High resolution/high frequency observing and data reduction

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thanks to ALMA and JBCA colleagues

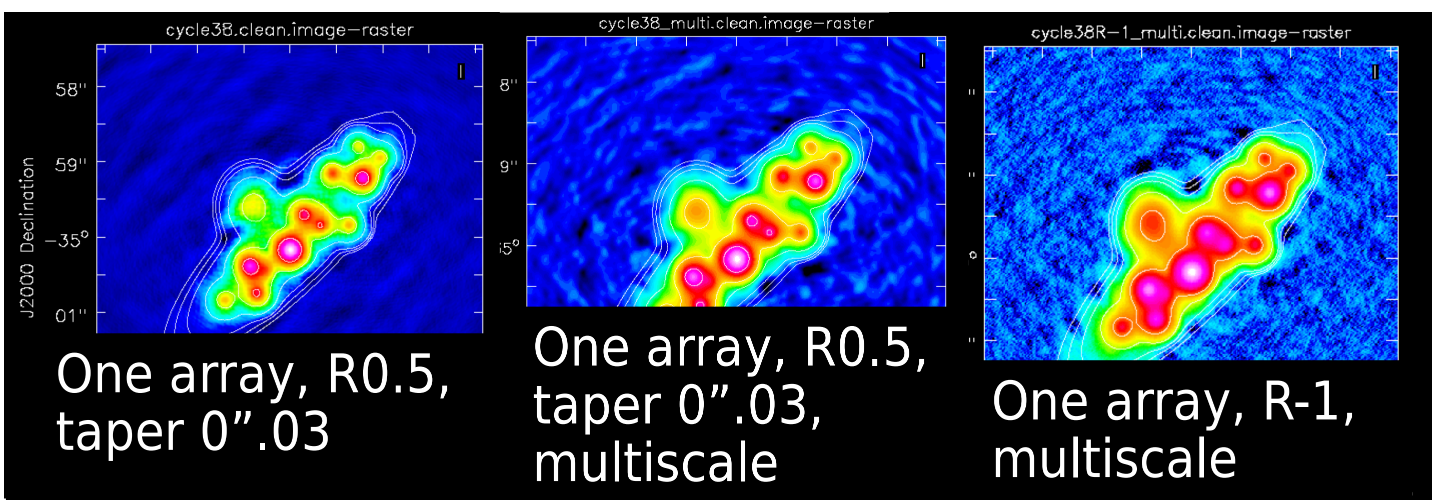
ALMA
EUROPEAN ARC
ALMA Regional Centre || UK

x12
NOEMA
project

eMERLIN
IVOA
EUROPEAN VLBI NETWORK
RadioNet

Weighting

- Natural weighting: Grid and FT samples
  - Weight zero in grid cells with no samples
- Uniform weighting:
  - All cells same weight
    - Makes resolution finer, but increases noise
- Robust [-2, 2]: intermediate weightings
- Taper: reduce weight of longest baselines
  - Increase sensitivity to large-scale emission
    - Increases noise if effective collecting area reduced



One array, R0.5, taper 0”.03

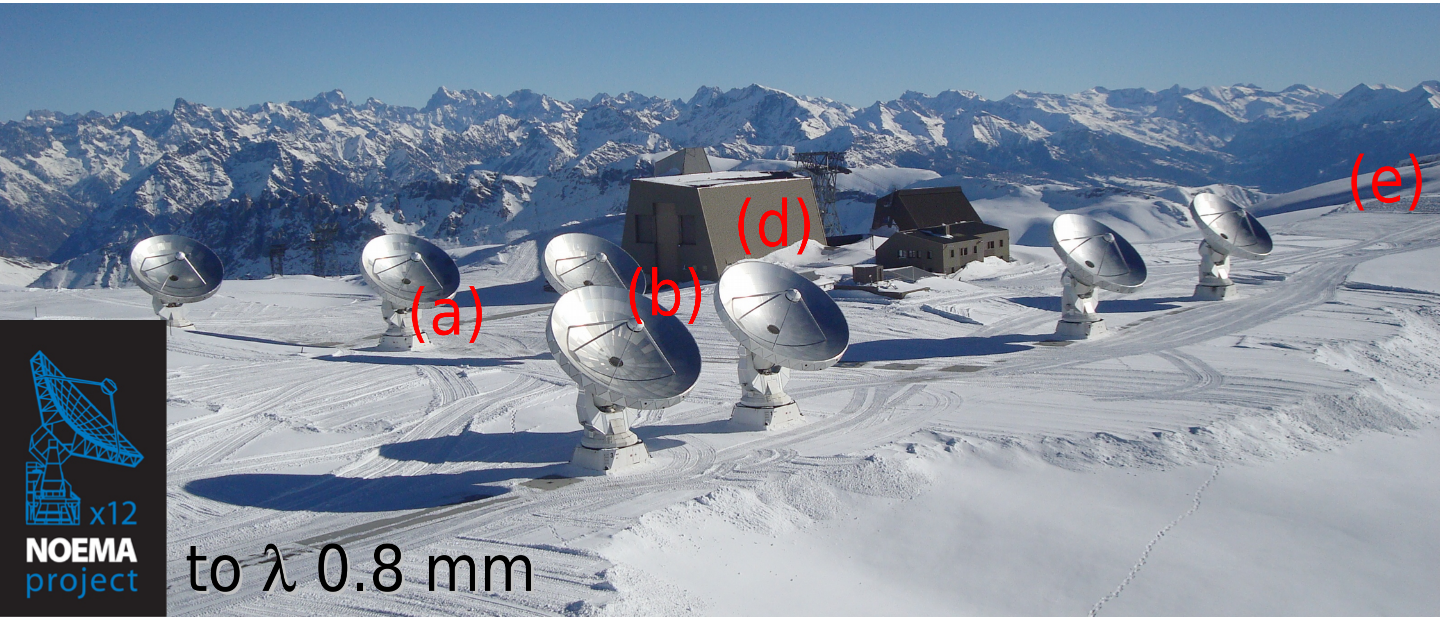
One array, R0.5, taper 0”.03, multiscale

One array, R-1, multiscale

Outline

- High-frequency observing
  - Hazards
- Calibration
  - Instrumental measurements
  - Astrophysical standards and phase referencing
  - Self-calibration
- Imaging
  - Clean
  - Weighting
- ALMA data products

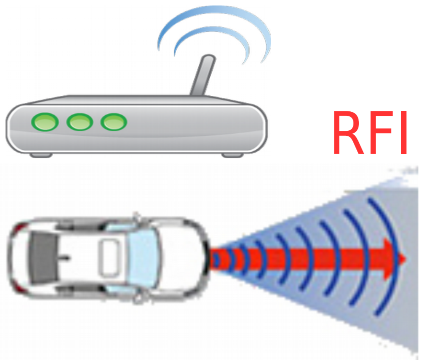
ALMA, NOEMA etc.

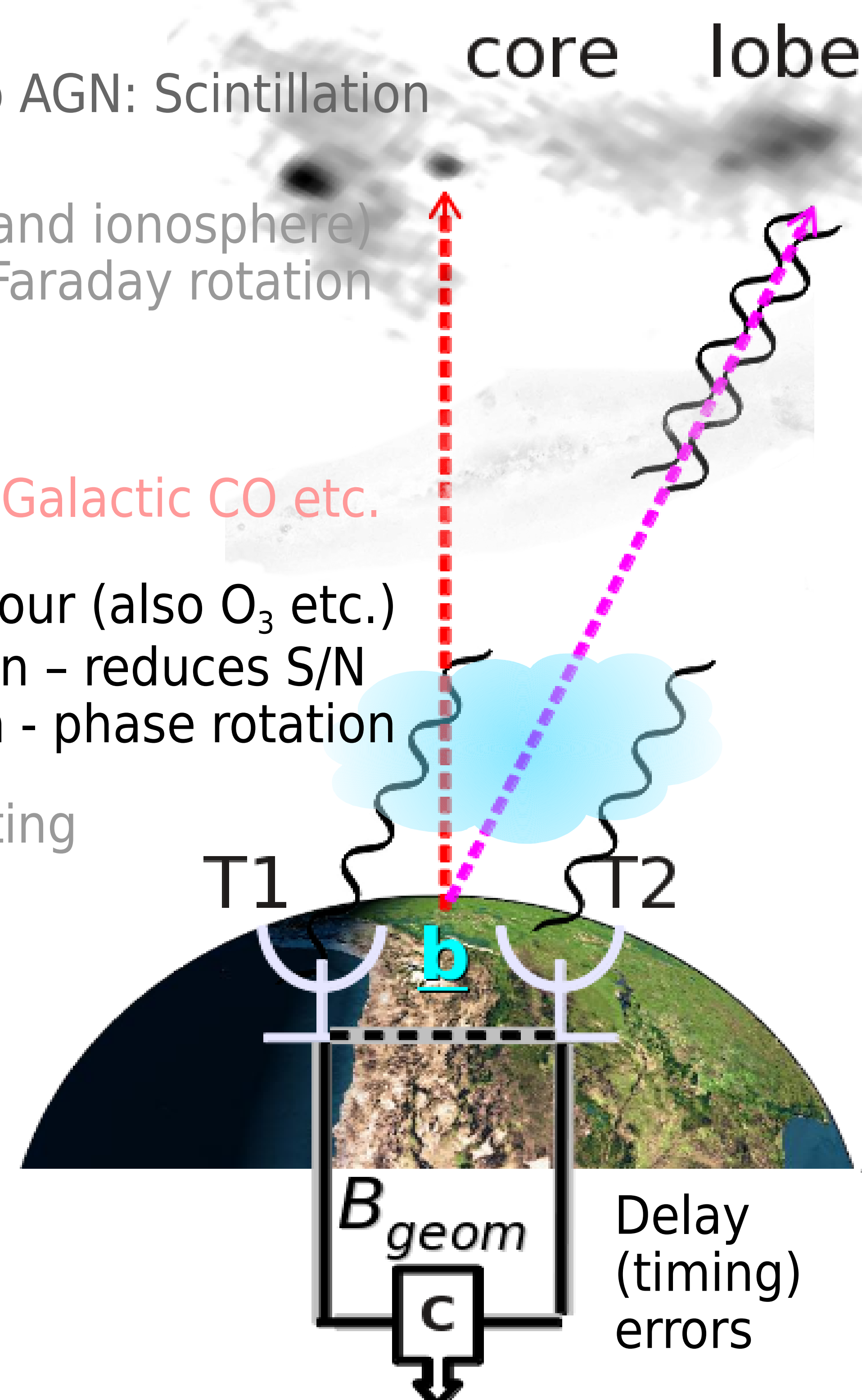


(a) Steerable dishes
(b) Subreflector
(c) (Multiple) receivers cabin
(d) Optical fibre links to correlator
(e) Reconfigurable

Also SMA $\gtrsim$0.45 mm; VLA $\gtrsim$6 mm; ATCA $\gtrsim$3mm; KVN $\gtrsim$2.5mm

Hazards

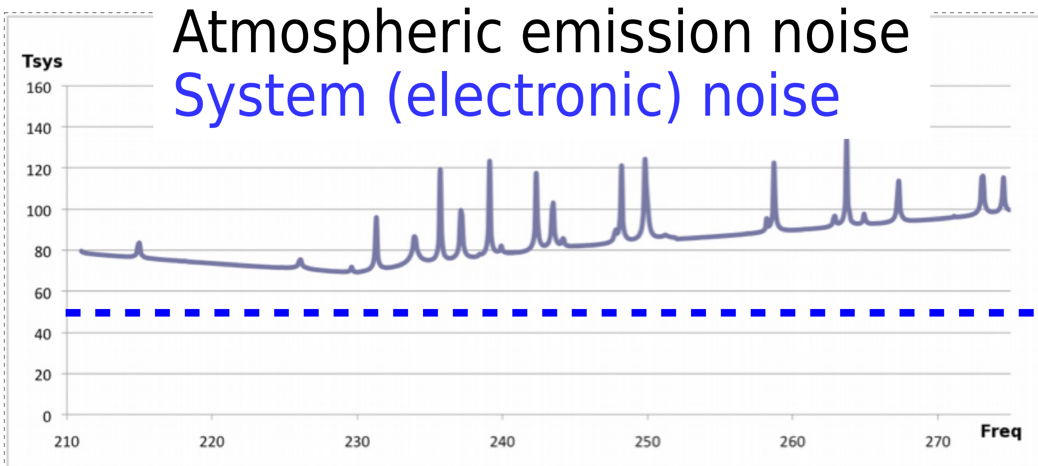




Atmospheric H_2O vapour (also O_3 etc.)
Absorption – reduces S/N
Refraction - phase rotation

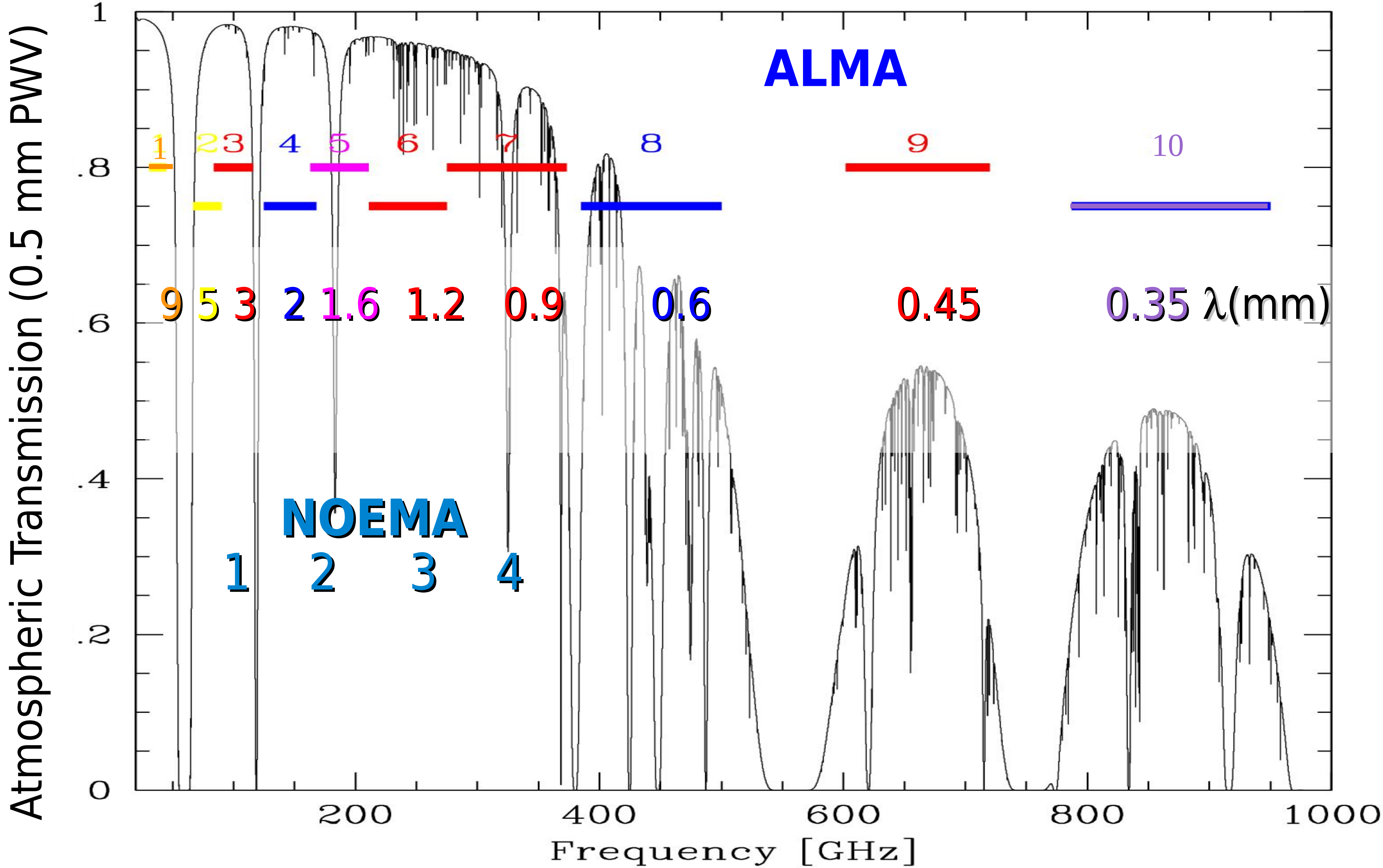
Antenna positions, efficiency, pointing

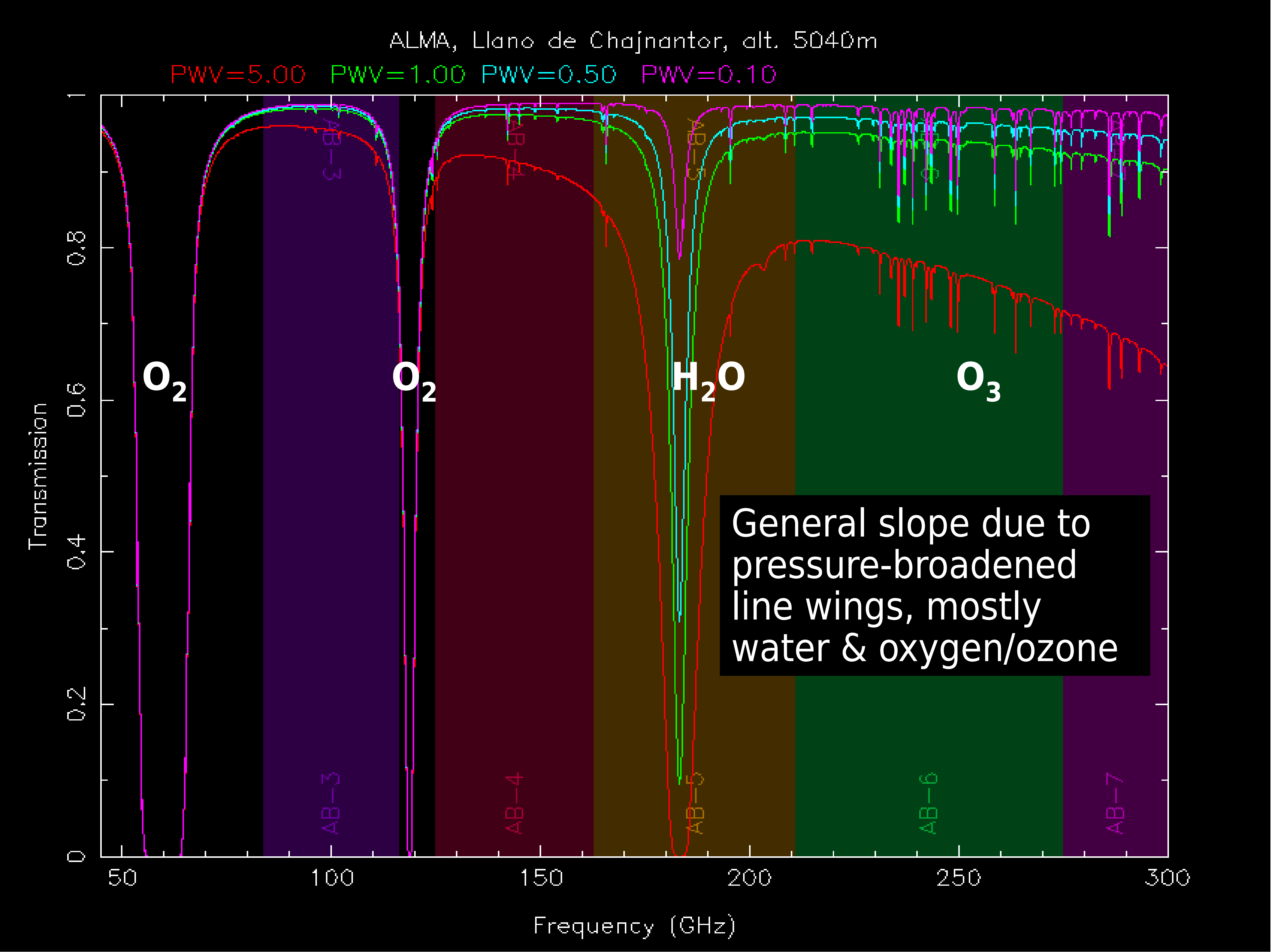
Atmospheric emission noise
System (electronic) noise



Bandpass response

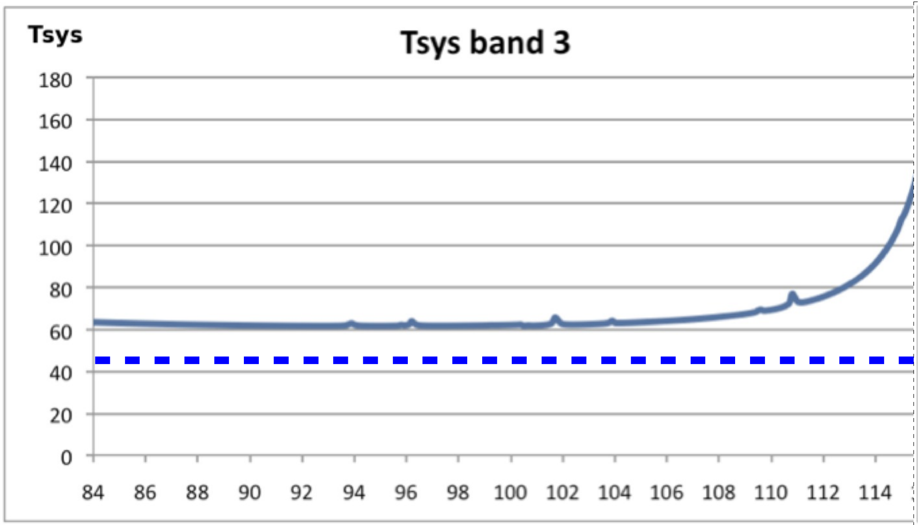
(sub-)mm windows & bands

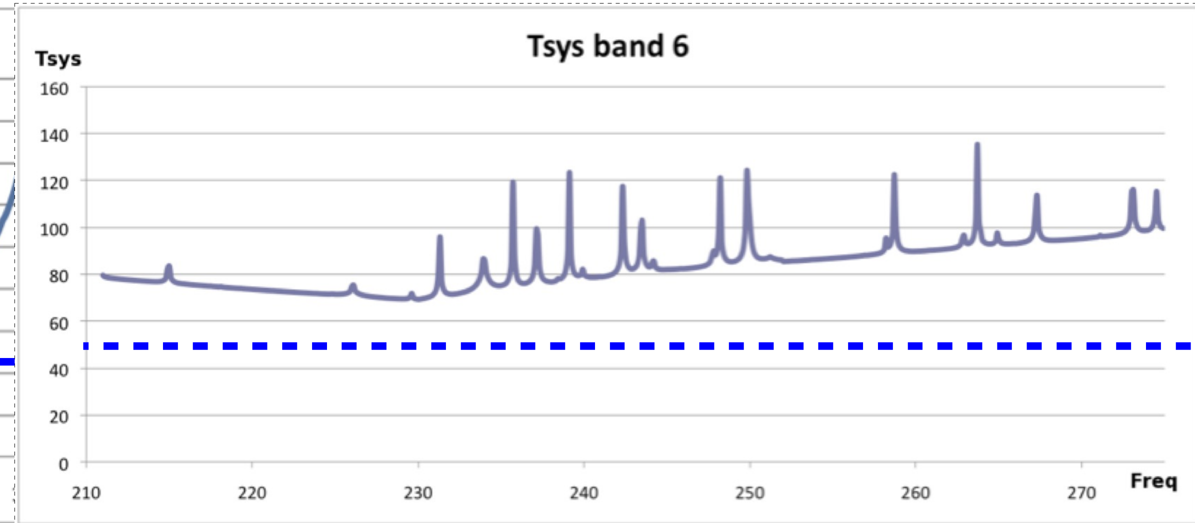


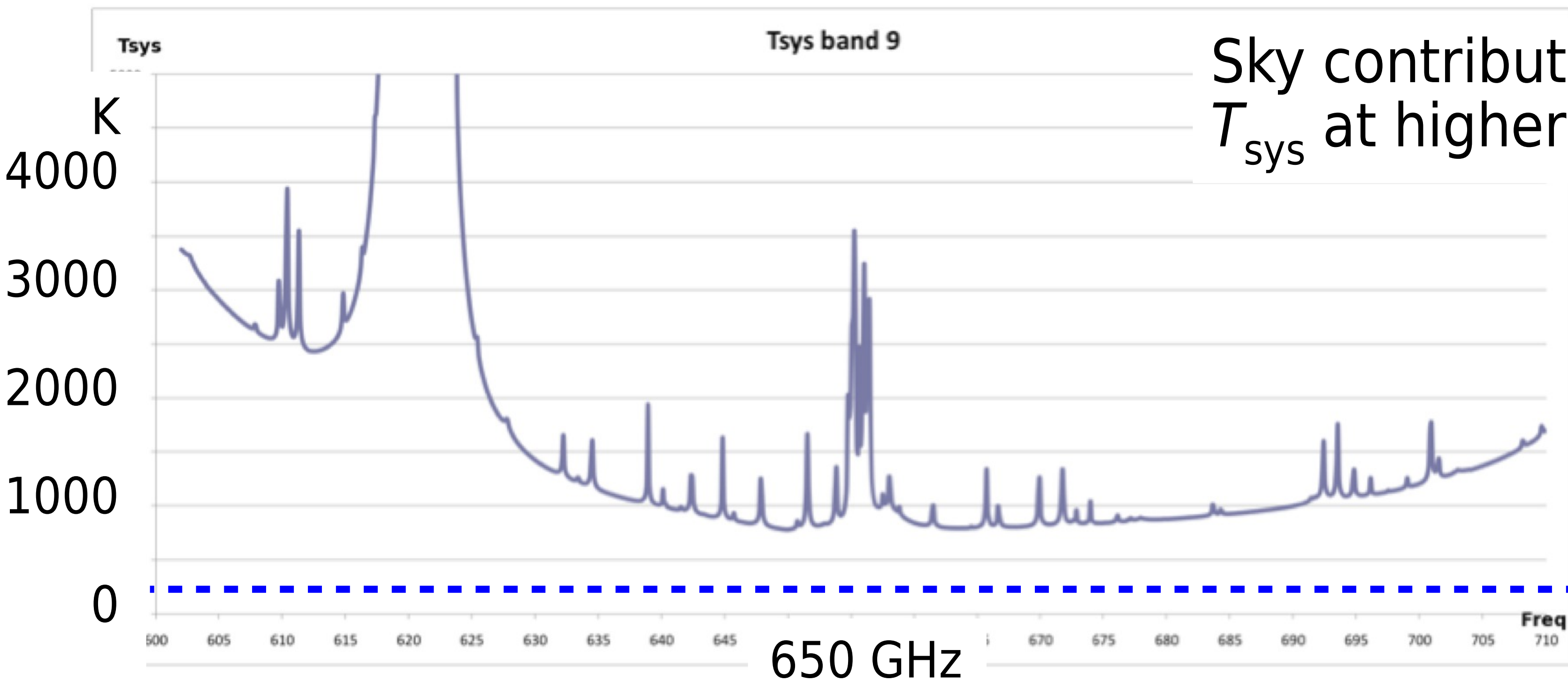


ALMA, Llano de Chajnantor, alt. 5040m
PWV=5.00 PWV=1.00 PWV=0.50 PWV=0.10
Transmission
Frequency (GHz)
0
0.2
0.4
0.6
0.8
1
50
100
150
200
250
300
AB-3
AB-4
AB-5
AB-6
AB-7
O2
O2
H2O
O3
General slope due to pressure-broadened line wings, mostly water & oxygen/ozone

Receiver temperatures





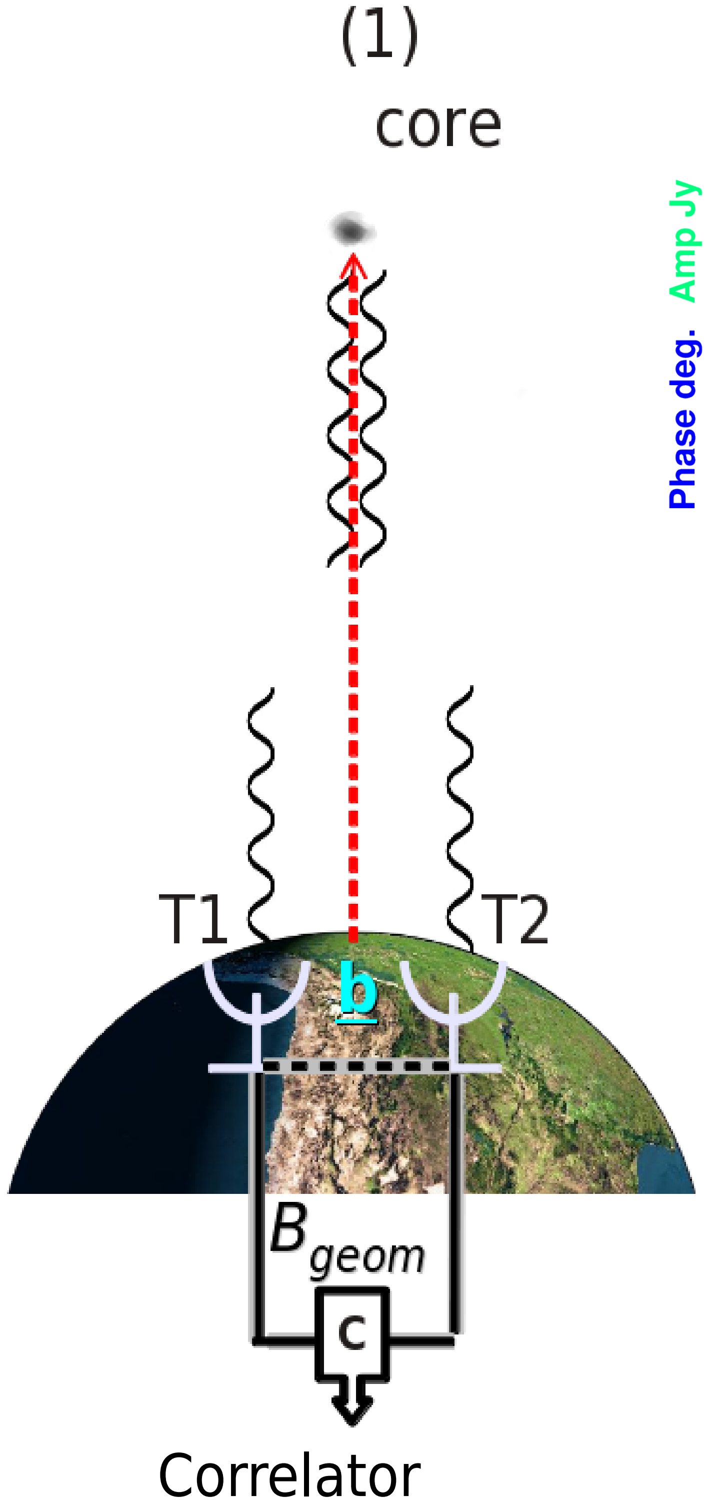


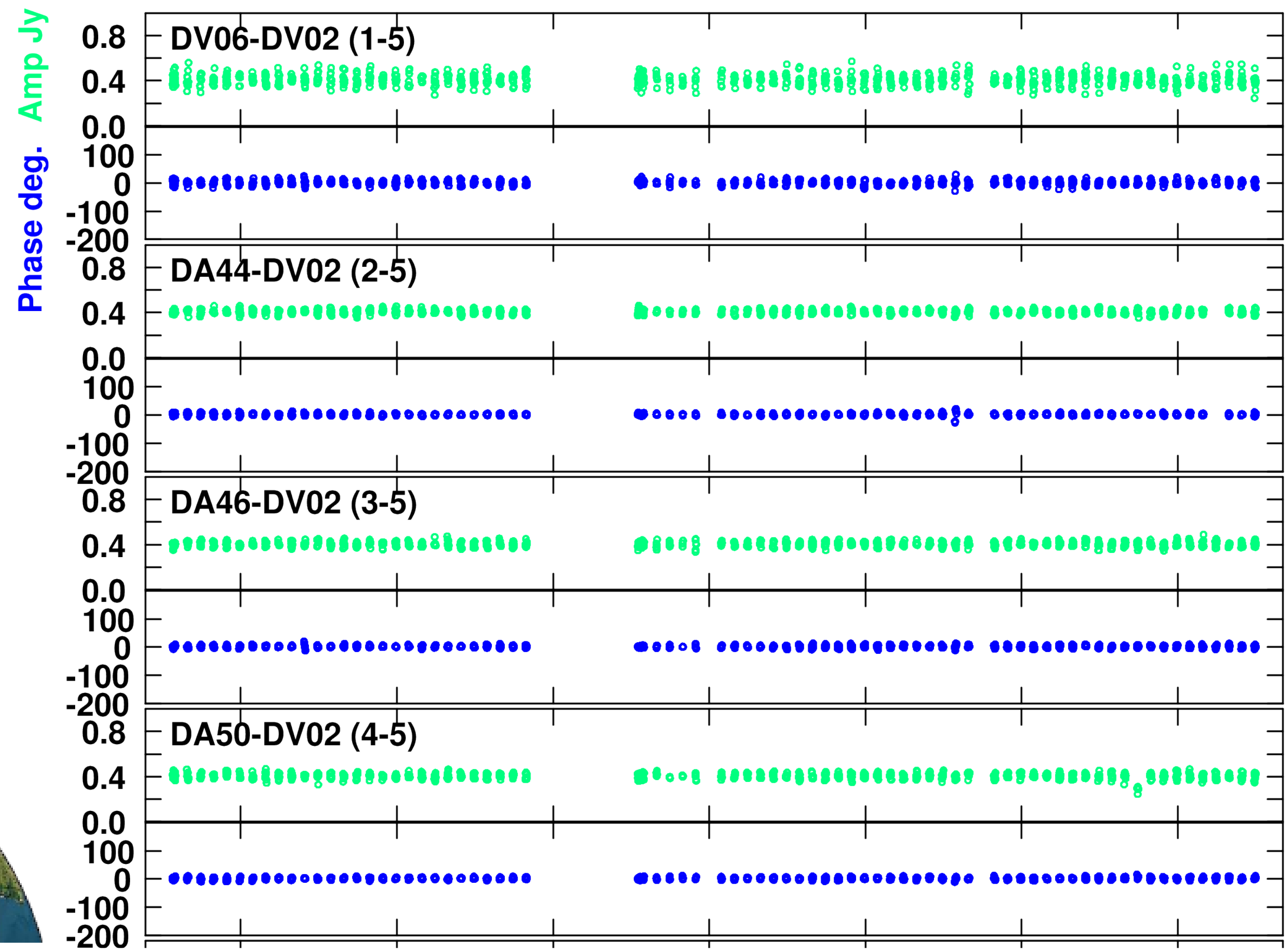
Sky contributes more to T_{sys} at higher frequencies

PWV 0.5mm

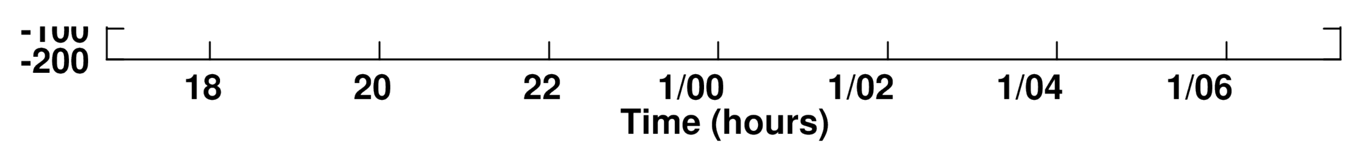
Approx. T_{Rx}

Point source overhead

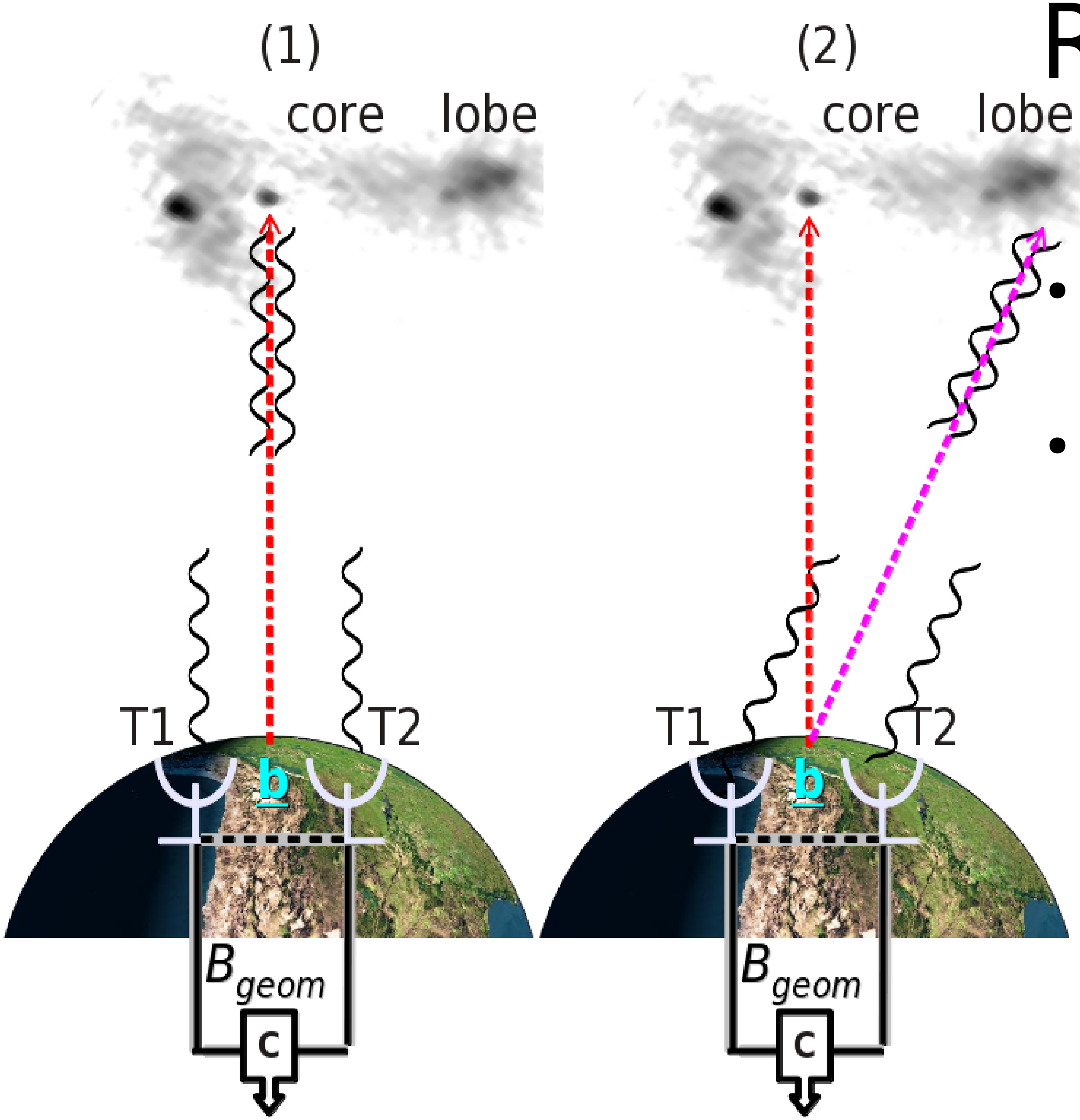




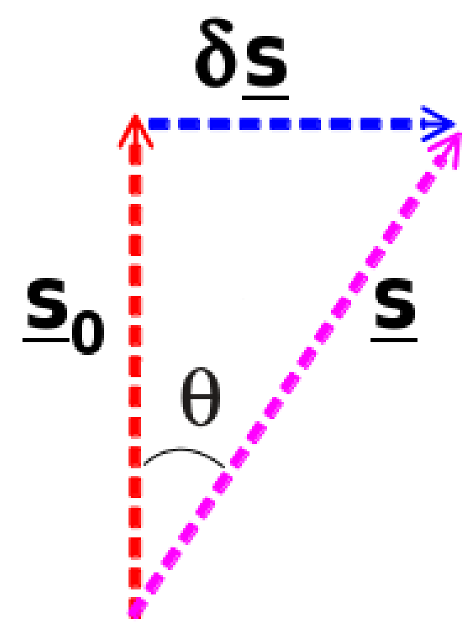
- Signals in phase, interfere constructively
  - Combined phase ϕ 0°, amp constant



Resolved source overhead

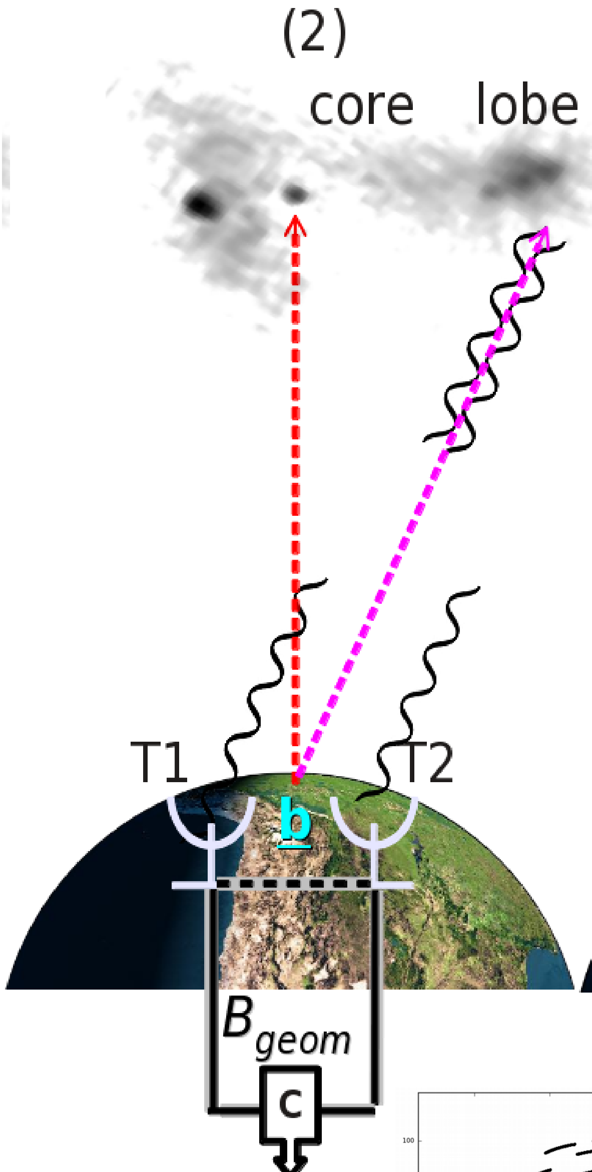


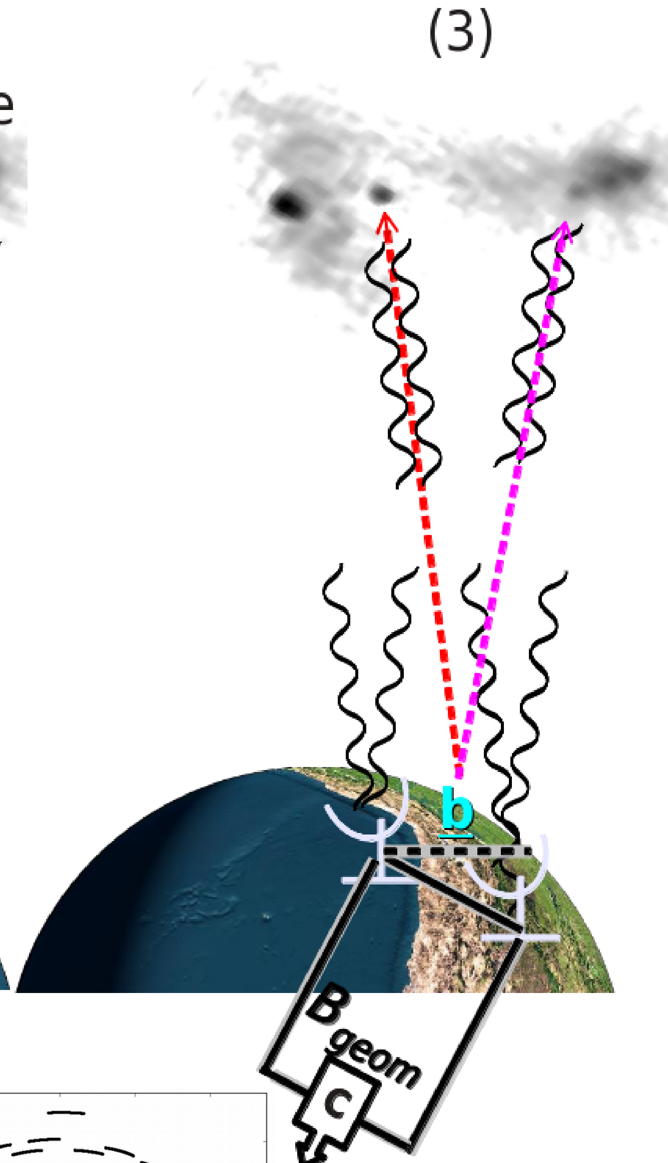
- Signals from overhead vector $\mathbf{s_0}$
- Signals from lobe
  - Angular offset vector $\delta\mathbf{s}$
  - Path length $\mathbf{s} = \delta\mathbf{s} \cdot \mathbf{s_0}$

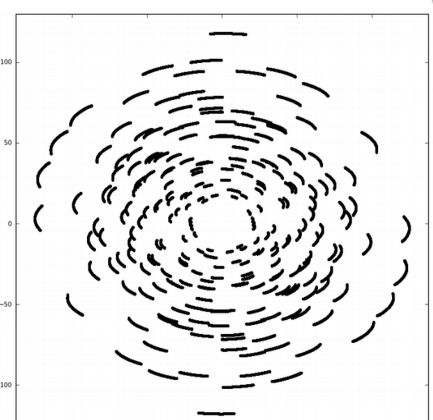


- Combined ϕ depends on $\delta\mathbf{s}$
- Complex visibility amplitude is sinusoidal function of ϕ

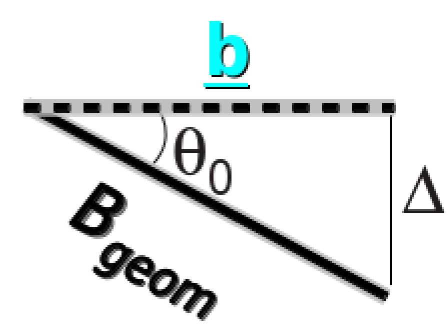
Earth rotates



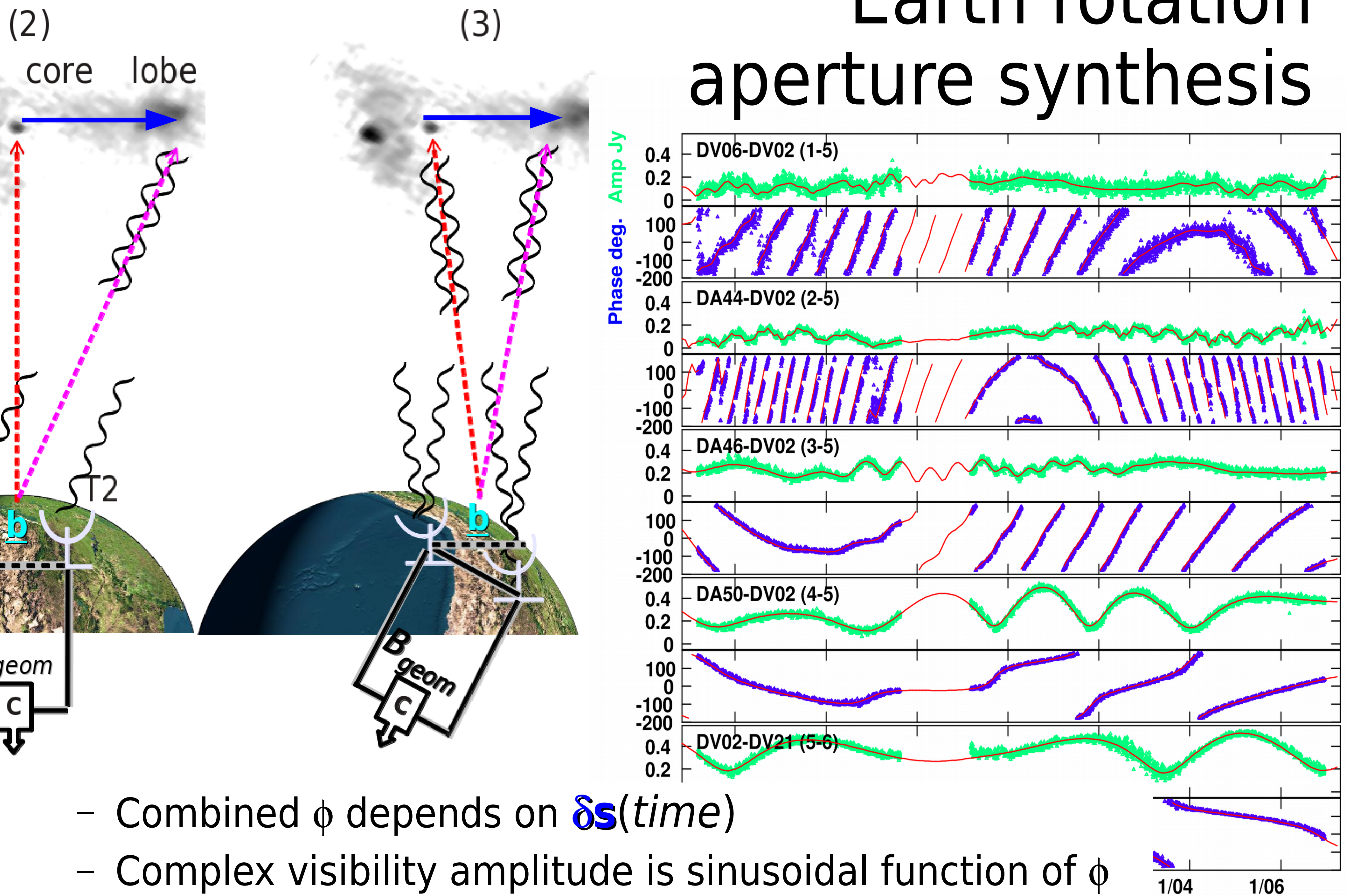




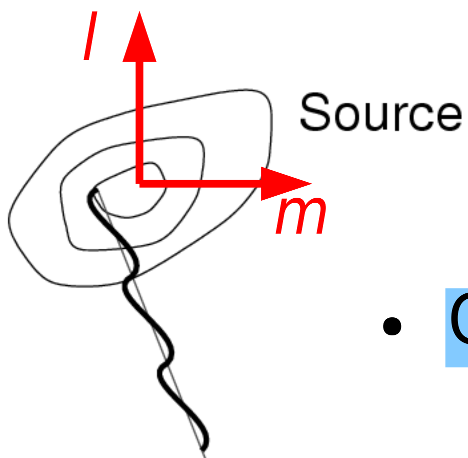
- Telescopes separated by baseline B_{geom}
- Earth rotates
  - Projected separation $b = B_{geom} \cos \theta_0$
- Samples different scales of source
- Additional geometric delay path Δ
  - Remove in correlator



Earth rotation aperture synthesis



- Combined ϕ depends on $\delta\mathbf{s}(time)$
- Complex visibility amplitude is sinusoidal function of ϕ

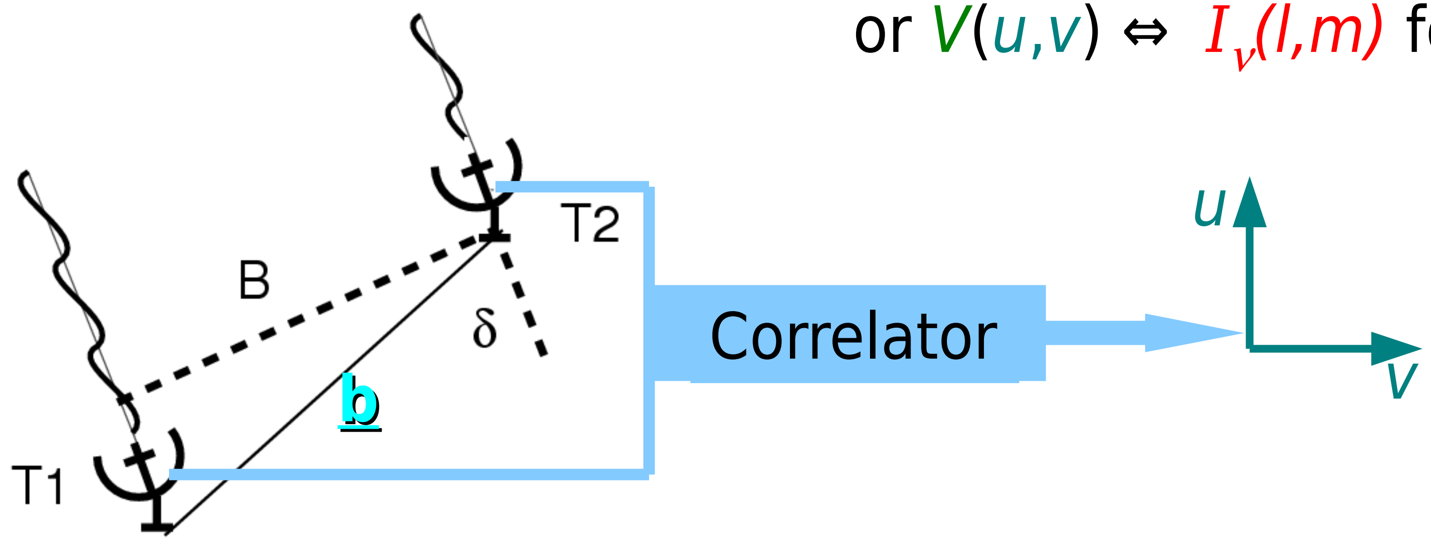


Interferometry to images

- Correlation makes complex visibilities $V_\nu(u_\nu, v_\nu)$
  - One V, $Ae^{i\phi}$, per ν-chan per baseline per τ_{int} per pol.
- Fourier transform gives sky brightness distribtion

$$\sum V_\nu(u_\nu, v_\nu)\, e^{[2\pi i(u\nu l + v\nu m)]}\, du dv = I_\nu(l,m)$$

or $V(u,v) \Leftrightarrow I_\nu(l,m)$ for short



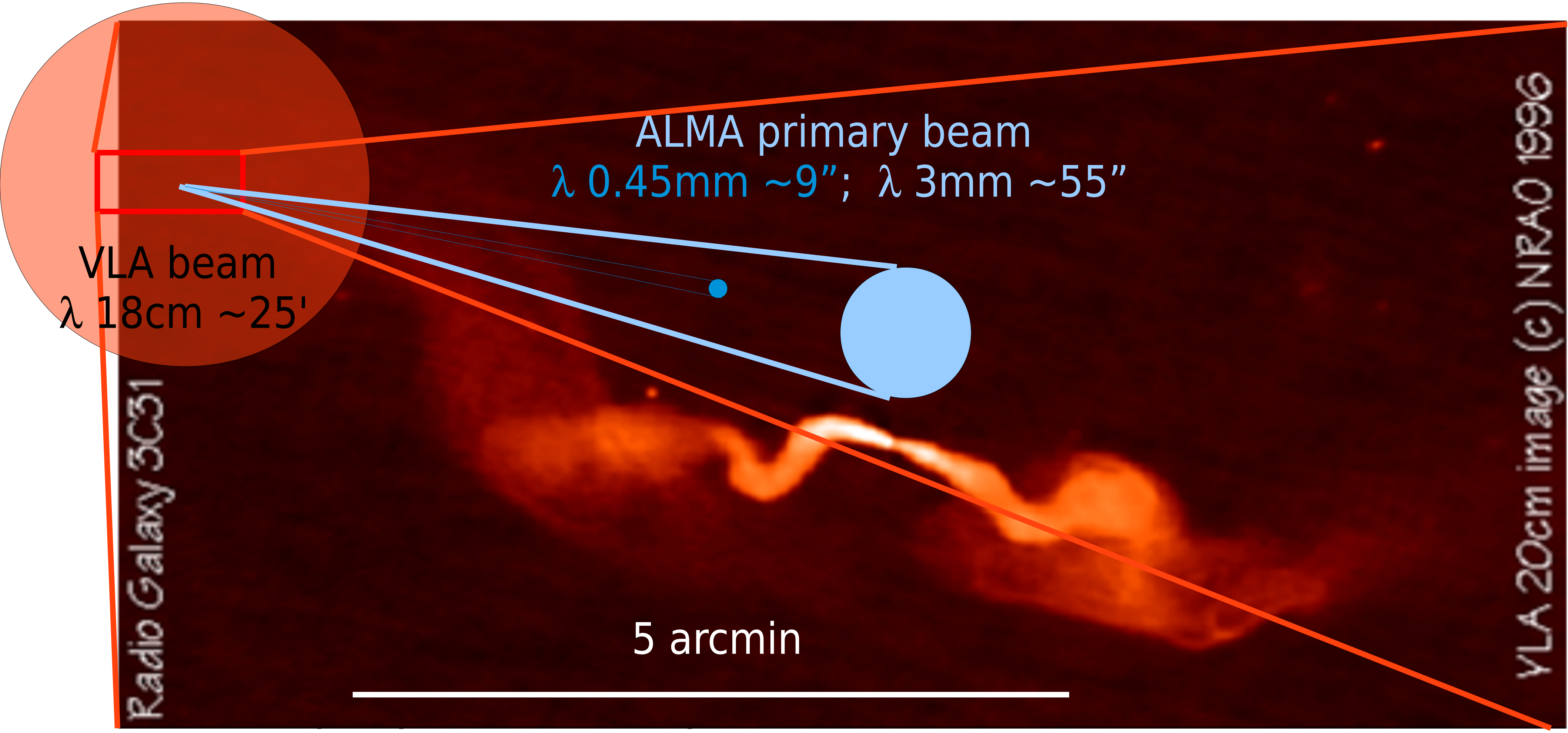
- Sensitivity:
  - Number antennas
  - $d\nu$ freq. width per image, Δt total time on source

$$\sigma_{rms} \propto \frac{T_{sys}}{\sqrt{N(N-1)/2\ \delta\nu\ \Delta t\, N_{pol}}}$$

High-frequency considerations

- Same principles as any radio interferometry
- You are *unlikely* to be bothered by:
  - Ionosphere ($\delta delay_{\mathrm{ionosphere}} \propto \lambda^2$)
  - Confusion ($\Theta_{\mathrm{PrimaryBeam}} \sim \lambda/B \sim 55''$ @ 3mm, 12-m dish)
    - Most bright extragal. sources have $\alpha<0$ where $S \propto \nu^{\alpha}$
- You *will* suffer from:
  - Tropospheric refraction ($\delta\phi_{\mathrm{troposphere}} \propto 1/\lambda$)
  - Tropospheric absorption and emission
  - Small field of view ($\Theta_{\mathrm{PrimaryBeam}} \sim 9''$ @ 0.45 mm)
    - Mosaicing

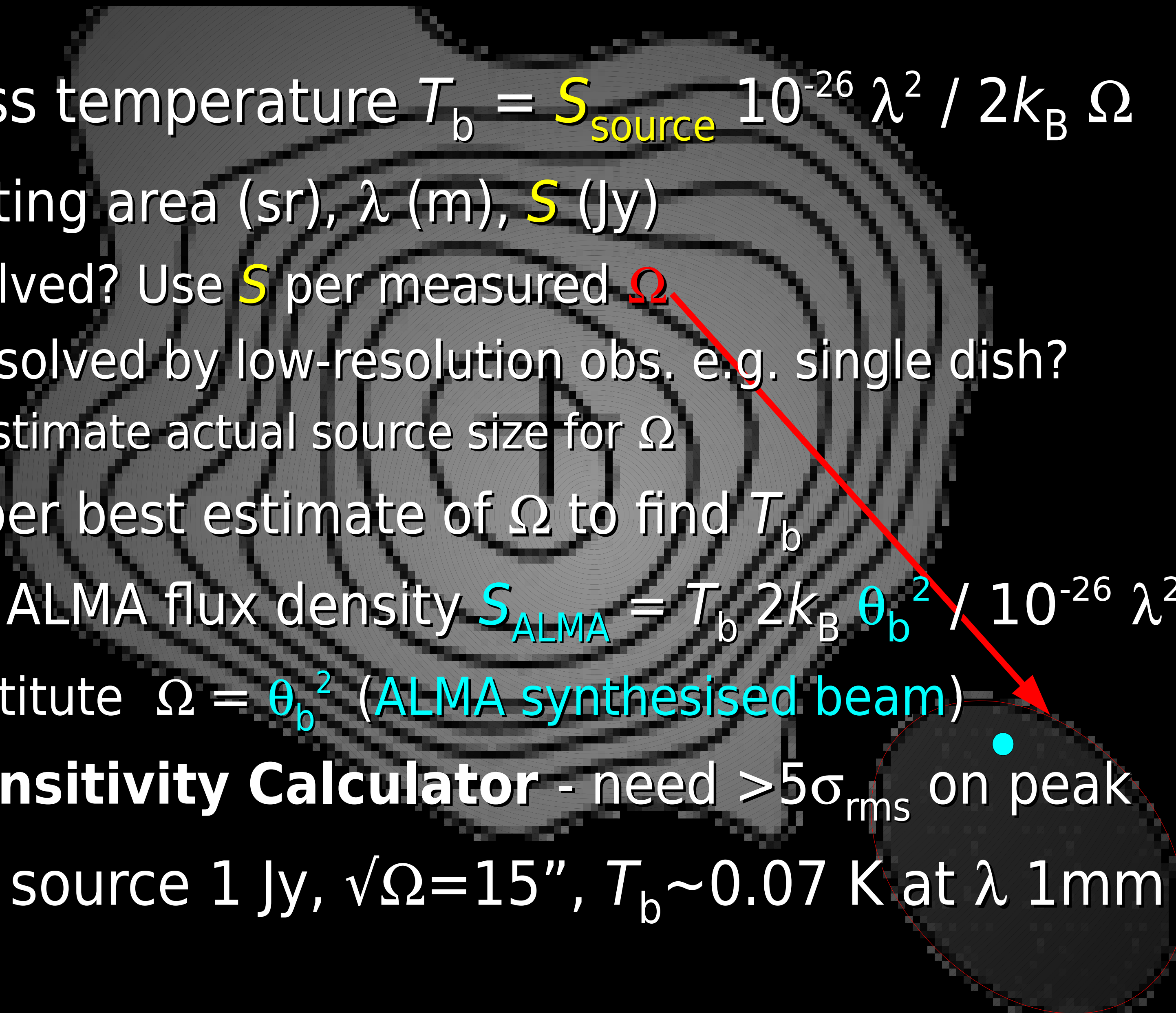
High-frequency considerations



- Small field of view ($\Theta_{PrimaryBeam}$ ~9” @ 0.45 mm)
  - Mosaicing

Estimate observability from low-res image

- Brightness temperature $T_b = S_{source}\ 10^{-26}\ \lambda^2 / 2k_B\ \Omega$
  - Ω emitting area (sr), λ (m), S (Jy)
    - Resolved? Use S per measured Ω
    - Unresolved by low-resolution obs. e.g. single dish?
      - Estimate actual source size for Ω
  - Use S per best estimate of Ω to find T_b
  - Predict ALMA flux density $S_{ALMA} = T_b\ 2k_B\ \theta_b^{\ 2} / 10^{-26}\ \lambda^2$
    - Substitute $\Omega = \theta_b^{\ 2}$ (ALMA synthesised beam)
  - Use **Sensitivity Calculator** - need $>5\sigma_{rms}$ on peak
- e.g. total source 1 Jy, $\sqrt{\Omega}$=15”, T_b~0.07 K at λ 1mm



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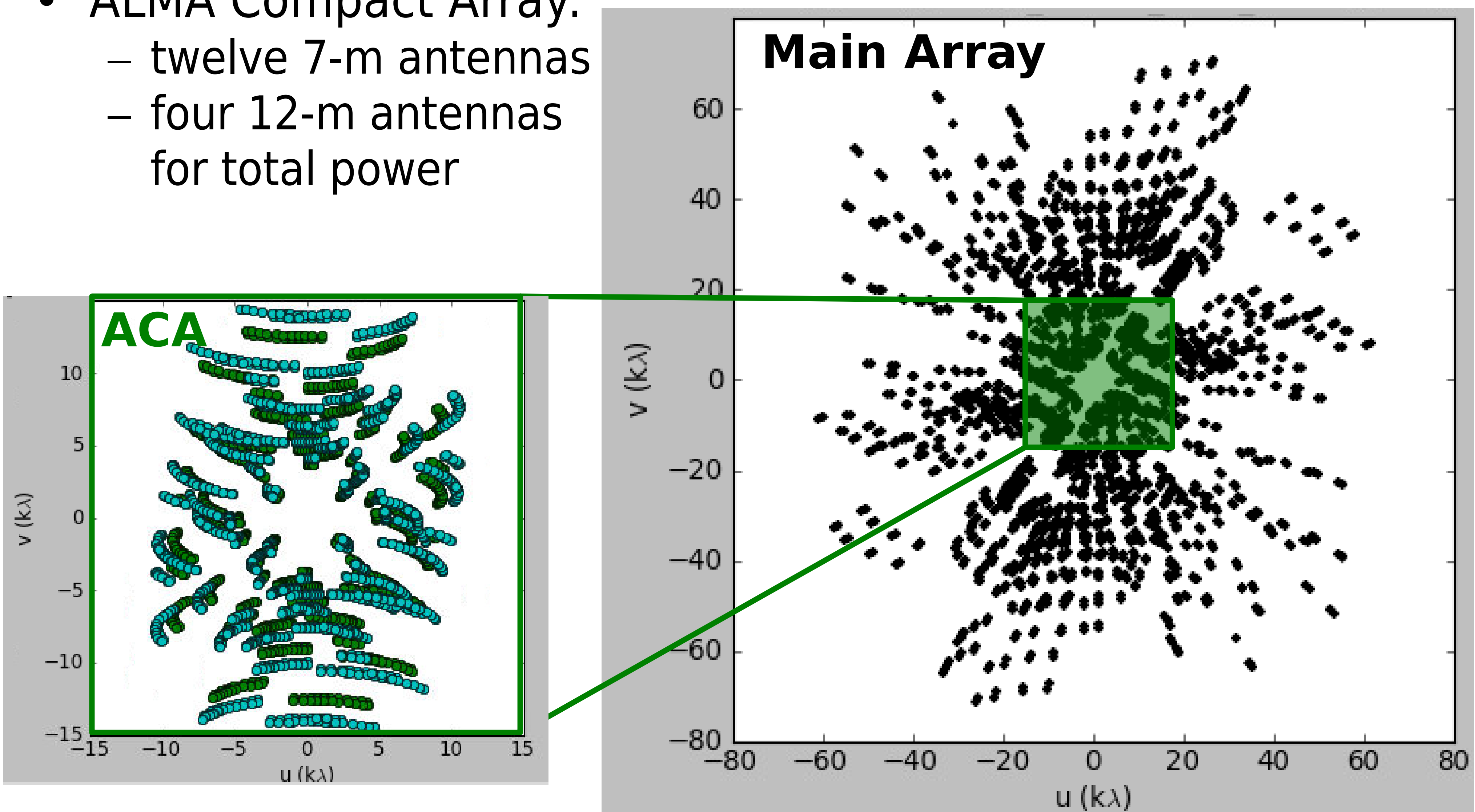
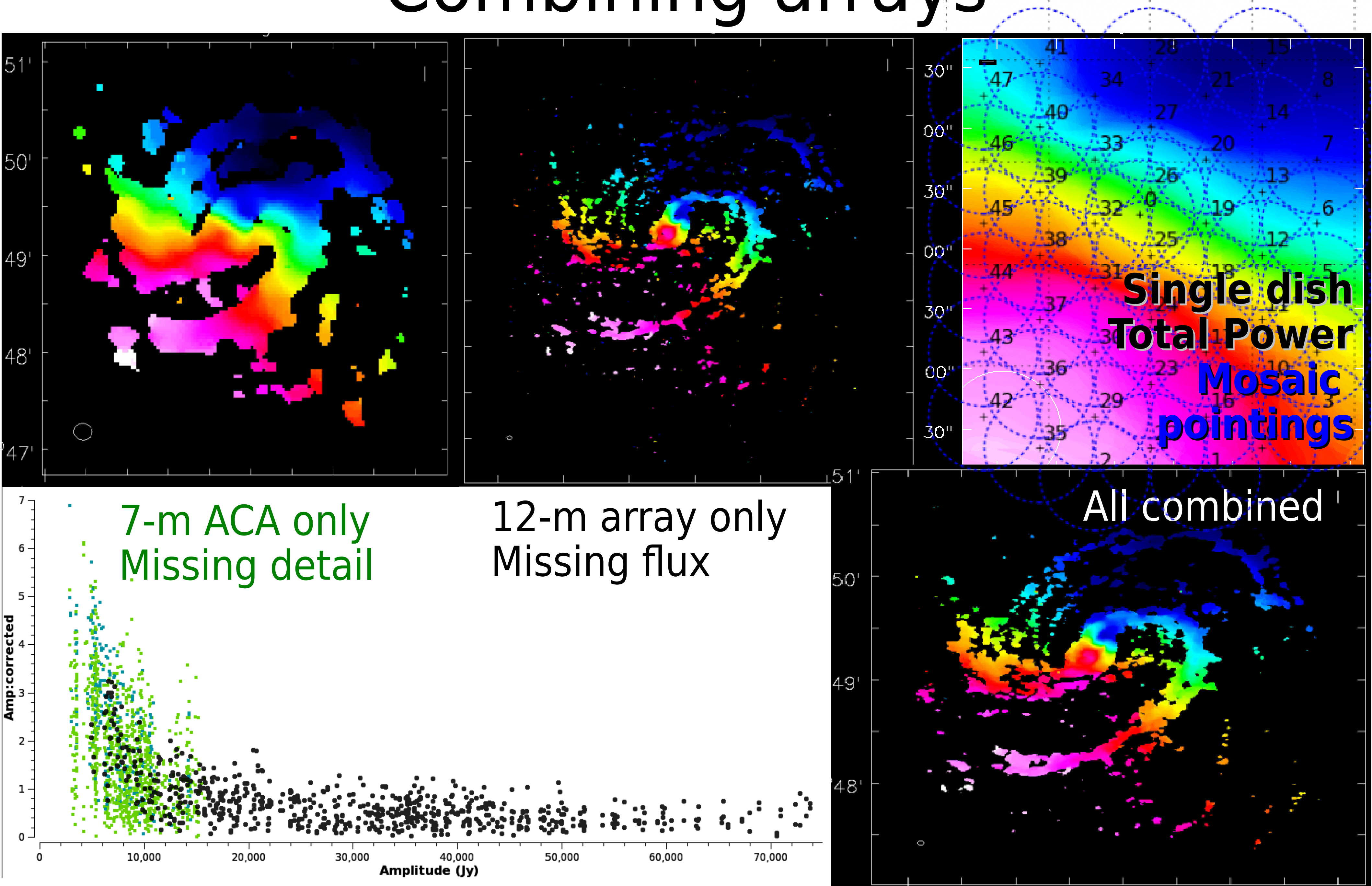
- e.g. total source 1 Jy, $\sqrt{\Omega}$=15”, T_b~0.07 K at λ 1mm
  - θ_b=0”.15, flux density $1\text{x}(15/0.15)^2 = 0.0001$ Jy/beam

Visibility plane coverage

- ALMA main array:
  - fifty 12-m antennas
- ALMA Compact Array:
  - twelve 7-m antennas
  - four 12-m antennas for total power

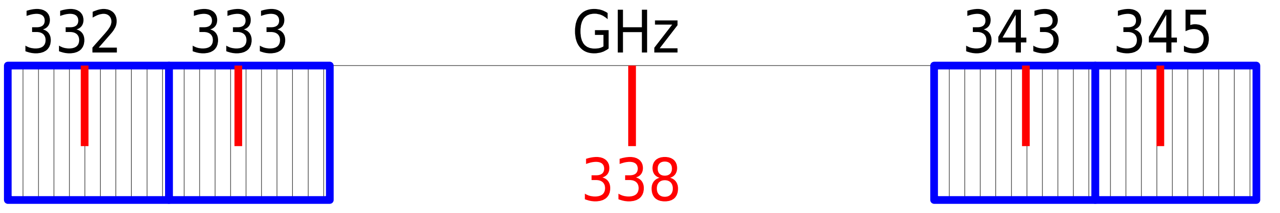


Combining arrays



Correlator configurations

- Two sidebands, fixed spacing depending on band
  - e.g. B7, B3 sideband centres separated by 12 GHz
    - Max. continuous b/w <4 GHz (8 GHz Bands 9, 10)



- Four basebands (BB), max. width 2 GHz
  - 128 chans per BB (dual pol) TDM
  - 4096 chans per BB (~0.5 km/s at 300 GHz) FDM
    - Useful max. 1.875 GHz (so 3840 channels usable)
- Narrower spectral windows for higher resolution
  - Factors of two down to 62.5 MHz (15.25 kHz chans)
  - Higher spectral resolution in single polarization
- *See documentation and OT for full details*

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Instrumental & atmospheric noise

- Noise σ_{sys} is given by $\sigma_{sys} = \frac{T_{sys}}{\eta_A A_{eff} \sqrt{N(N-1)/2 \;\; \Delta\nu \;\; \Delta t \, N_{pol}}}$

  antenna area A_{eff}, efficiency η_A

  N antennas, frequency span $\Delta\nu$, time span Δt, N_{pol} Rx pols

- System temperature T_{sys}

$$T_{sys}(DSB) = \frac{1+g_{SB}}{\eta_A e^{-\tau_{atm}}}\left[T_{Rx} + \eta_A T_{sky} + (1-\eta_A) T_{amb}\right]$$

  contributions from Receiver, sky and 'ambient' e.g. hardware, ground temperature

  - g_{SB} = 1 if there is an unwanted if sideband

- Noise increases exponentially with opacity and zenith angle

$$T_{received} = T_{source} e^{\tau_{atm}/\cos z} + T_{atm}\left(1 - e^{\tau_{atm}/\cos z}\right)$$

Absorption and emission

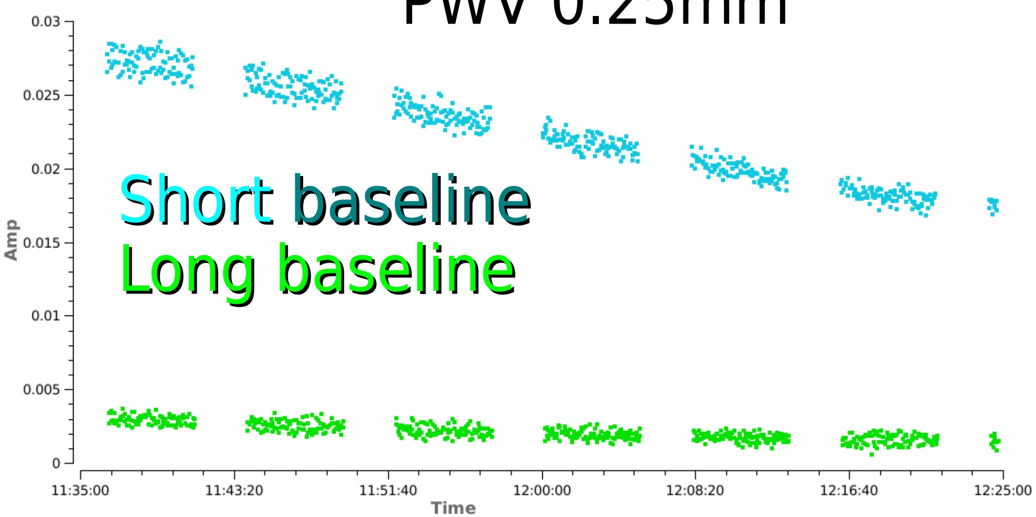
- The atmosphere both absorbs the astrophysical signal, and adds noise

$$T_{received} = T_{source} e^{\tau_{atm}/\cos z} + T_{atm}\left(1 - e^{\tau_{atm}/\cos z}\right)$$

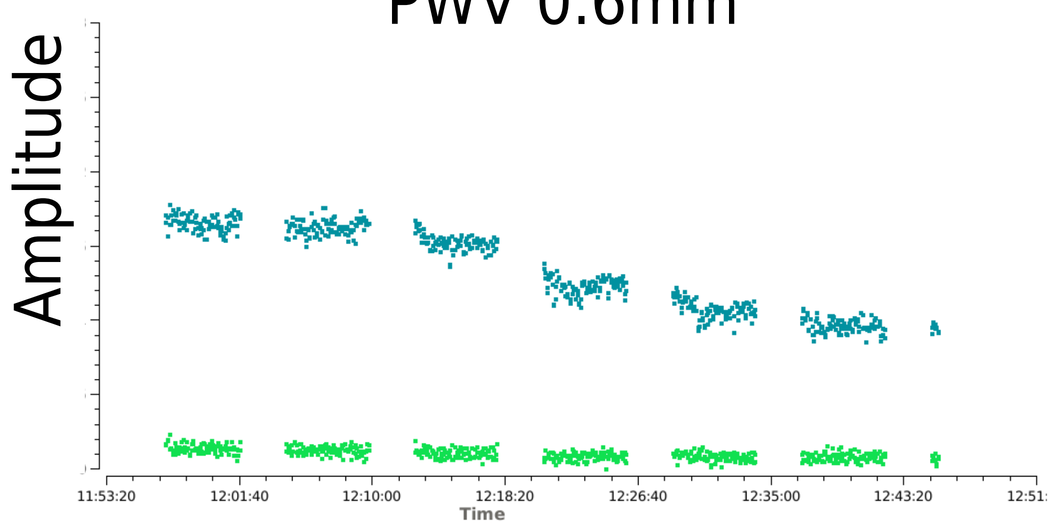
where the source would provide temperature T if measured above the atmosphere and z is the zenith distance

- Same source, same baselines
  - Raw amps lower at higher **P**reciptable **W**ater **V**apour

PWV 0.25mm



PWV 0.6mm



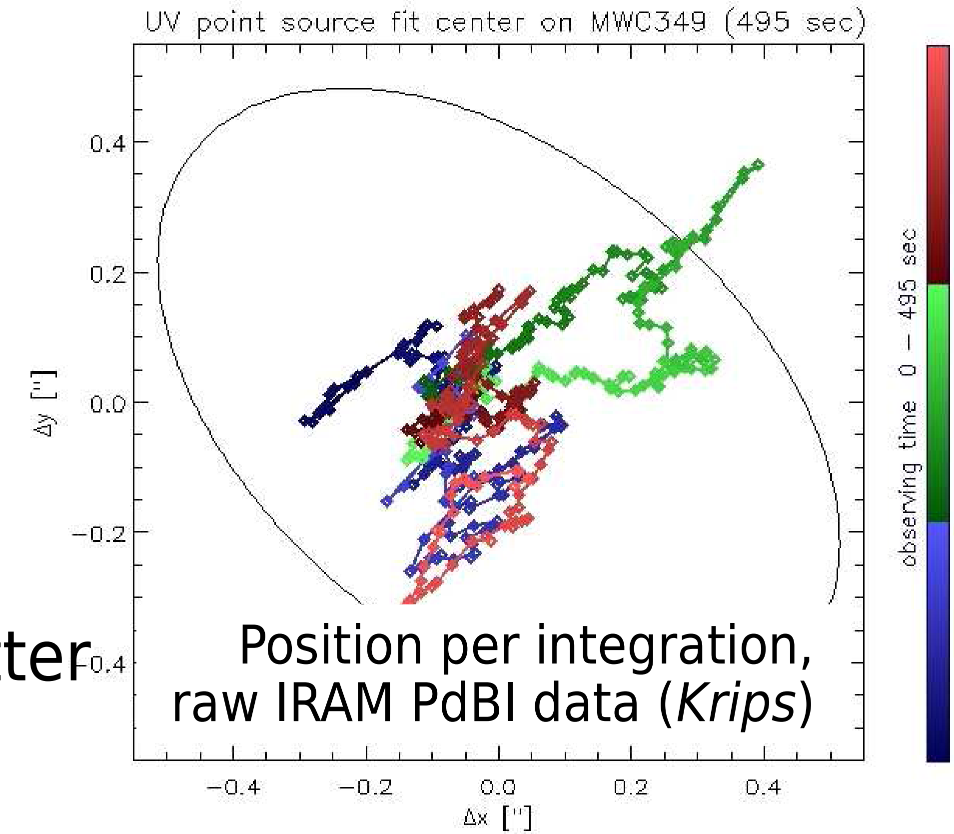
Phase errors cause position errors

- Averaging over phase fluctuations causes decorrelation of amplitudes
  - Visibility $V = V_o e^{i\phi}$

    $$\langle V \rangle = V_o \langle e^{i\varphi} \rangle = V_o e^{-(\varphi_{rms}^2)/2}$$

    ϕ_{rms} in radians

  Lose 9% amplitude for 5° ϕ_{rms}
- Fluctuations on time-scales of few sec: raw data position jitter
- **W**ater **V**apour **R**adiometry
  - Measure PWV, each antenna, every ~second
  - Calculate phase delay
    - Apply corrections to all observed data

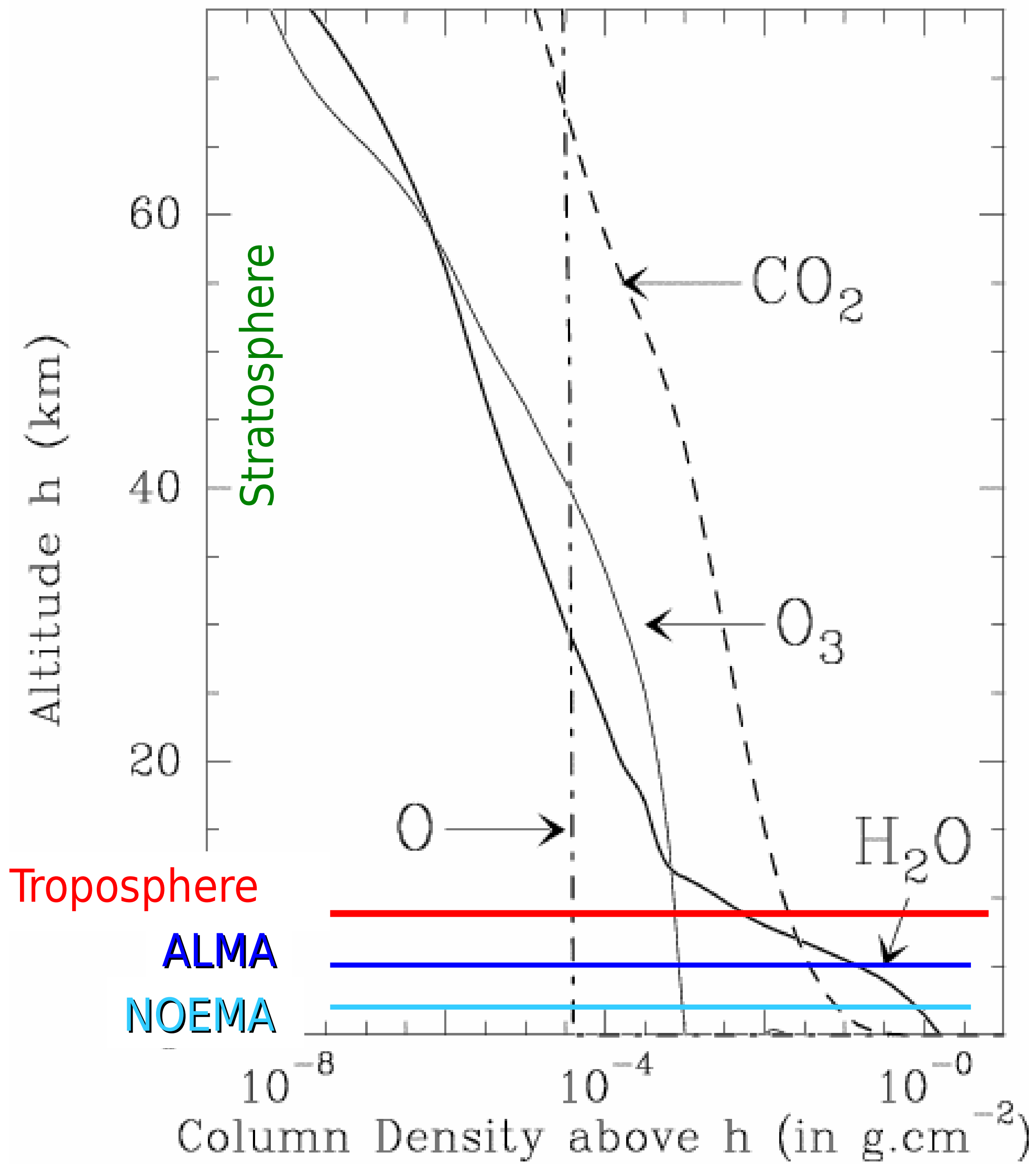


Position per integration, raw IRAM PdBI data (*Krips*)

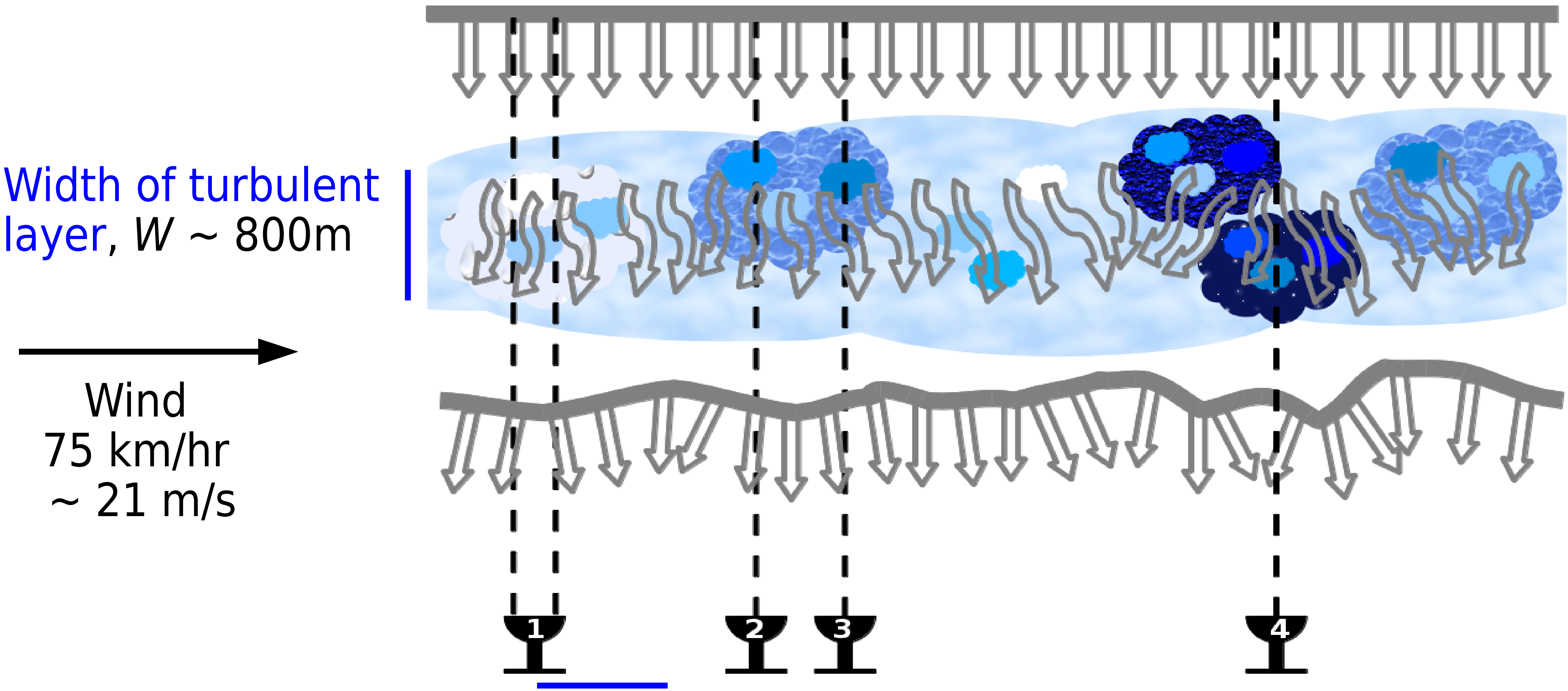
Atmosphere

- 'Dry' component:
  - Worst O_2, O_3
- 'Wet' component:
  - H_2O vapour/clouds
  - Highly turbulent layer
    - Measure PWV = precipitable water vapour
- Atmospheric depth increases at lower elevation
  - Larger zenith distances *z*

Column density as function of altitude

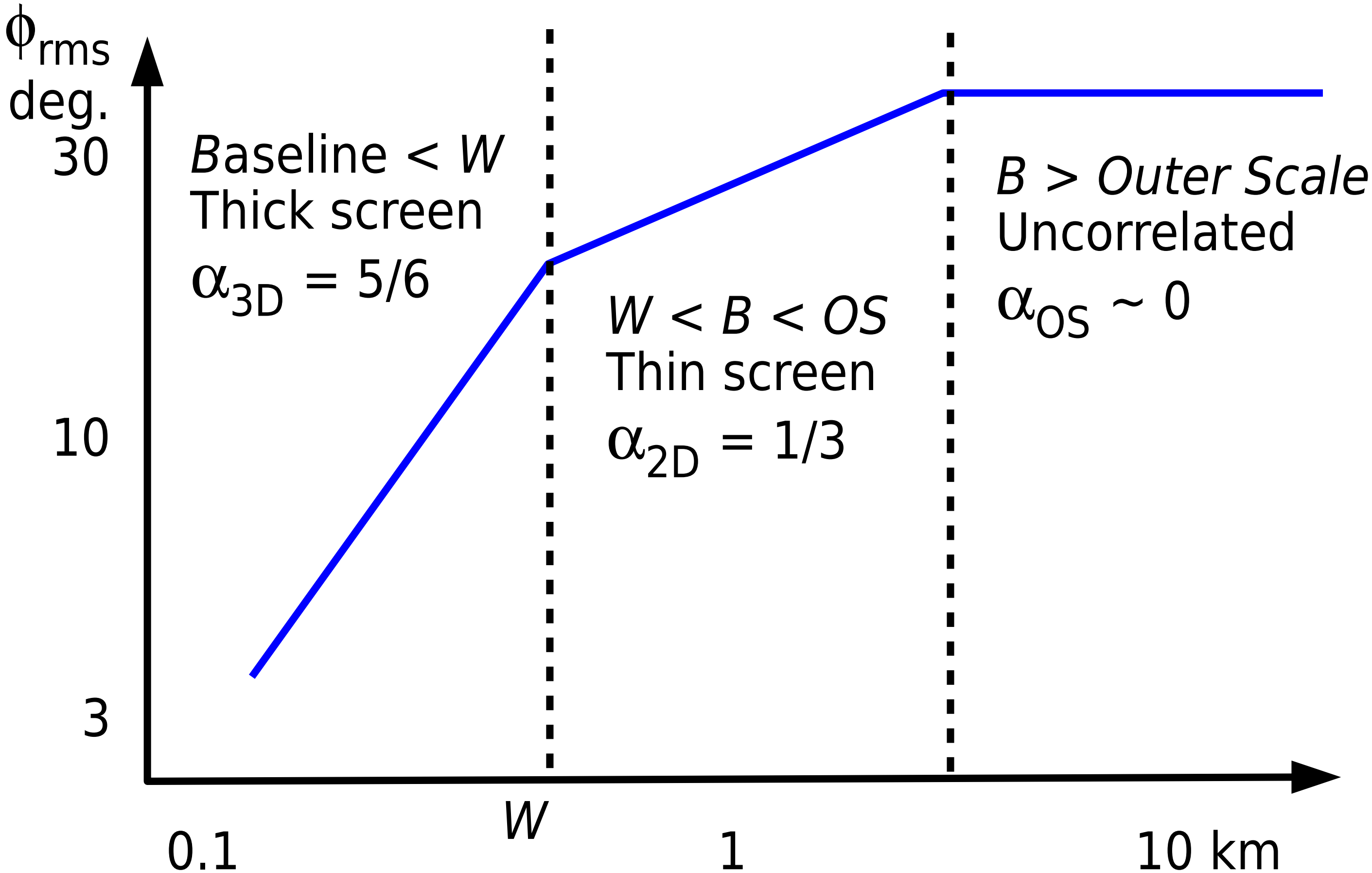


Troposphere variability scales



- Isoplanatic patch > sky area above single mm antenna
- Antenna 2 – 3 separation < *W*, phase stable, noise rather correlated
- 1 – 2, 1 – 3 higher but less correlated phase fluctuations
- Baselines to 4 see higher but uncorrelated noise

Kolmogorov turbulence



Kolmogorov prediction (*Coulman*'90)

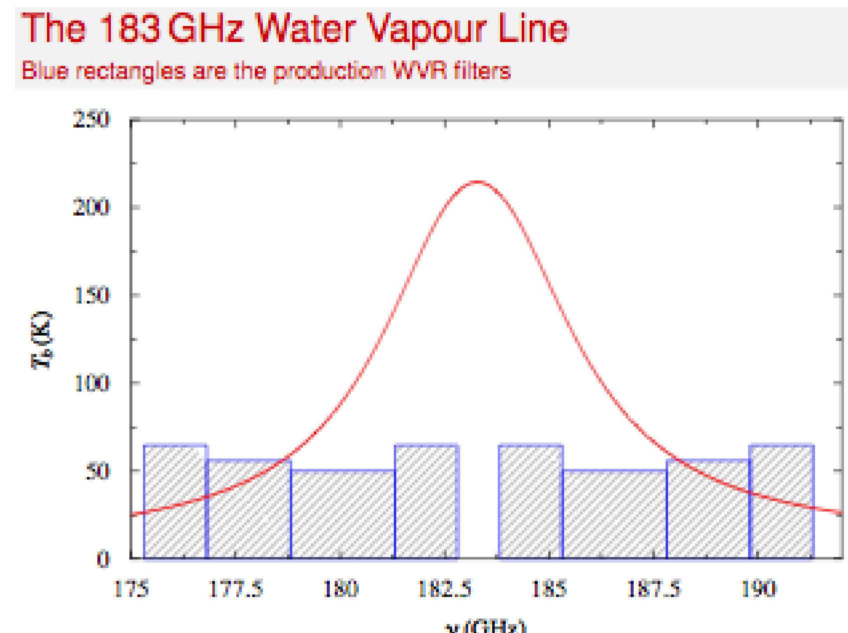
$$\varphi_{rms} = \frac{K}{\lambda} B^{\alpha}$$

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

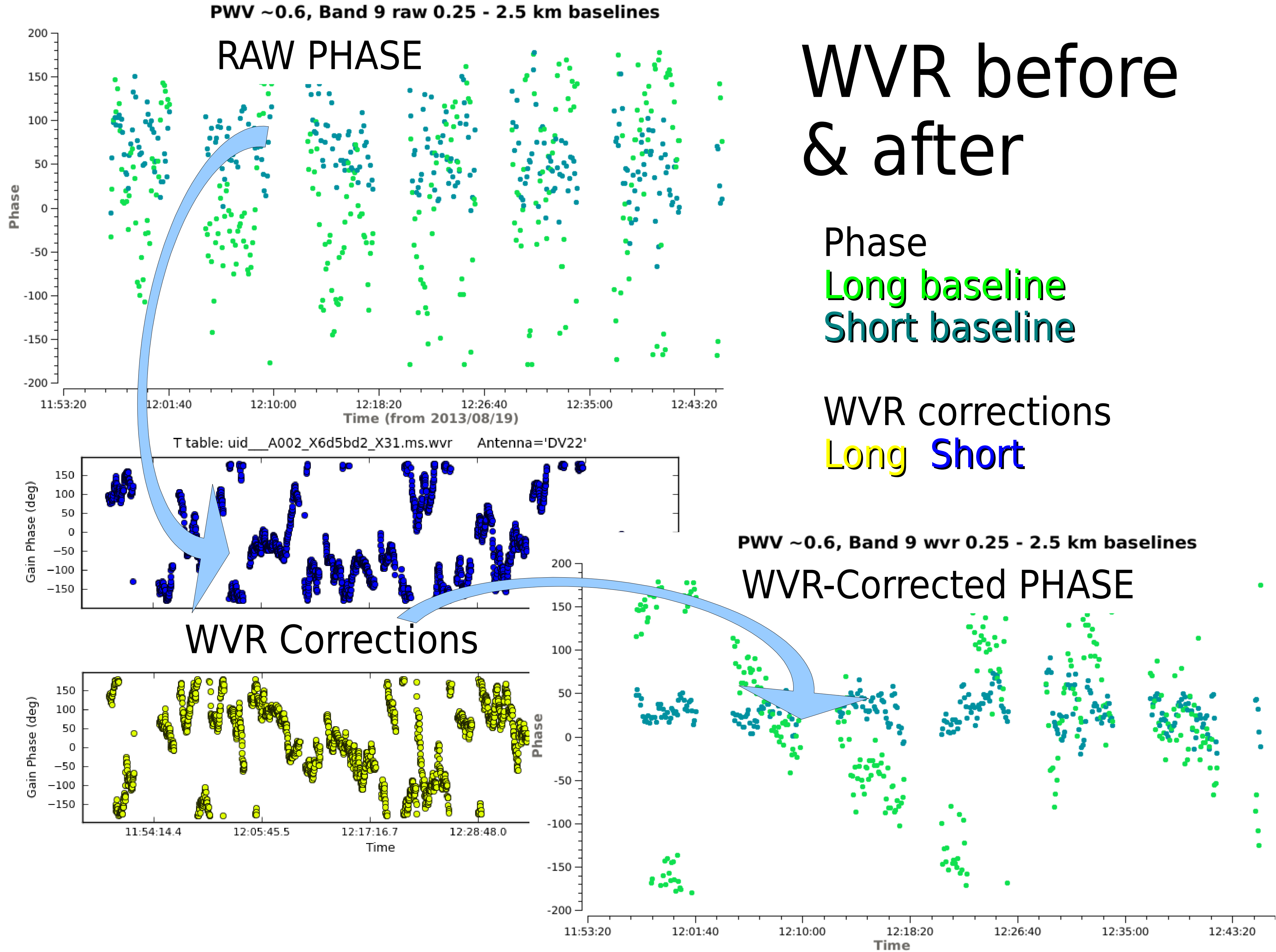
- Baseline 2-3 < *W*
  - Phase noise ϕ_{rms} increases as $B^{5/6}$
- Baselines 1-2, 1-3 > *W* but < *OS*: $\phi_{rms} \propto B^{1/3}$
- Baselines 4-* in outer scale regime: ϕ_{rms} levels off

Water Vapour Radiometry

- PWV=precipitable water vapour
  - Changes refractive index, speed of radio propagation
  - Phase error $\Phi_e \propto (2\pi/\lambda)\mathrm{PWV} \,/\, T_{atm}$
  - 1 mm PWV ~ 0.7 mm extra path ~ 0.0023 ns delay



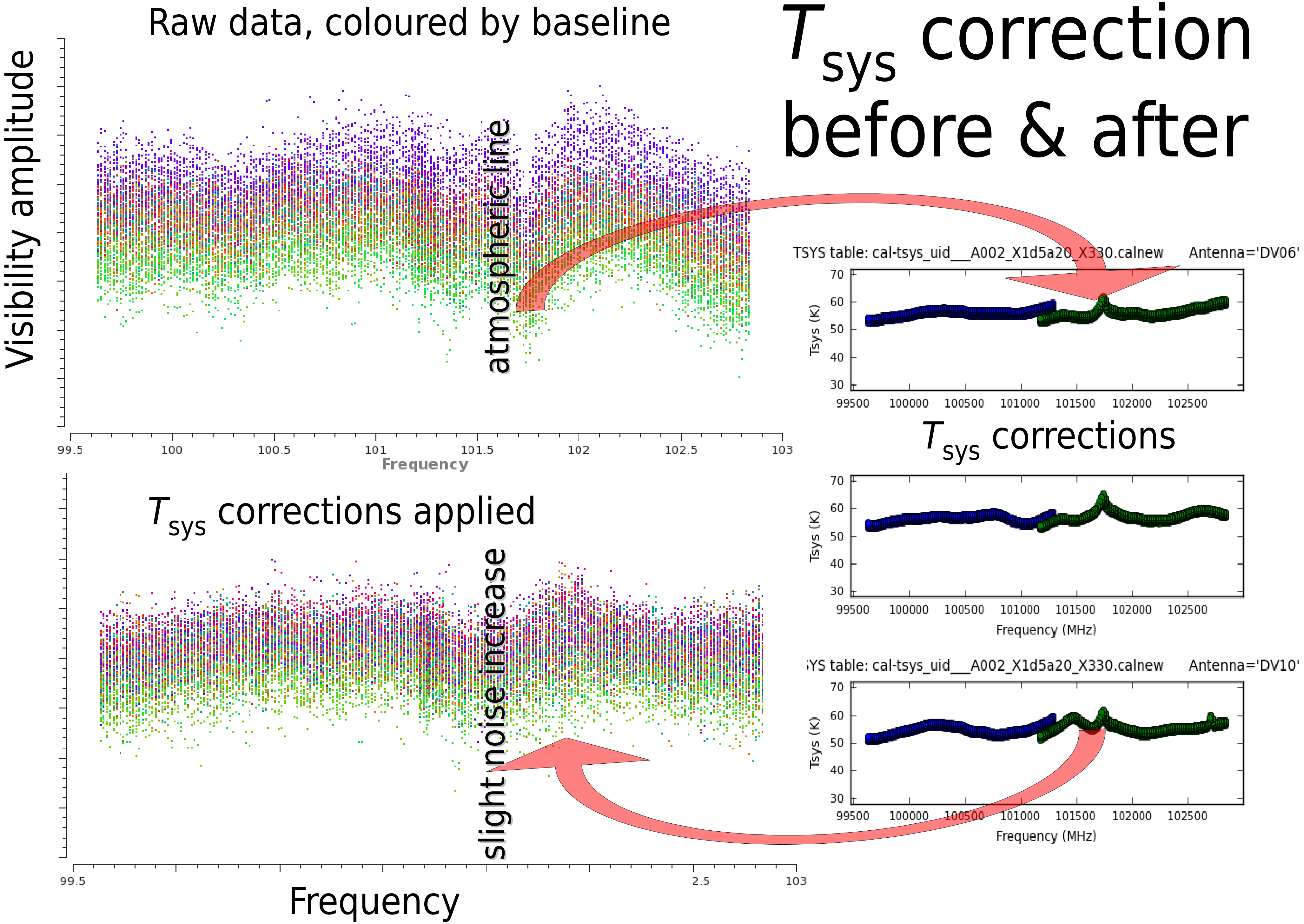
  - Each ALMA 12-m has water vapour radiometer
  - Apply bulk correction during observations
  - Use ~1Hz WVR measurements to correct residual fluctuations on-line or during data processing
- PdBI measures PWV at 22 GHz, corrects amplitudes


WVR before & after
Phase
Long baseline
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
Phase
Time

Measure total noise T_{sys}

- Measure T_{sys} using hot & cold loads
  - ALMA every few min, 128 channels per 2-GHz baseband
  - NOEMA per baseband
- Tracks atmospheric & instrumental fluctuations
  - Applied during data reduction

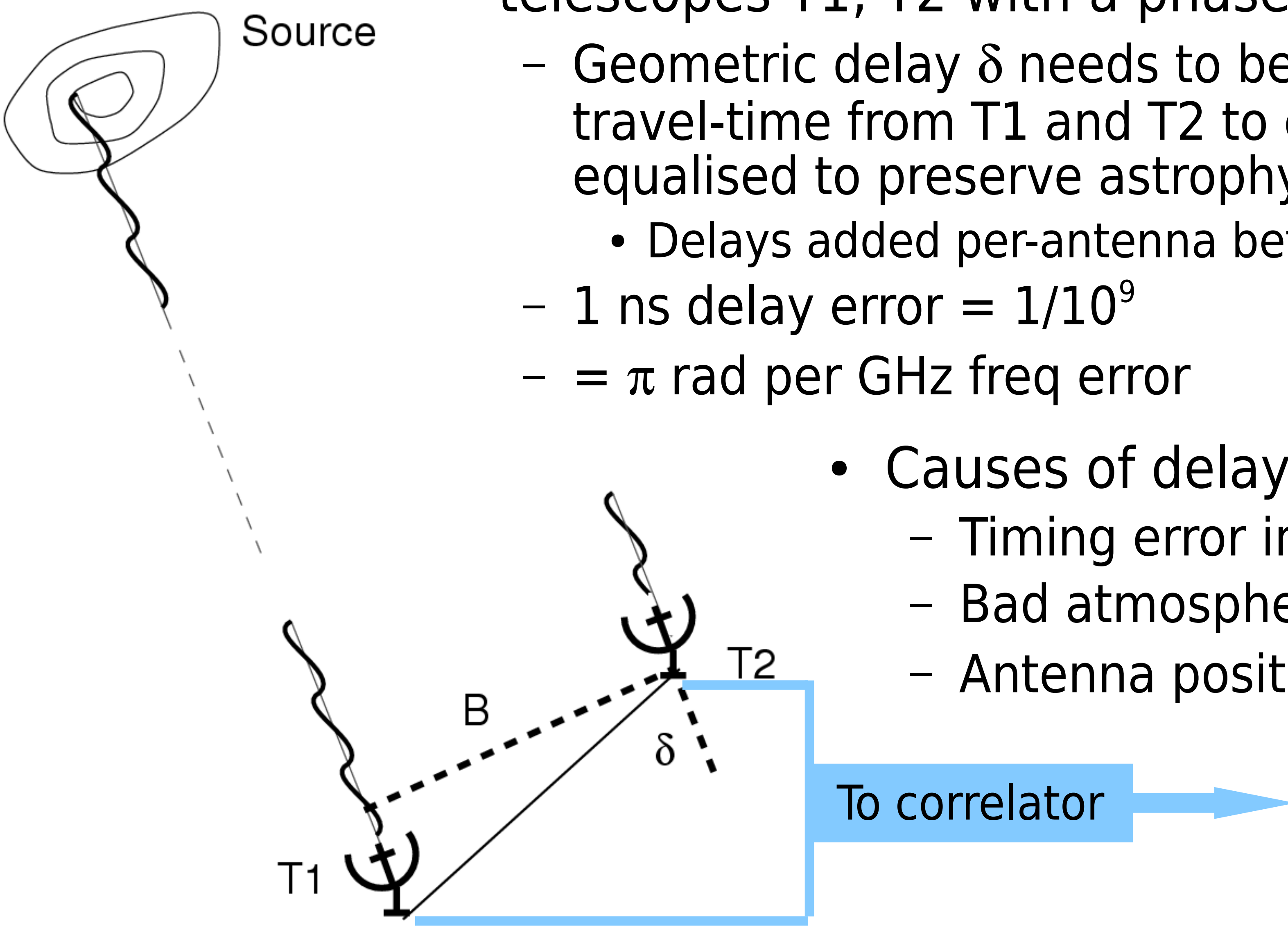
T_{sys} correction before & after



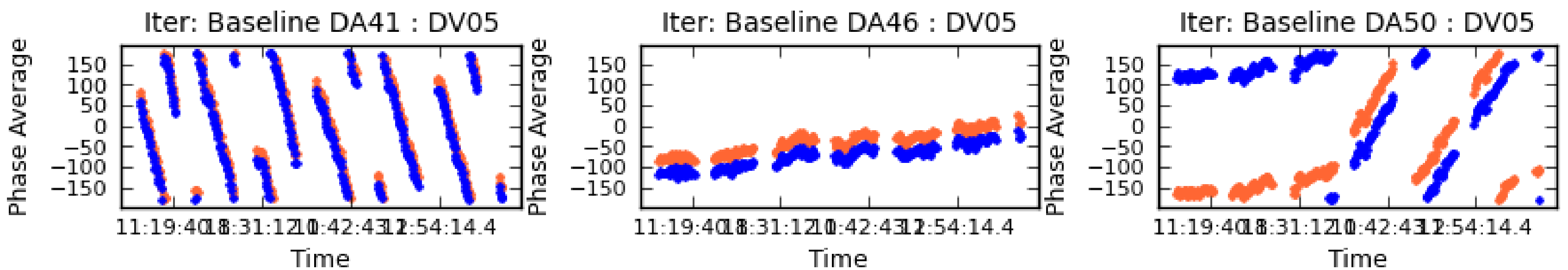
Timing and antenna position errors

- Signals from off-centre source reach telescopes T1, T2 with a phase shift
  - Geometric delay δ needs to be removed and travel-time from T1 and T2 to correlator equalised to preserve astrophysical phase
    - Delays added per-antenna before correlation
  - 1 ns delay error = $1/10^9$
  - = π rad per GHz freq error

- Causes of delay error include:
  - Timing error in correlator
  - Bad atmospheric model
  - Antenna position error

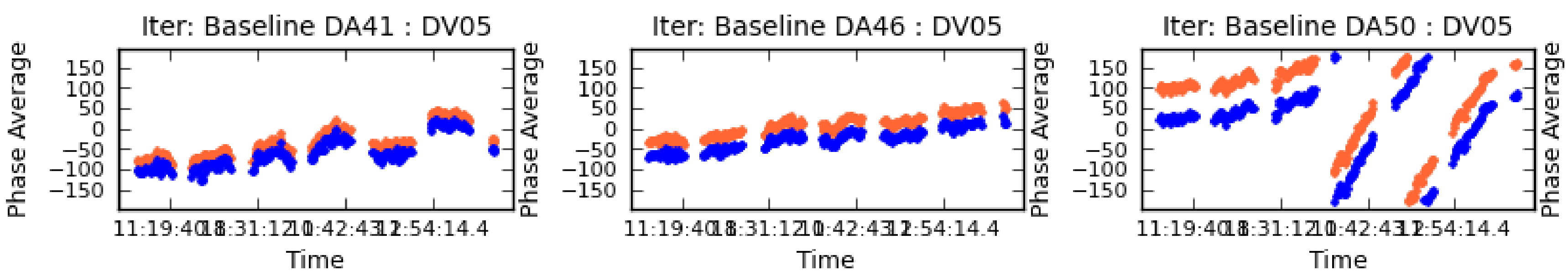


Antenna positions



DA41 position error

DA50 ????



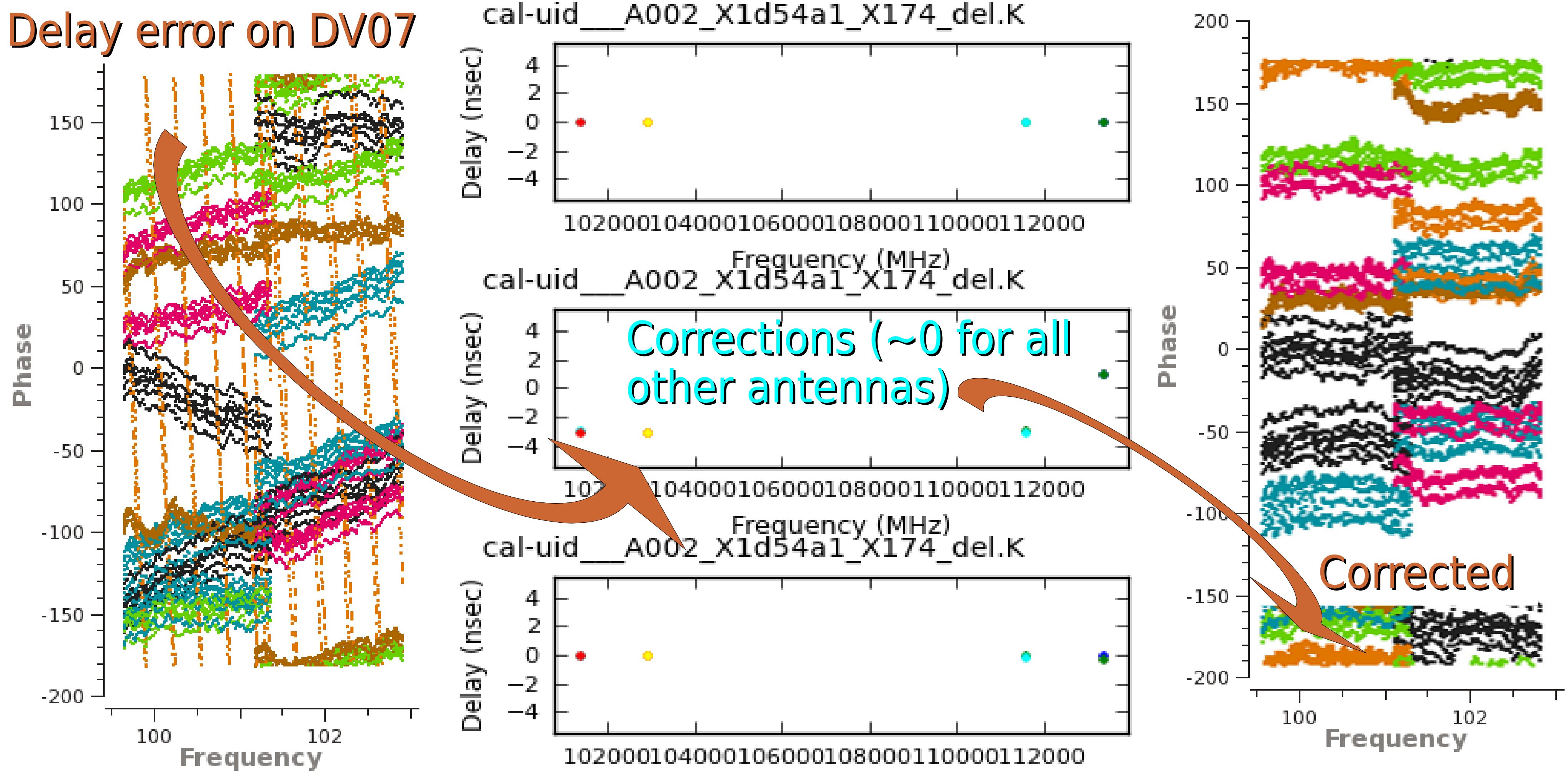
DA41 position corrected during data processing

DA50 ????

- Antenna positions measured after every move
  - May need updating
  - DA41 ~10 cm position error ~ 0.33 ns delay error
  - Also causes time-dependent phase error
    - Incorrect model for updating geometric delay

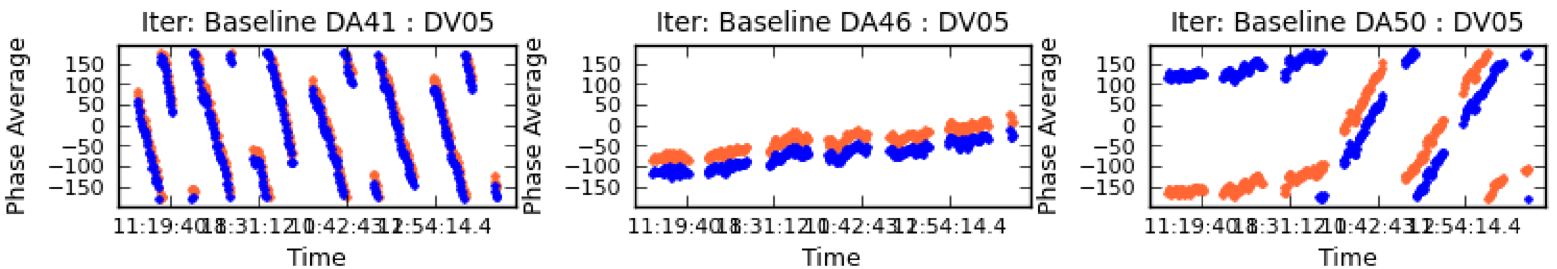
Delay error (rare in cycle >0)

- Phase across 2 GHz undergoes 6 full turns on one antenna
  - Delay error $6/2\times10^9 = 3$ ns

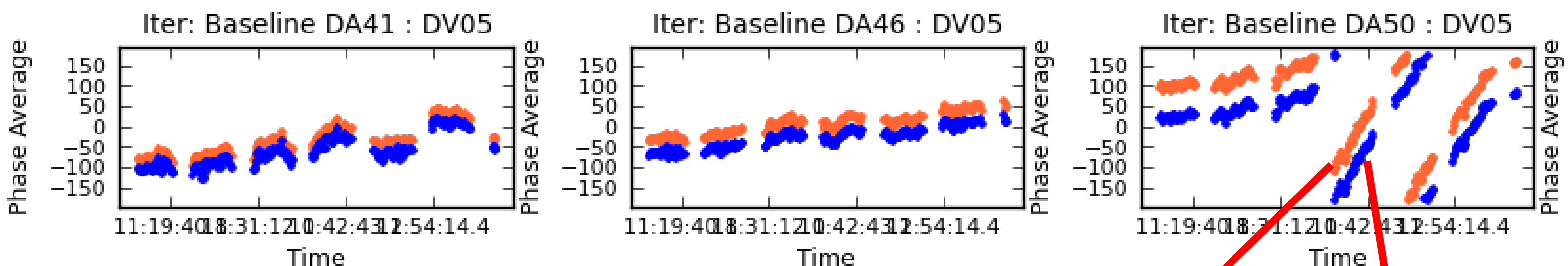


Two x 2-GHz spw. Each baseline is shown in a different colour

Timing and antenna position errors



DA41 position error

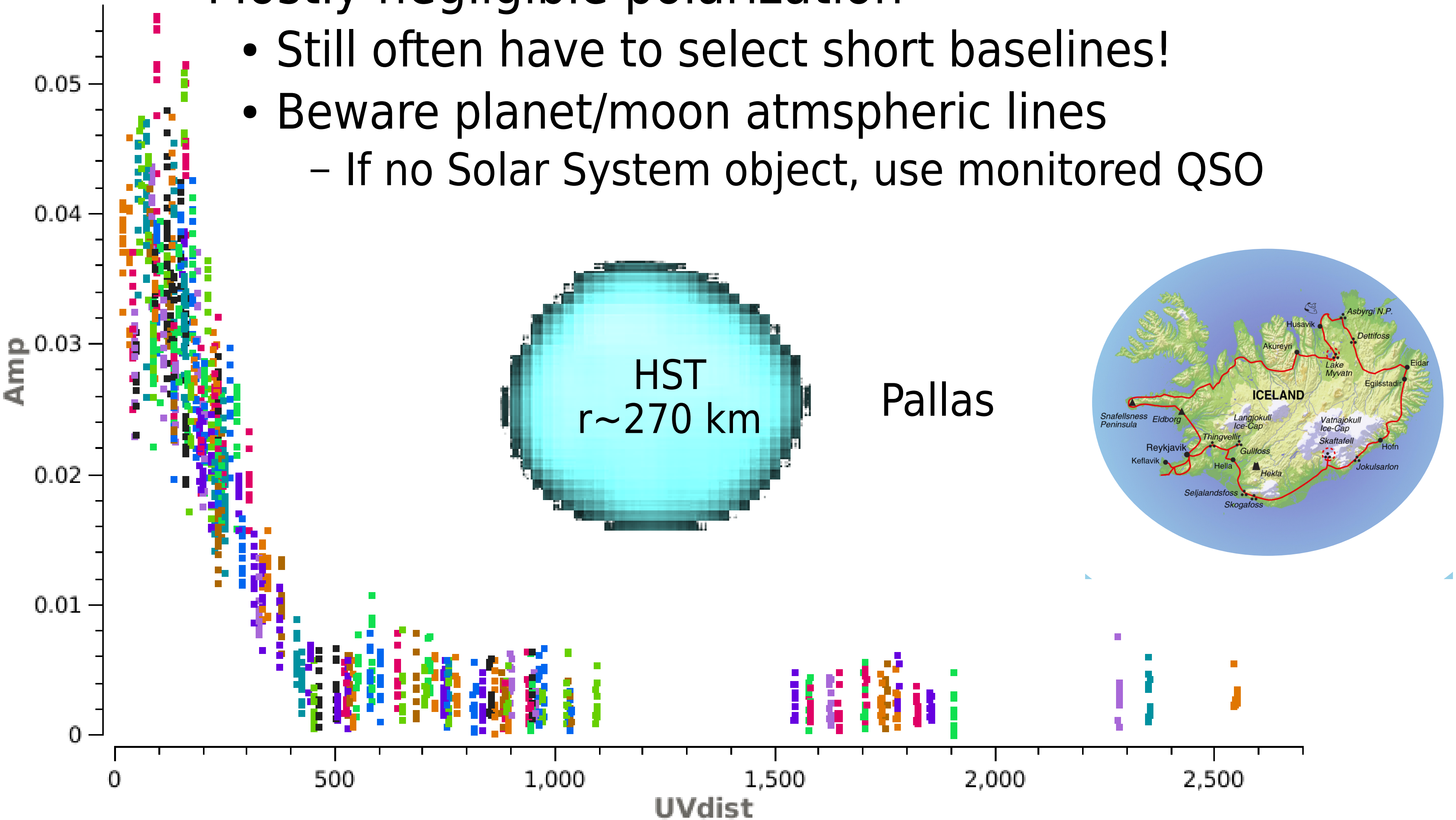


DA41 position corrected

DA50 ????

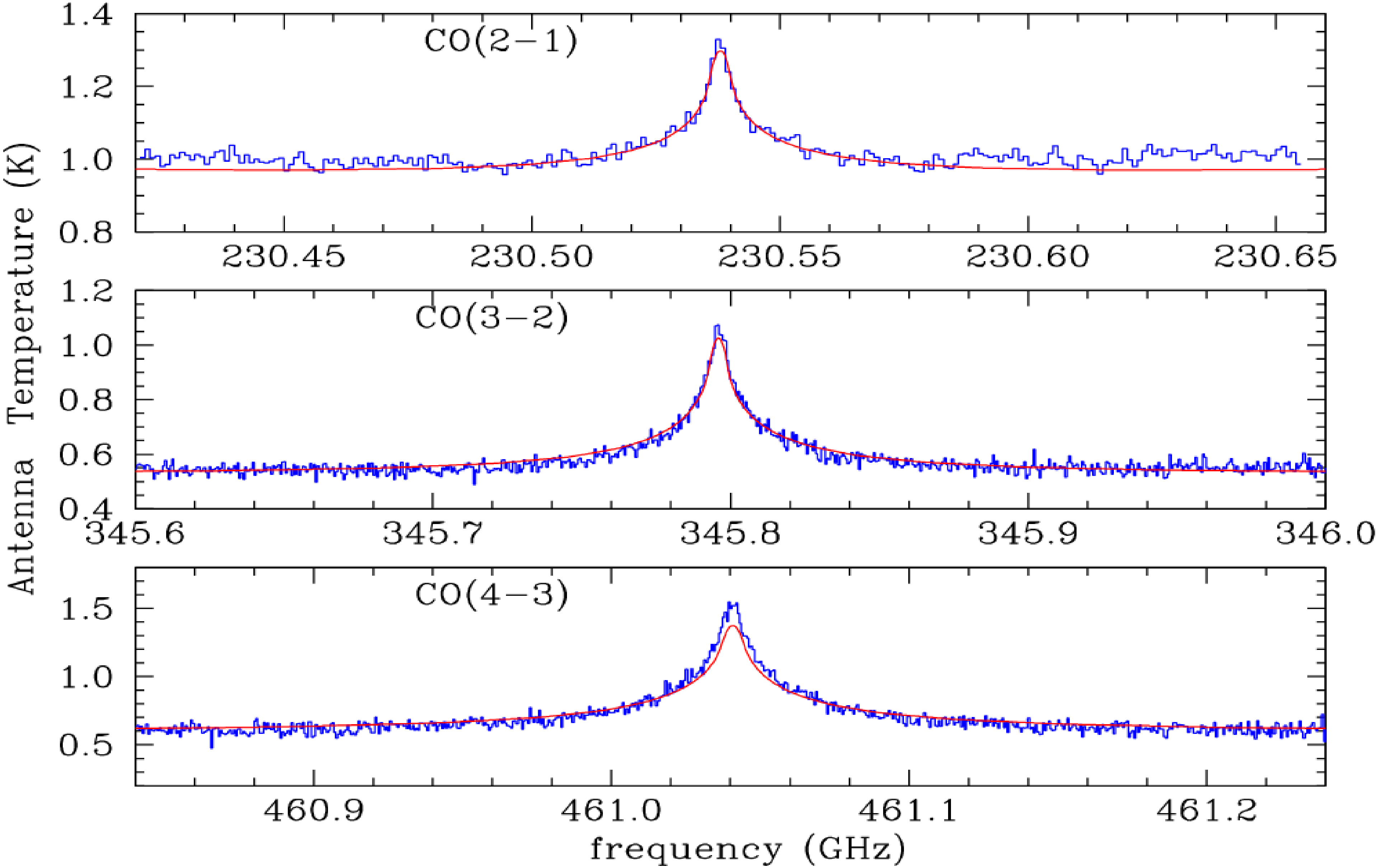
Calibration sources: flux density

- Primary flux calibration uses planets, moons, asteroids
  - Models and ephemerides available
  - Mostly negligible polarization
    - Still often have to select short baselines!
    - Beware planet/moon atmspheric lines
      - If no Solar System object, use monitored QSO



Pallas

Calibration sources have lines too



Neptune *Marten et al. 2005*

Astrophysical calibration sources

- Calibrate amplitude and phase as a function of :
  - *Frequency* (delay and BandPass calibration)
    - Mostly instrumental errors, stable for hours
      - Solve per-channel for TDM, or average up to 20 GHz
    - Calibrator within 45^{o}
  - *Time* (phase (& amplitude) referencing applied to target)
    - NB in practice use time & bandpass calibration for all calibrators, sometimes refine interatively
- Phase error ϕ radians gives fractional amp error ~ϕ
- Need signal/noise $S_{\mathrm{calsource}}/\sigma_{\mathrm{ant}} > 15$
  - ~1/15 radians ~ 7% amp decorrelation ~ 4^{o} phase error
    - Average spw or transfer from wide to narrow if necessary

Astrophysical calibration sources

- Most errors are antenna based

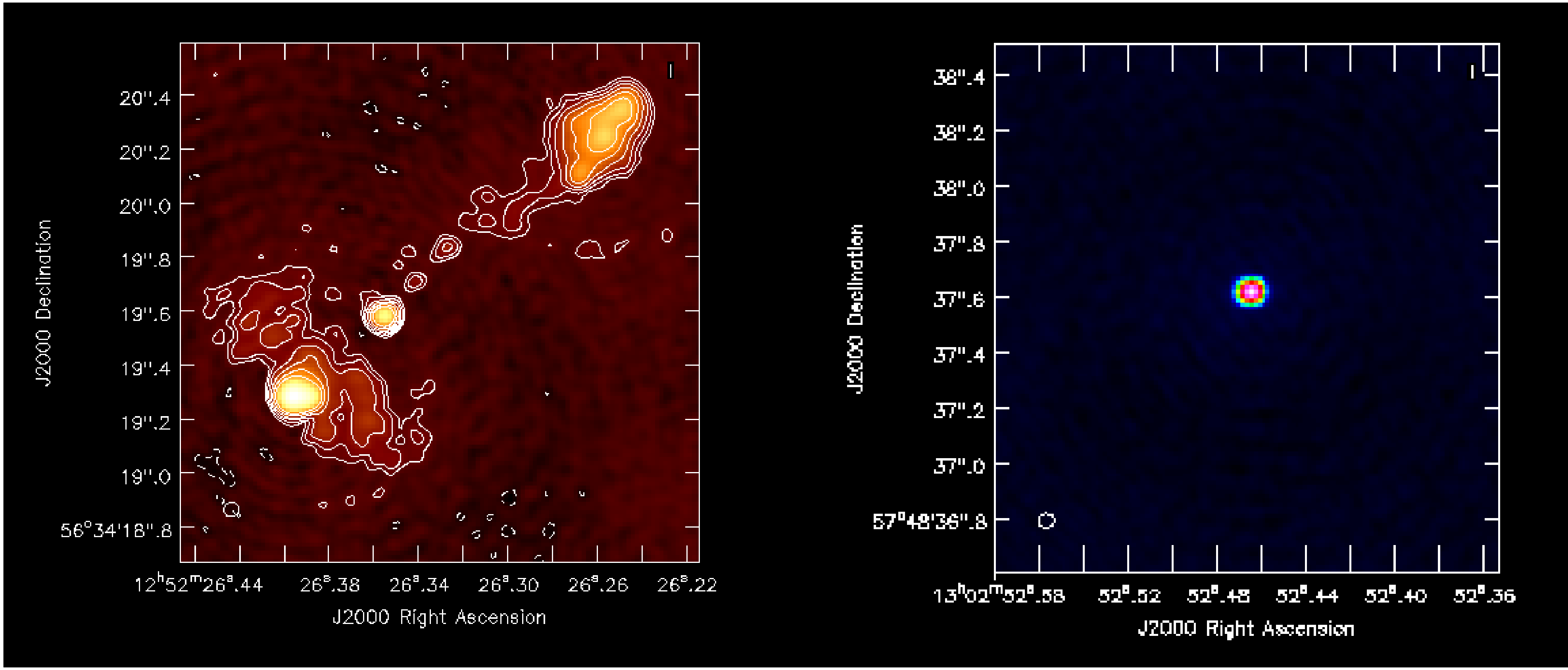
$$\sigma_{ant}(\delta t, \delta \nu) \approx \sigma_{array}\sqrt{\frac{N(N-1)/2}{N-3}}$$

  - σ_{array} is noise in all-baseline data per interval
  - e.g. 36 antennas, σ_{ant} ~ 4.5 x map noise per interval/pol.
- – Band 7: rms per TDM spw 1.875 GHz ~0.5 mJy/minute
  - x √2 per polarization ~0.7 mJy
  - x 15 (SNR) x 4.5 (per antenna) ~ 50 mJy
    - – In practice aim for ~ 100 mJy at B7, if possible
- – More compact configs/low ν: within 10-15 deg
  - Cycle time 5-10 min
- – Extended configs/high ν: within ~4 deg
  - Cycle time 1-few min

Phase referencing

- Observe phase-ref source close to target
  - Point-like or with a good model
  - Close enough to see same atmosphere
    - ~2-15 degrees (isoplanatic patch)
  - Bright enough to get good SNR much quicker than atmospheric timescale τ
    - τ 10 min/30 s short/long B & low/high ν
  - Nod on suitable timescale e.g. 5:0.5 min
    - Derive time-dependent corrections to make phase-ref data match model
    - Apply same corrections to target
  - Correct amplitudes similarly
- Self-calibration works on similar principle

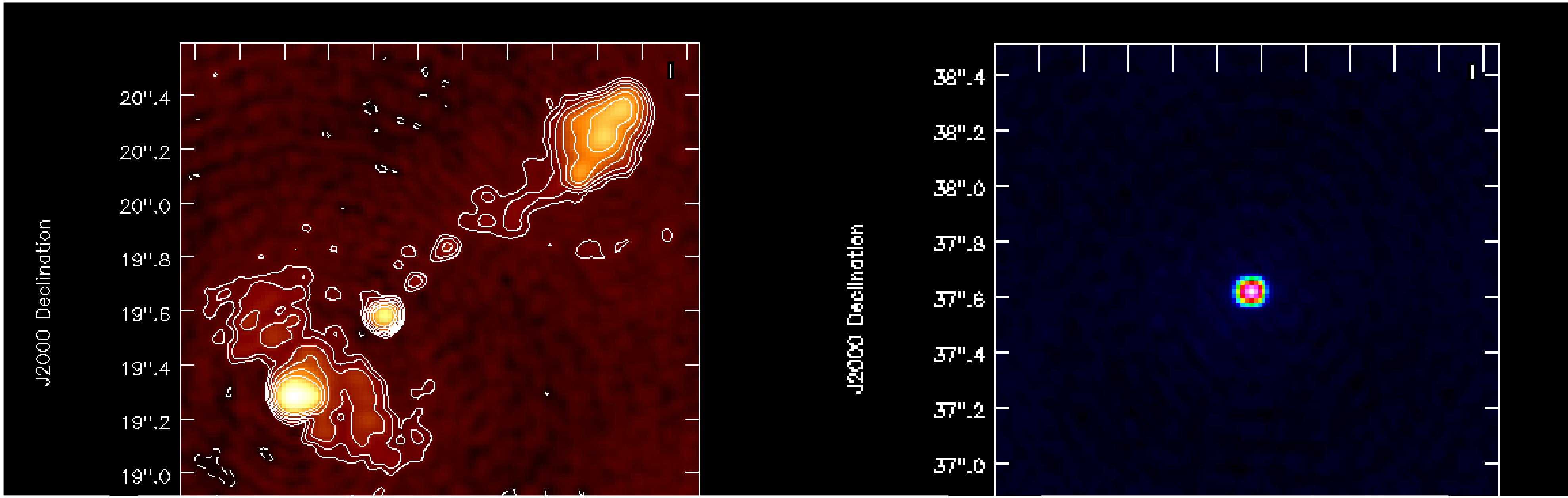
Phase referencing



Target 3C277.1

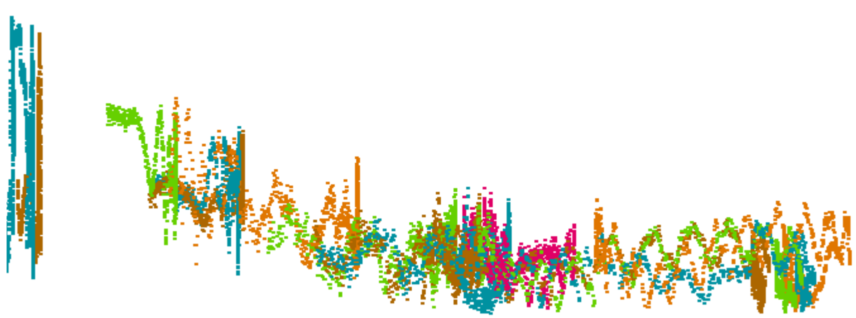
Phase-ref 1300+580
~3° from target
Unresolved point

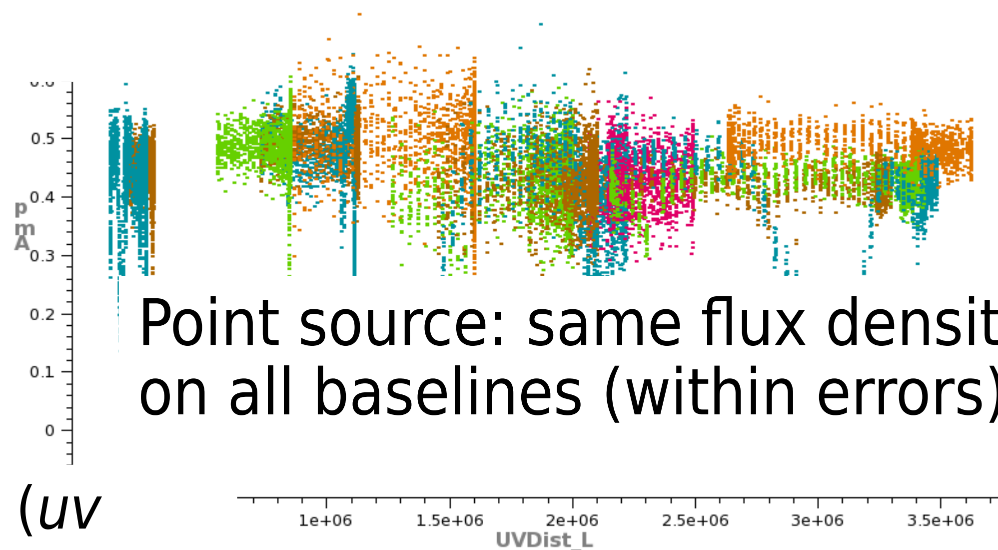
Source structure in *uv* plane



Extended source: more flux on short baselines

Visibility amplitudes

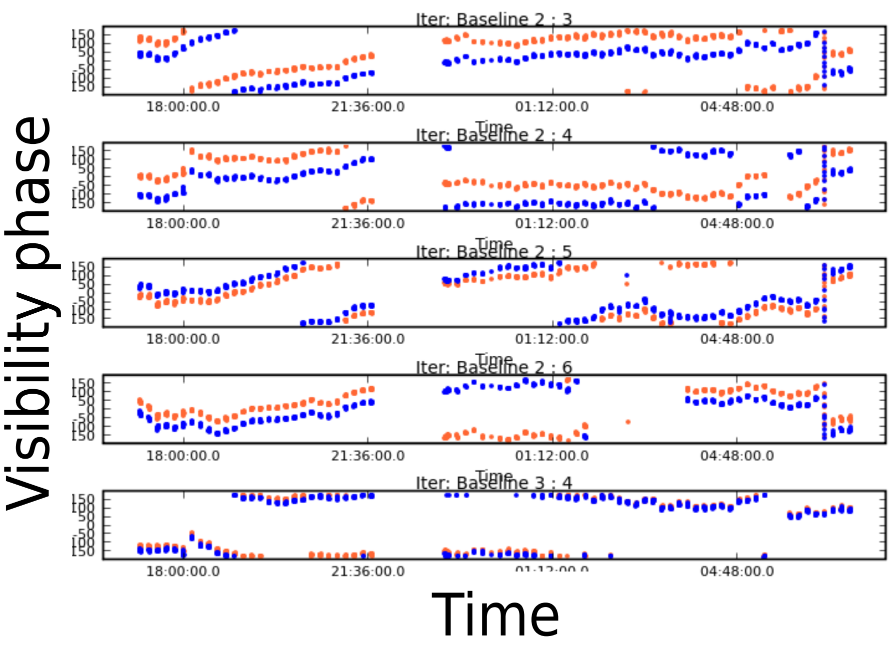


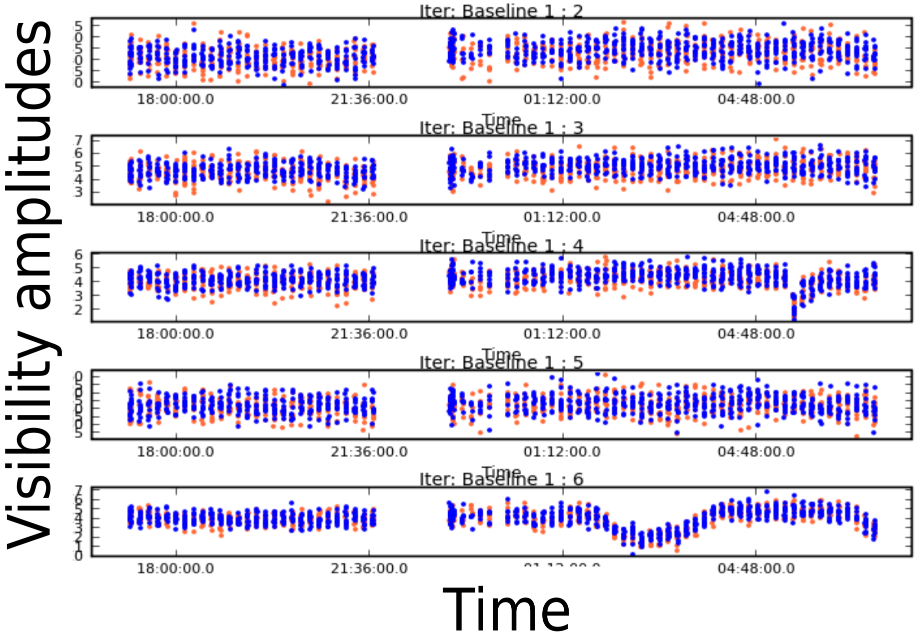


Point source: same flux density on all baselines (within errors)

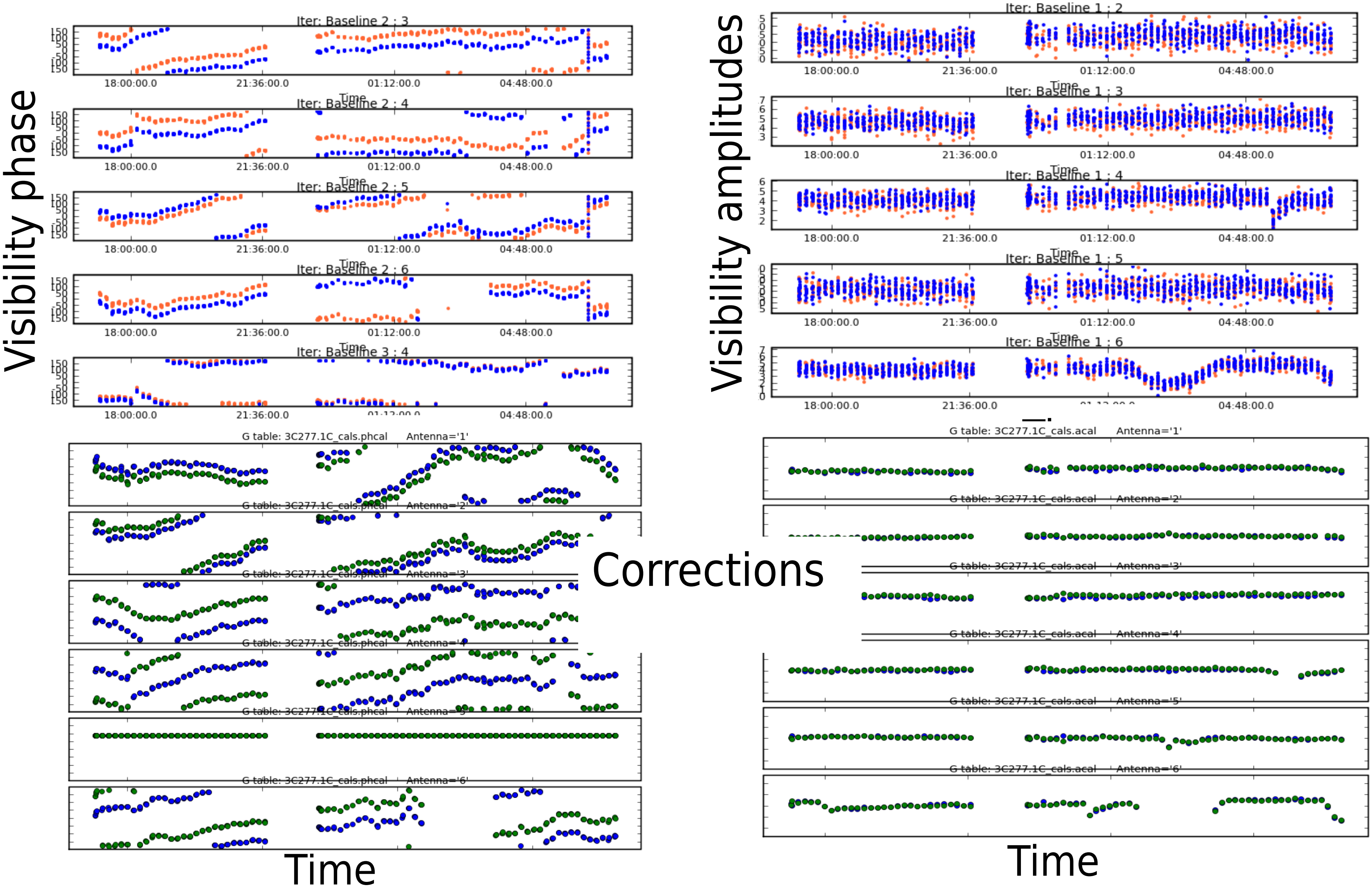
Baseline length in wavelengths (*uv* distance)

Phase-reference visibilities

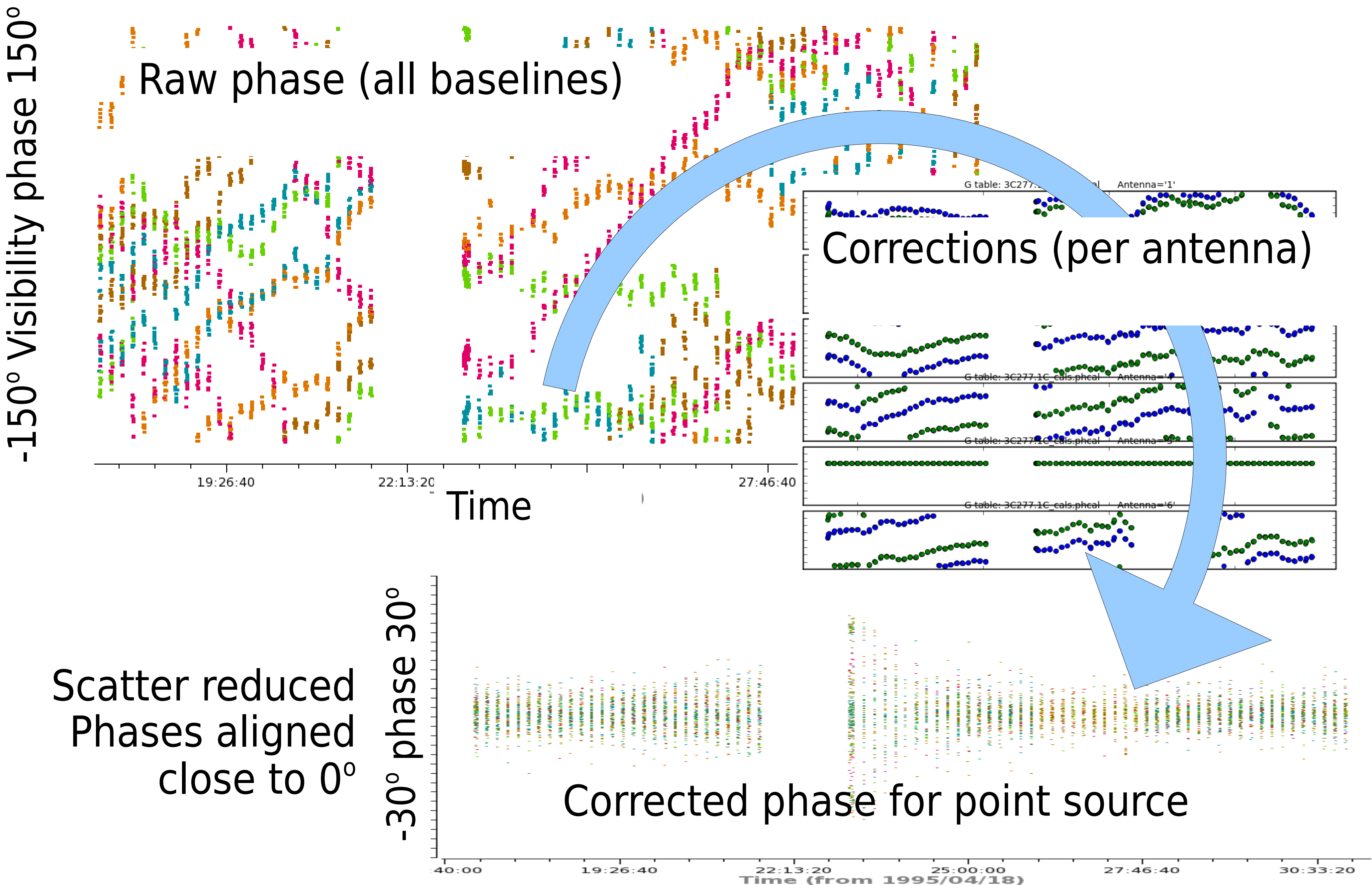




Corrections for point model



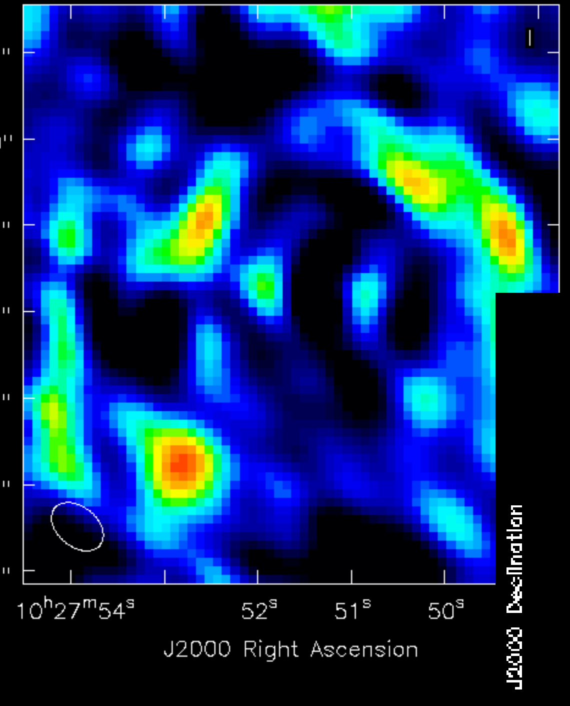
Corrected phase-ref visibilities



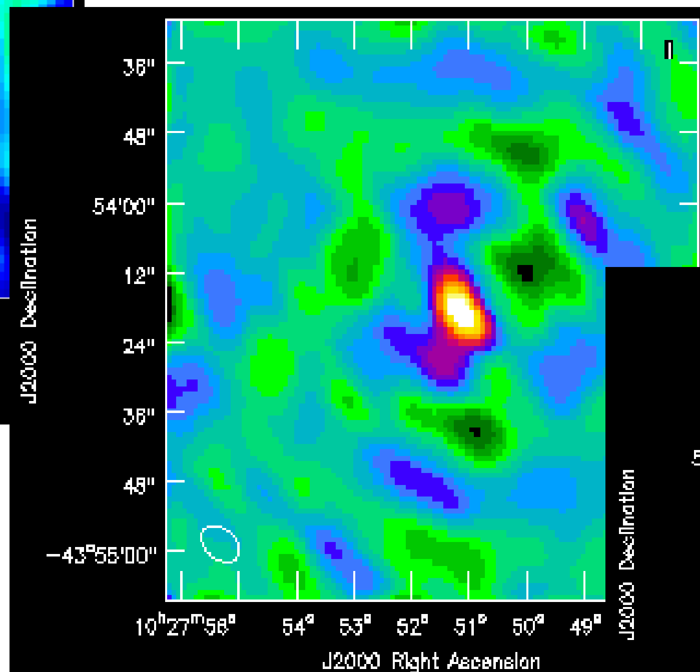
Time-dependent (self-)calibration

- ALMA data are calibrated by observatory staff
  - Pipeline or scripts
  - Instrumental corrections are usually standard
    - You can refine them but not usually necessary
  - Sample images provided
- If target bright, you can self-calibrate
    - rule of thumb: worth trying if S/N >20 in few min
  - Starting model is the image made by applying phase-ref (and previous) corrections
- You may also want to make images differently

Effects on imaging

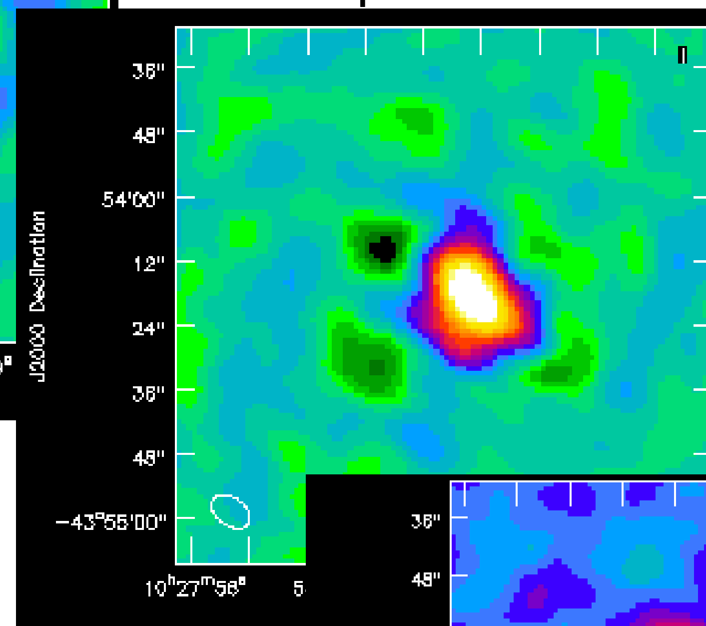


No astrophysical calibration:
no source seen

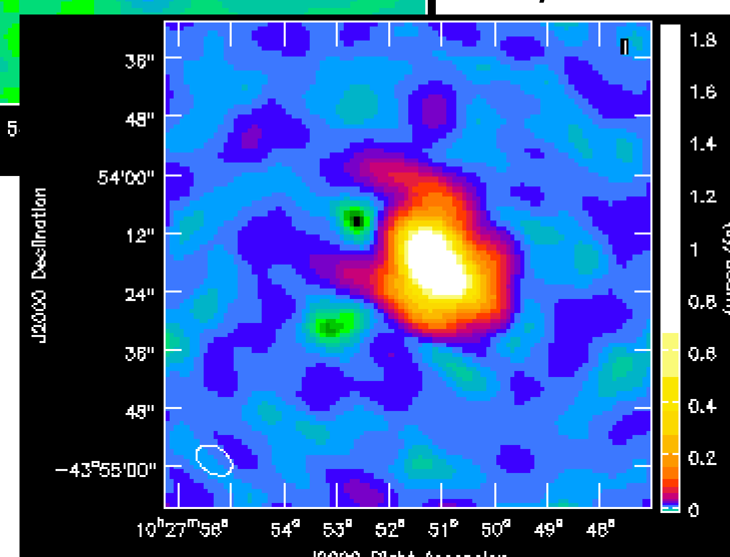


Bandpass, phase-ref
etc. solutions applied:
S/N 20
Anti-symmetric
artefacts dominate
- residual phase errors

Phase-only self-cal:
S/N 40
Residual, symmetric
amplitude errors



Amp &
phase
self-cal:
S/N 50



Calibration: Measurement Equation

basis for calibration in CASA

$$\underline{V}_{ij} = \mathbf{M}_{ij}\mathbf{B}_{ij}\mathbf{G}_{ij}\mathbf{D}_{ij}\int \mathbf{E}_{ij}\mathbf{P}_{ij}\mathbf{T}_{ij}\mathbf{F}_{ij}\, S\, \underline{I}_n\,(l,m)\,e^{-i2\pi(u_{ij}l+v_{ij}m)}\,dl\,dm + \underline{A}_{ij}$$

Vectors

$\underline{V}$ isibility = *f(u,v)*

$\underline{I}$ mage to be calculated

$\underline{A}$dditive baseline error

Scalars

S (mapping $\underline{I}$ to observer pol.)

l,m image plane coords

u,v Fourier plane coords

i,j telescope pair

Jones Matrices

Multiplicative baseline error

Bandpass response

Generalised electronic gain

Dterm (pol. leakage)

E (antenna voltage pattern)

Parallactic angle

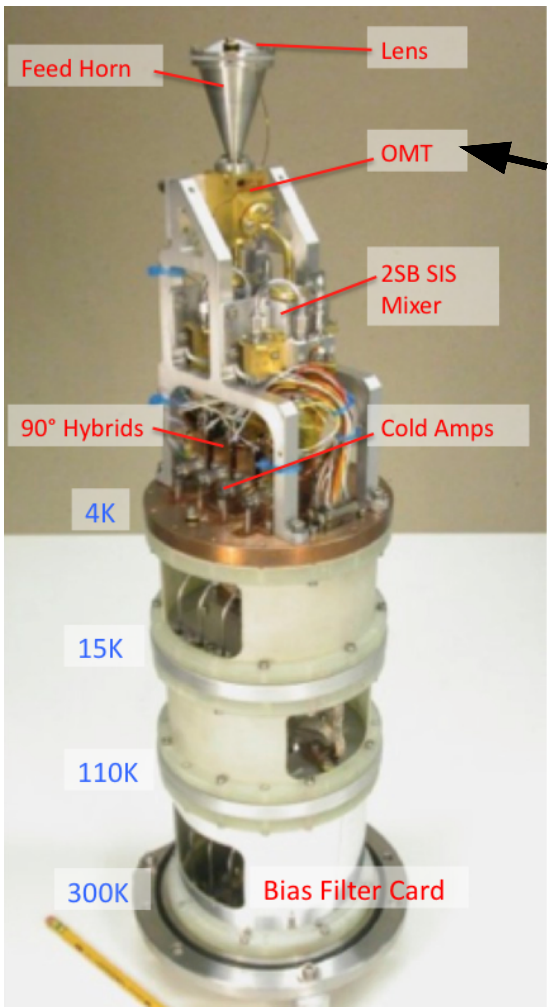
Tropospheric effects

Faraday rotation

etc.

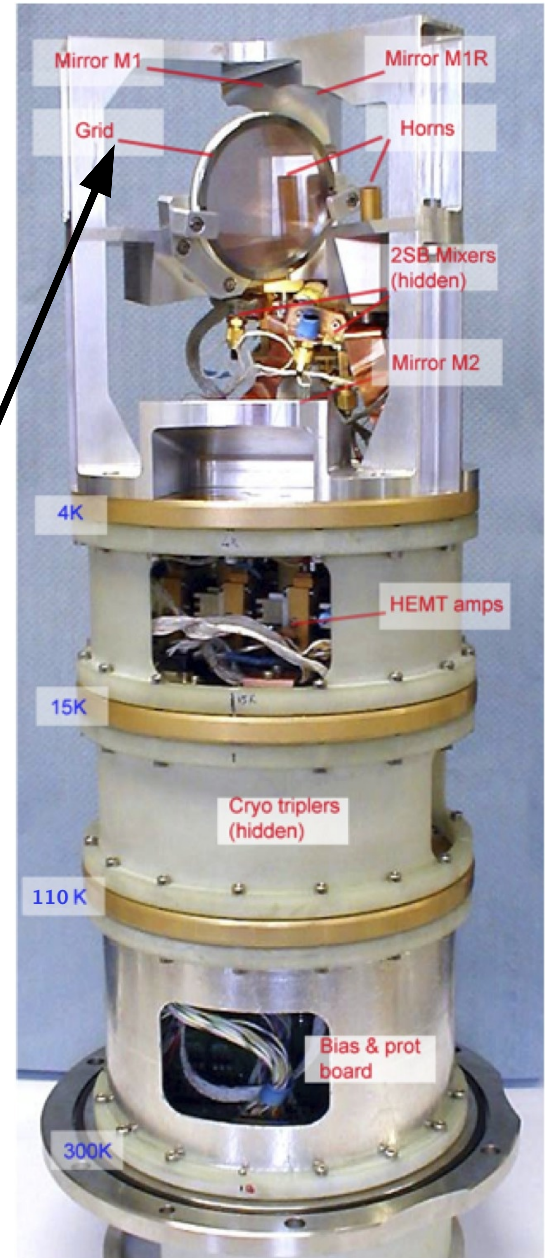
Polarization

Most (sub-)mm Rx use linear polarization
X and Y combined in correlator



ALMA Band 3 (λ~3mm) uses Ortho Mode Transducer

Band 9 (λ~0.45mm) uses wire grid



XX, YY for total intensity

XX, YY, XY, YX used to provide Stokes IQUV

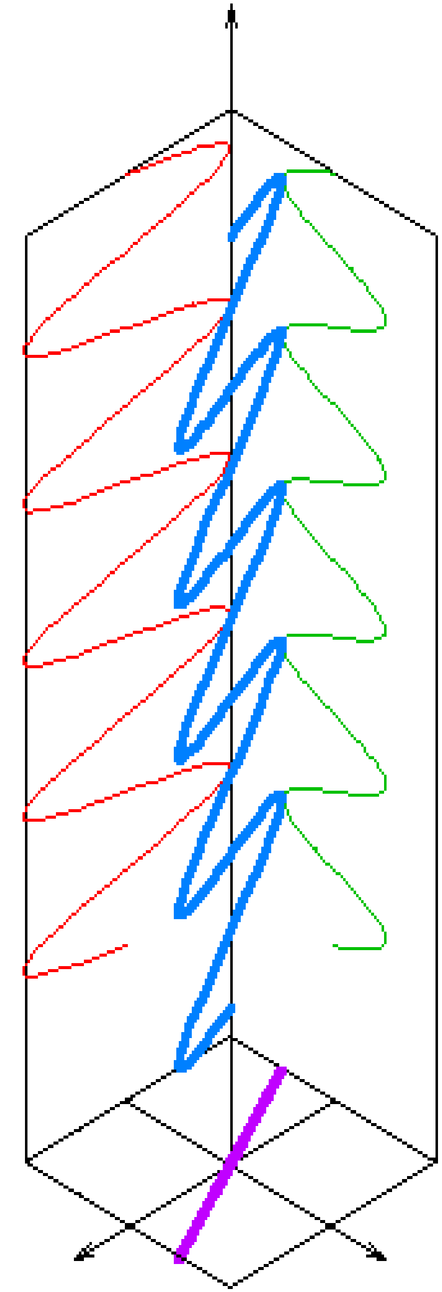


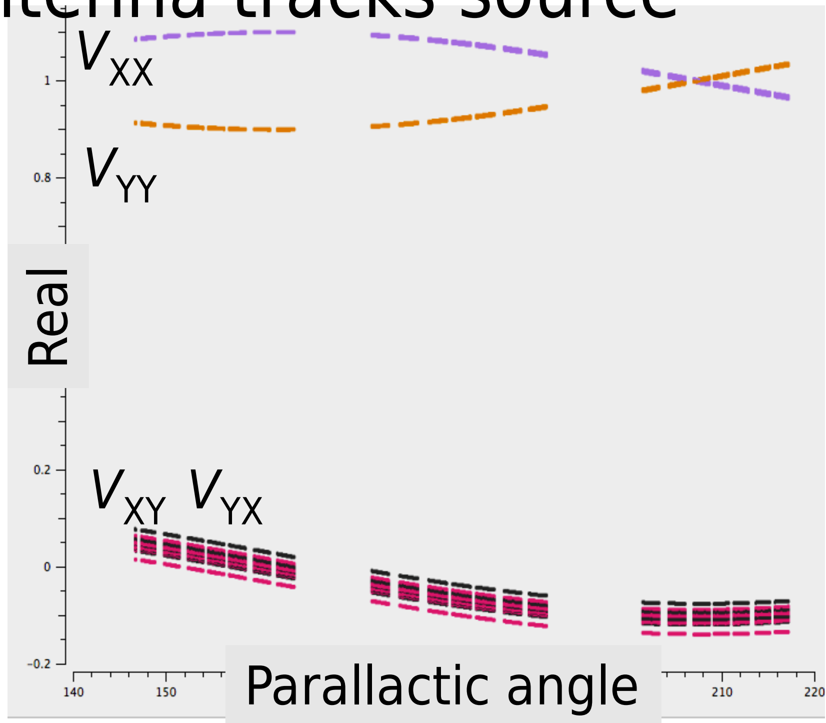
Diagram thanks to Wikipaedia

ALMA polarization calibration

- Calibration source has unknown linear polarization
  - Gain solutions decomposed into *X* and *Y* per antenna

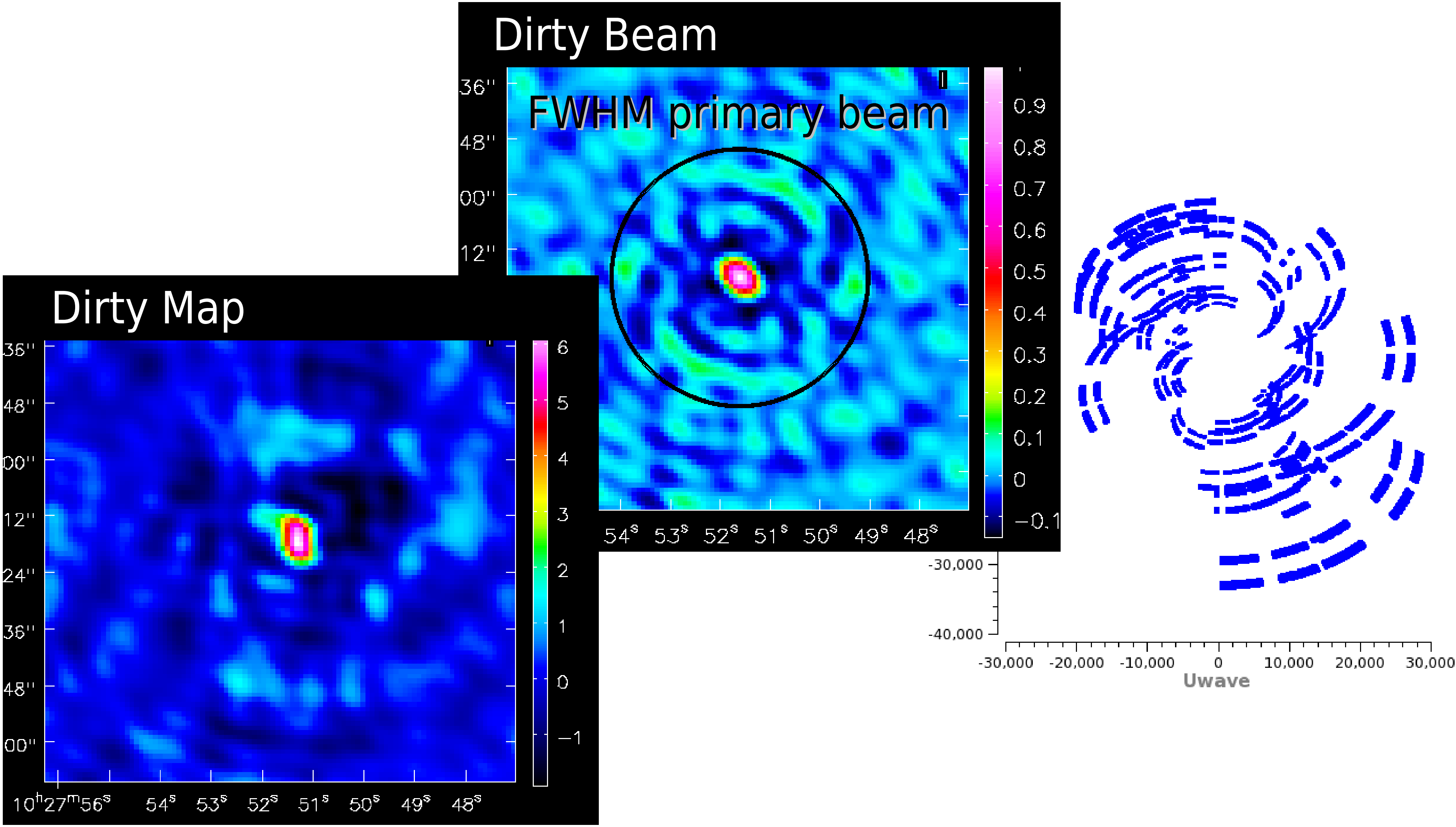
$$g_x' = g_x(1+Q/I)^{0.5} \qquad g_y' = g_y(1 - Q/I)^{0.5}$$

- Leakage between *X* and *Y* feeds ('*D*'-terms)
- Feeds rotate on sky as alt-az antenna tracks source
  - Parallactic angle rotates
  - Q_{obs} time-dependent
- Known feed orientation
  - Directly correct pol. angle
  - Refine after leakage correction
- 3+ scans, >3hr HA coverage
  - Solve for leakage and source polarization



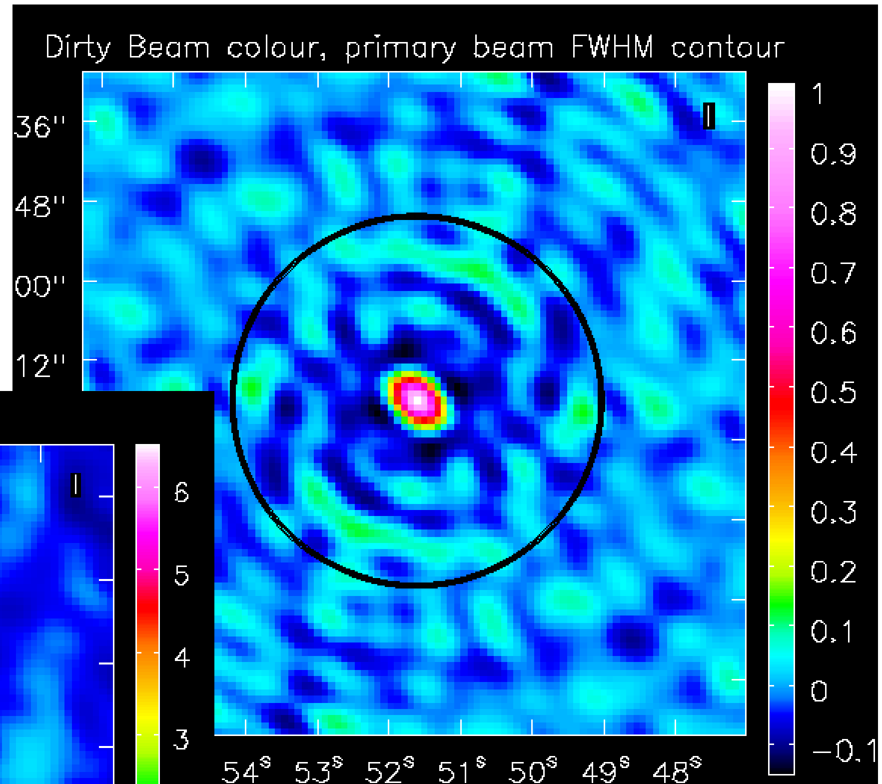
Cleaning

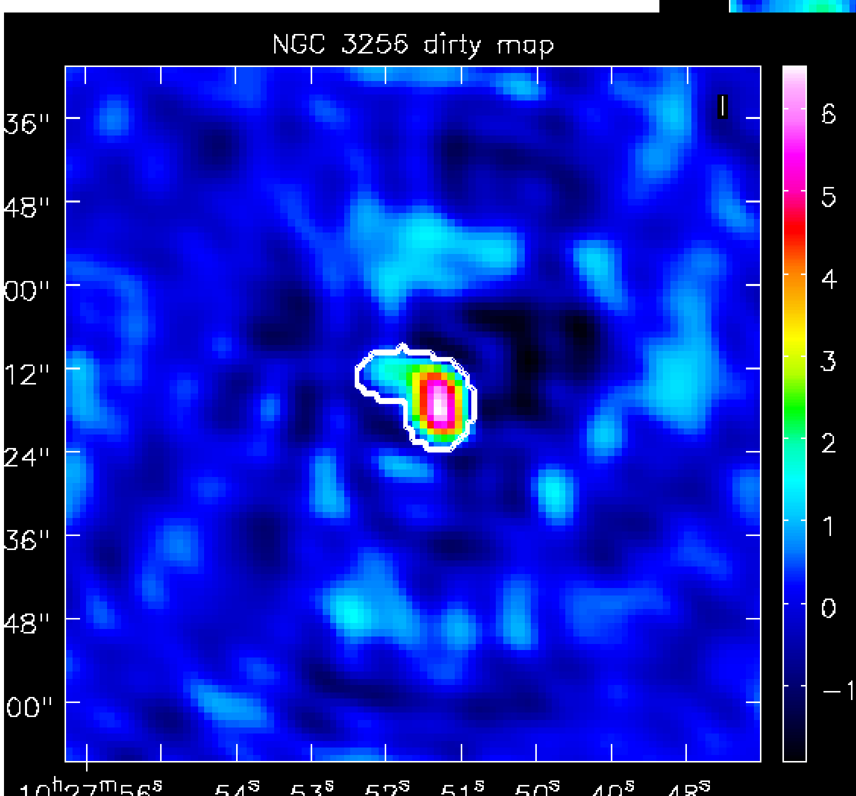
- Fourier transform the visibilities and the *uv* tracks



Cleaning

- Fourier transform the visibilities and the *uv* tracks
- Set a mask to include obvious emission

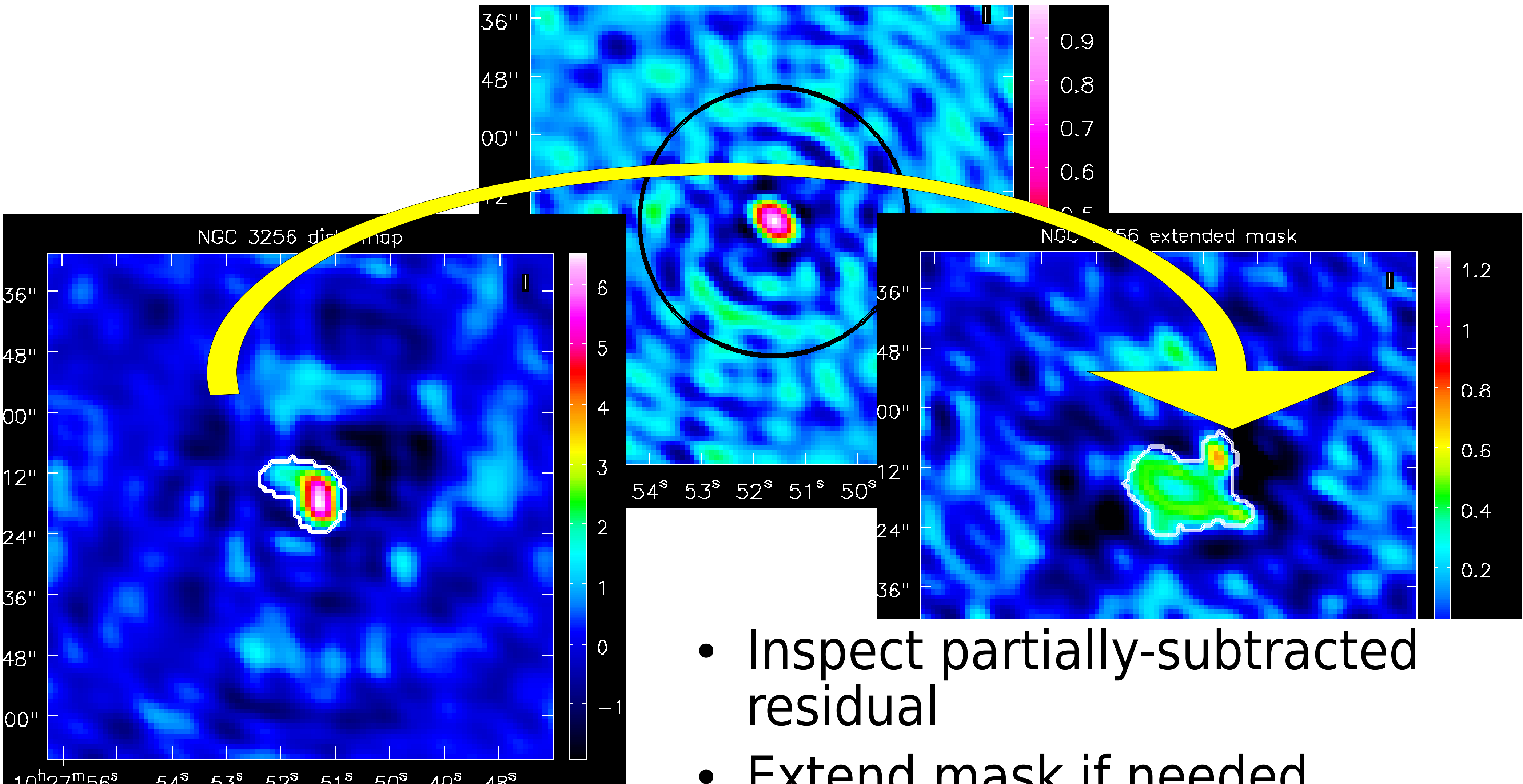




- CLEAN algorithm identifies brightest pixels
- Store e.g. 10% of each peak as Clean Component

Cleaning

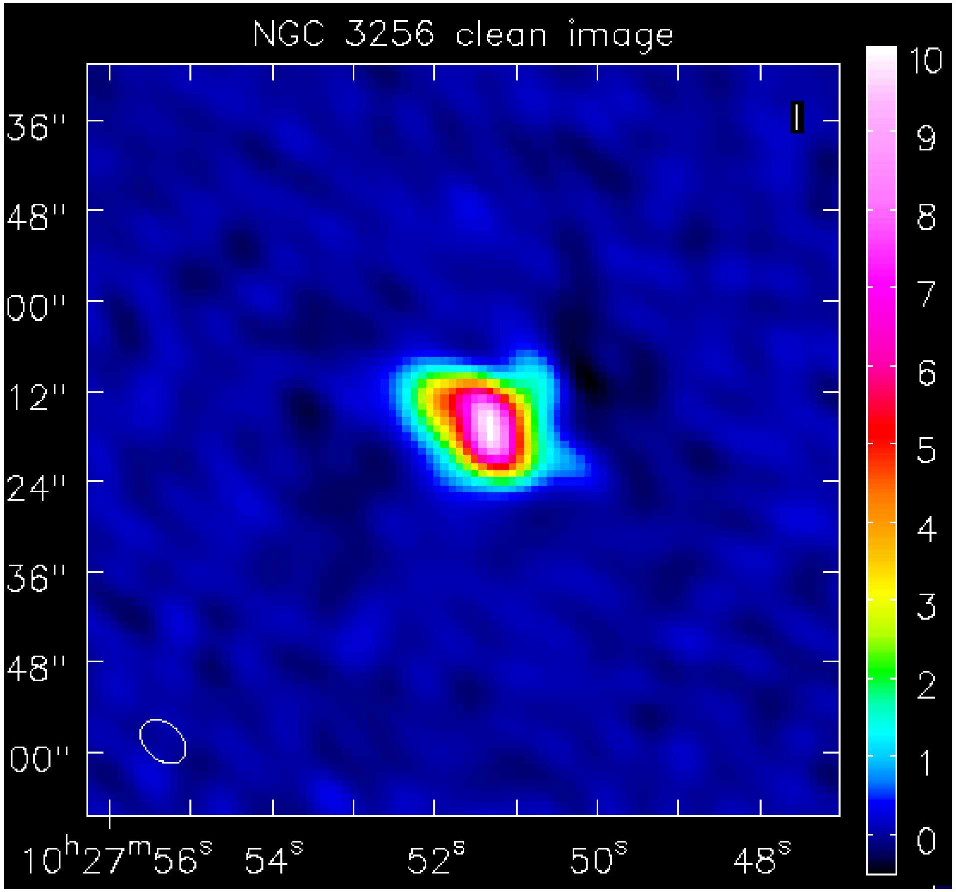
- Iteratively subtract scaled dirty beam at positions of bright pixels



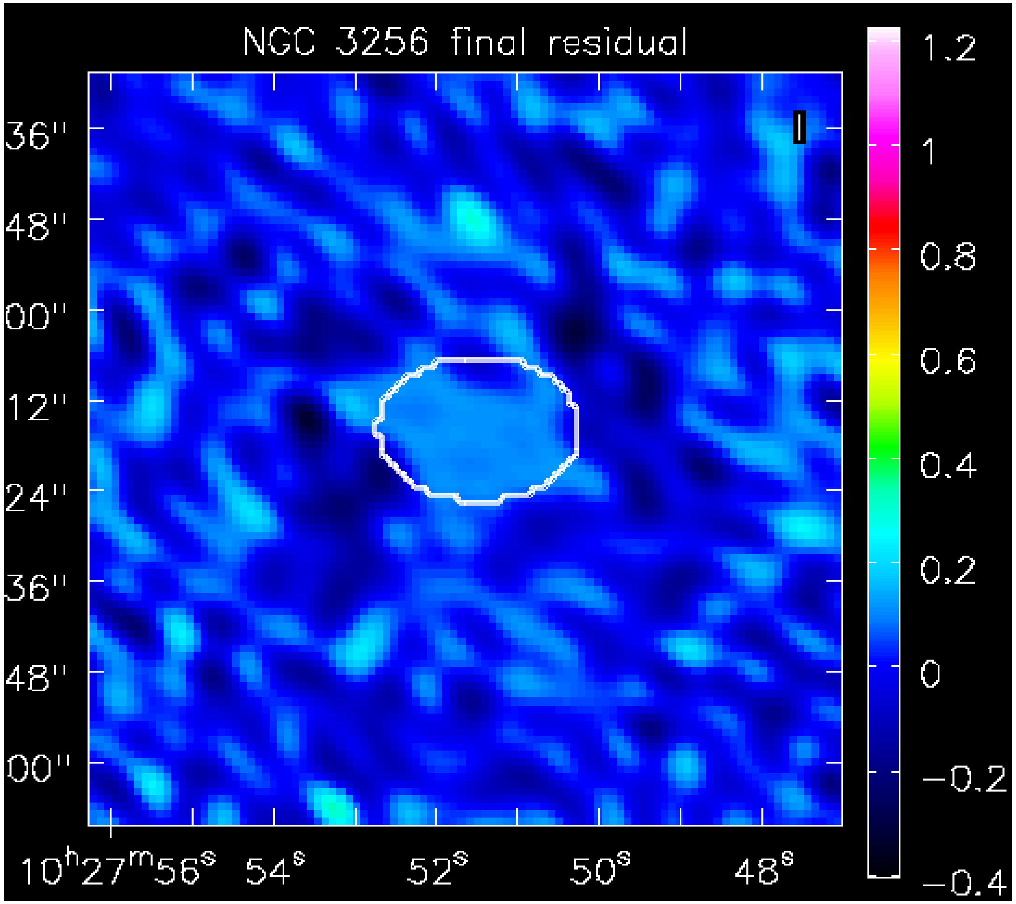
- Inspect partially-subtracted residual
- Extend mask if needed

CLEANed image

- Improved signal-to-noise in final image

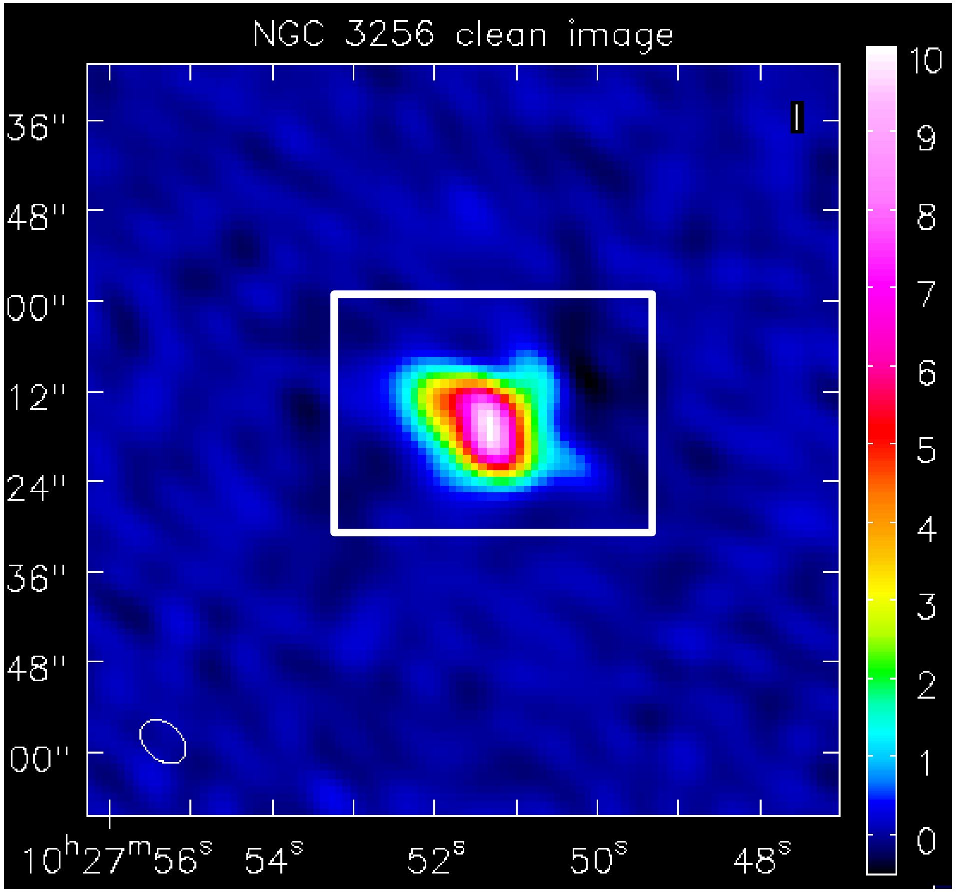


- Residual is just noise
  - Note different flux scale

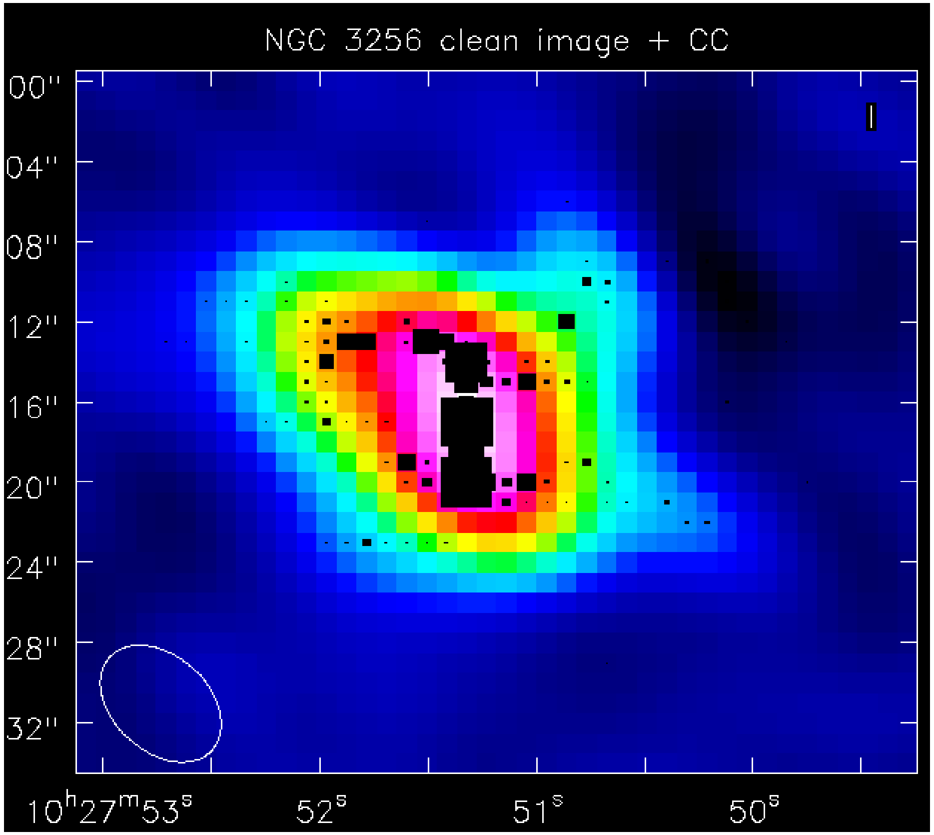


CLEANed image

- Note improved signal-to-noise in image

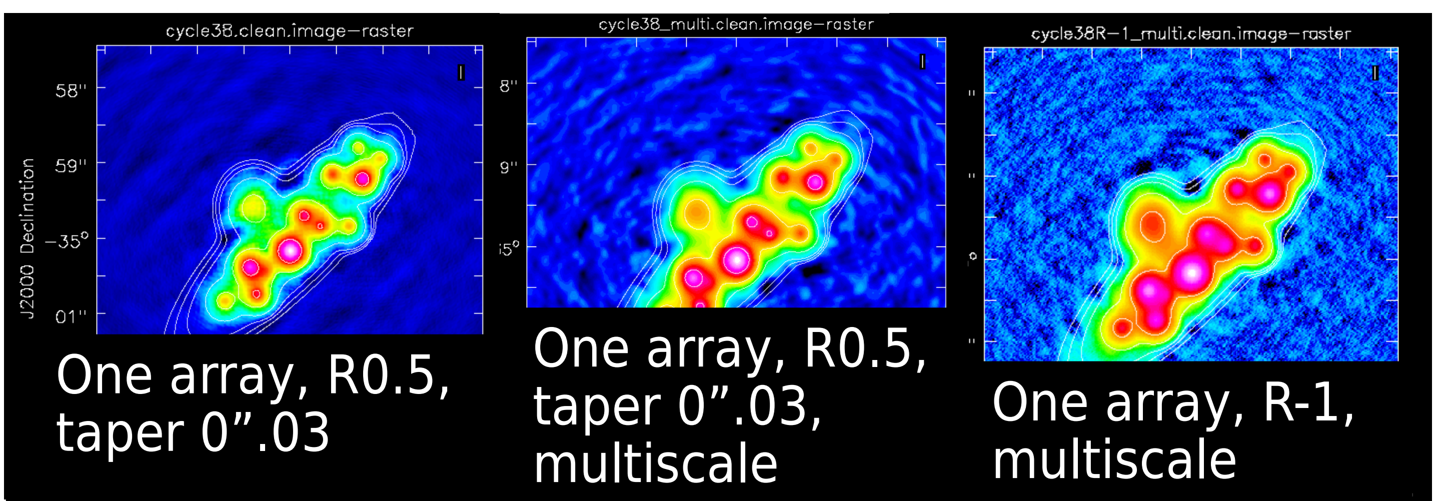


- Final image is combination of residual and Clean Components convolved with restoring beam



Weighting

- Natural weighting: Grid and FT samples
  - Weight zero in grid cells with no samples
- Uniform weighting:
  - All cells same weight
    - Makes resolution finer, but increases noise
- Robust [-2, 2]: intermediate weightings
- Taper: reduce weight of longest baselines
  - Increase sensitivity to large-scale emission
    - Increases noise if effective collecting area reduced

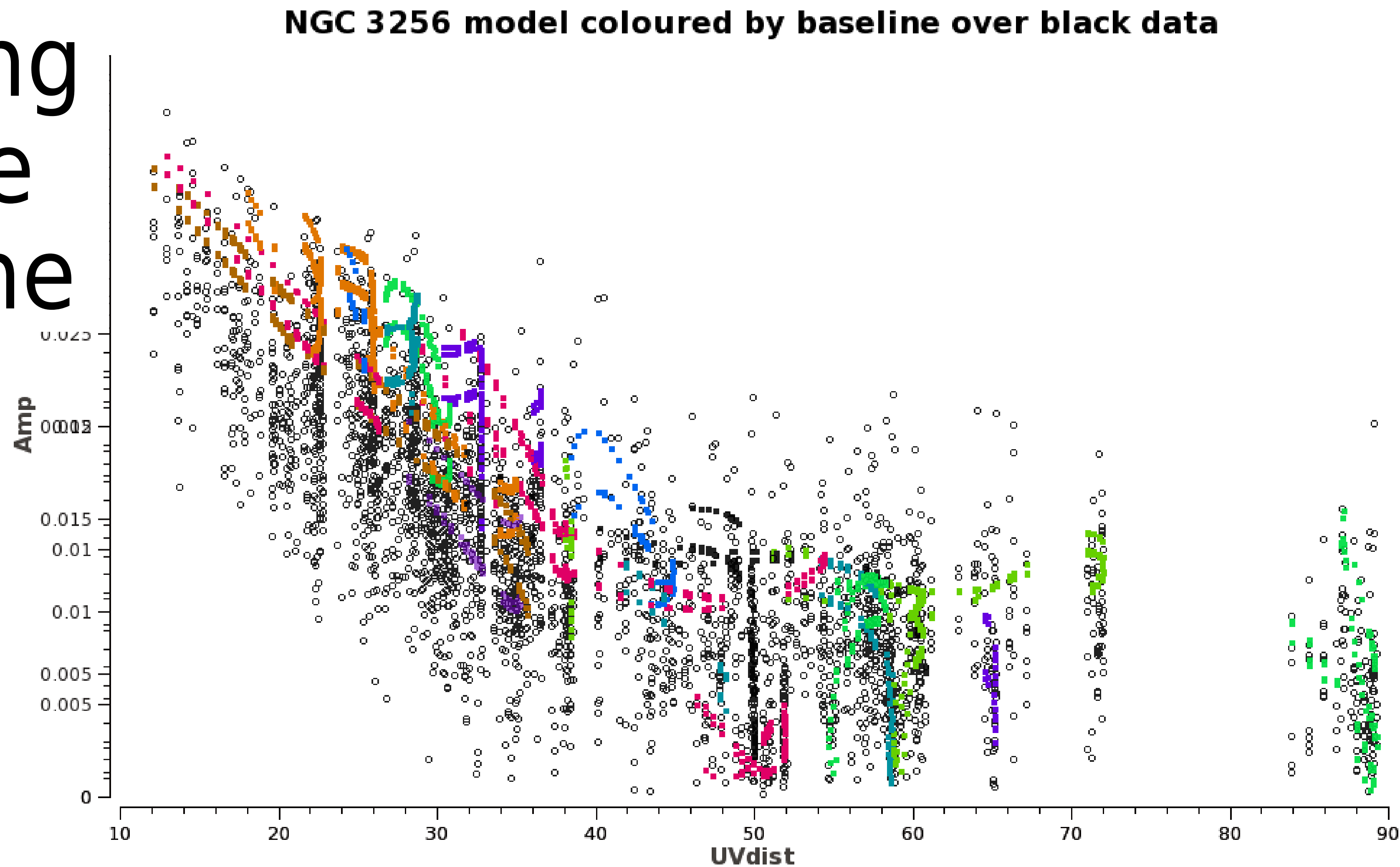


One array, R0.5, taper 0”.03

One array, R0.5, taper 0”.03, multiscale

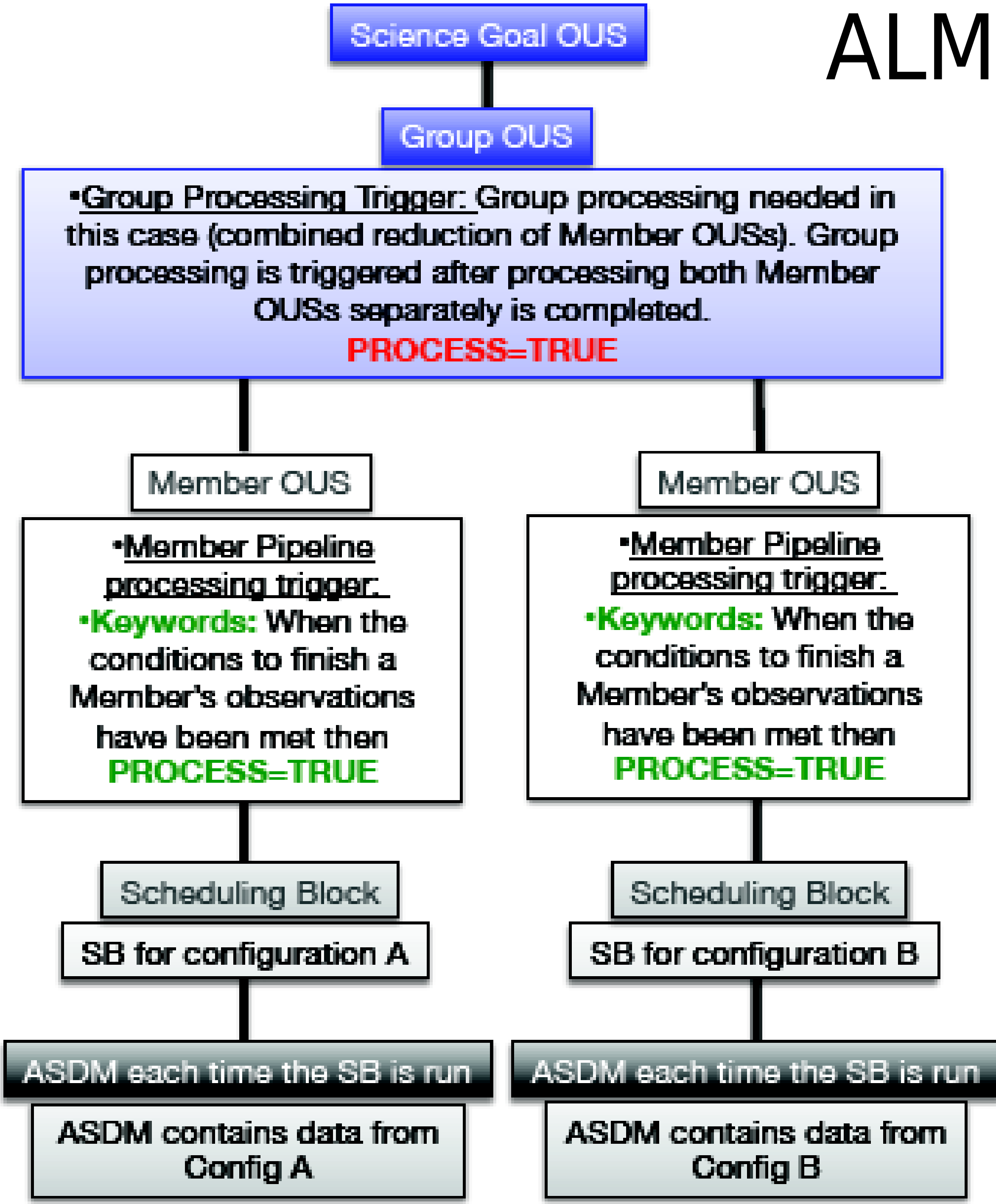
One array, R-1, multiscale

Cleaning and the *uv* plane



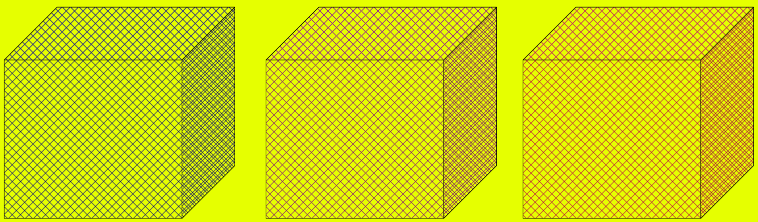
- *uv* model is Fourier transform of Clean Components
  - 'Major Cycles' subtract model from *uv* data and re-make dirty residual image
- Compare model with data to assess quality
  - Use for further rounds of self-calibration

ALMA data processing



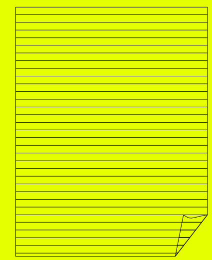
- Each SB self-contained
  - Pointing, flux scale, BP, (pol.) cal scans
  - ~20-40 mins target(s)/phase ref
  - Execute (EB) until sensitivity is reached
    - same spectral & array configuration
- Initial data processing (pipeline or staff script)
  - Convert ASDM to Measurement Set
  - Calibrate
- Combine EBs for target imaging

What ALMA data do you get?



Images/cubes for principal science target channels

Processing summary



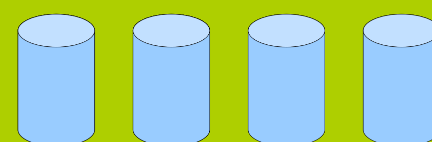
Data processing / pipeline scripts so you could tweak imaging/ self-cal using:

Science products & scripts

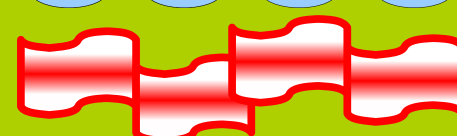
might be all you need

or you could use

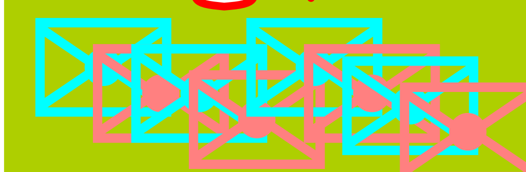
CASA scripts to regenerate edited, calibrated *uv* data



ASDM (one per EB)



Flag tables



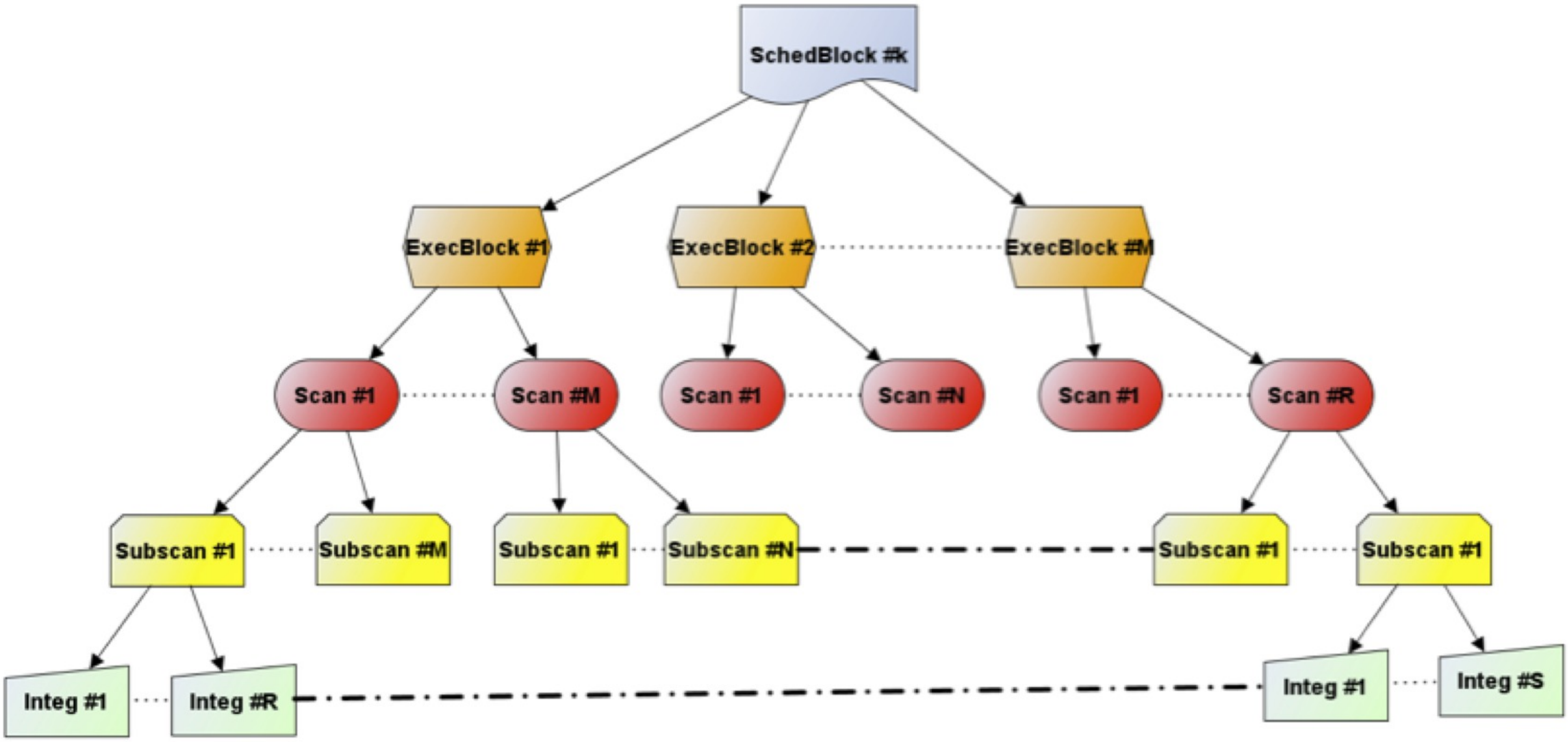
Calibration tables

- Self-calibrate if bright enough (S/N >~20 per scan)
- Re-image
  - Weighting for higher spatial sensitivity/lower resolution or v.v.
  - Change spectral resolution, make spectral index image etc. etc.....

ALMA observing terminology

- Scheduling Block: self-contained observation series
  - Short pointing, flux scale, bandpass, (pol.) cal scans
  - ~20-40 mins alternating between target(s)/ph ref(s)
    - Including multiple mosaic pointings
  - Execute (EB) until desired sensitivity is reached
    - All in same spectral and array configuration
    - Each EB produces one ASDM (ALMA Science Data Model) with binary data and lots of metadata
- Initial data processing (calibration, editing) per-EB
  - Convert ASDM to Measurement Set
- Combine EBs for final target imaging
- May also combine different SBs e.g. ACA+main

Individual scheduling block



CASA

- Common Astronomy Software Applications
  - All ALMA, VLA and similar data reduction tasks
- Python wrapper to aips++ library
  - Access to toolkit, extensions for ALMA etc. fixes
- Uses Measurement Set format
  - Can be converted to/from FITS (some caveats)
    - Export images to use specialised analysis tools
- http://casa.nrao.edu/
  - Cookbook
  - CASA Guides
- https://casaguides.nrao.edu/index.php?title=Analysis_Utilities

(sub-)mm Interferometry Summary

- Atmospheric refraction/absorption dominates quality
  - Cold dry sites OK $\lesssim$370 GHz, exceptional sites $\lesssim$1 THz
  - Troposphere affects phase & amp on $\gtrsim$1s timescales
    - Instrumental calibration (WVR, T_{sys}) etc.
  - ALMA / NOEMA μJy sensitivity, 10 / 100 mas resolution
    - Good sites, many or large antennas
  - Sub-mJy sensitivity at sub-arcsec resolution
    - Extended sources need multiple arrays/SD fill in
    - Large fields need mosaicing
- Normally observe two separate sidebands
  - May have 'mirror' or noise
- Plan night-time, dry season observing at λ sub-mm
- ALMA delivers calibrated data, sample images
  - May want to self-calibrate, reimage changing resolution