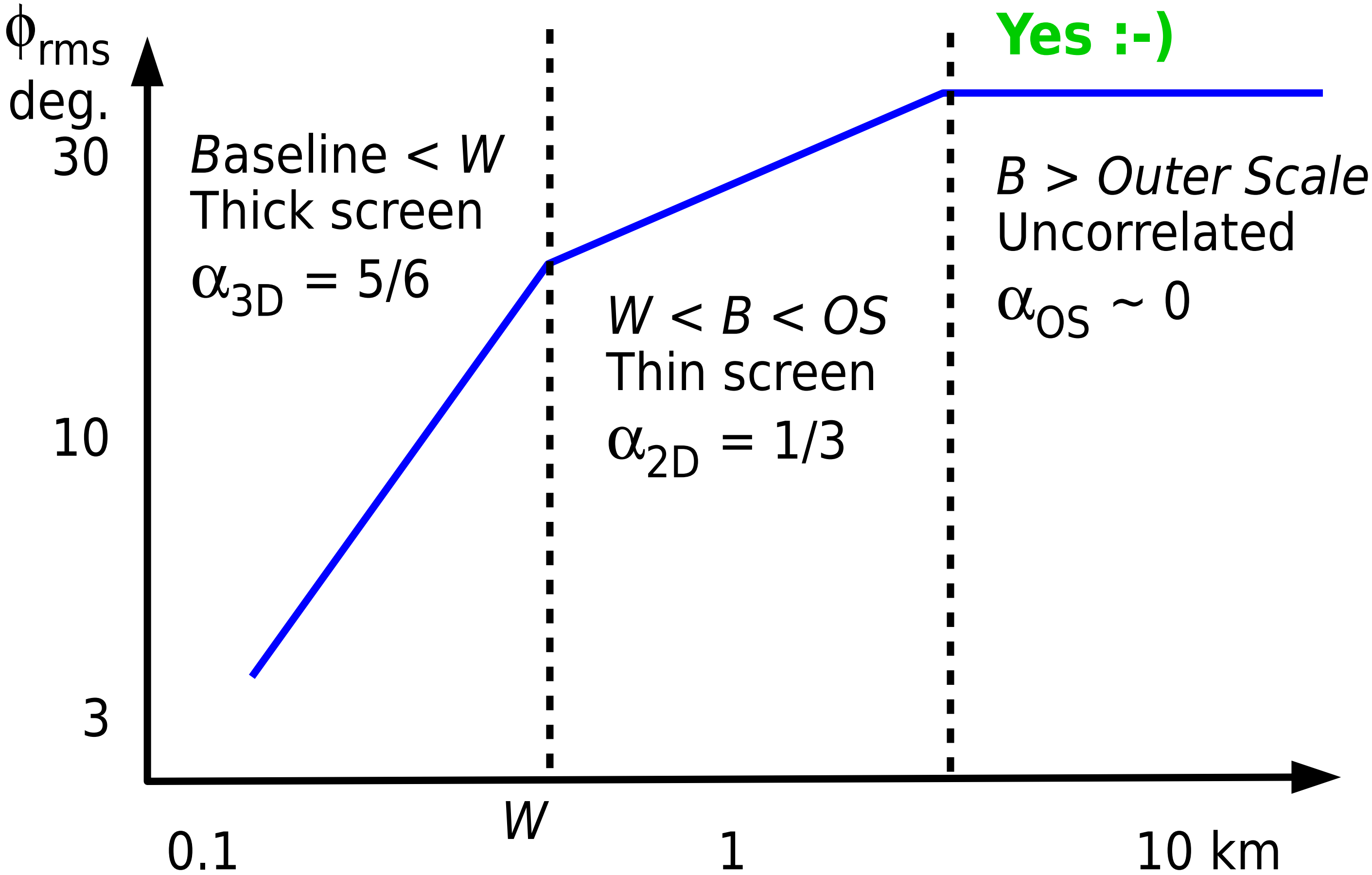
- Variations in T at <1 km decoupled from higher
- PWV linear relation, diurnal variation > 3.5 km
- Clouds!
  - Courtesy GB



Summary

- Long (10-16 km) baselines work very well
  - Residual errors no worse than on few-km in good conditions
- WVR 1-sec corrections good *if PWV is the problem*
- Few-min scale phase-referencing corrections OK *but*
  - can have $\pi/4$, apparently unrelated, drifts per minute
    - Limits dynamic range to few hundred
    - 30-sec self-cal reduces noise rms to ~1.5 x expected
- 3 min phase-ref:target cycling ≈1.5^{o} separation on sky @ el 60^{o}
  - 5 km/s wind, 5.5 km above ALMA, crosses 9^{o}
- Few sec – min residual phase drifts tens deg
  - Dry component?
  - Imprecision in using WVR?

Kolmogorov turbulence



Kolmogorov prediction (*Coulman*'*90*)

$$\varphi_{rms} = \frac{K}{\lambda} B^{\alpha}$$

where *K*~100 at ALMA for λ in mm and α depends on the length of baseline *B* compared with *W*, the thickness of the turbulent layer

- Baseline 2-3 < *W*
  - Phase noise ϕ_{rms} increases as $B^{5/6}$
- Baselines 1-2, 1-3 > *W* but < *OS*: $\phi_{rms} \propto B^{1/3}$
- Baselines 4-* in outer scale regime: ϕ_{rms} levels off

Obs. models/offline data reduction

- Fix/create offline data reduction CASA tasks
  - Fitting rate as well as delay (fring) – MK/GM progress!
  - Fit spline for phase connection – gspline broken
    - Fix other interpolation/extrapolation restrictions
  - More use of existing capability e.g. parallactic angle corr., MFS ...
- Techniques (happy to expand on!):
  - Bandwidth switching – optimise estimates of phase offsets
  - Better use of WVR (if justified)
  - Heuristics/real basis for when to self-cal
    - All have CASA/pipeline/QA2 implications
- Expand/correct documentation including underlying princples!

Conclusions: short-scale ϕ corrections (tentative, small sample!)

- WVR: better to apply before data averaging to 3 or 6 sec integrations? or to smooth offline/apply to averaged?
  - More use of data:
    - Per-antenna coefficients?
    - Update atm model, fine-grained if dispersive e.g. 183 GHz
- Oxygen sounder(s) implementation (software mostly)
  - Dry component, clouds...
- Fast switching needs v. close calibrators
  - ~70 mJy OK per 2-4 GHz at B7 any baseline (low PWV)
  - Wind speed main timescale factor in good conditions?
  - Weak/high ν cal survey resources (data reduction, archiving.)

Phase errors and dynamic range

- Image is formed by Fourier transform
  - $I(x) = \int V(u)\, e^{i2\pi ux}\, du$
    - Each baseline contributes at position u_k and complex conjugate $-u_k$ in the visibility plane
- Evaluating the term in the integral for each of the $[N(N-1)/2]-1$ good baselines gives $2\cos(2\pi u_k x)$
- Bad baseline gives $2\cos(2\pi u_0 x - \phi)$
  - $\sim 2[\cos(2\pi u_0 x) + \phi \sin(2\pi u_0 x)]$ for small ϕ (in radians)
- The image integral thus sums to

$$I(x) = 2\varphi \sin(2\pi u_0 x) + 2 \sum_{k=1}^{N(N-1)/2} \cos(2\pi u_0 x)$$

Phase errors and dynamic range

- The synthesised beam is given by

$$B(x)=2\sum_{k=1}^{N(N-1)/2}\cos(2\pi u_0 x) \quad = \text{N(N-1) for u = 0}$$

- Deconvolution is the subtraction of the beam from the image leaving the residual error

$$R(x)=\left[2\varphi\sin(2\pi u_0 x)+2\sum_{k=1}^{N(N-1)/2}\cos(2\pi u_0 x)\right]-2\sum_{k=1}^{N(N-1)/2}\cos(2\pi u_0 x)$$
$$=2\varphi\sin(2\pi u_0 x)$$

  - an 'odd' sinusoidal function of amplitude 2ϕ, period $1/u_0$

- To maintain the flux scale, integrals are normalised:

$$\frac{R(x)}{N(N-1)}=\frac{A\,I(x)}{N(N-1)}-\frac{B(x)}{N(N-1)}$$

Here, 'true' amplitude A = 1

Calibration errors and dynamic range

- The rms of the residual $R(x) = \frac{2\varphi \sin(2\pi u_0 x)}{N(N-1)}$

  over the whole map is $\sqrt{2}\,\phi / N(N-1)$
- For small phase error ϕ, large N, the ratio of the peak / noise residual is thus
  - Dynamic range $D_B(\phi) \sim I(x) / R(x) \sim N^2 / \sqrt{2}\,\phi$
    - e.g., radians (5^o)~0.09
- Amplitude error ε on a single baseline has the effect

  $V(u) = (1+\varepsilon)\delta(u - u_0)\, e^{-i\phi}$ leading (via a cos function) to
  - Dynamic range $D_B(\varepsilon) \sim N^2 / \sqrt{2}\,\varepsilon$
- **A phase error of 5° is as bad as a 10% amp error**
- **Phase errors are sin (odd), amp are cos (even)**

Calibration errors and dynamic range

- So far considered one-baseline error, one integration
- All baselines to one antenna affected by same error:
  - (N-1) bad baselines (~N for large N)
  - $\boldsymbol{D}_{\mathbf{ant}} = D_{\mathrm{B}} /(\mathrm{N}-1) = [N^2/(N-1)] /\sqrt{2}\phi \quad \boldsymbol{\sim N / \sqrt{2}\phi}$
- If all baselines are affected by random noise,
  - $\boldsymbol{D}_{\mathbf{all}} = D_{\mathrm{B}} / \sqrt{[N(N-1)/2]} = \sqrt{[N(N-1)/2]}/\phi \quad \boldsymbol{\sim N/\phi}$
- If errors are correlated in time, e.g. single phase-ref scan, ~constant u, these expressions hold.
- For M periods (scans?) between which noise is uncorrelated
  - $\boldsymbol{D}_{\mathbf{all}} \boldsymbol{\sim \sqrt{\mathrm{M}}\, N/\phi}$

Calibration for good dynamic range

- Implications so far: take a 10-antenna array
  - Twelve independent scans on a target, phase reference and other calibration applied, well edited
    - Residual phase scatter 20° : $\boldsymbol{D_{\mathrm{all}} \sim \sqrt{\mathrm{M}}\, N/\phi}$
    - ~ 100 dynamic range limit
      - Can you improve by self-calibration?
        - No if you have reached the T_{sys} limit
    - No, if remaining errors are pure noise. If not:
    - Maybe, if some antennas are still imperfectly calibrated
      - Calibrate per antenna, per scan (or longer)
        - Need potential S/N per interval high enough to get $\phi < 20°$

Phase-referencing dynamic range

- Most correctable errors are per-antenna

$$\sigma_{ant}(\delta t, \delta \nu) \approx \sigma_{array} \sqrt{\frac{N(N-1)/2}{N-3}} \sqrt{N_{spw} N_{pol}}$$

  - Sensitivity calculators generally give σ per total b/w
    - 8 spw, 2 polarizations, 1 min, 10-ant EVN σ_{array} 0.15 mJy
      - from www.evlbi.org/cgi-bin/EVNcalc.pl
    - σ_{ant} ~1.5mJy for 1 min
  - Use $\boldsymbol{D}_{\mathbf{ant}} \sim \boldsymbol{N} / \sqrt{\mathbf{2}\phi}$, say want 5° phase accuracy
  - $S_{\mathrm{phsref}} / \sigma_{ant} = D_{\mathrm{ant}} \sim N / \sqrt{2\phi}$
    - Need phase-ref flux density S_{phsref} > 120 mJy
      - In practice, need more to allow for bandpass etc. errors
        - This is assuming solutions per 1-min scan