High Frequency Radio Interferometry

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June 2, 2026

Outline

- Definition of ‘High Frequency’
    - Science @ high frequencies
- Requirements for High Frequency Observing
    - Transmission
    - Stability
    - Phase Referencing
        - Fast Switching
        - WVRs
        - Band-to-Band Calibration
- Epilogue
    - Self-calibration

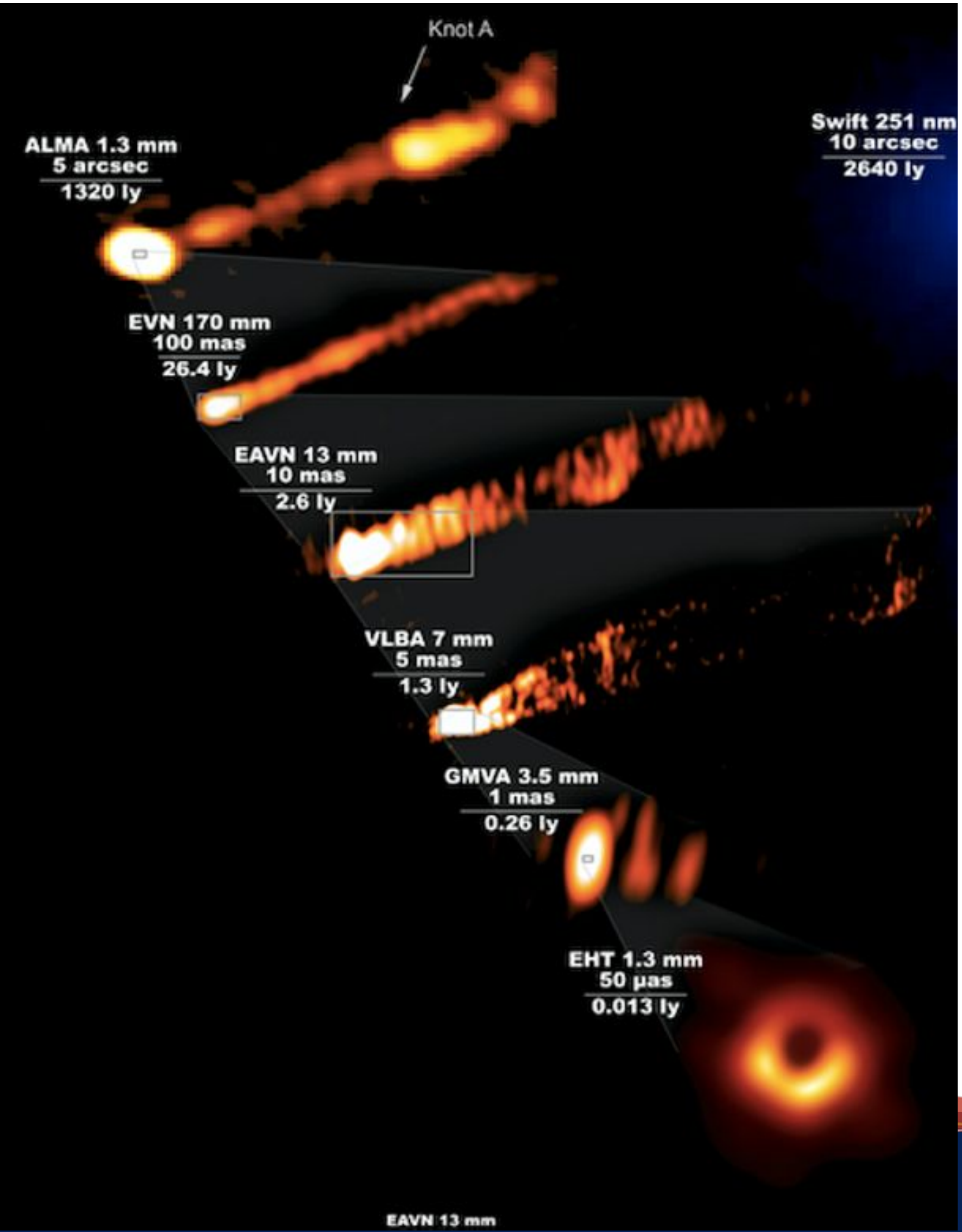
Points to Note

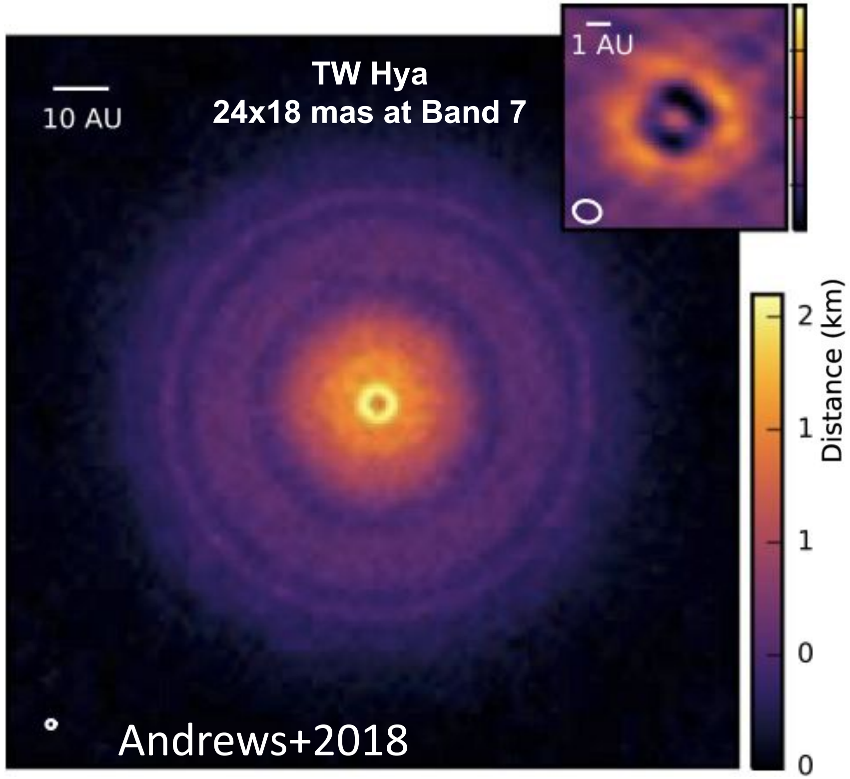
- **Gain Calibrator** = **Phase calibrator** - sometimes called Complex Gain calibrator
- Phase errors can have two effects
  - Random phase variations can decorrelate, reducing the peak amplitude
  - Systematic phase offsets can introduce position shifts
- **Coherence** - peak intensity/true flux density (valid for point sources only)
  - reductions from 1.0 == **Decoherence**
- **Phase RMS (Noise)** - variations in phase wrt their average over a period of time
- **Atmospheric opacity** (or its inverse **transmission**) - how much incoming signal arrives at telescope

High Frequencies

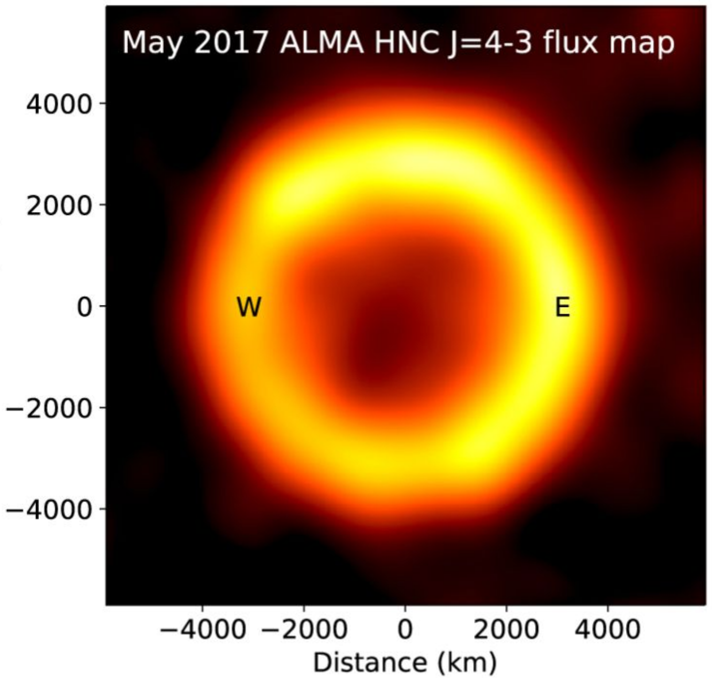
- Definition is subjective
  - @VLA ν ~12 - 50 GHz; ALMA entirely high frequency 30 - 900 GHz
    - However $\nu > 385$ GHz (Bands 8, 9, and 10) can require special considerations
- Why are high frequencies interesting?
  - Dust brightest toward higher frequencies
  - Many bright molecular lines, RRLs, some atomic lines
  - Higher frequencies always provide highest angular and spectral resolution at a given configuration/spectral setup
    - 5 mas - ALMA best resolution (Band 10); ~30 mas VLA best resolution (Q-band)
  - Lower synchrotron opacity

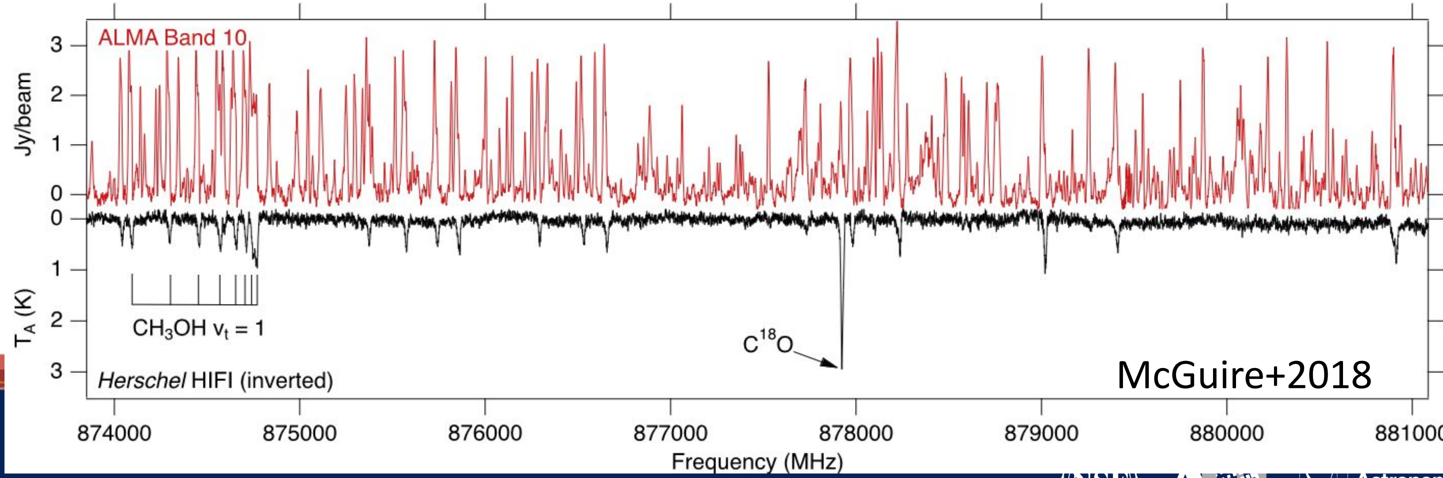
High Frequencies





Titan - Cordiner et al. 2020





Requirements for Good Data at High Frequencies

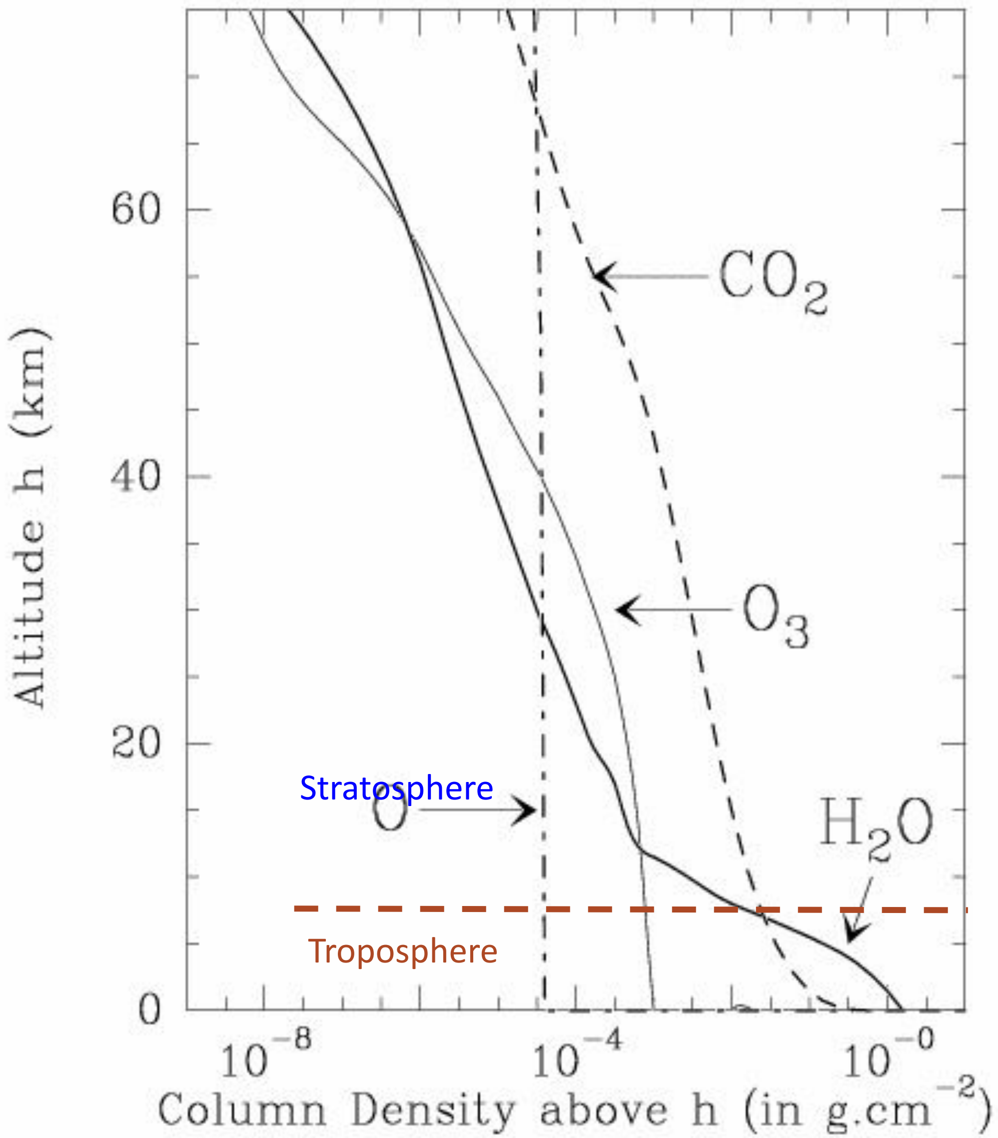
- High atmospheric transmission for the band observed
- Stable atmosphere over a long enough time for phase referencing
- Phase referenced to a point-like phase calibrator, close to the target source

- Other considerations
  - Good pointing solutions, calibrator at center of antenna PB (target at least near)
    - VLA pointing updates necessary ~hourly for high-frequencies
  - Low wind speed
    - can blow the dish off-source (effects similar to poor pointing and phase errors)
  - Accurate antenna surface for observing frequency
    - Otherwise most flux scattered away

Atmospheric Opacity/Transmission

Constituents of Atmospheric Opacity

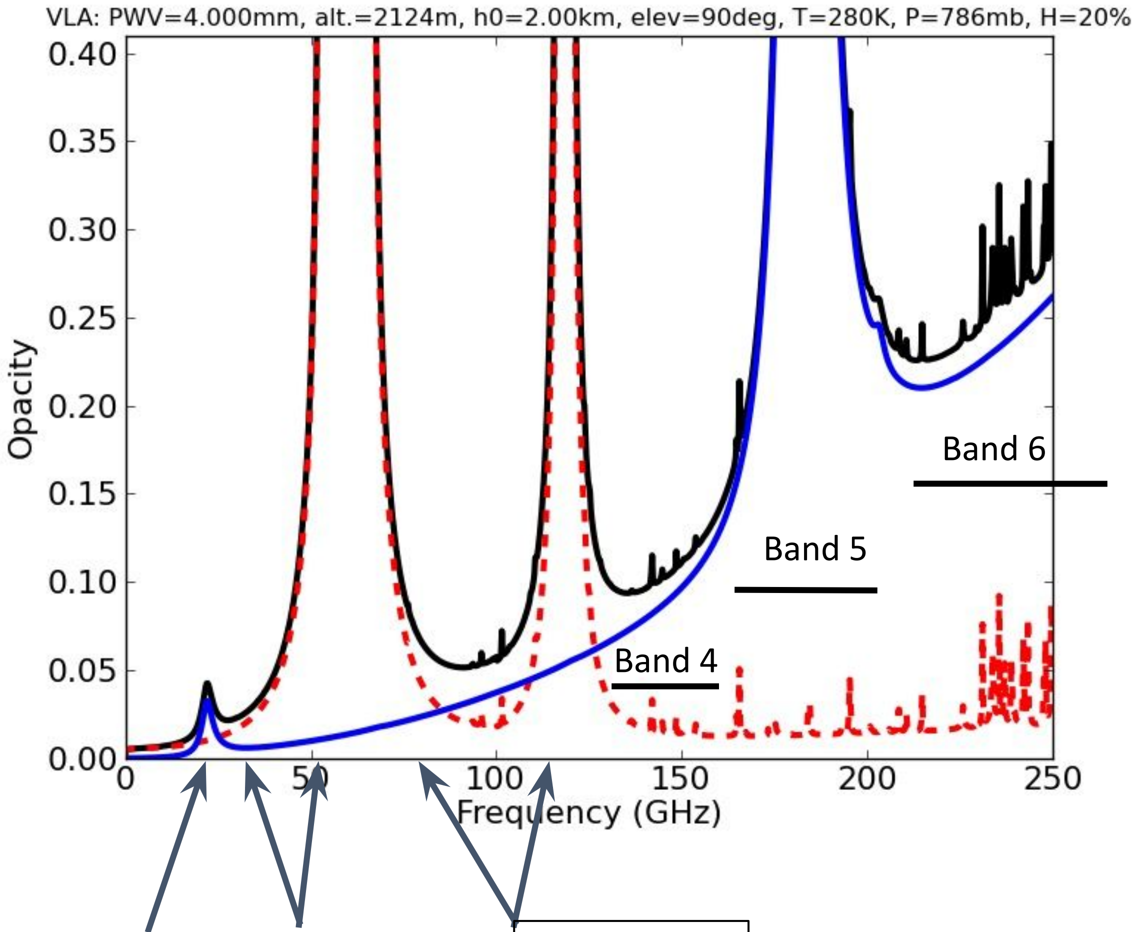
- Due to the troposphere (lowest layer of atmosphere (h < 10 km)
- Temperature drops with increasing altitude
    - clouds/convection
- 'Dry' constituents: O_2, O_3,CO_2, Ne, He, Ar, Kr, CH_4, N_2, H_2
- H_2O: abundance is highly variable but < 1% in mass, mostly in form of water vapor
- Typically express opacity in terms of precipitable water vapor (pwv) - thickness of water layer if all converted to liquid



Opacity vs. Frequency

- Typically express opacity in terms of precipitable water vapor (pwv)
- Wavelengths > 1.5 cm, dry atmosphere, little opacity
- ~1.3 cm opacity mostly from H_2O vapor
- 10mm-6.5 mm opacity mostly from dry atmosphere
- At 3mm both are significant
- < 3mm mostly H_2O
- ‘hydrosols’ (water droplets, i.e., clouds) can also add significantly to the opacity

VLA site at 4mm pwv (good conditions!)



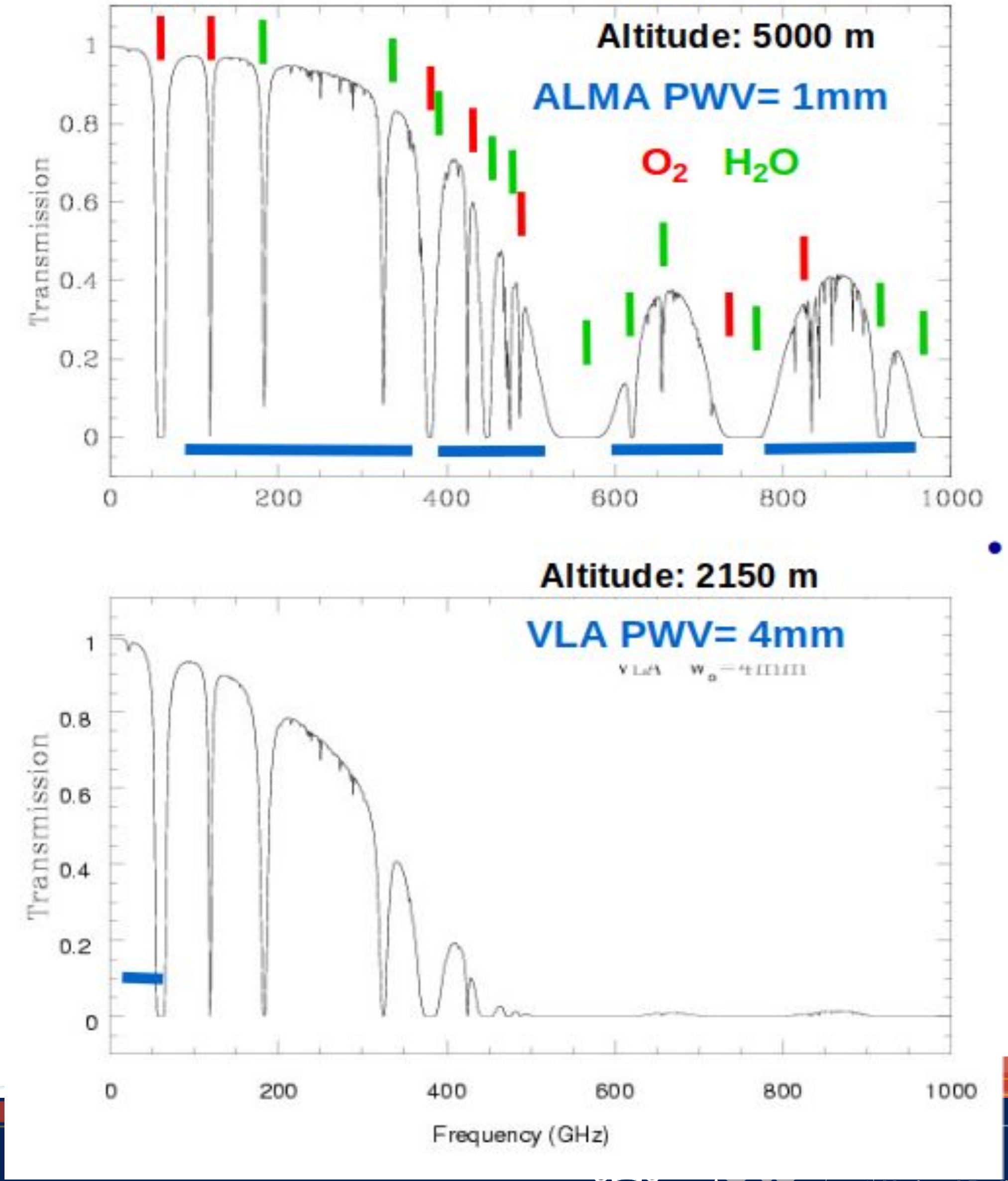
1.3cm
VLA K-band
ngVLA

10mm-6.5mm
VLA Ka/Q
ALMA Band 1
ngVLA

3mm- ALMA
Bands 2-3
ngVLA

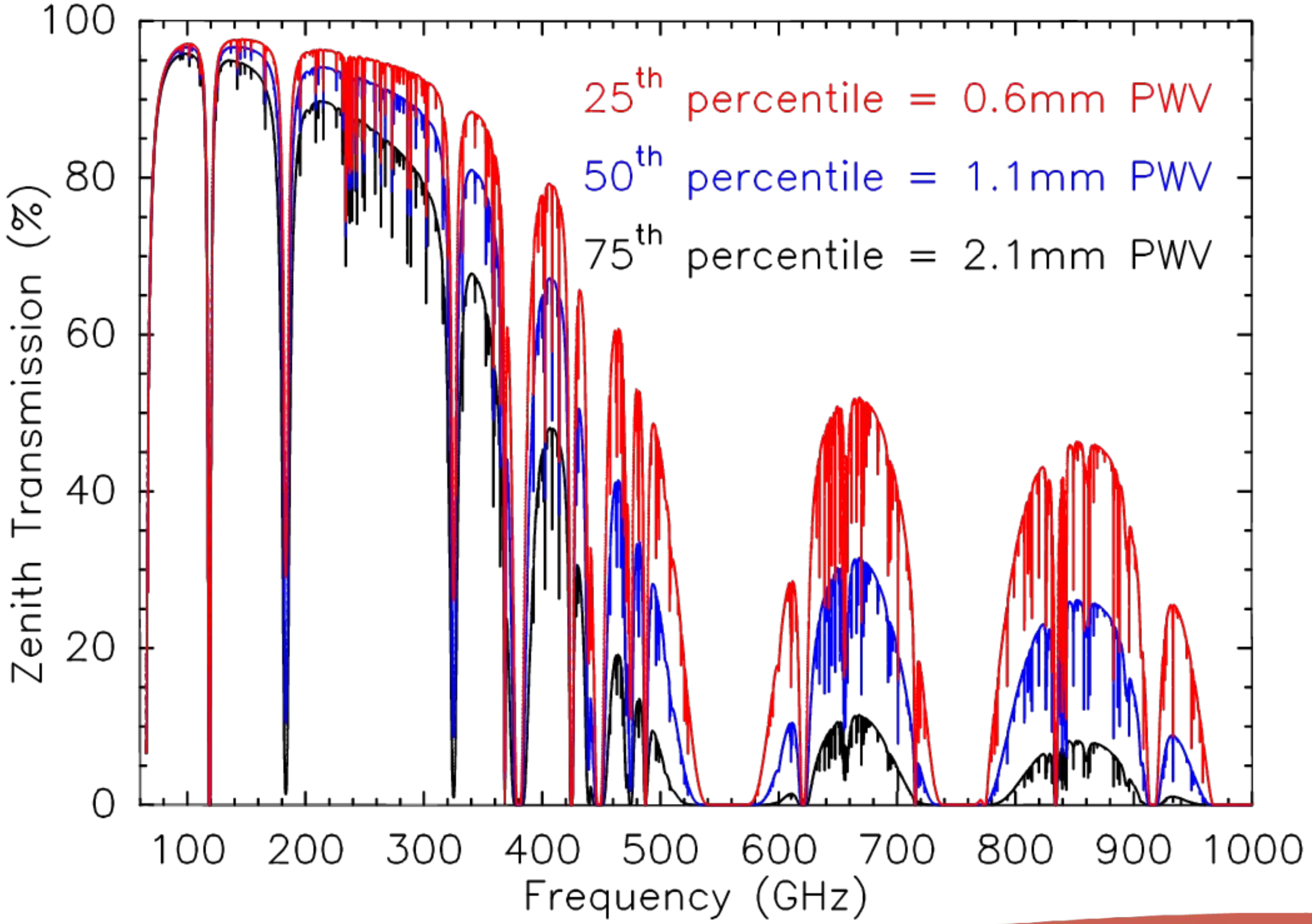
Transmission/Opacity depends on Altitude

- Transmission is inverse of opacity
- Transmission is not a problem for most VLA bands (<50 GHz)
- Serious problem for ALMA at >300 GHz
- Differences are primarily due to elevation vs. scale height of the water vapor, not how ‘dry’ a place is on the surface

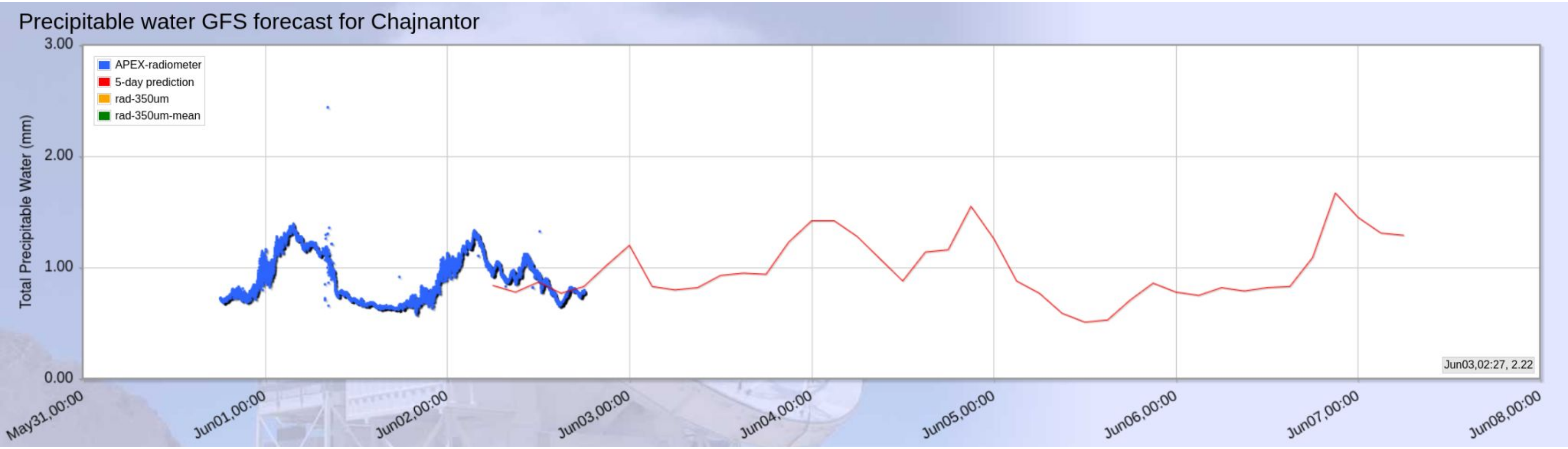


Transmission at ALMA for different PWV

Octile	PWV (mm)	
1	0.472	Band 5*, 9 ,10
2	0.658	Band 8, 9
3	0.913	Band 7, 8
4	1.262	
5	1.796	Band 6
6	2.748	Band 4
7	5.186	Band 1,2,3



PWV Monitoring and Forecasting



Requirements for Good Data at High Frequencies

- ✓High atmospheric transmission for the band observed
  - High dry site
  - Dynamic scheduling
    - no choice but to wait for optimal PWV

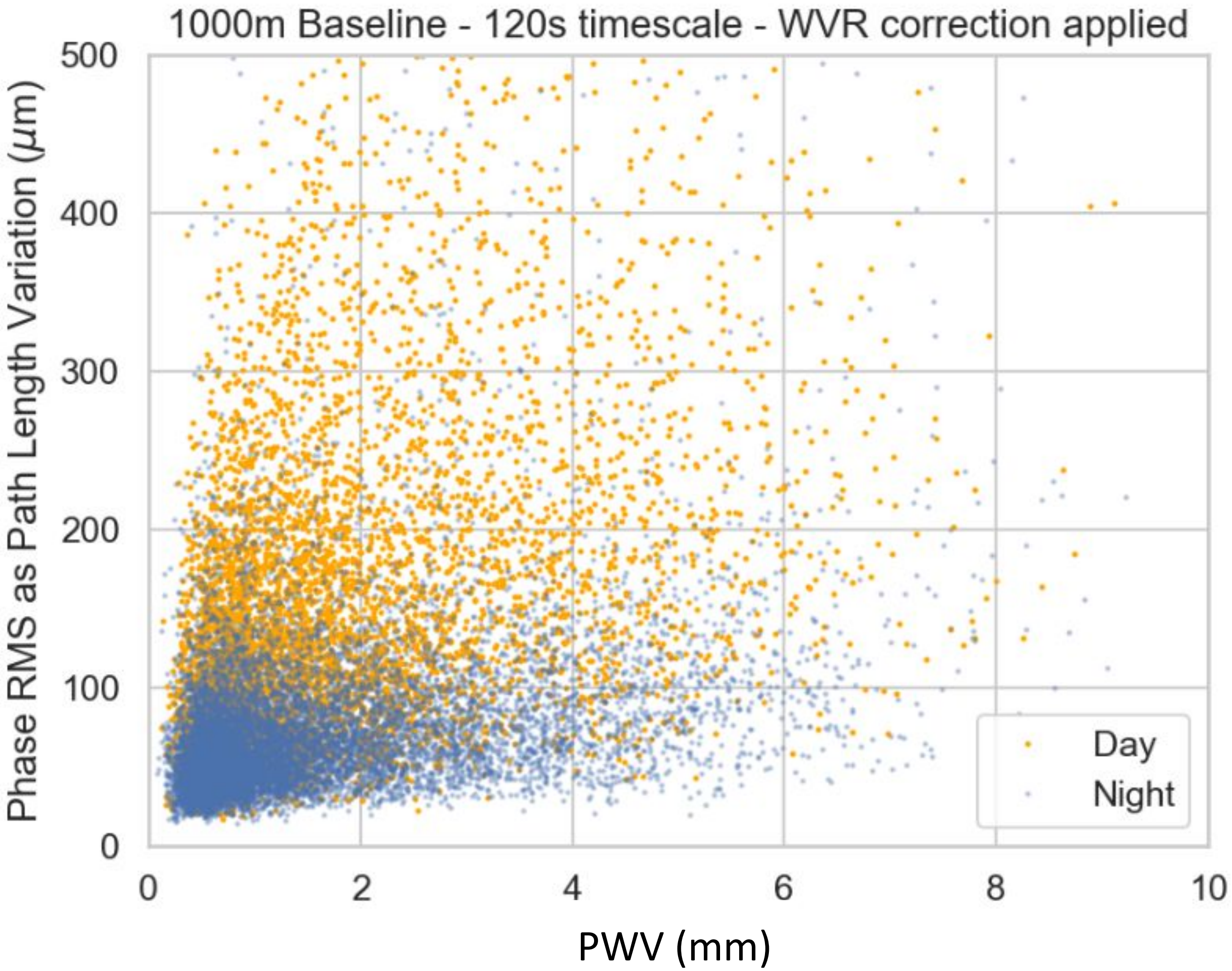
- Stable atmosphere over a long enough time for phase referencing

- Phase referenced to a point-like phase calibration, close to the target source

Atmospheric Stability

- Transmission is one aspect of high frequency observing
- Low PWV/or high transmission does not always mean 'good observing'
- Also need good phase stability
  - possible to have one without the other

- Path length variation corresponds to difference in arrival time at antennas -> phase shifts
  - Can be highly time variable



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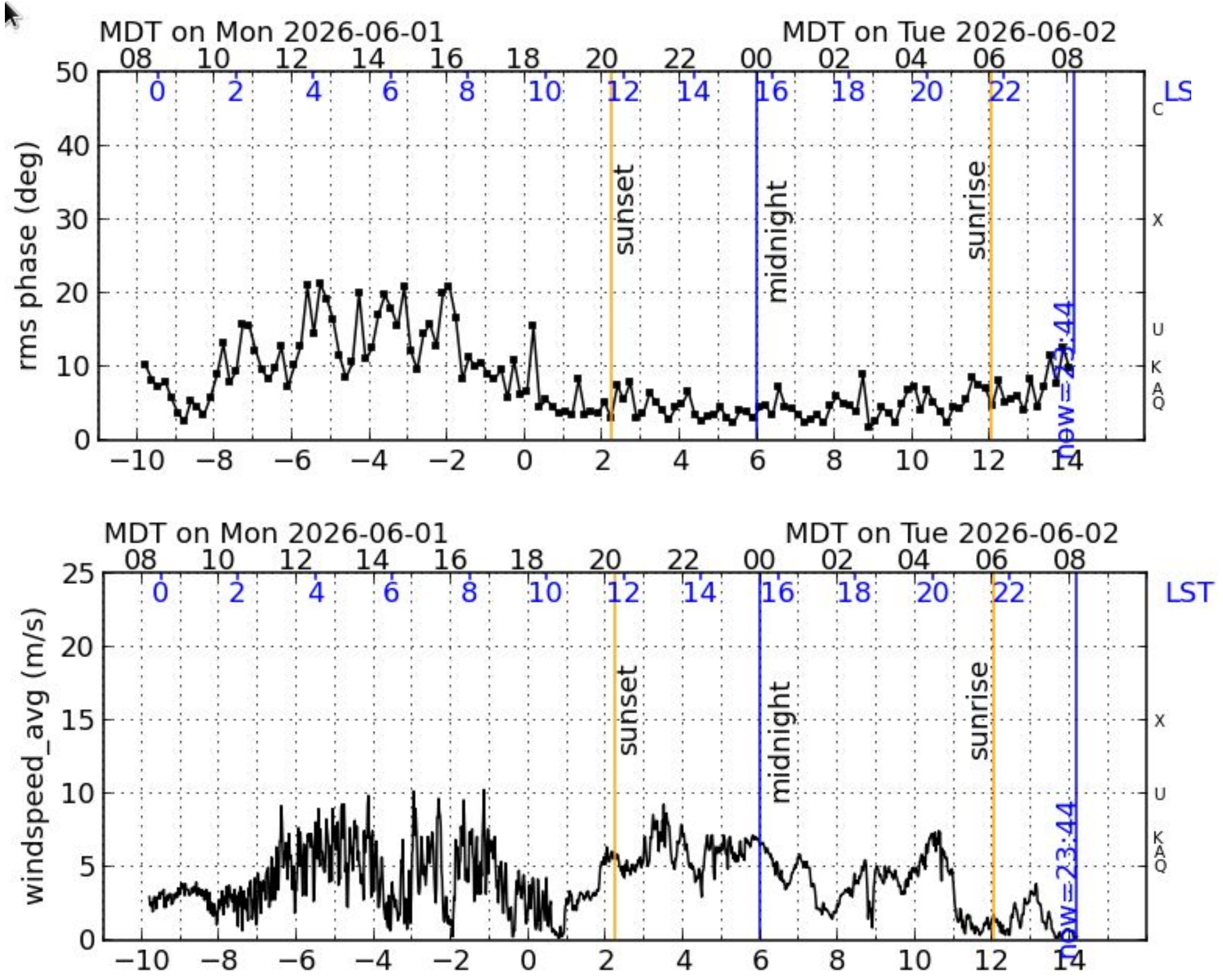


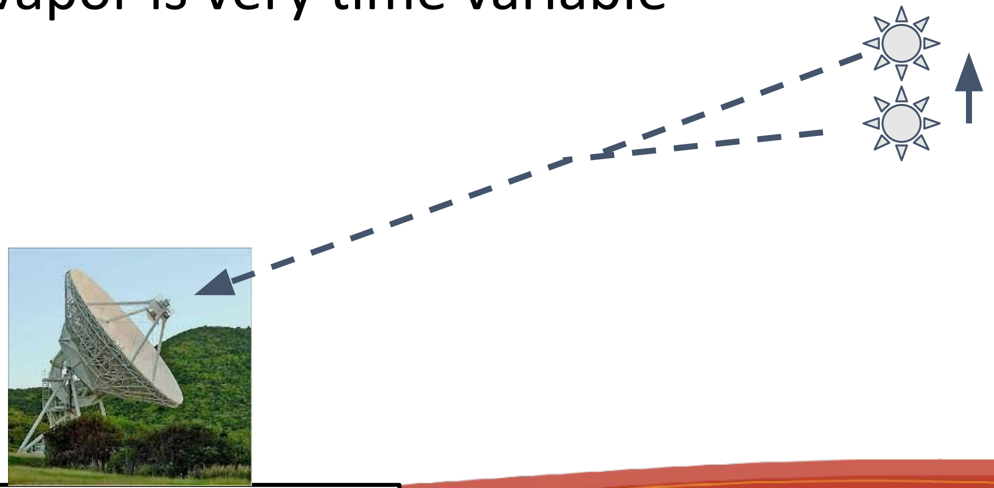
https://www.aoc.nrao.edu/cgi-bin/weather/apipg.cgi

Mean Effect of Atmosphere on Phase - Refraction

- Index of refraction of atmosphere ≠ 1, an EM wave will experience refraction
- The phase change is related to the index of refraction of air and the distance travelled by $\delta\varphi = 2\pi/\lambda \times n\, D$
- $N = (n - 1) \times 10^6$ is typically separated into ‘dry’ air and water vapor components

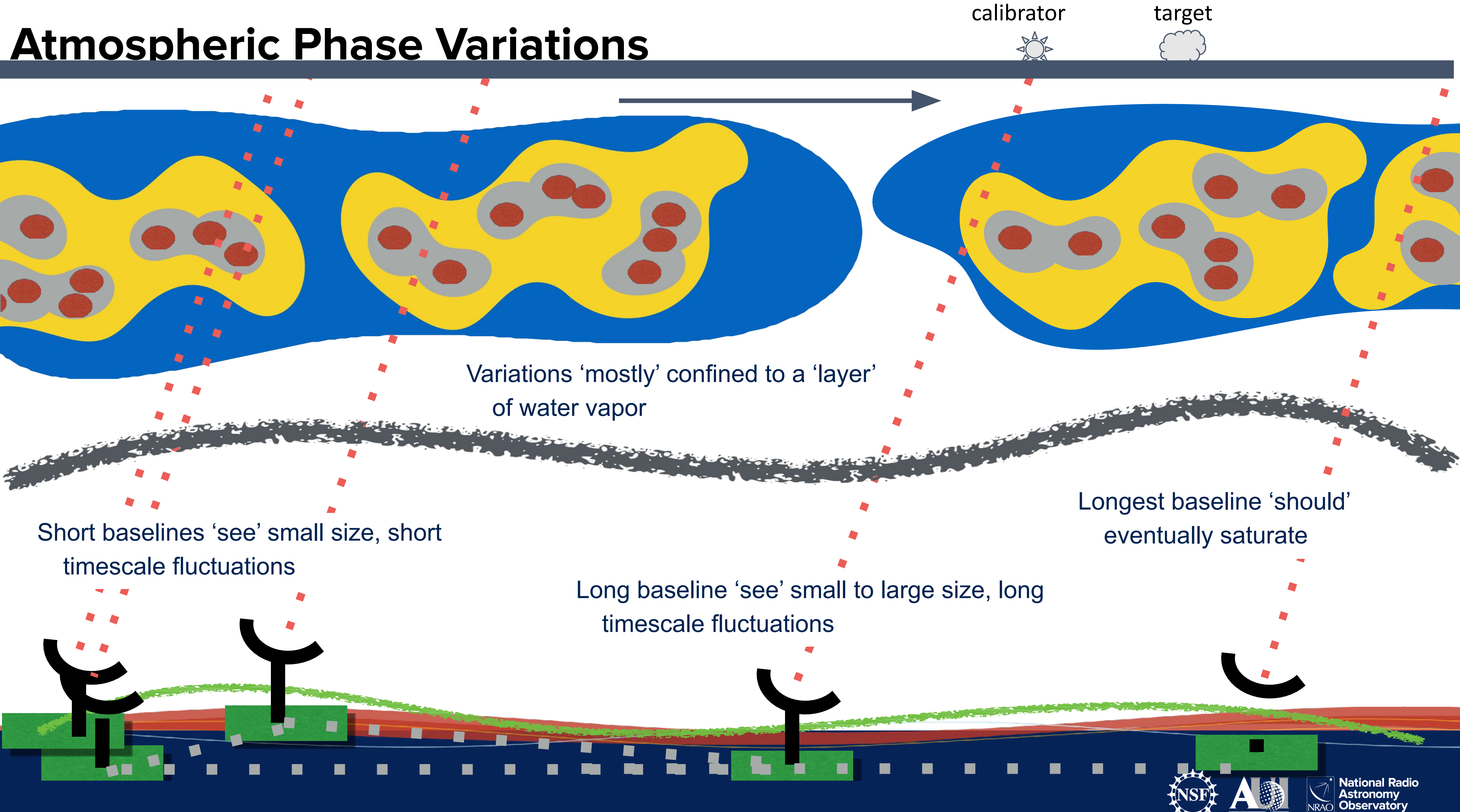
  $N_{dry} = 2.2 \times 10^5 \rho_{tot}$ $\rho_{tot} \sim 700 - 1000\ \mathrm{g\ m^{-3}}$

  $N_{H2O} = 1.7 \times 10^9 \rho_{H2O}/T_{atm}$ $\rho_{H2O} \sim 0.01 - 0.001 \rho_{tot}$ and $T_{atm} \sim 270$ K
- Dry air dominates the refraction by ~10x, but water vapor is very time variable
- $\delta\varphi \cong 6.3 \times 2\pi/\lambda \times W$ where W is the PWV in mm
- Refraction causes:
  - Pointing offsets, $\Delta\theta \approx 2.5 \times 10^{-4} \times \tan(z)$ (radians) @ zenith angle z=45° typical offset is ~1 arcmin
  - Delay offsets (photon time of arrival)



These `mean’ effects are generally removed by the ‘online’ system at the observatory

Atmospheric Phase Variations



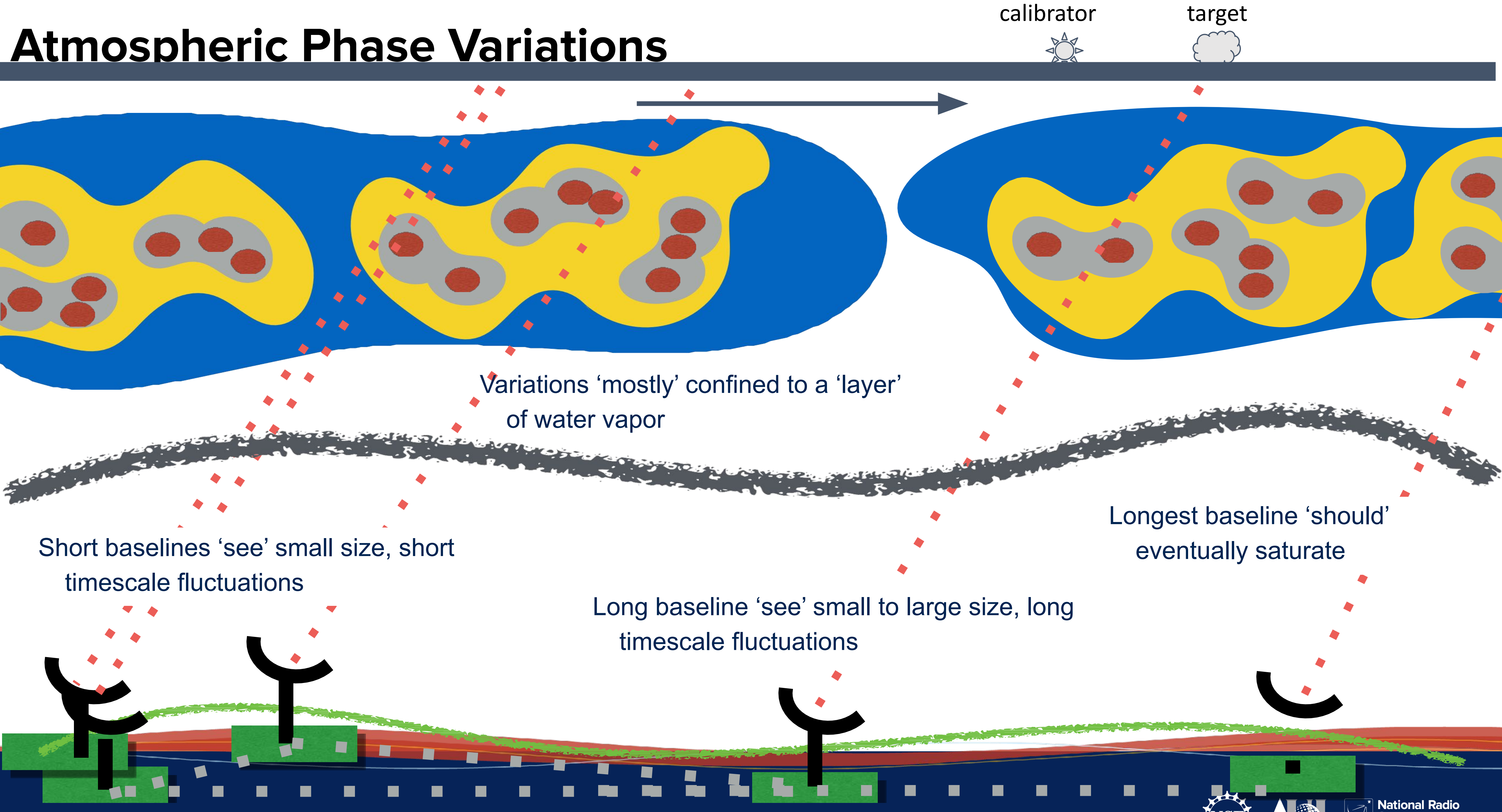
Variations ‘mostly’ confined to a ‘layer’ of water vapor

Short baselines ‘see’ small size, short timescale fluctuations

Long baseline ‘see’ small to large size, long timescale fluctuations

Longest baseline ‘should’ eventually saturate

Atmospheric Phase Variations



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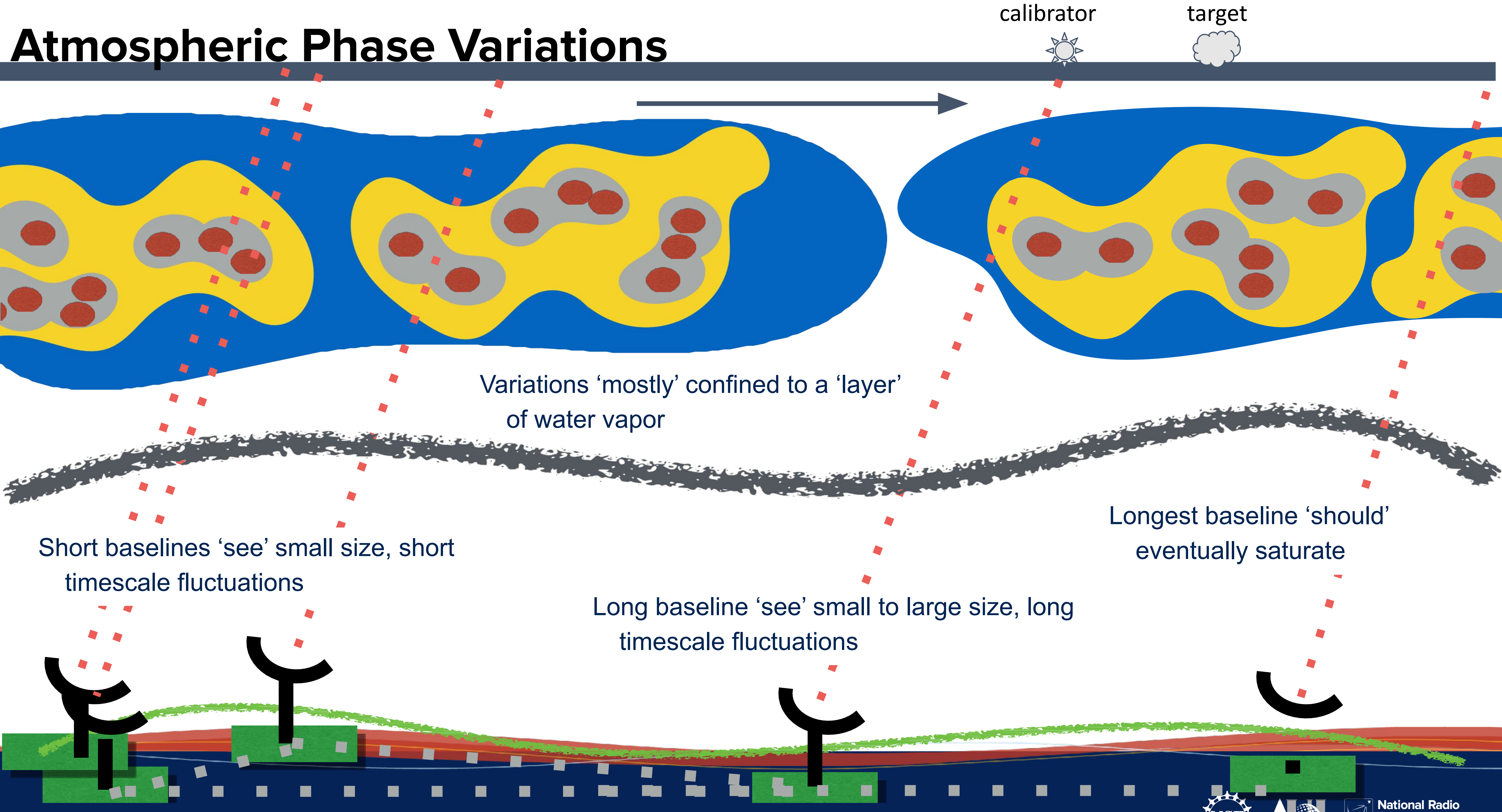

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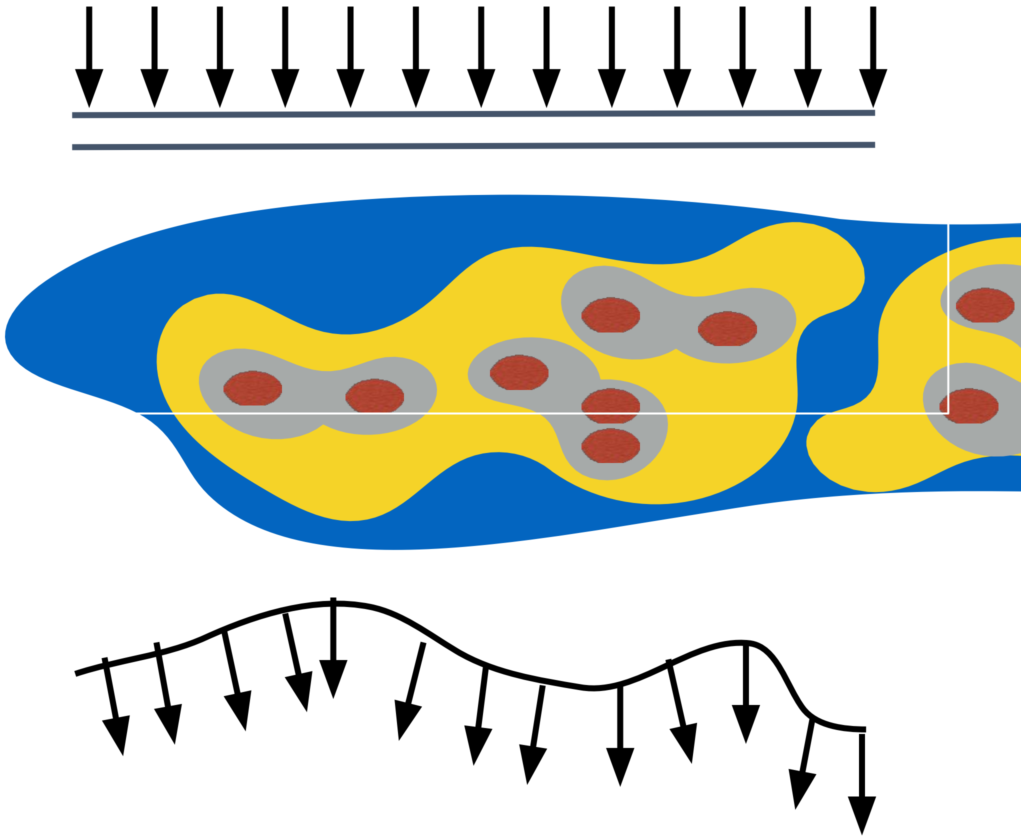
Mean Effect of Atmosphere on Phase - Refraction

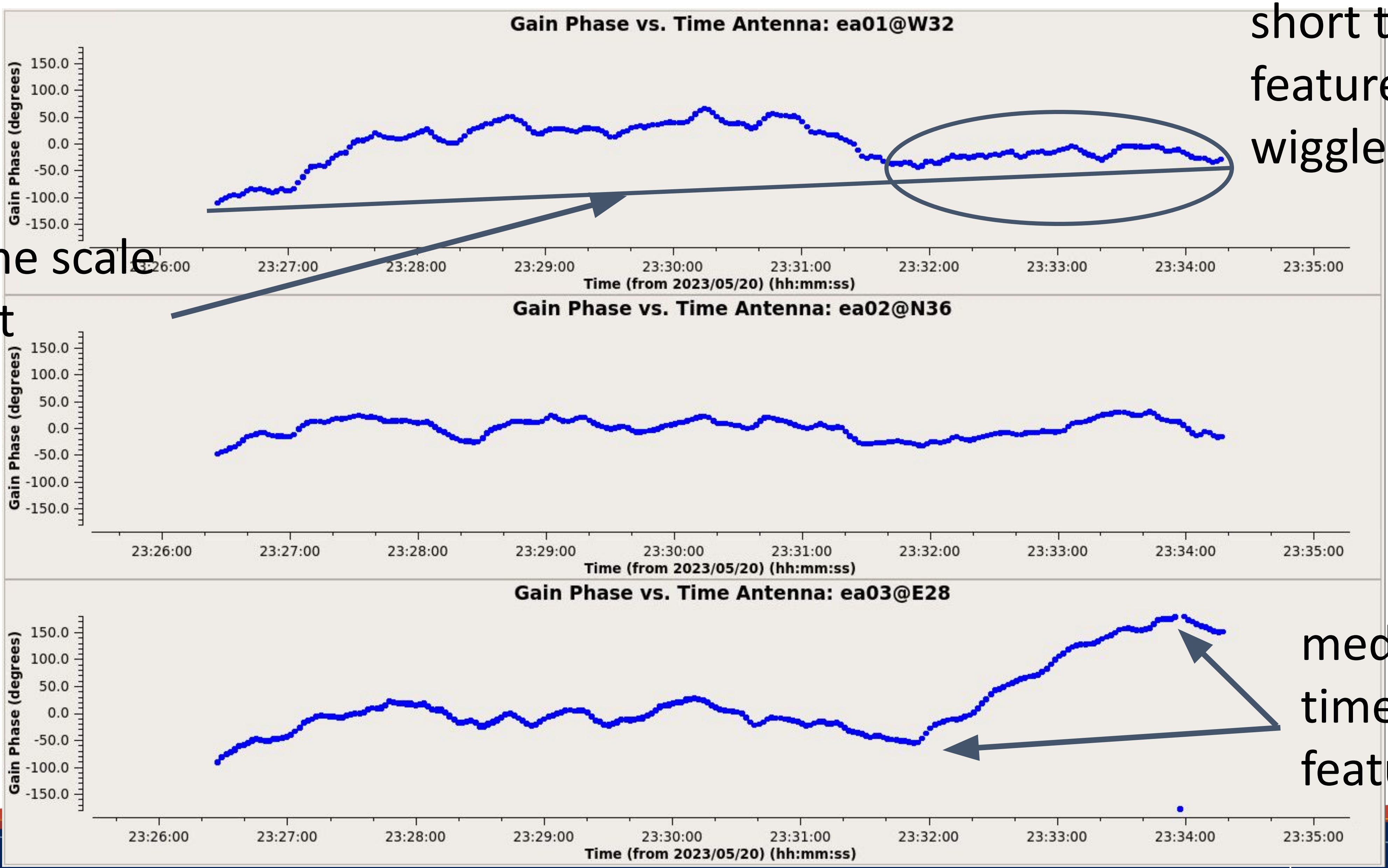
- Spatial and temporal variations in the amount of PWV causes phase variations, which are worse at higher frequencies and result in:
  - Loss of coherence (reduced detected signal)
  - radio ‘seeing’ typicalling 0.1 - 1” at 1.3 mm
  - Anomalous pointing and delay offsets



Patches of air with different water vapor content (and hence index of refraction) affect the incoming wavefront differently.

Atmospheric Phase Variations

VLA K-band data, mediocre weather



short time scale features (small wiggles)

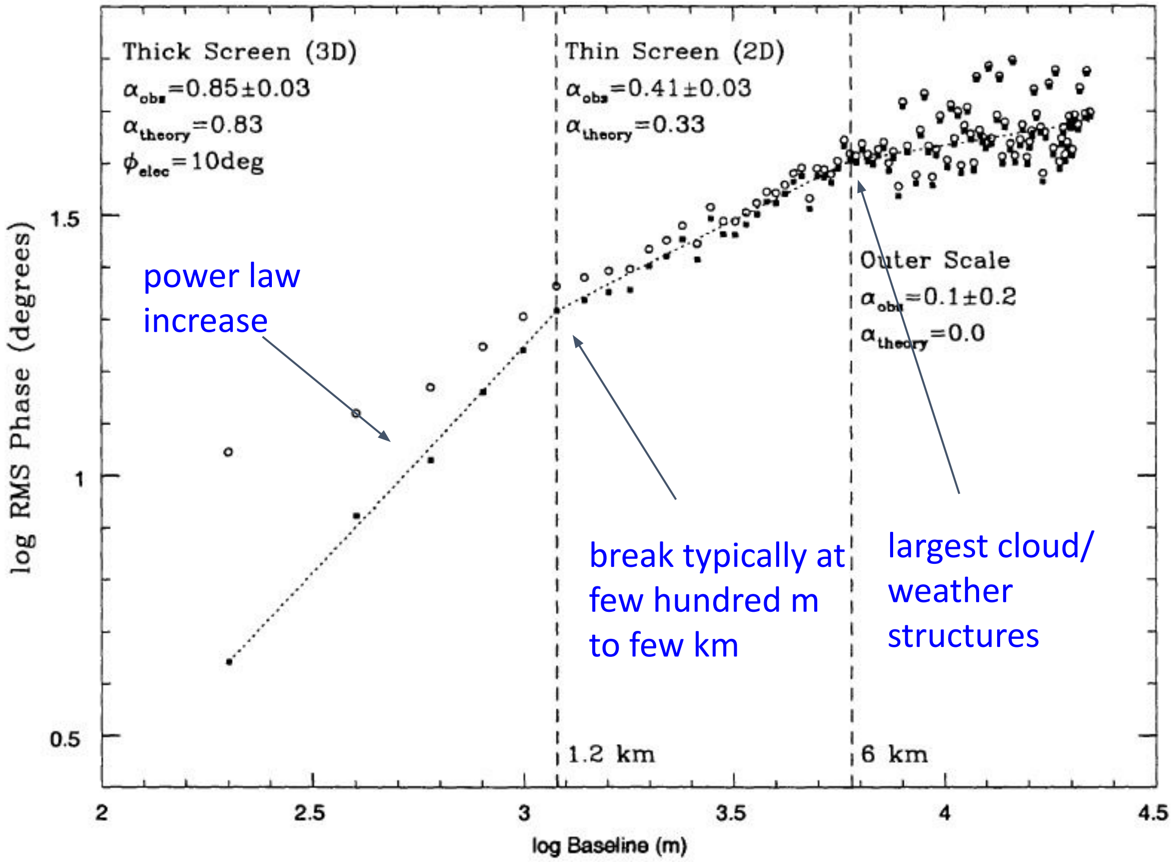
long time scale gradient

medium timescale feature

Atmospheric Phase Fluctuations

- ‘Root phase structure function’ Carilli+1999
- RMS phase variations grow with baseline length until break when baseline length ~ turbulent layer thickness
- Position of break and the maximum variation depends on weather, wavelength, and site
- RMS phase of variations given by Kolmogorov turbulence theory
  - f_{rms} - $Kb^{a}/\lambda(\mathrm{mm})$ (degrees)
  - b= baseline (km, $a = \frac{1}{3} - \frac{5}{6}$, thick 3D vs thin 2D atmosphere
  - K=constant (~100 for ALMA, 300 for VLA)

VLA phase variations vs. baseline length at 1.3 cm



power law increase

break typically at few hundred m to few km

largest cloud/ weather structures

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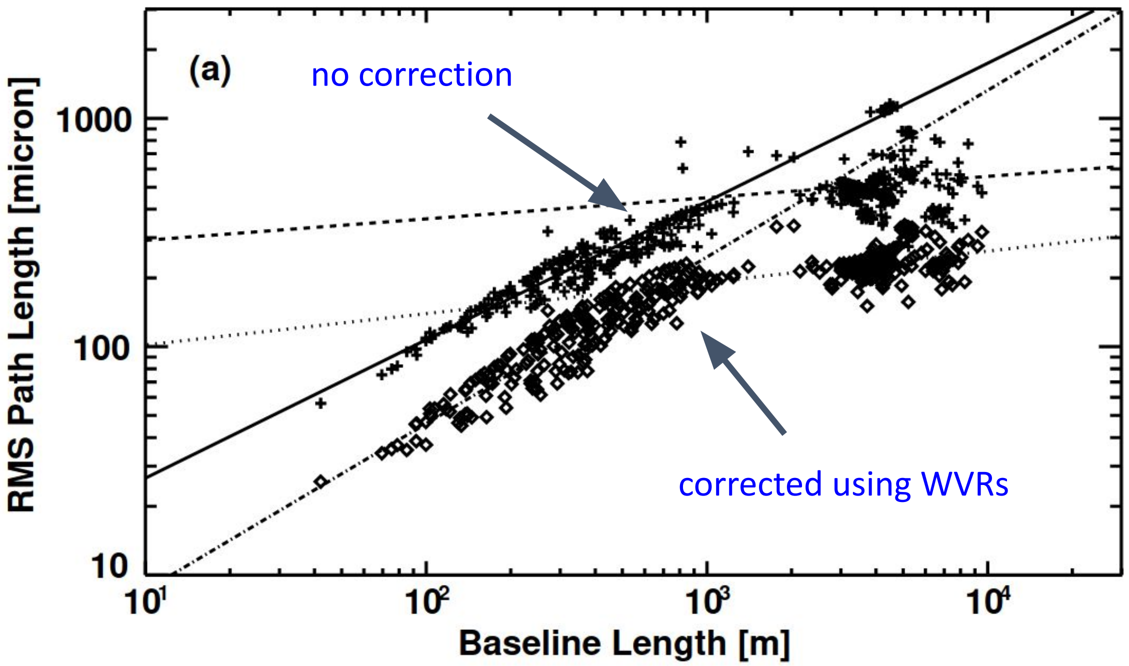
ALMA phase variations vs. baseline length



Significant increase in coherence from application of WVR correction

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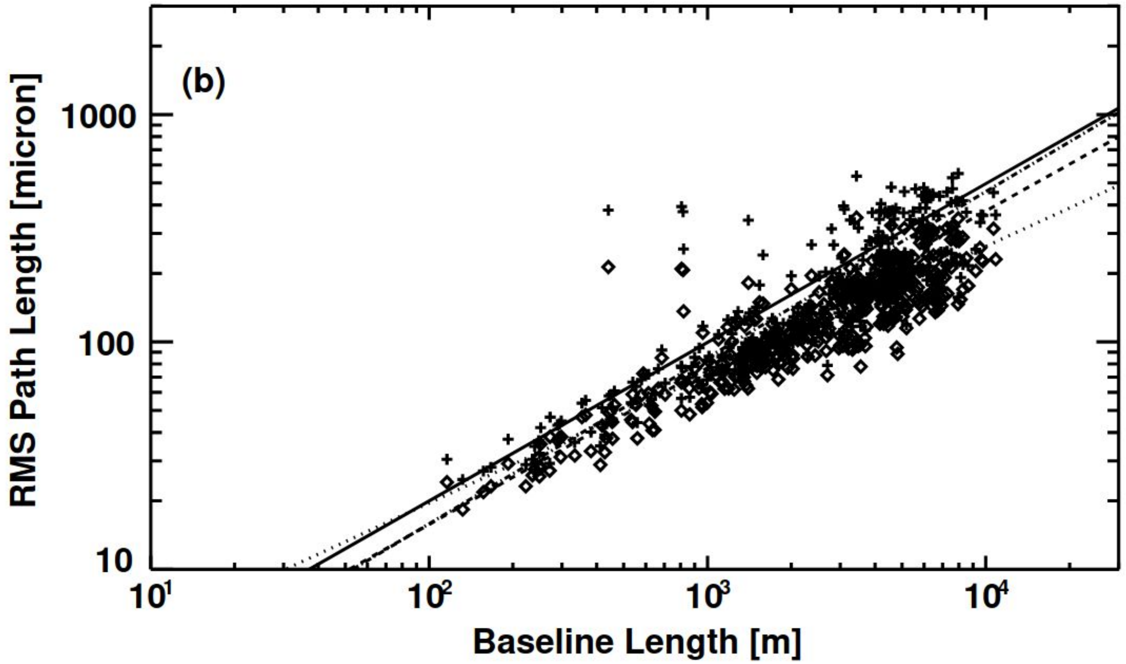
ALMA phase variations vs. baseline length



No break in structure function, turbulent layer > 10 km in thickness, like due to dry air opacity and not water

Residual Phase and Decorrelation

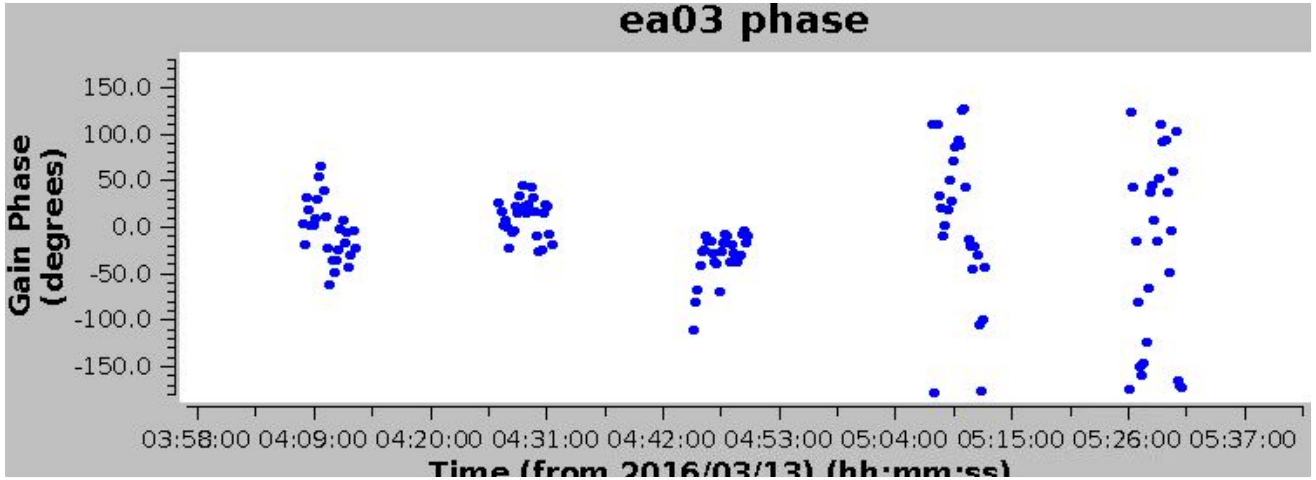
- Atmosphere needs to be stable enough to calibrate phase
- **Coherence** = [vector avg]/[true vis amp] = $\langle V\rangle/V_o$ where, $V=V_o e^{i\phi}$
- $\langle V\rangle = V_o\langle e^{i\phi}\rangle = V_o e^{-\phi_{rms}^2/2}$ (Gaussian phase fluctuations)

Degrees	**Coherence**
10	**0.98**
30	**0.87**
~57	**0.61**
100	**0.22**

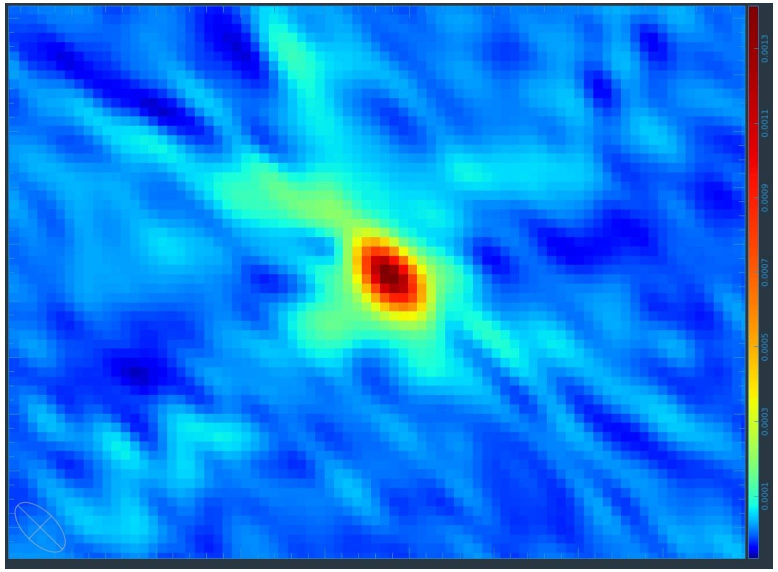
- Example: if ϕ_{rms} = 1 radian (~60°), coherence = $\langle V\rangle = 0.60V_o$
- $\phi_{rms} = 30^o$ coherence (ideal) ~0.9 V_o (ideal)
- Decorrelation on shortest calibration timescale can introduce fluxscale errors

Residual Phase and Decorrelation

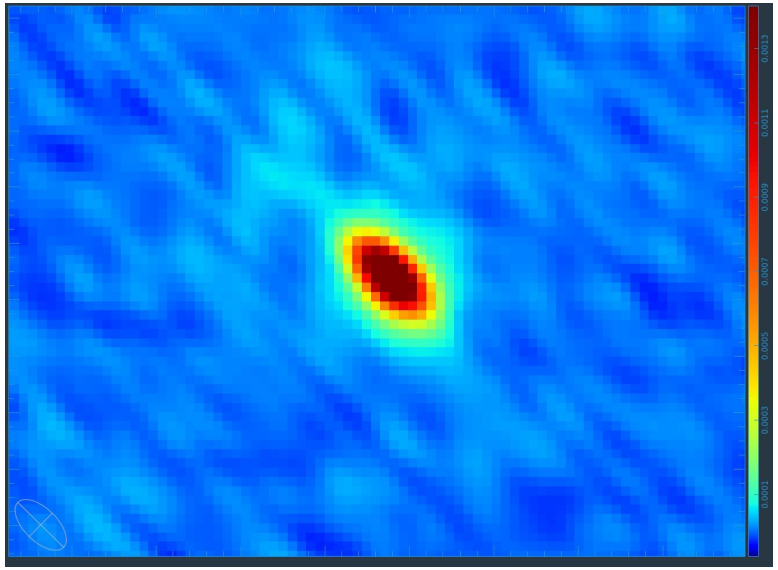
- Decoherence does not (always) manifest in RMS noise for science target
- Overall image RMS may not change but peak intensity is reduced
- VLA Ka-band data, C-config
    - ~7 minute cycle time



VLA Ka-band observations; C-config. 16A-197;HOPS-87



Standard phase referencing:
Peak = 1.35 mJy/bm
rms ~11.2 uJy/bm

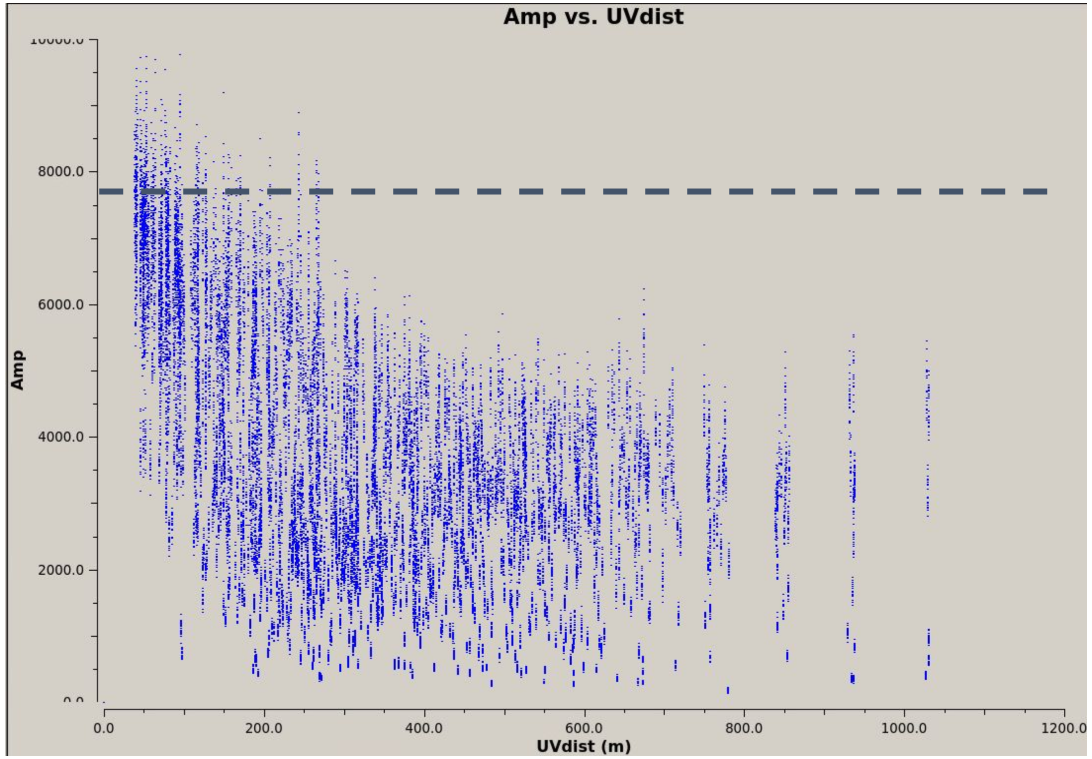


Self-calibration 12s
Peak = 2.31 mJy/bm
rms ~10.2 uJy/bm

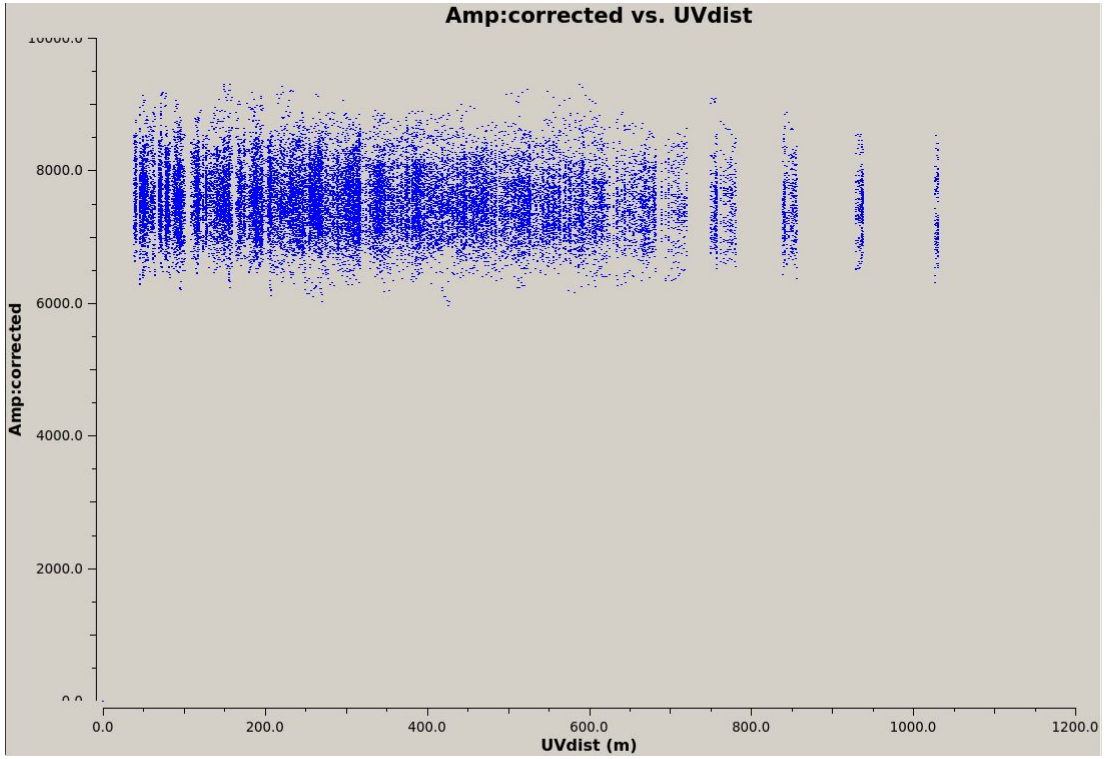
Decoherence/Decorrelation in Visibilities

- Example of point-like maser in K-band
  - decorrelation reduces amplitude as function of uv-distance
  - recall point-source has zero-phase and constant amplitude

standard calibration



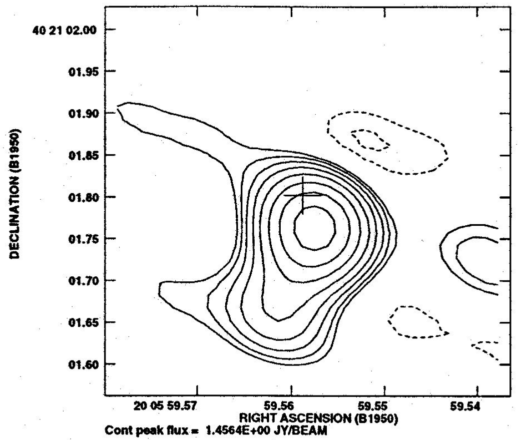
after self-calibration

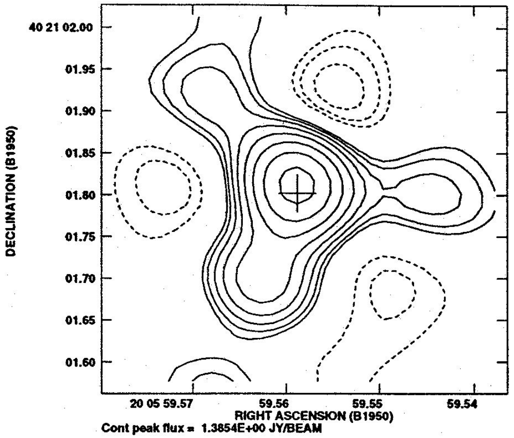


1 hour of 22 GHz VLA observations of the calibrator 2007+404

one-minute snapshots of raw data at t = 0 and t = 59 minutes

Position offsets due to large scale structures that are <u>correlated</u> ➪ phase gradient across array



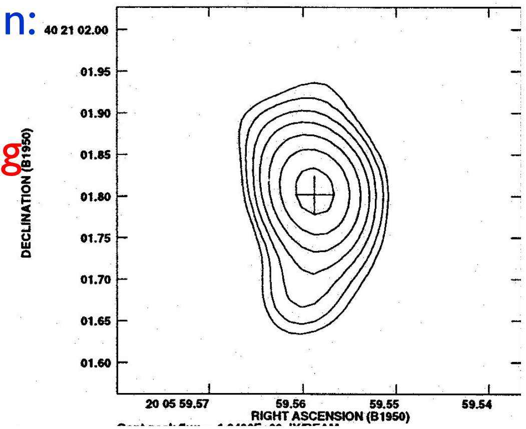


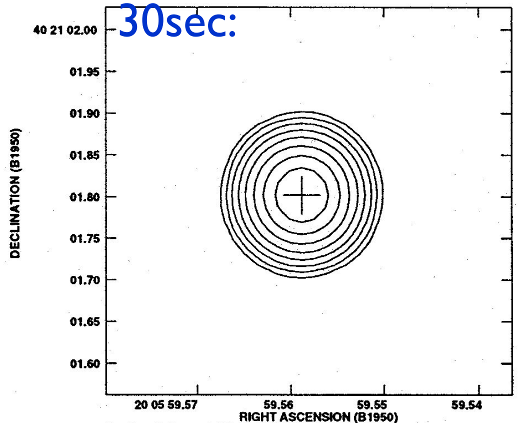
Sidelobe pattern shows signature of antenna based phase errors ➪ small scale variations that are <u>uncorrelated</u>

All Data: Corrections 30min:

Corrections 30sec:

Reduction in peak flux (decorrelation) and smearing due to phase fluctuations over 30 min





No sign of phase fluctuations errors with correction timescale ~ 30 s

⇨ Uncorrelated phase variations degrades and decorrelates image

➪ Correlated phase variations = position shift

Requirements for Good Data at High Frequencies

✓ High atmospheric transmission for the band observed

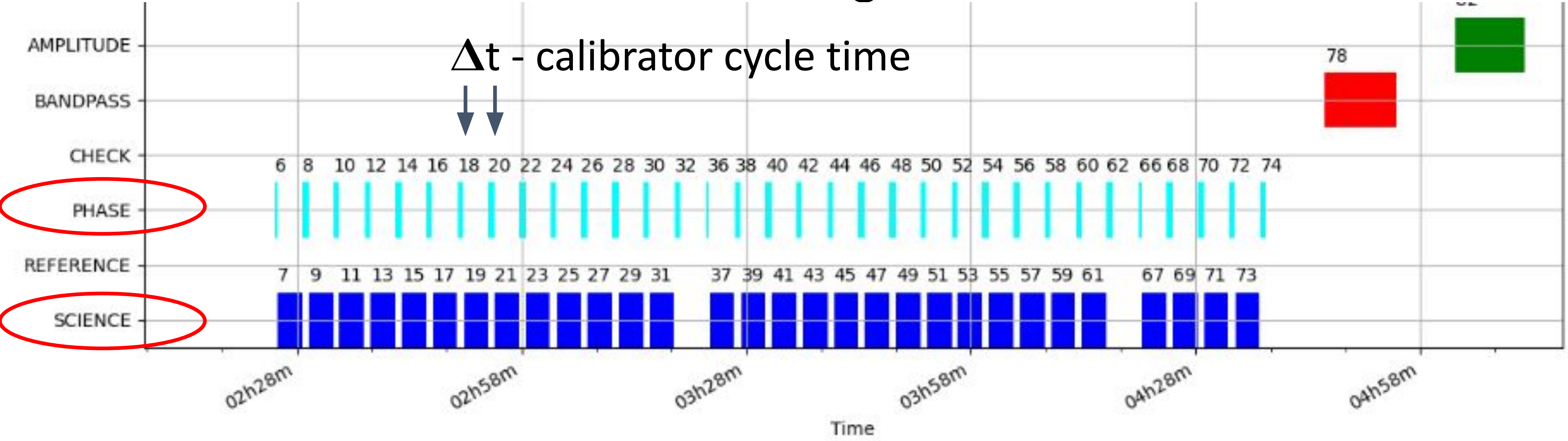
- High dry site, suitable for highest frequency desired
- Dynamic scheduling
  - no choice but to wait for optimal PWV

✓ Stable atmosphere over a long enough time for phase referencing

- High dry site, suitable for highest frequency desired
- Dynamic scheduling
  - cannot wait forever, fast switching and WVRs mitigate

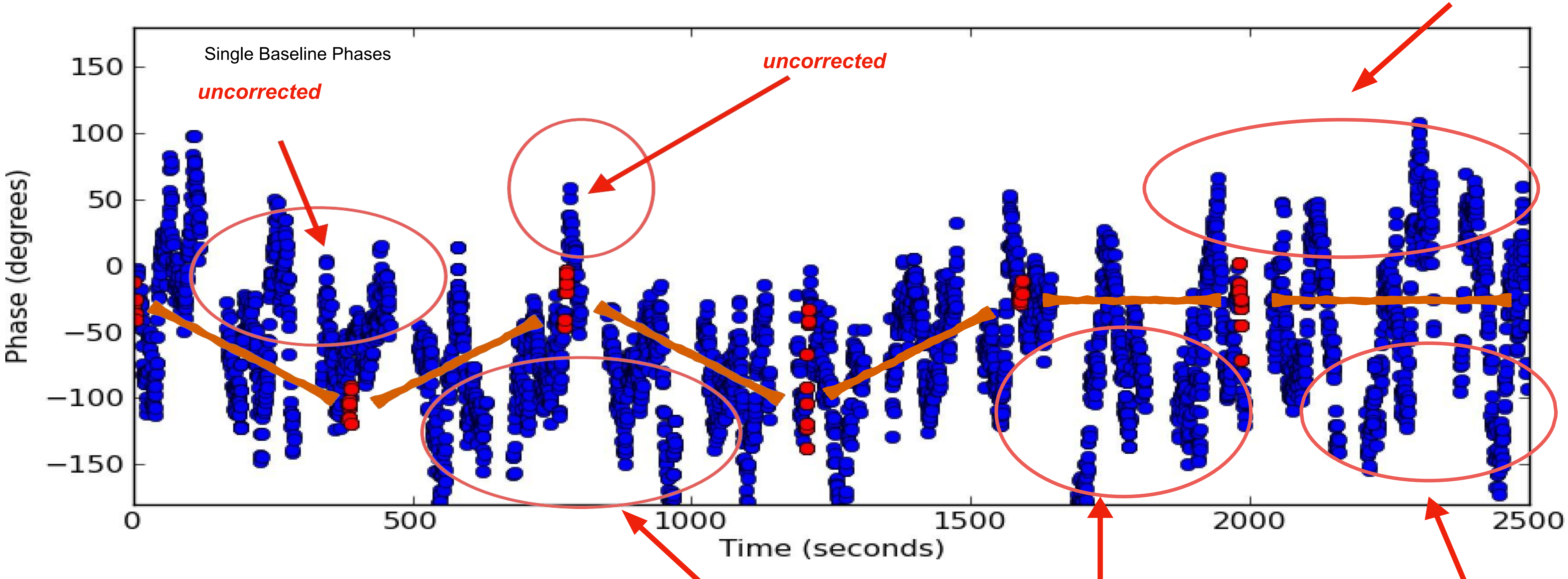
- Phase referenced to a point-like phase calibration, close to the target source

Phase Correction - Phase Referencing



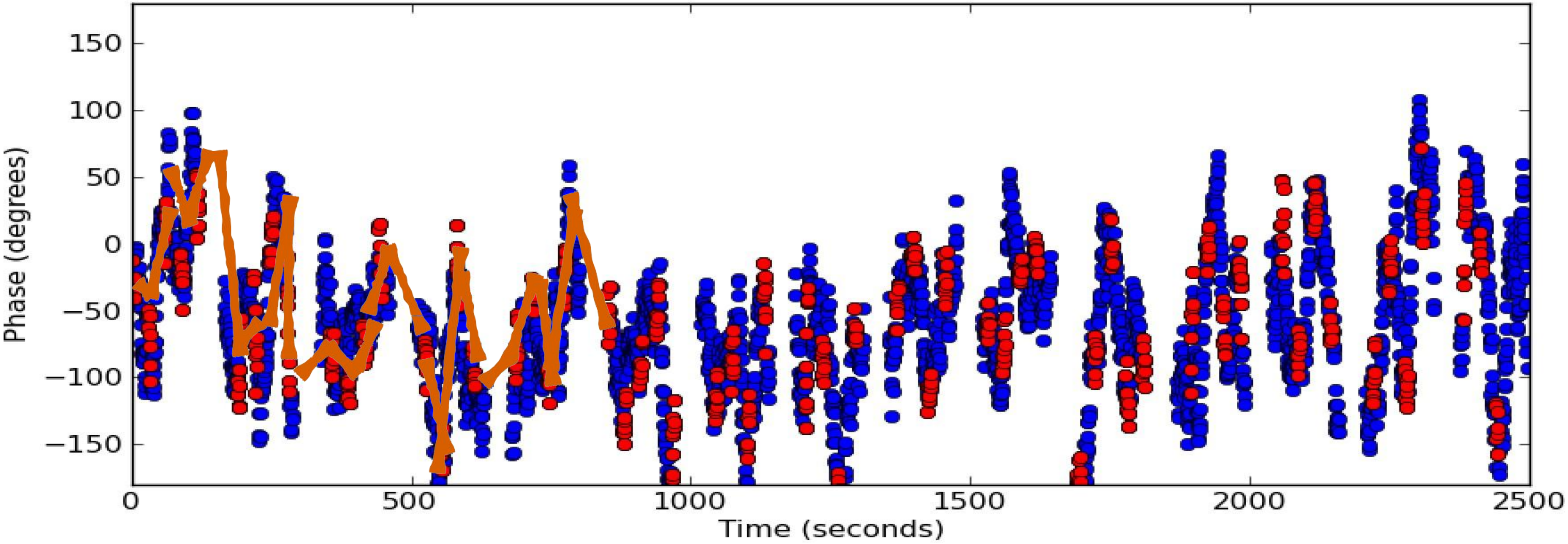
- Like lower frequencies, high-frequency calibration requires referencing to a nearby phase calibrator
- Must visit phase calibrator on timescales shorter than the atmosphere is changing

Phase Correction - Residual Phase



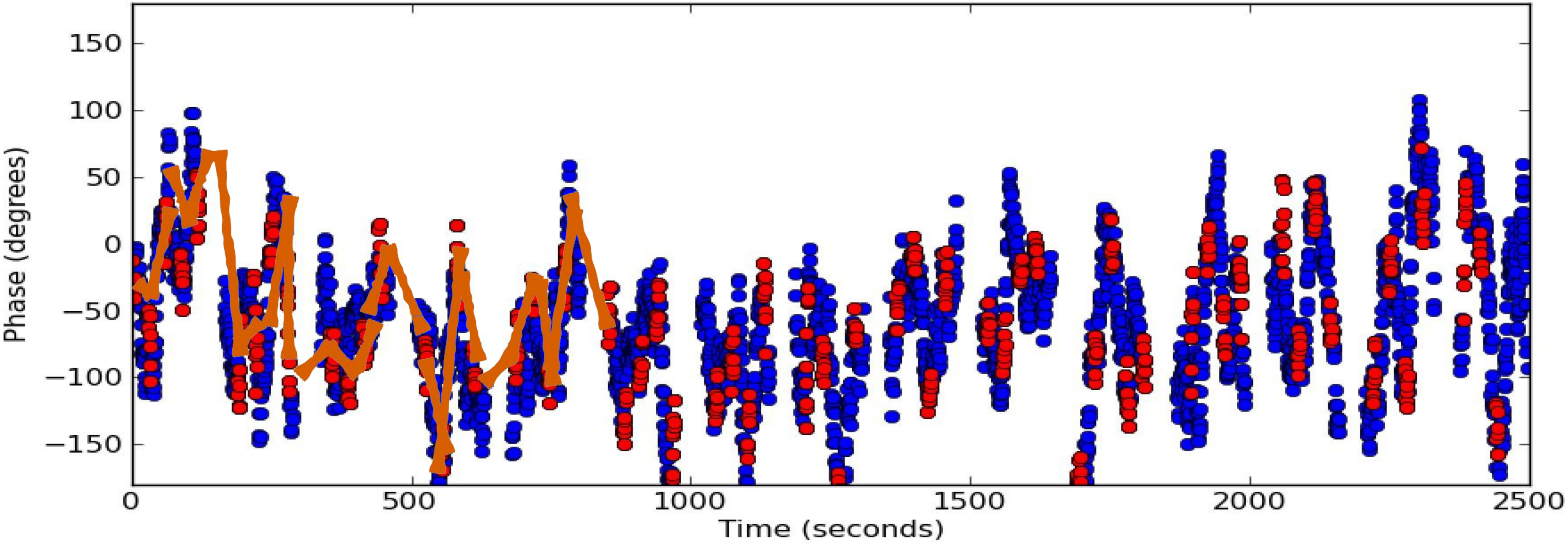
- Infrequent visits to phase calibrator will leave uncorrected residuals while on-source

Phase Correction - Fast Switching



- More frequent visits can reduce the RMS of the residual phases

Phase Correction - Fast Switching



- More frequent visits can reduce the RMS of the residual phases
- Can make observing with high coherence possible

Phase Correction - Fast Switching Considerations

- Fast switching is not free, need to consider observing efficiency
  - Target scans/(Target scans + Phase scans + overheads)
  - Overheads = slew and stabilzation
    - ~2-3 seconds for ALMA
    - ~10-20 seconds for VLA (ideally, depends on calibrator distance)

Pros/**Cons**** *** *with respect to a given fixed length observation*	Longer Scan	Shorter Scan
Target	**Efficient** **Higher Image Sensitivity** **Possibly very variable phases**	**Inefficient** **Lower Image Sensitivity** **Lower chance of phase changes**
Phase	**Inefficient** **Better SNR for solutions Weaker calibrators** **Phases can vary excessively**	**Efficient** **Low SNR for solutions** **Stronger calibrators only** **“No” phase change in the scan**

Phase Correction - Fast Switching Considerations

- Ultimately, need to do what is necessary to obtain good data
  - ALMA chooses for you, VLA recommends based on the observing conditions and configuration
  - **Follow this advice! Never cut corners on your calibrations**
  - **Will only hurt your data**
- Times listed are calibrator cycle time
  - Start to end of cal-target-cal sequence
  - 2x 20s on calibrator +2x 15s slew +50s on source =2 min (42% eff.)

Calibrator Cycle Time (Min.)	A	B	C	D
Ku (12-18 GHz)	6	7	8	8
K (18-26.5 GHz)	4	5	6	6
Ka (26.5-40 GHz)	3	4	5	6
Q (40-50 GHz)	2	3	4	5

Phase Correction - Fast Switching Considerations

- Fast switching does not solve all issues
  - Still looking through different atmosphere target vs. calibrator
  - Still phase variations shorter than calibrator cycle time
- How do we track the phase while still observing the target?

Phase Correction - Fast Switching Considerations

- Fast switching does not solve all issues
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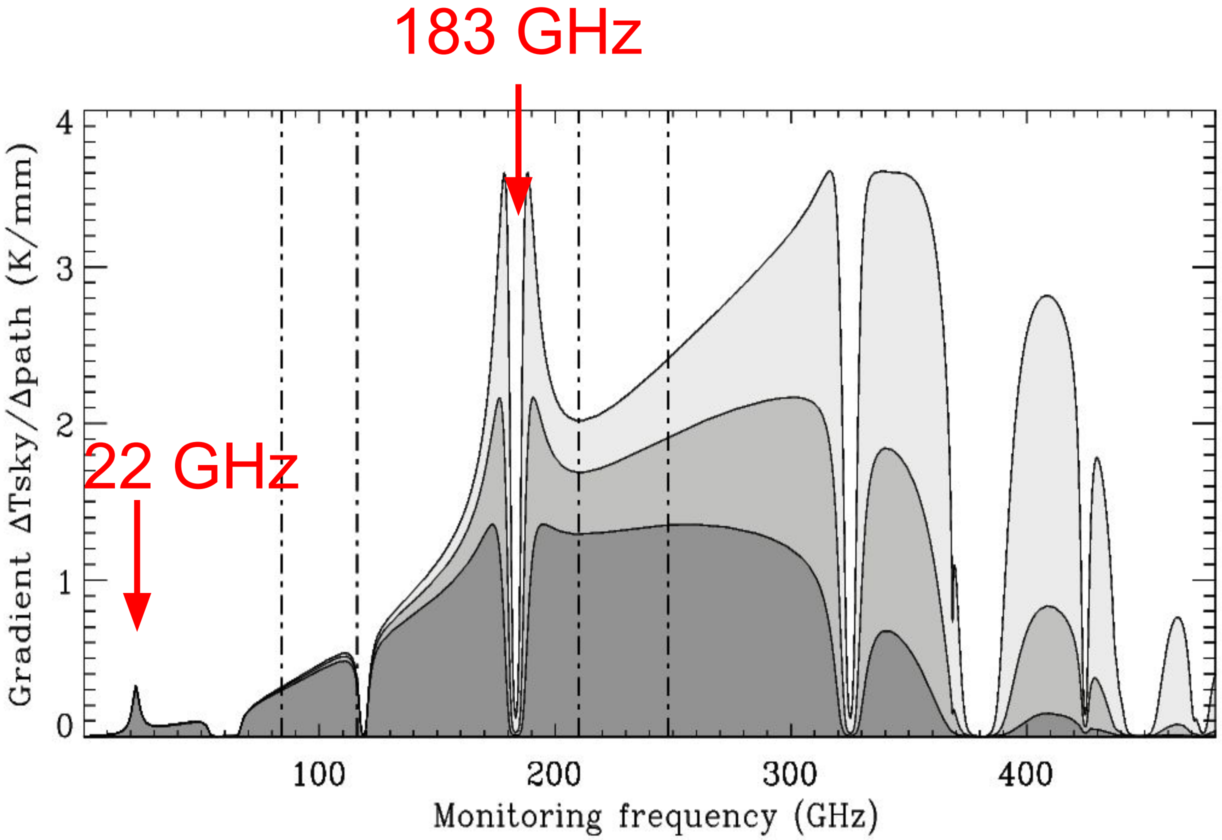
- How do we track the phase while still observing the target?
  - Paired Antenna Calibration
    - ‘Buddy’ antenna stares at close calibrator while antenna on-source
    - Inefficient, needs 2x the antennas
      - CARMA used a variant of this system Perez+2010)
  - Water Vapor Radiometers
    - Measure path length change due to water vapor column in real time

Phase Correction - Water Vapor Radiometers (WVRs)

- Measure fluctuations in T_B^{atm} at water line with a radiometer, use these to derive changes in water vapor column (ΔW) path length and convert this into a phase correction using:

  $\delta\varphi \cong 6.3 \times 2\pi/\lambda \times W$ (W is the PWV in mm)

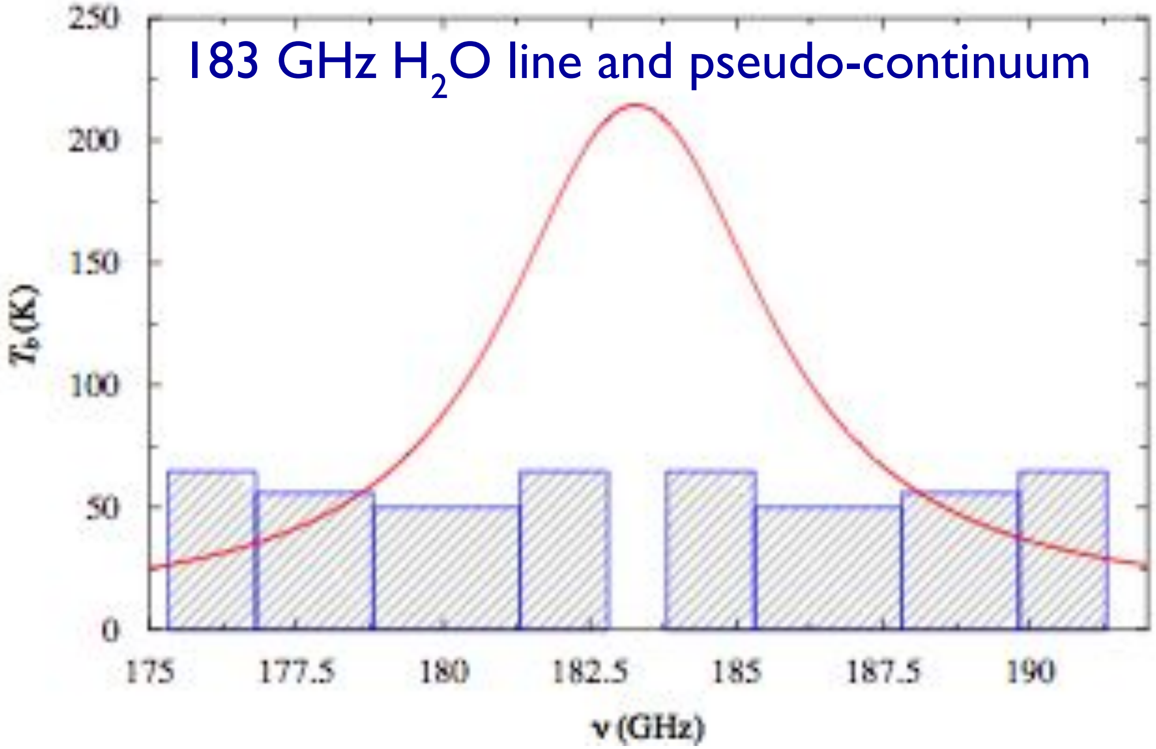
- Facilities Applying Corrections:
  - 183 GHz H_2O line (ALMA)
  - 22 GHz H_2O line (NOEMA, ATCA)
    - ngVLA planned



(Bremer 1997/2000 IRAM Summer School)

Phase Correction - ALMA's Need for WVRs

- Observations at 300 microns (Band 10) require a path error less than 25 microns to keep the phase fluctuations < 30 degrees (~90% coherence)
- At the ALMA site the median path fluctuation due to the atmosphere is ~200 microns on 300 m baselines (compared to max of 15 km)
- These fluctuations increase with baseline length (up to several km, see slide 23/24) with a power of about 0.6 for the ALMA site
- Changes on timescales as small as the Antenna diameter/wind speed are possible = 1 sec
- ALMA WVRs monitor changes in water line brightness



There are 4 “channels” flanking the peak of the 183 GHz water line

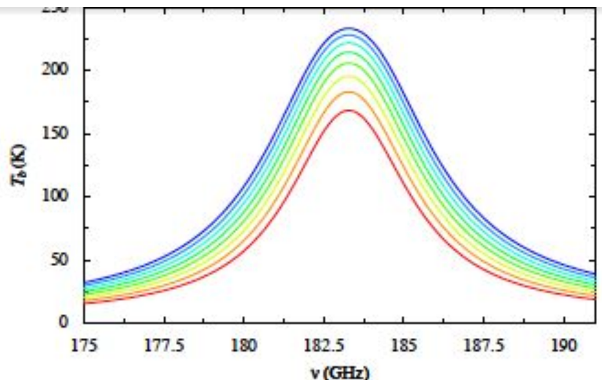
- Data taken every second
- Installed on all the 12m antennas
- Matching data from opposite sides are averaged
- The four channels allow flexibility for avoiding saturation

Phase Correction - Modeling the Path Change

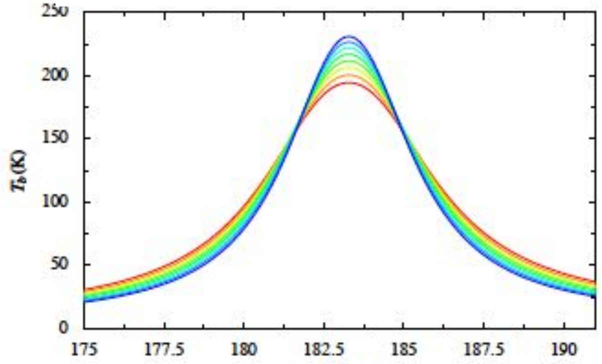
- Challenge is converting the 183 GHz brightness into a phase correction
- 3 unknowns: PWV, temperature, pressure (in water vapor layer) <u>in a simple plane parallel, thin layer model</u>
- HITRAN and radiative transfer is used to derive the line shape, opacity and hence brightness temperature T_B(H2O) as a function of frequency
- The observed "spectrum" is then compared to the model predictions for a range of reasonable values of PWV, Temperature, and pressure
- After dropping smaller terms:

  Δ(path) = Δ(PWV) * 1741/T(H2O layer)
- The path change is converted to phase for the mean frequency of each "science" spectral window
- See ALMA Memo 587

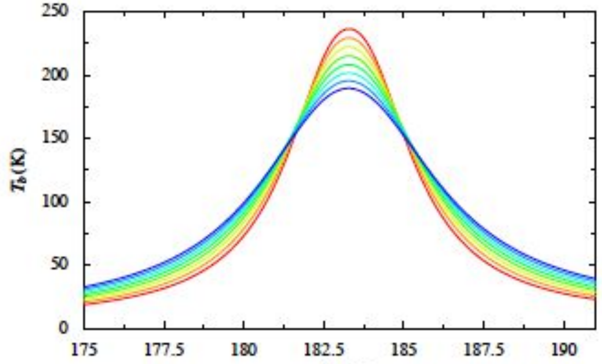
- Implemented offline in CASA task wvrgcal



PWV from 0.6 to 1.3mm



Temperature from 230 to 300 K



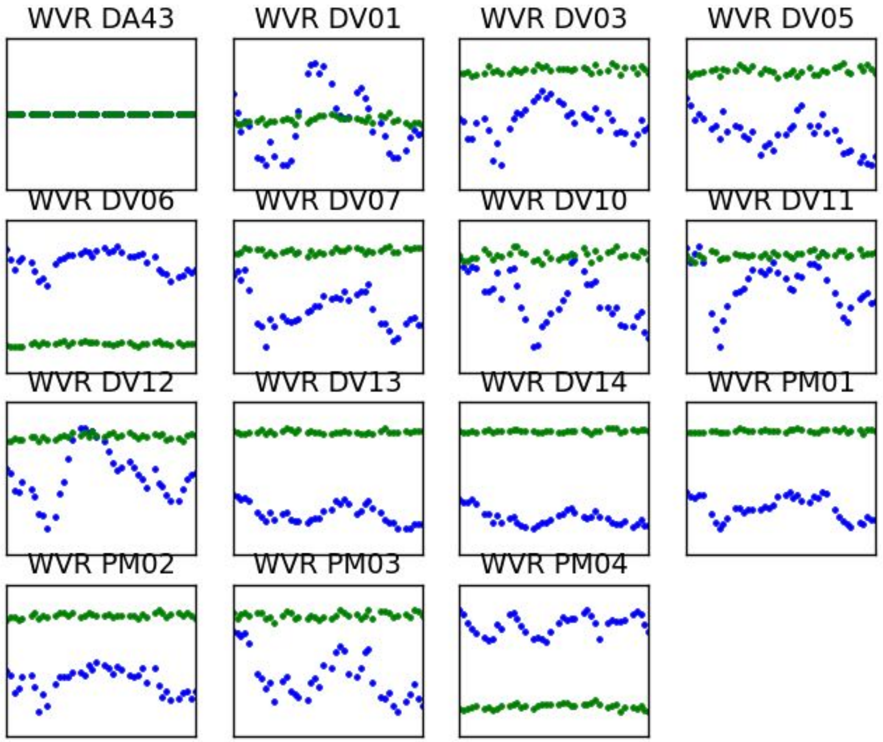
Pressure from 400 to 750 mBar

Phase Correction: Examples of WVR Correction

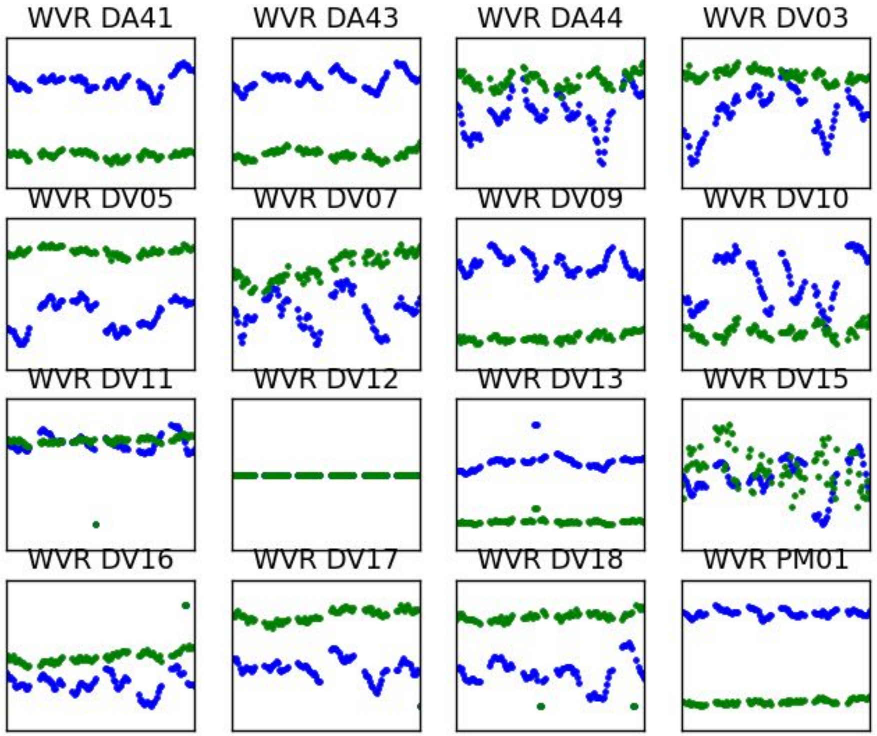
- Works well to remove common mode variations in typical conditions
- Simplicity of model results in not all phase errors being removed, fast switching at long baselines & self-calibration still typically needed for high dynamic range
- Cannot fix directional issues (phase referencing, antenna position errors)
- Little improvement in dry conditions
- Typically marginal improvement at Bands 8-10

ALMA Memo 624

Band 6 (230 GHz) Compact config



Band 7 (340 GHz) Extended config

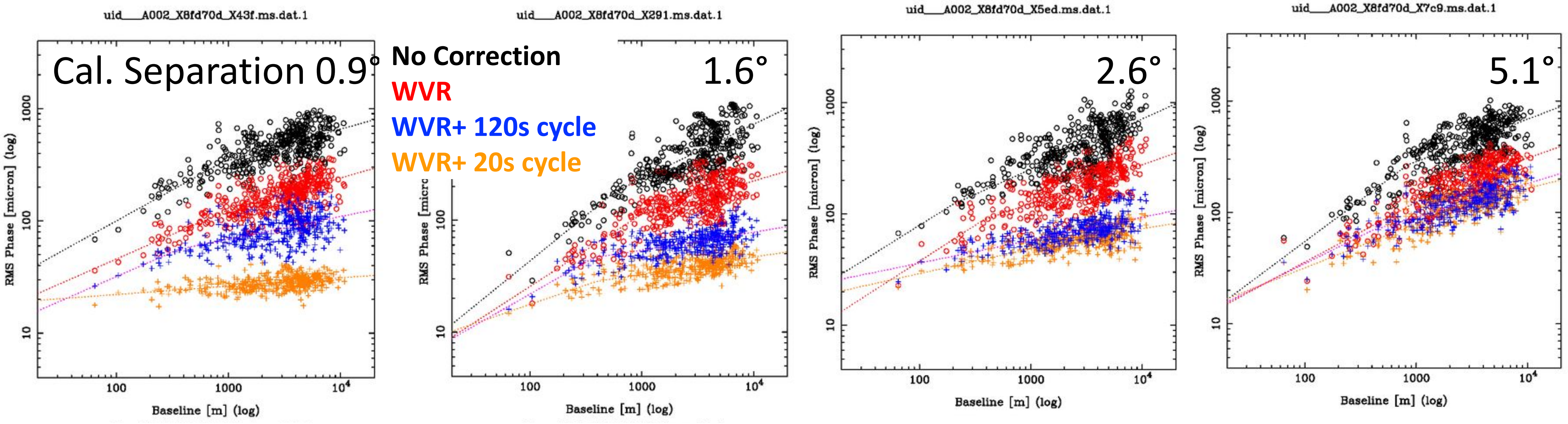


Raw phase & **WVR corrected phase**

(from gaincal solutions)

Phase Correction - Calibrator Separation

- Being able to phase reference is essential for interferometry at any frequency
- Calibrator-source separation matters, and not just for your overheads



- At larger separations, significant phase RMS
- Uncertainties in the global delay model (manifests as antenna position errors)

Asaki+2016 SPIE 9906

Phase Correction - Calibrator Separation

- Being able to phase reference is essential for interferometry at any frequency
- Calibrator-source separation matters, and not just for your overheads
- Phase offset $\Delta\phi = 2\pi\nu_{obs}/c\ \ \Delta b\ (\Delta\theta_{src\text{-}cal})$
  - $\Delta b \sim 0.2\ (\Delta z)$ mm/km (offset of z component of antenna position)
- Nearby calibrators highly desirable for highest frequencies
- Also a consideration for VLA with 36 km baselines
  - c.f. VLA antenna positions measured in X-band where atmosphere far more transparent

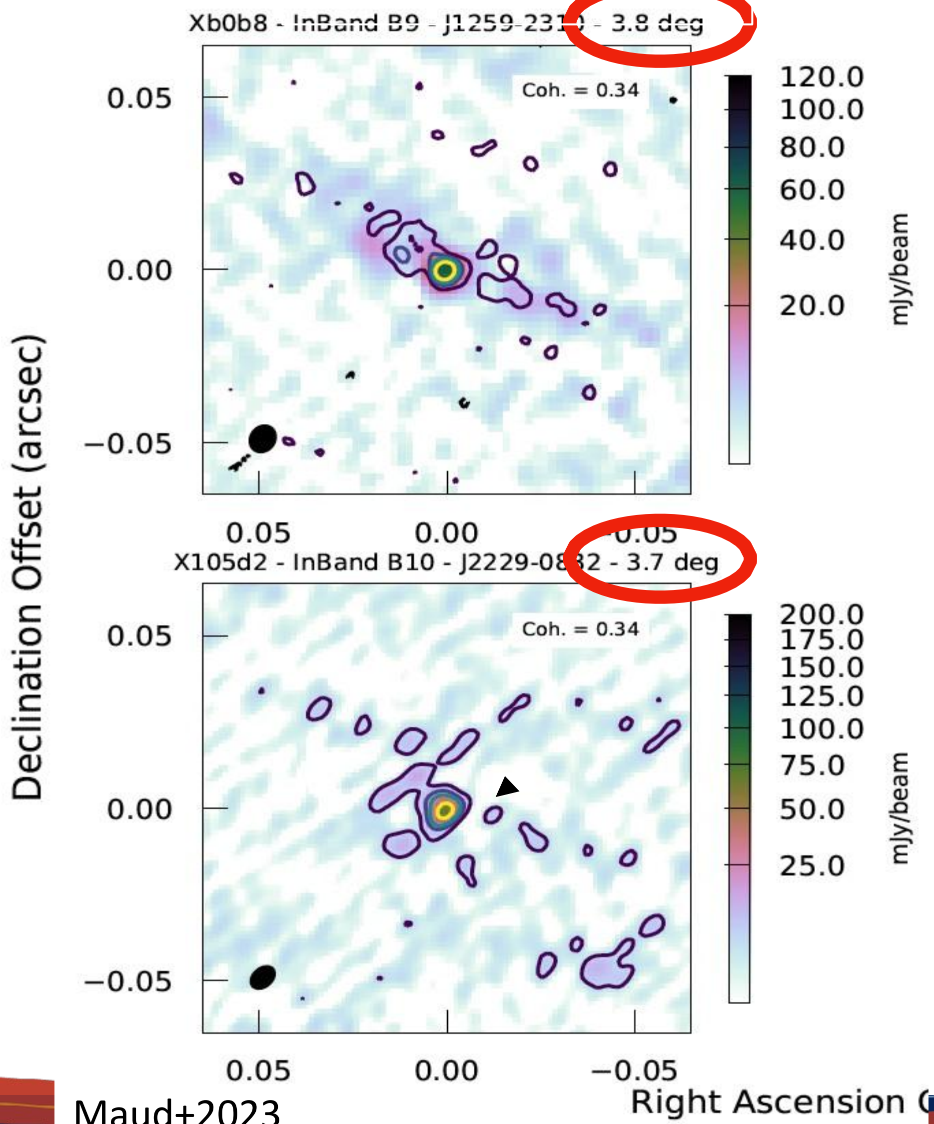
Max. Phase Offsets - deg *(per 1 km baseline)*	Target-to-Calibrator Separation (10x worse at 10 km)		
Band	1(deg)	5(deg)	10(deg)
8	**1.8**	**9.4**	**18.8**
9	**2.7**	**13.6**	**27.2**
10	**3.6**	**17.8**	**35.6**

Phase Correction - Calibrator Separation

In band

Band 9

Band 10

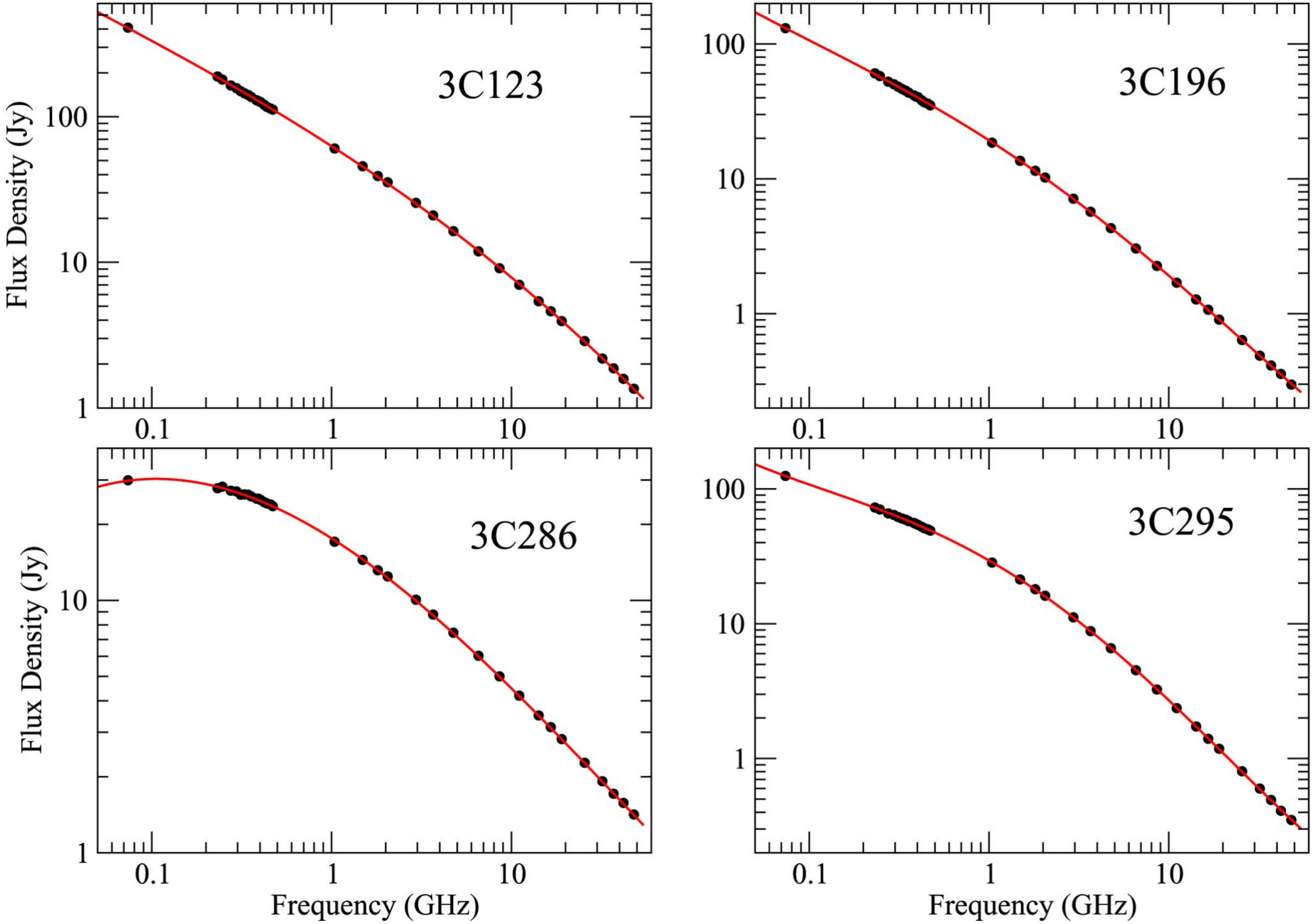


Maud+2023

also see Error Recognition talk

Phase Correction - Calibrator Separation

- Radio sources fill the sky at cm-wavelengths, but many have steep spectra and are very faint at high frequencies
- Difficult to find nearby calibrators, esp. @ Bands 8-10
- Median (90th pct.) separation angles for a suitable calibrator
    - B8 - 3.6° (7.8°)
    - B9 -7.5° (13.1°)
    - B10 - 18.5° (33°)
  - ***Too Distant on average***

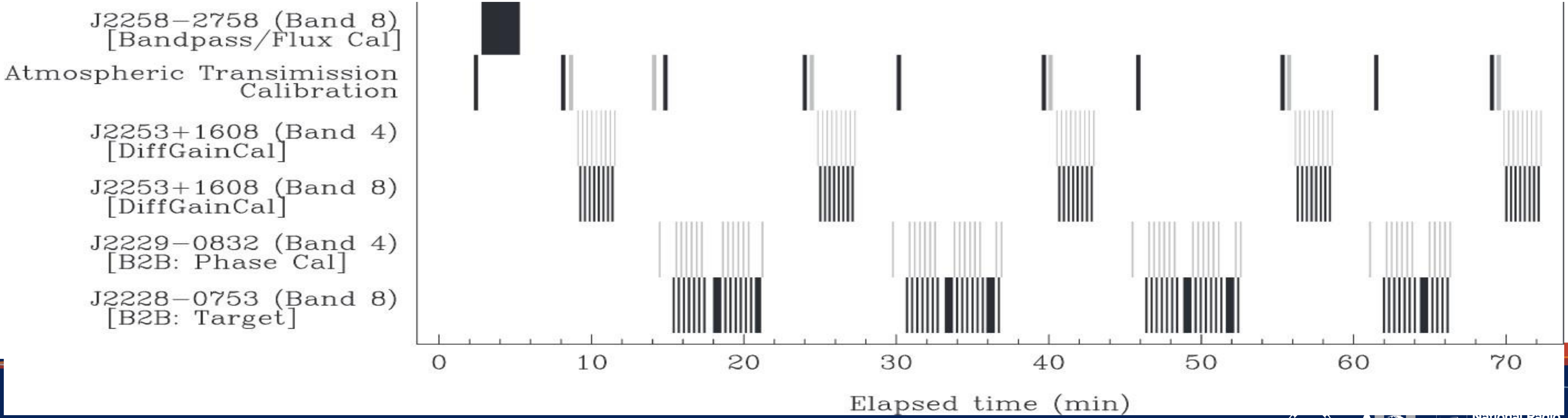


Perley&Butler 2017

Phase Correction - Band-to-Band (B2B) Phase Transfer

- Conceptually simple
  - observe calibrator at lower frequency and transfer phase to higher frequency
  - account for phase scaling between bands
- Still need low phase RMS at high frequencies
- Some additional overhead associated with calibration of per-band scaling

e.g., Asaki+2020



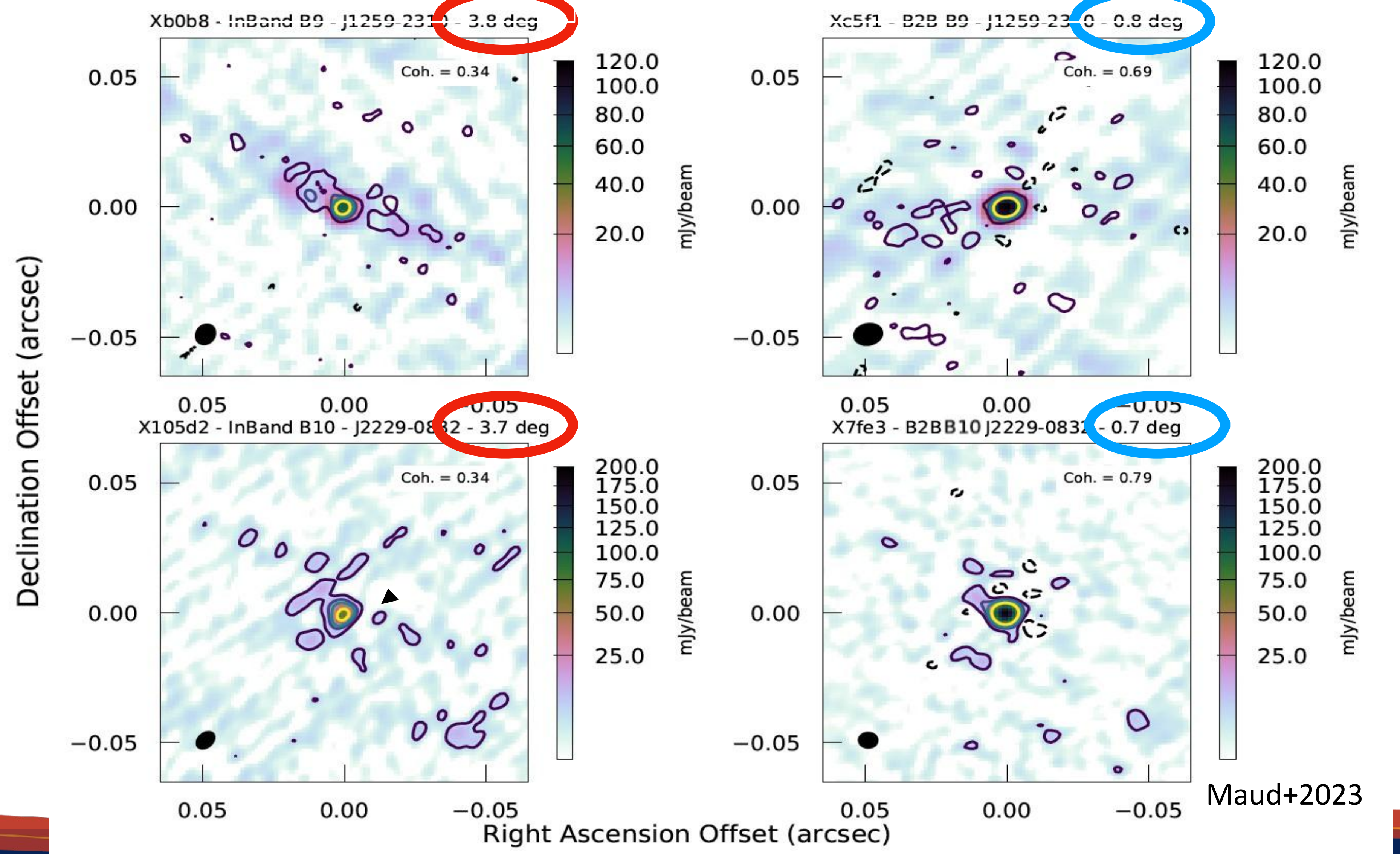
Phase Correction - Calibrator Separation

In band

Band2Band

Band 9

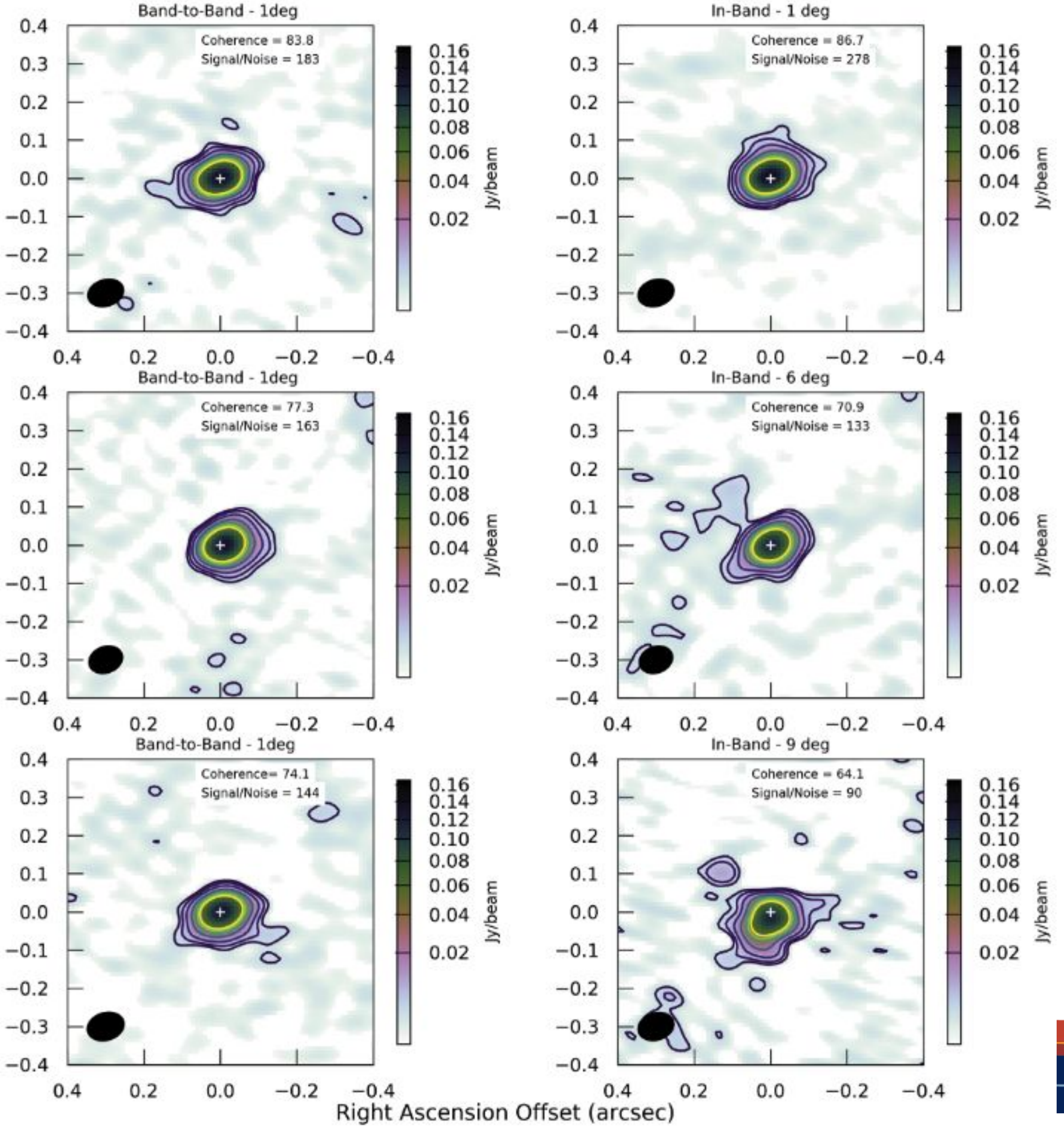
Band 10



Maud+2023

Phase Correction - Band-to-Band (B2B) Phase Transfer

- Works very well
  - some reduction S/N from phase transfer
  - Vastly superior when no close calibrator is available
- Some projects were previously infeasible due to lack of a calibrators
- B2B opens up the sky for ALMA's highest frequencies



e.g., Asaki+2020

Requirements for Good Data at High Frequencies

✓ High atmospheric transmission for the band observed

- High dry site, suitable for highest frequency desired
- Dynamic scheduling
  - no choice but to wait for optimal PWV

✓ Stable atmosphere over a long enough time for phase referencing

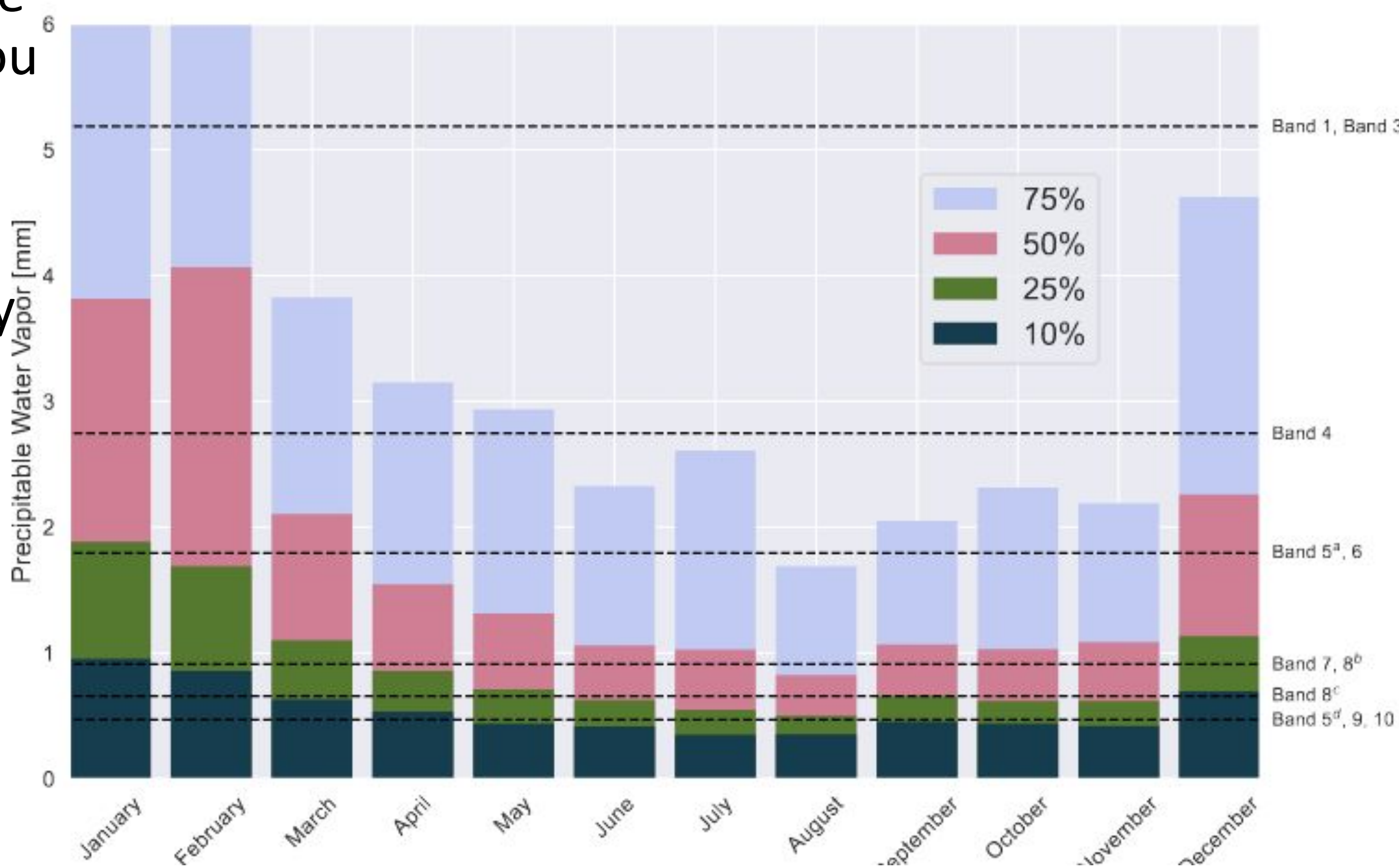
- High dry site, suitable for highest frequency desired
- Dynamic scheduling
  - cannot wait forever, fast switching and WVRs mitigate

✓ Phase referenced to a point-like phase calibration, close to the target source

- Fast switching +WVRs + Band-to-Band essential for full-sky observing

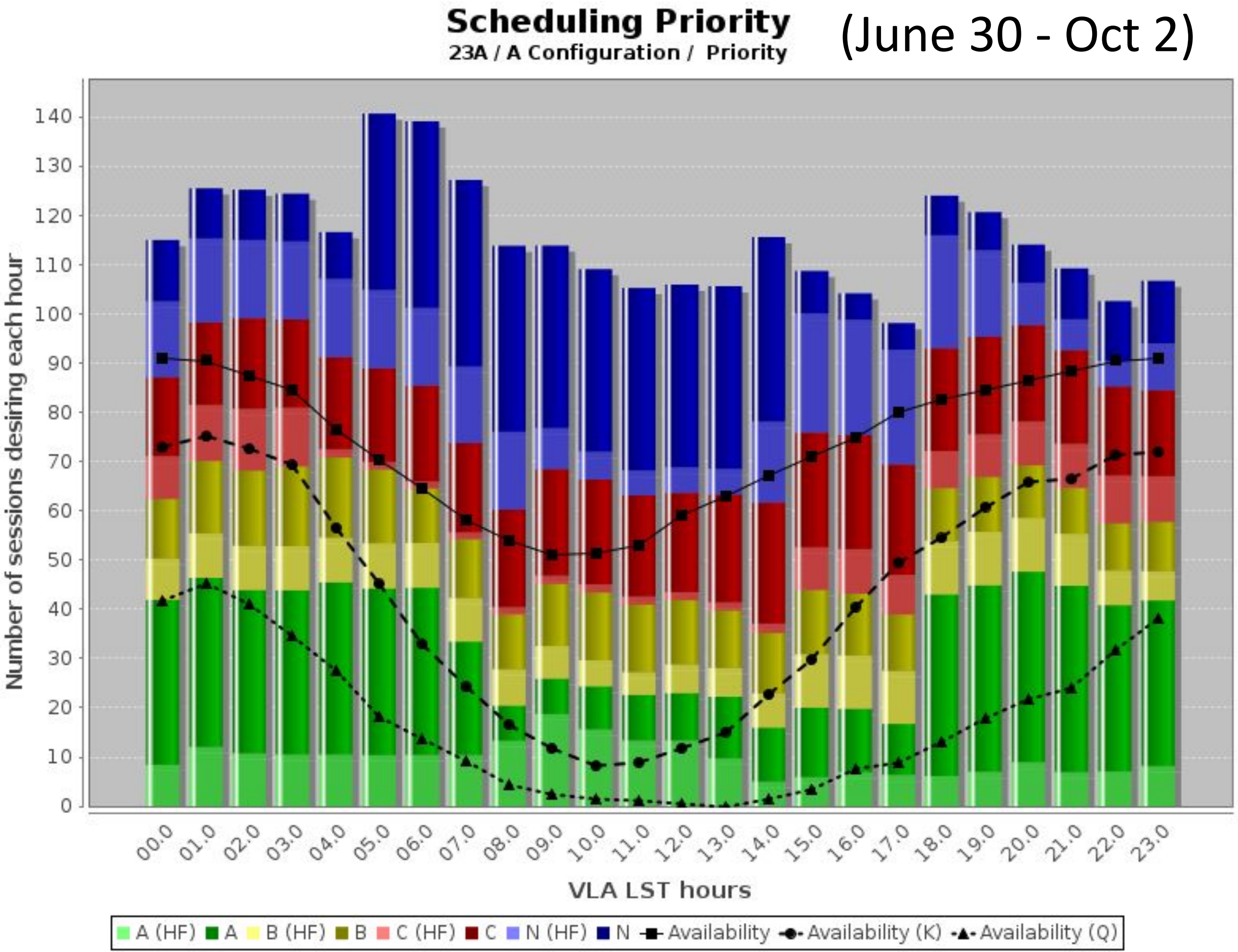
Practical Considerations

- Absolutely propose to do HF science
- Ask for what you need, not what you think they'll give you
- Be aware of some practical considerations
  - Band 9/10 weather is a minority of the time available
  - Most is available in southern hemisphere winter



Practical Considerations

- Absolutely propose to do HF science
- Ask for what you need, not what you think they'll give you
- Be aware of some practical considerations
- VLA has similar HF challenges for K, Ka, and Q-bands depending time of year
  - Summer daytime has little HF time available
  - Governed by combination of phase RMS, wind, and clouds



(June 30 - Oct 2)

Practical Considerations

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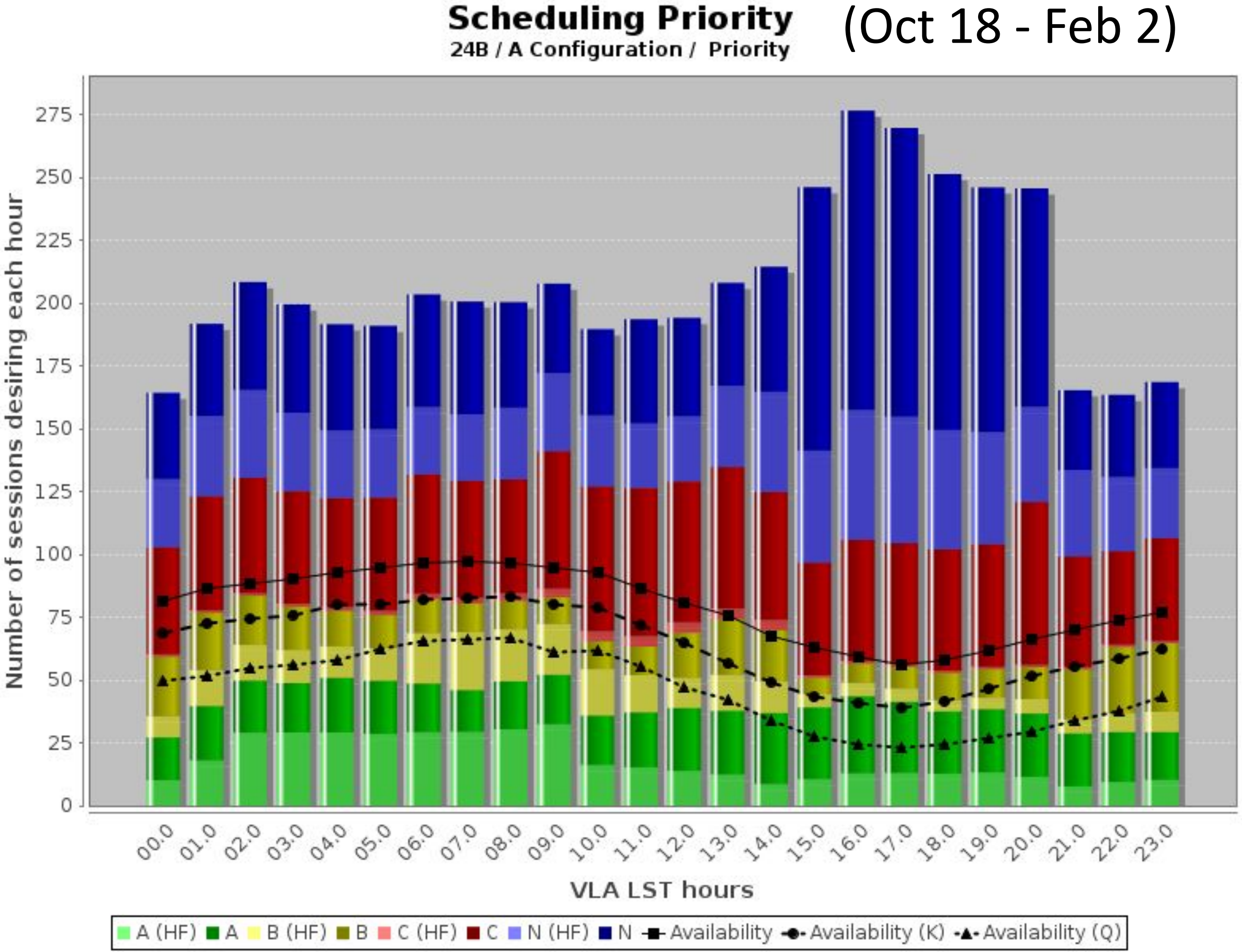


(Oct 18 - Feb 2)

Summary

- Good transmission (low opacity) and low phase RMS (frequency-dependent) is absolutely necessary for interferometry
- Water Vapor Radiometers can significantly correct phases, esp. in Bands 3-7
- Phase referencing is essential to calibrate data
- Calibrator observations must be interleaved with target quickly enough to track atmosphere
  - Phase RMS still needs to be low enough to have efficient observing
  - Fast switching means different things at ALMA vs. VLA, at VLA it’s ‘fast’
- Calibrator separation from target is an important consideration
  - larger separations reduce coherence
- Band-to-band transfer for ALMA Bands 8-10 essential for unlocking more nearby calibrators

Special acknowledgement to Luke Maud, many slides derived from his 2023 lecture.

Epilogue: Self-calibration

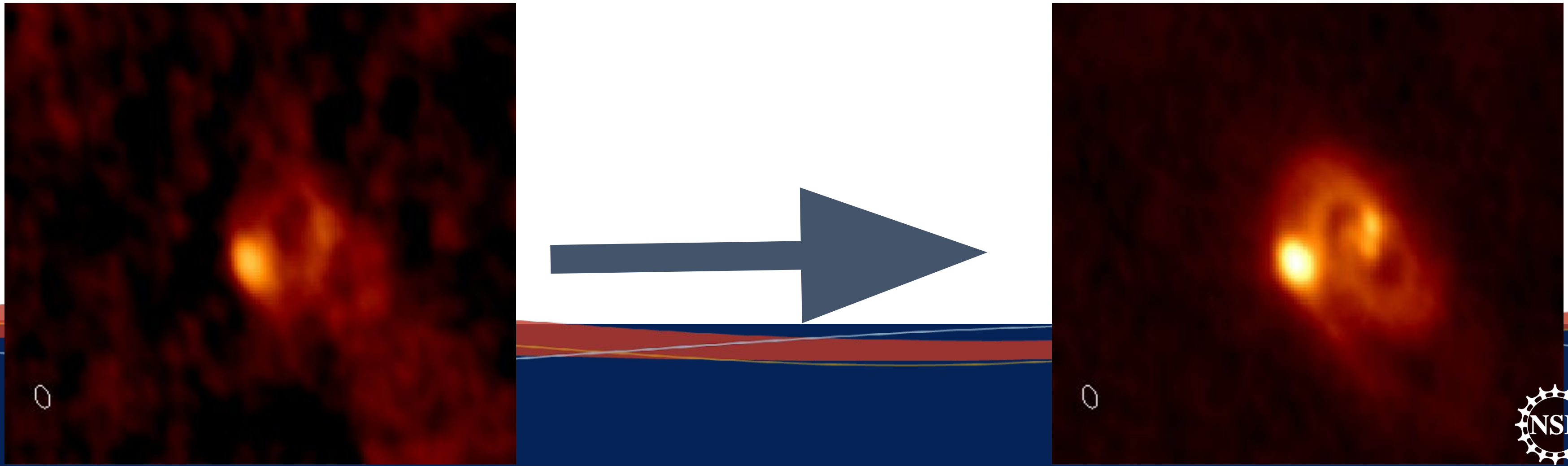
- After all this effort to get WVRs, switch fast enough, and select close enough calibrators (especially enabled with band to band)
  - Dynamic range is still limited when only using standard calibration
    - ~100:1 for ALMA
    - ~1000:1 for VLA
  - Phase transfer errors and phase variations while on source limit dynamic range
- Self-calibration is needed to achieve highest possible dynamic range
  - However, good standard calibration is a pre-requisite to self-calibration

Epilogue: Automated Self-calibration

- Automated self calibration is now a reality for continuum data (Tobin & Sheehan in prep.)
  - Standalone tools developed by John Tobin and Patrick Sheehan
    - Stable version, supporting single-pointing, mosaics, long-baseline observations:
      - https://github.com/jjtobin/auto_selfcal

- CASA-integrated pipeline version (based on stable version 1.2 (Oct. 2025)
  - https://science.nrao.edu/srdp/self-calibration
  - https://casa.nrao.edu/download/distro/casa-pipeline/release/linux/casa-6.6.6-18-pipeline-2025.1.0.36-py3.10.el8.tar.xz
  - Also available via ALMA reimaging service within NRAO archive (https://data.nrao.edu)

This example is from fully automated routines!



Epilogue - Self-Calibration

- Uses science target as a model to compute further phase (and amplitude if desired) gains
- **Misconceptions:**
  - **X** Only useful if phase is changing more rapidly than calibrator cycle time
    - **Untrue,** phase transfer is never perfect, self-calibration will always help
    - e.g., antenna position errors, different line of sight, uncertainties in global delay model
  - **X** ‘The resulting image isn’t scientifically valid because "you can make an image look like anything you want with self-cal"’
    - **Untrue** given the number of elements in linked interferometers and redundancy of data
    - Model for selfcal is created from the data, so if reasonable S/N this will not happen
  - **X** ‘If I self-cal, all the position information will be lost’
    - **Untrue** in most cases where have reasonable S/N and model is created from observed source
    - Only true if starting with a point source model at phase center and not using intrinsic source structure as model (generally VLBI cases)

Epilogue - Self-Calibration

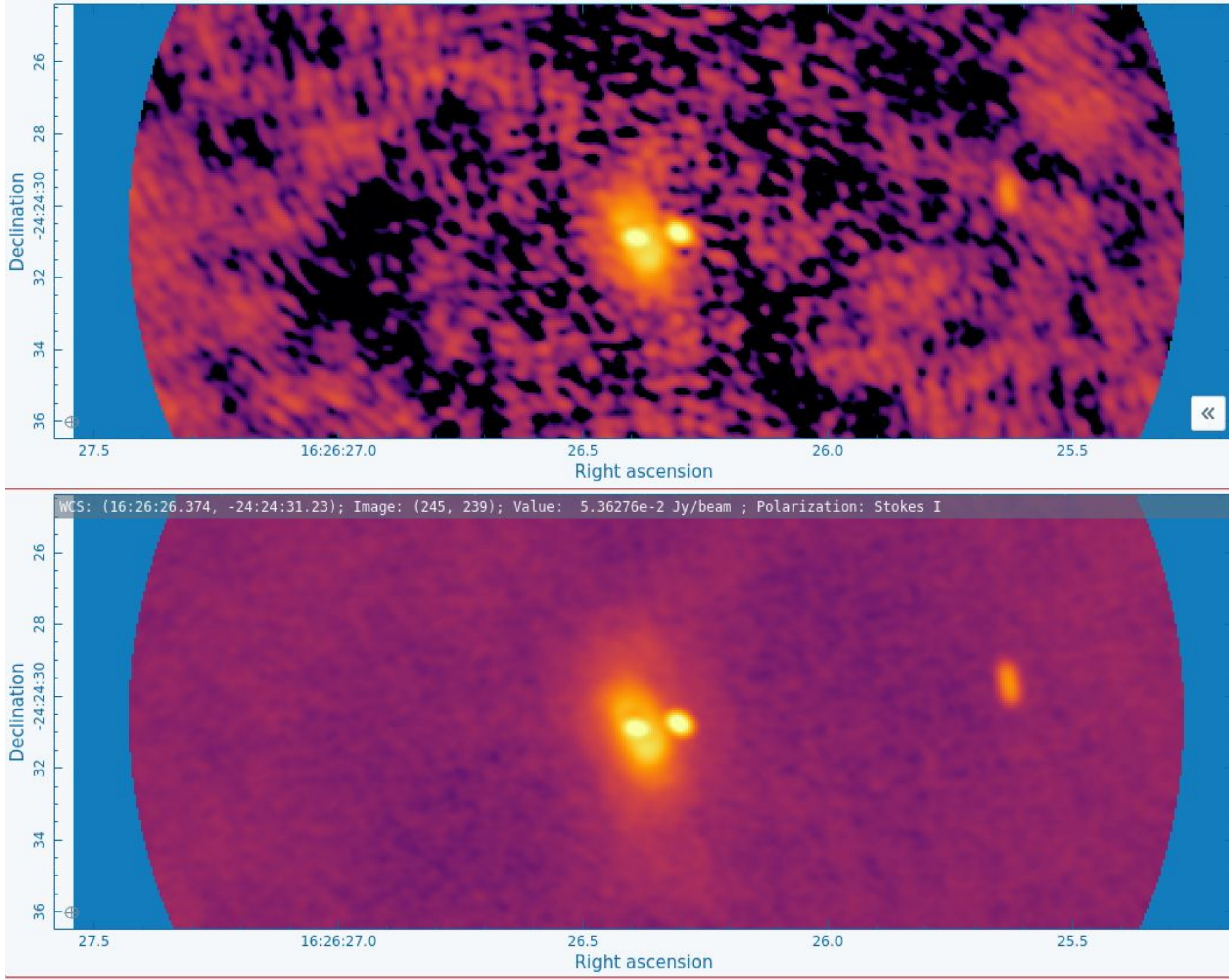
- Best Practices:
  - Ensure there is enough signal-to-noise (S/N) to create a model
  - Be conservative in your iterative approach
    - Cannot make weak, but real emission disappear by not including it in the model
    - Can create weak features by including noise or artifacts in your model
  - Read Brogan+2018

- Self-calibration has typically been done manually with interactive clean
- At high frequencies, generally fewer sources
  - Direction Dependent calibration typically not necessary

Self-calibration Example: ALMA 2018.1.01089.S - Band 7

- Overall ~10x improvement from original image!
    - RMS ~ 0.163 mJy/bm
    - Peak ~ 181 mJy/bm
    - S/N ~ 1110

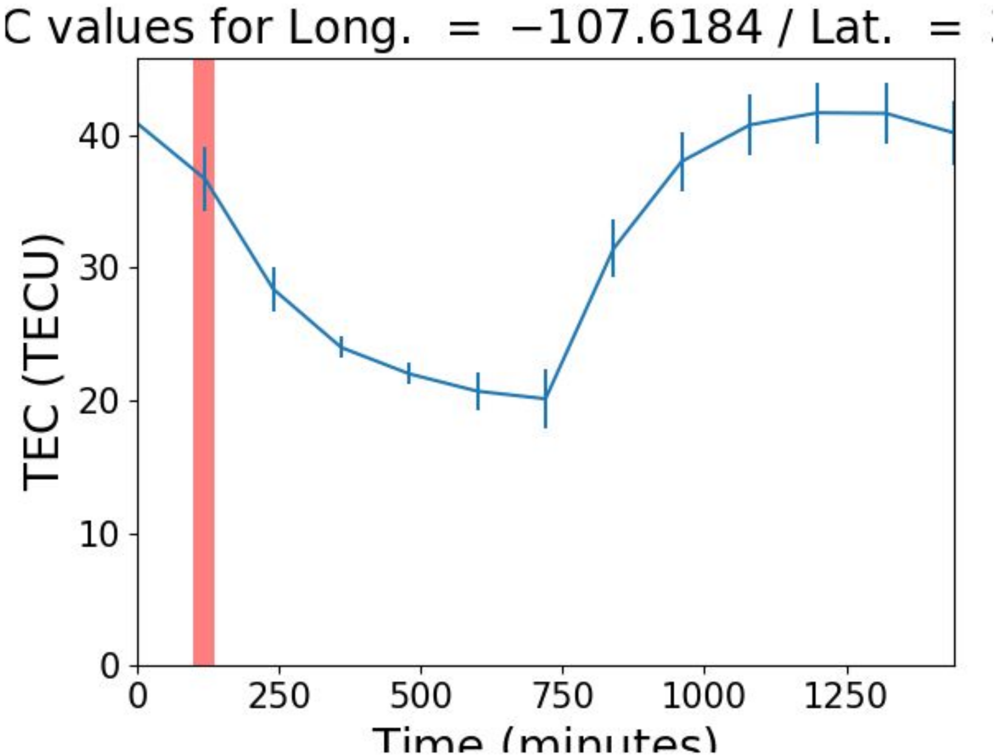
- RMS is still ~3x theoretical sensitivity, = dynamic range limit



WCS: (16:26:26.374, -24:24:31.23); Image: (245, 239); Value: 5.36276e-2 Jy/beam ; Polarization: Stokes I

Phase at low (<4 GHz) frequencies

- Phase decoherence also possible at low frequencies, but origin different
- Tropospheric phase fluctuations scale ~linearly with increasing frequency
- Ionosphere causes phase fluctuations whose amplitudes are inversely proportional to frequency
    - Correction techniques
        - self-calibration
        - Total Electron Content correction
        - TEC information available from CASA/VLA pipeline
        - Uses information from GPS satellites and provided by NASA



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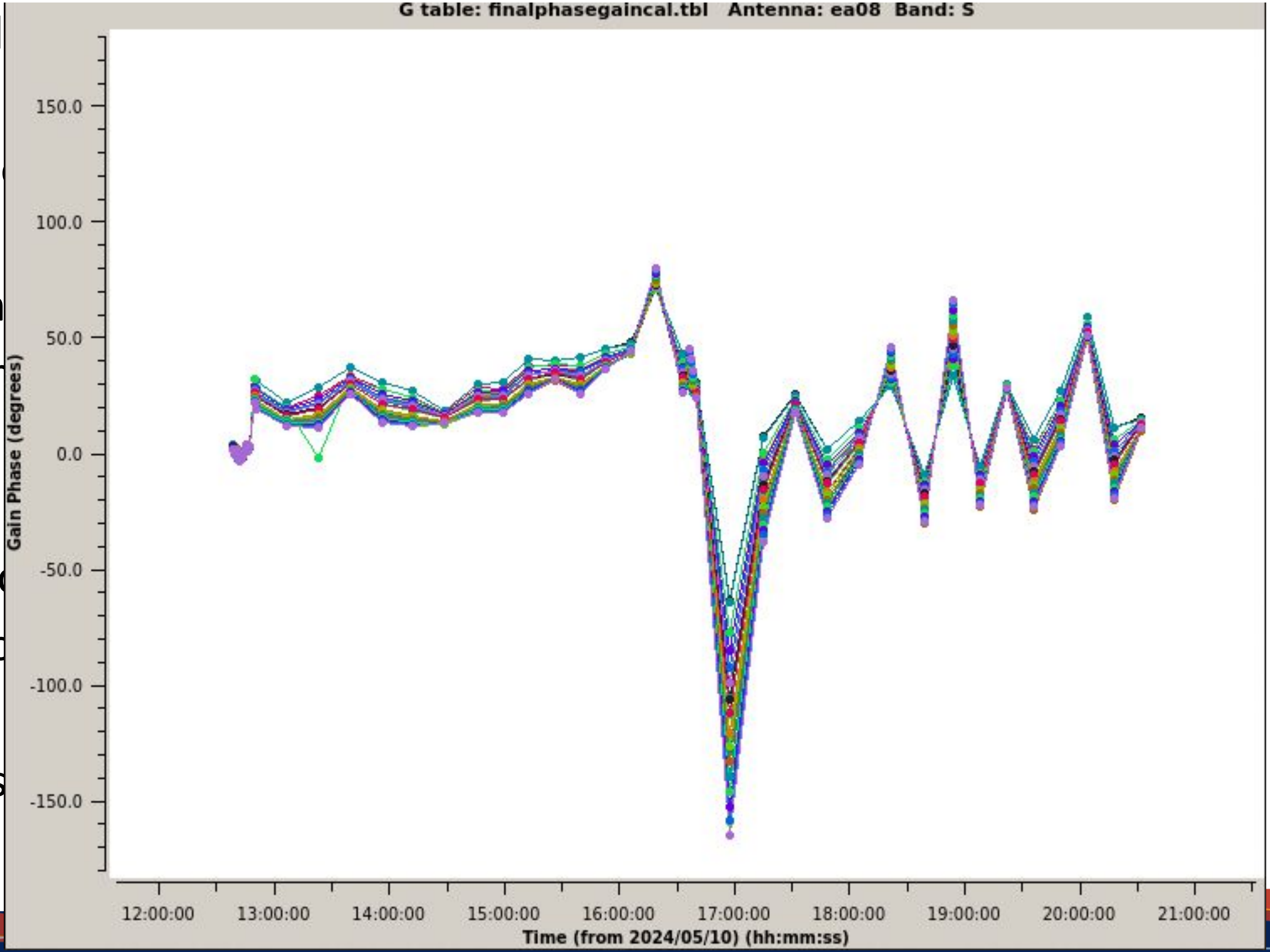

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