Short intro to Interferometry calibration

Elisabetta Liuzzo
INAF- Istituto di Radioastronomia
Italian node of European ALMA Regional Centre

Credits to R.Paladino, A. Mignano

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EUROPEAN ARC
ALMA Regional Centre || Italian

Interferometry basics

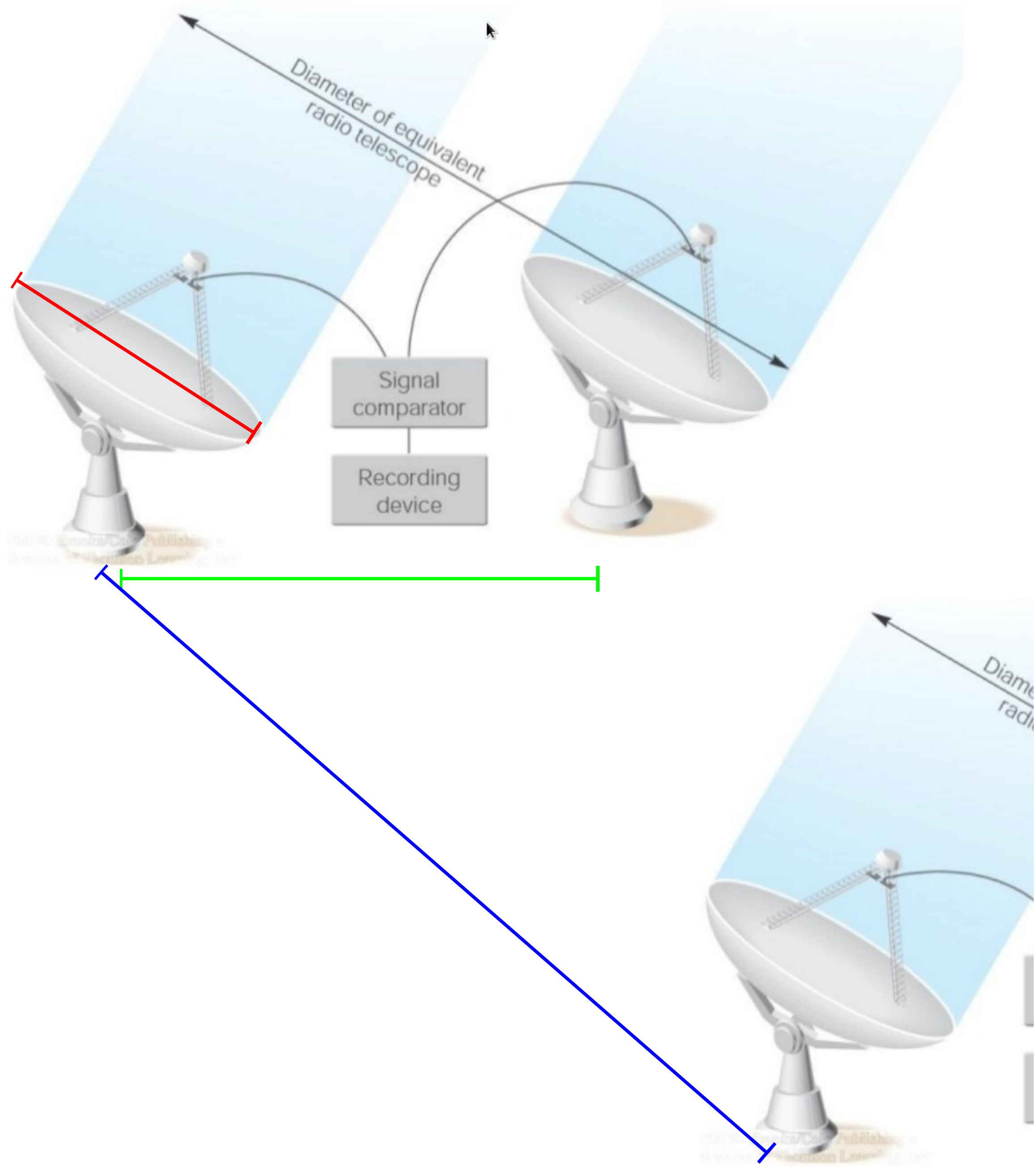
Field of View $$FOV \propto \frac{\lambda}{D}$$

Resolution

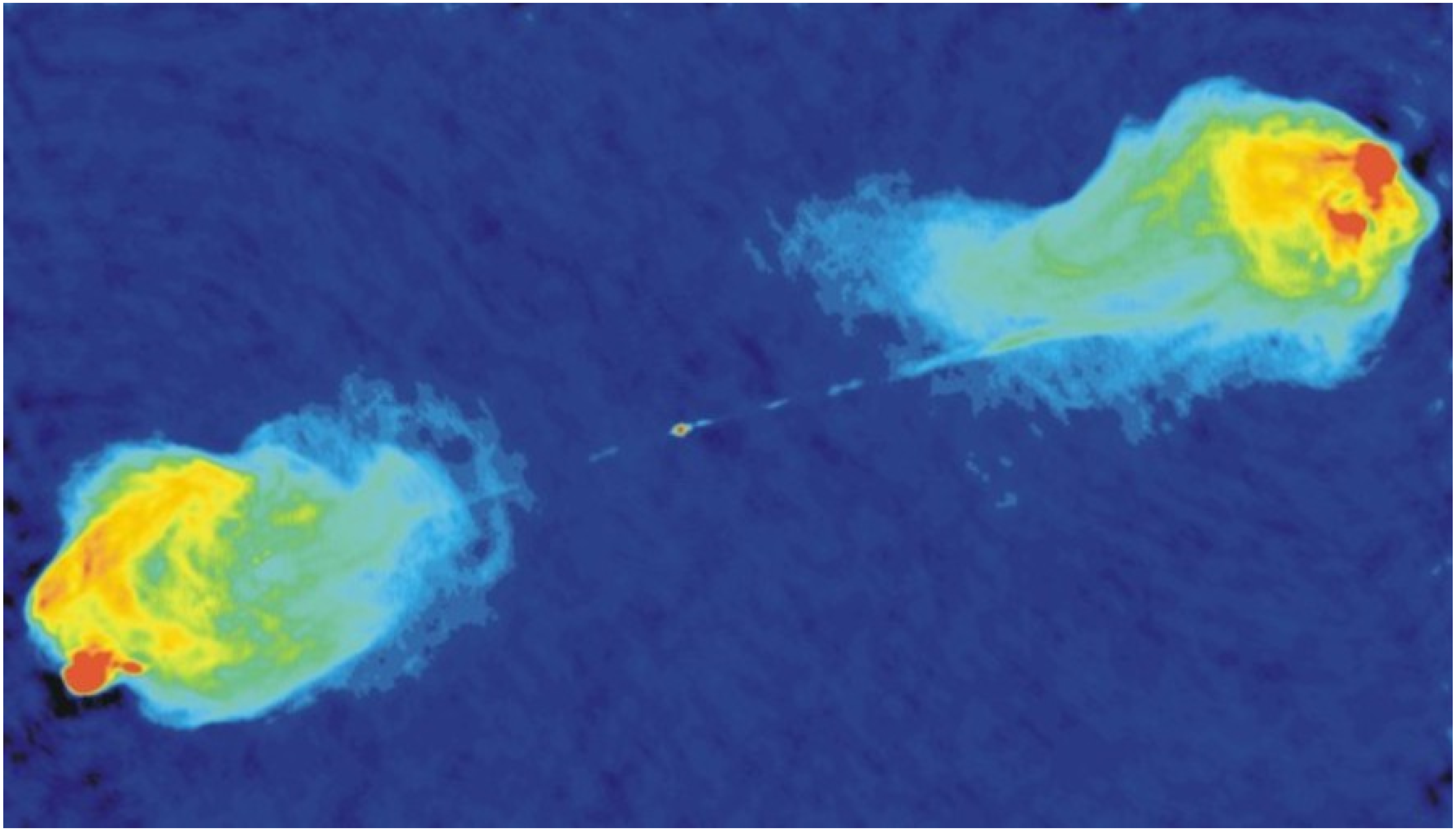
$$\theta_{res} \approx \frac{\lambda}{B_{max}}$$

Largest recoverable scale

$$\theta_{MRS} \approx \frac{\lambda}{B_{min}}$$



How to get this image of Cygnus A?



Credit: Image courtesy of NRAO/AUI; R. Perley, C. Carilli & J. Dreher

Peculiarities @ mm

With increasing frequency:

- **No external human interferences in the data**

- **No ionospheric effect**

- Tropospheric effects: absorption and delay of signal
  - → stronger weather dependency
  - → T_{sys} dominated by atmosphere noise

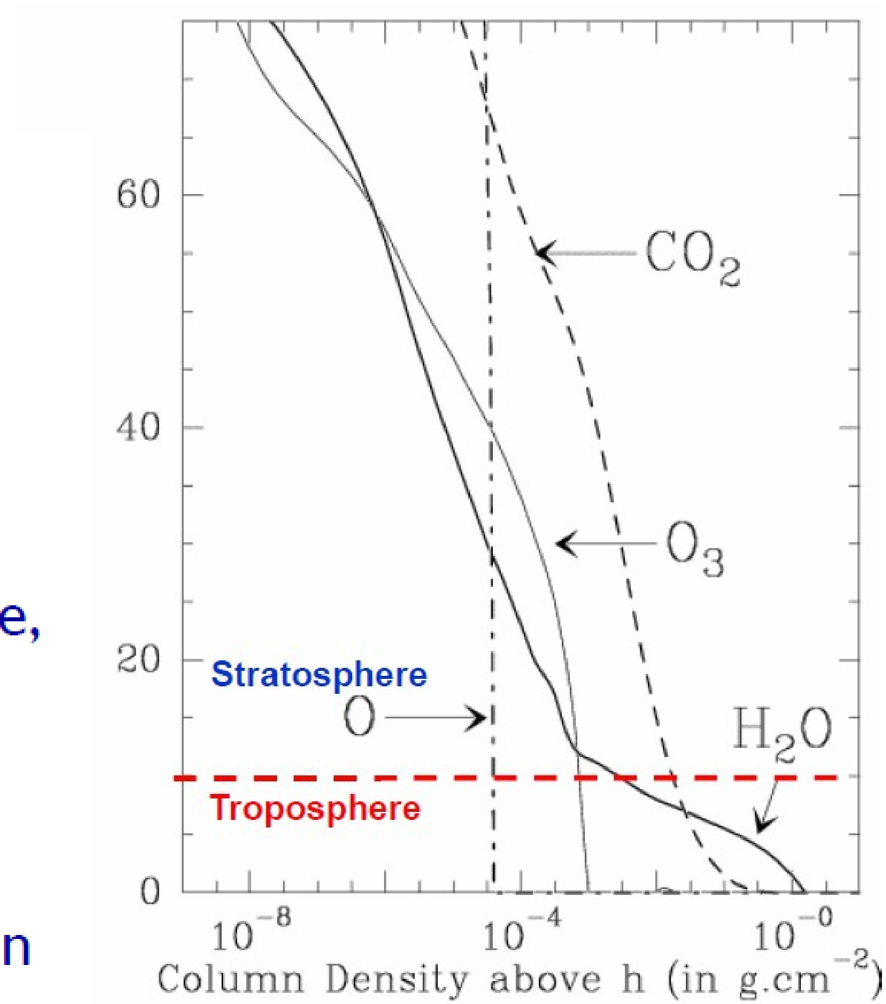
- Time variability of quasar increases
  - → which flux calibrators?

Peculiarities @ mm

The role of troposphere

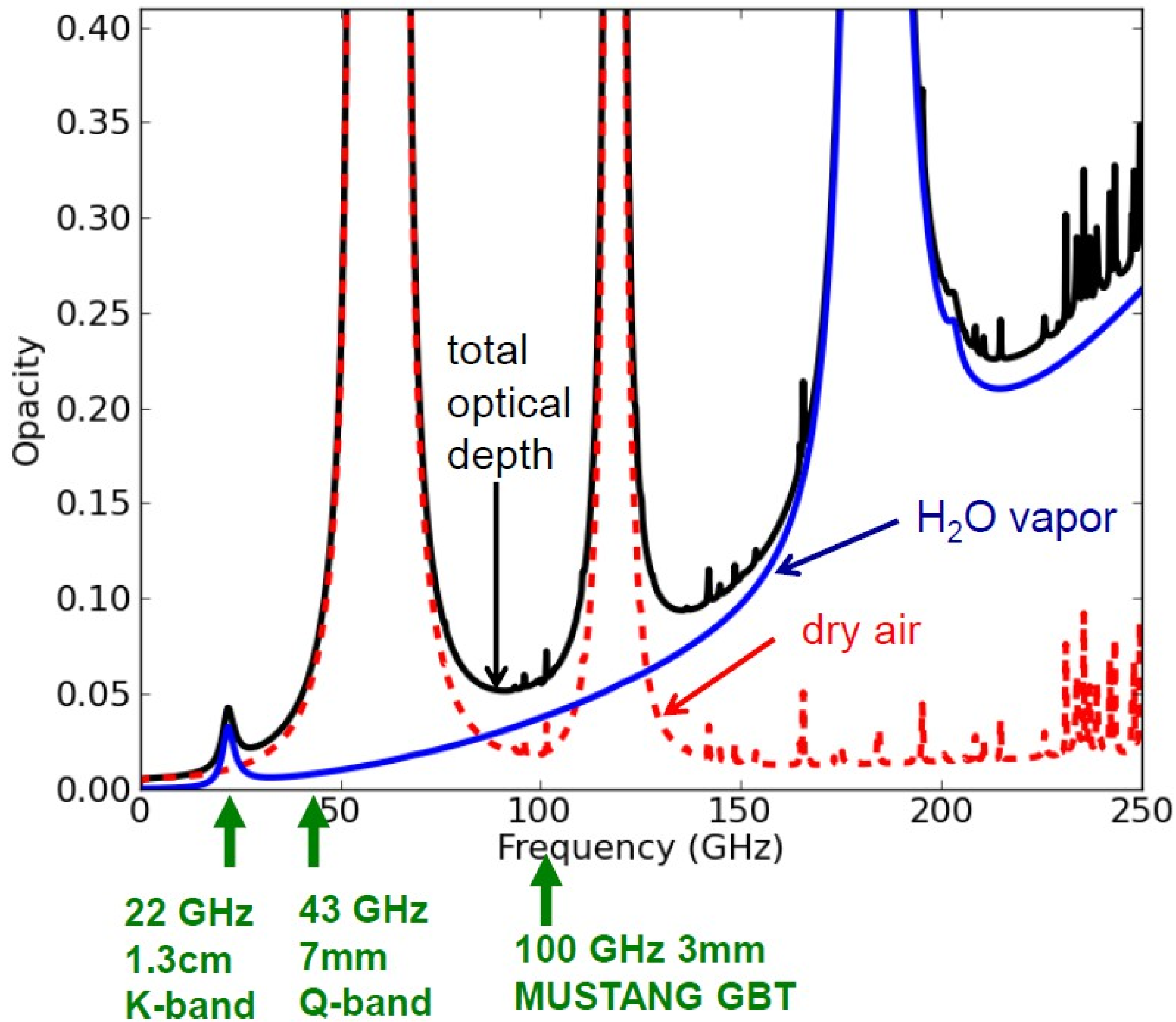
- H_2O (mostly vapor)
- "Hydrosols" (water droplets in clouds and fog)
- "Dry" constituents: O_2, O_3, CO_2, Ne, He, Ar, Kr, CH_4, N_2, H_2
- clouds & convection = time variation

Column density as function of altitude



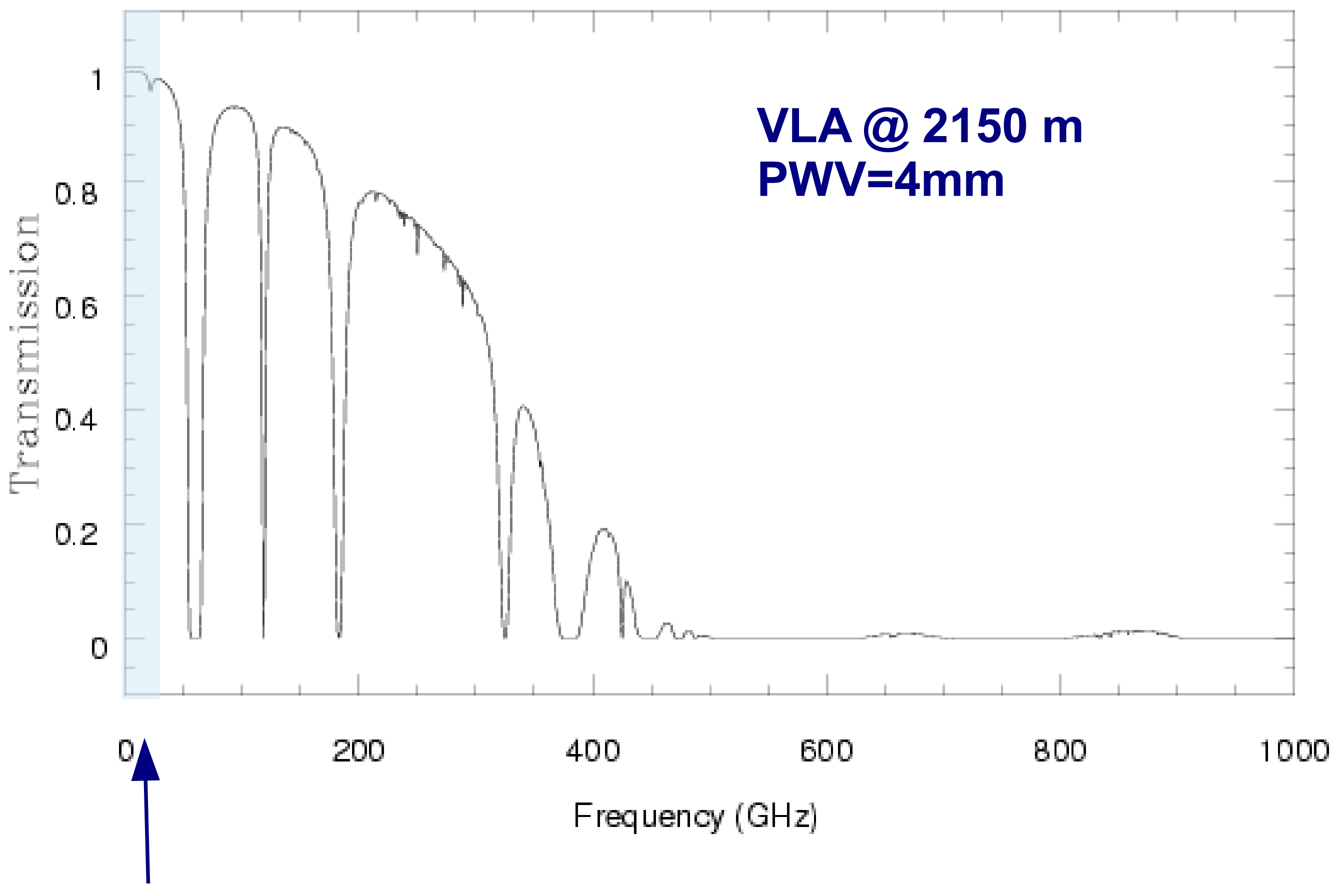
Peculiarities @ mm

Optical depth as function of frequency



Peculiarities @ mm

Tropospheric opacity depends on altitude

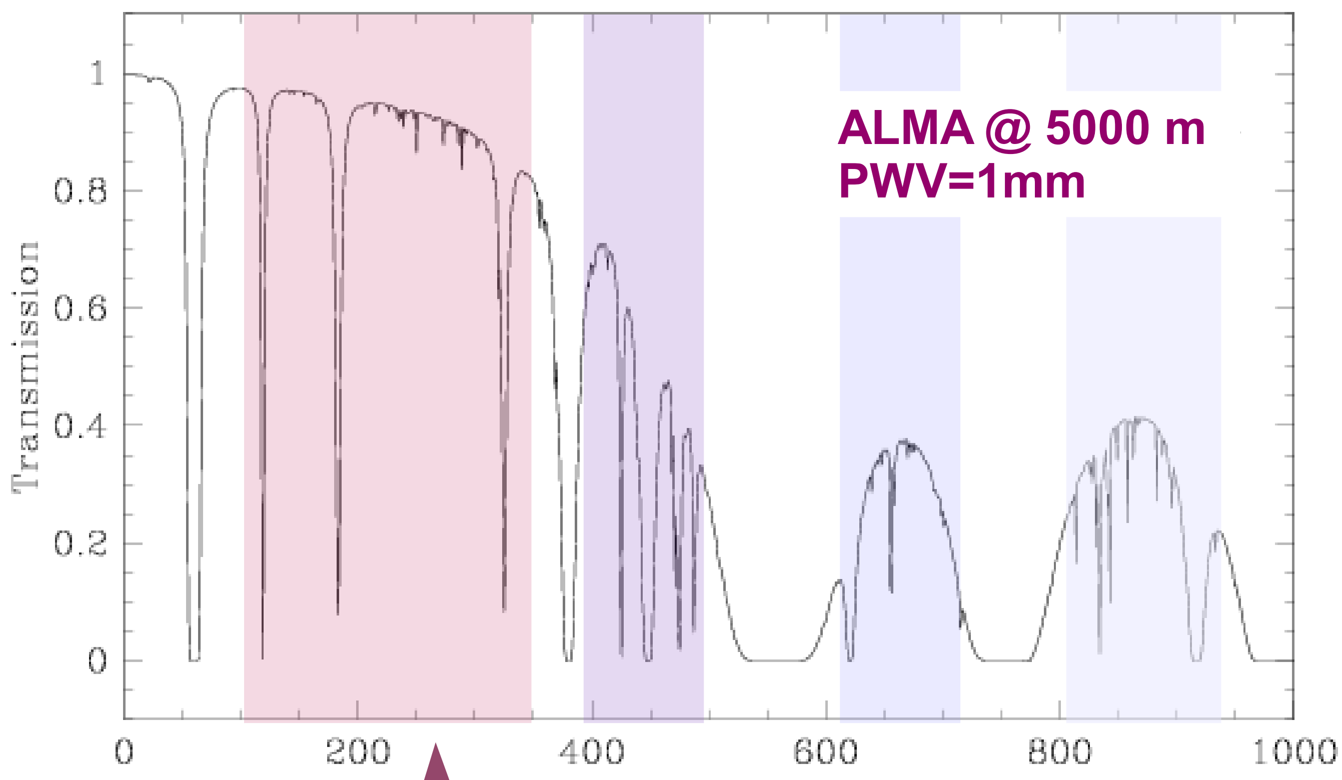


VLA bands

Atmospheric transmission not a problem @ $\lambda >$ cm

Peculiarities @ mm

Tropospheric opacity depends on altitude

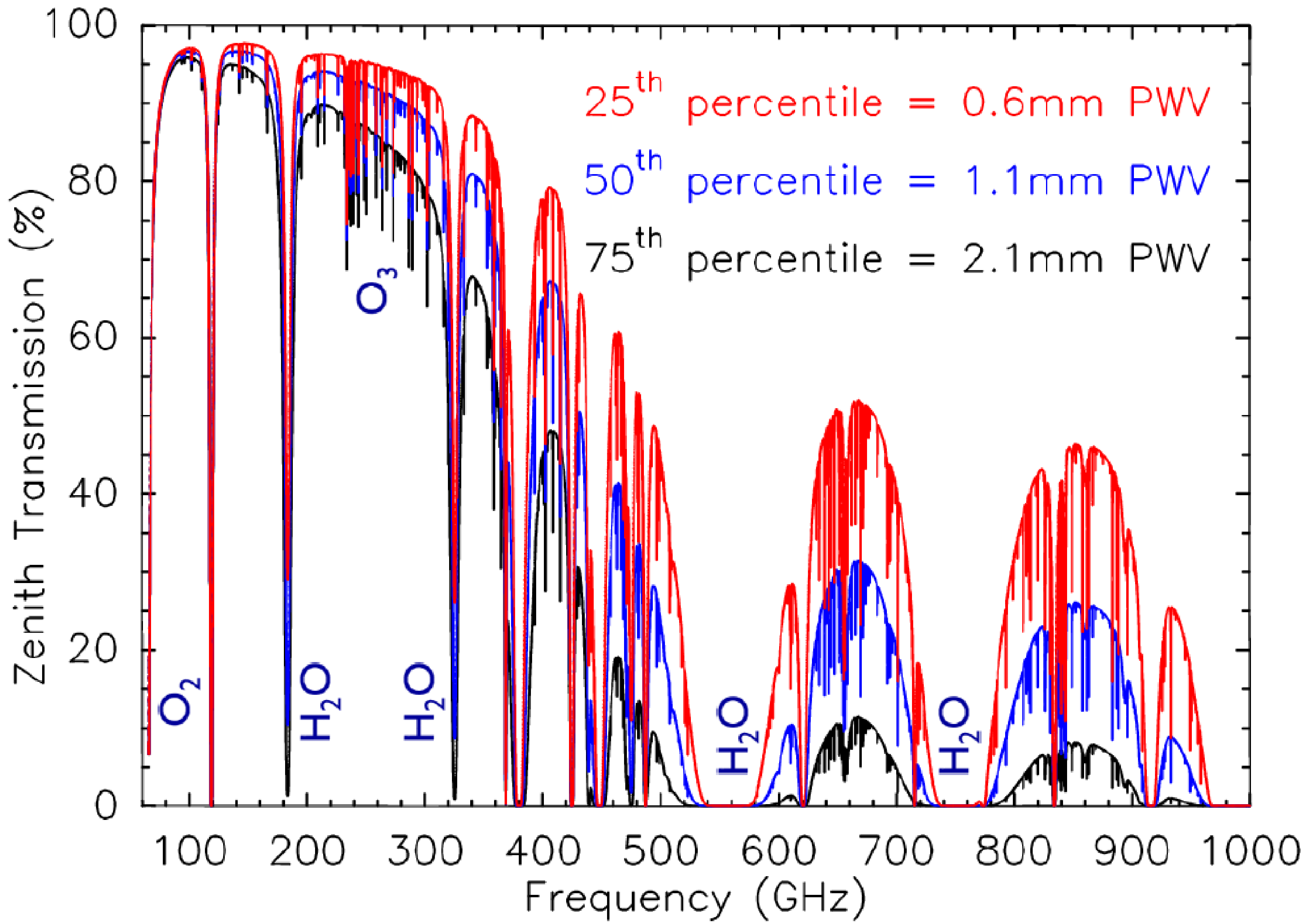


Difference due to the scale height of water vapor

ALMA bands

Peculiarities @ mm

PWV= Precipitable Water Vapour



Peculiarities @ mm

System noise temperature

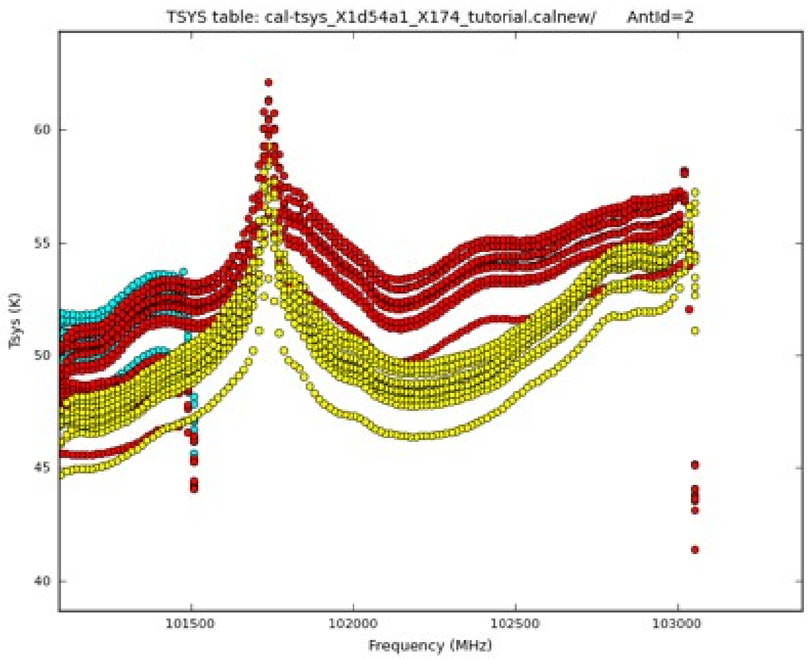
$$T_{sys} \sim T_{atm}\,(e^{\tau} - 1) + T_{rx}\,e^{\tau}$$

At lower frequencies T_{rx} is dominant

ALMA front end are equipped with an Amplitude Calibration Device (ACD)

$\longrightarrow$ T_{sys} and T_{rx}

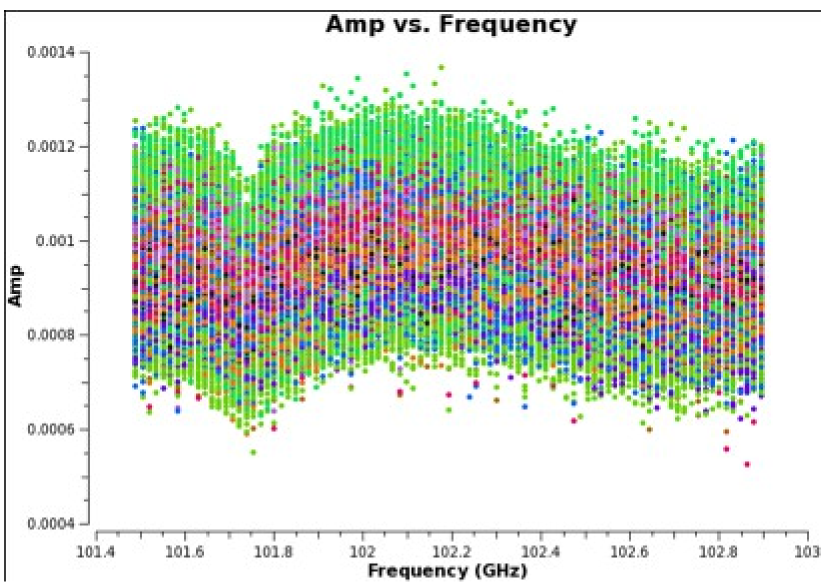
Peculiarities @ mm



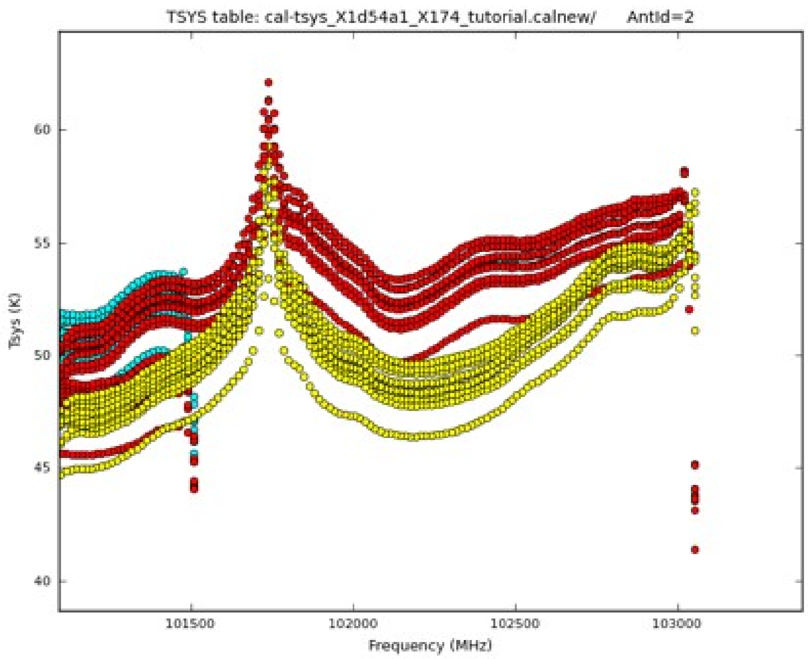
Tsys calibration

Spectral Tsys
band 3 (~100 GHz)

Before



Peculiarities @ mm



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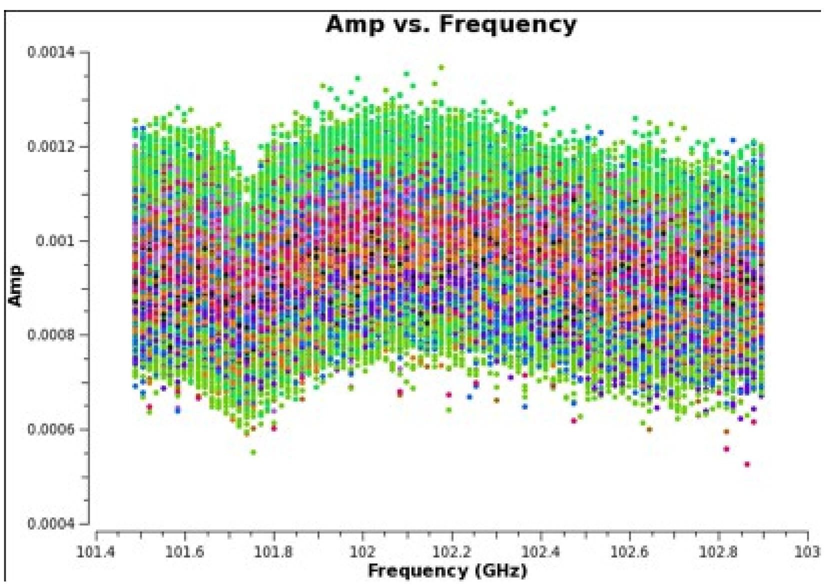
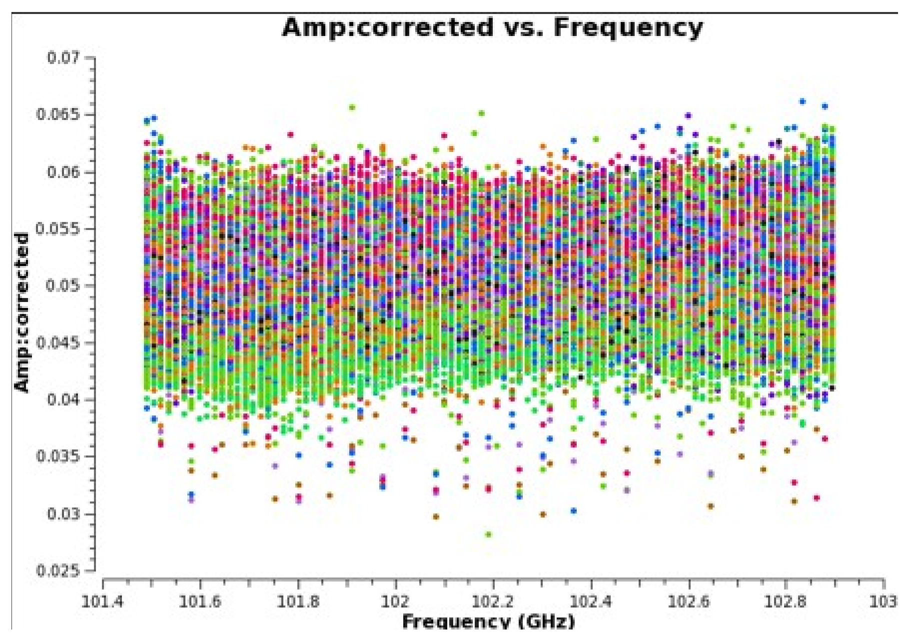


After



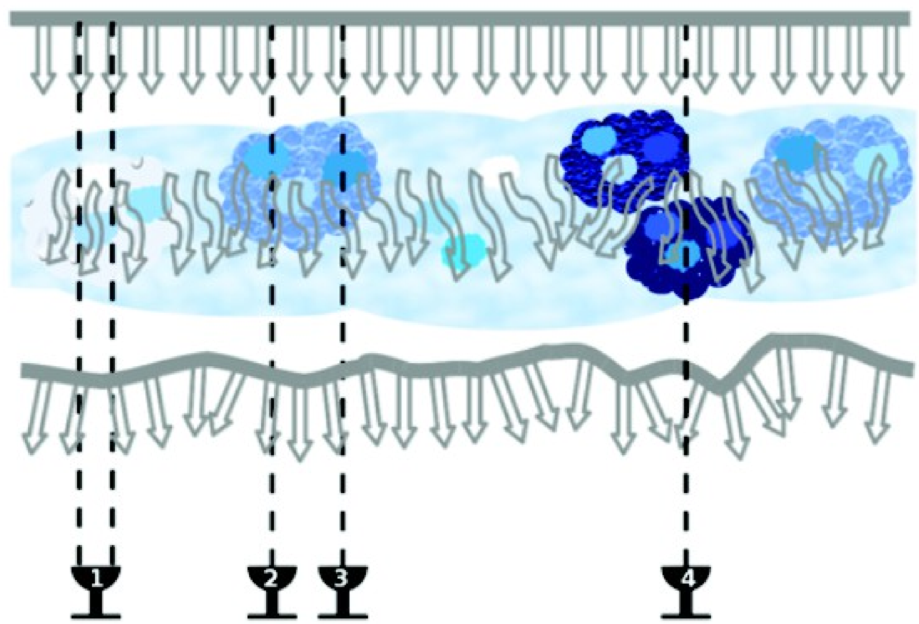
Peculiarities @ mm

Mean effect of atmosphere on Phase

Variations in precipitable water vapor (PWV) cause phase fluctuations, worse at higher frequencies, resulting in:

- Phase shift due to refractive index n $\neq 1$
- Low coherence (loss of sensitivity)

Patches of air with different pwv
(and hence index of refraction)
affect the incoming wave front differently.



Antenna 1, 2, 3 see slightly different disturbances

Sky above antenna 4 varies independently

The phase change experienced by an e.m. wave can be related to pwv

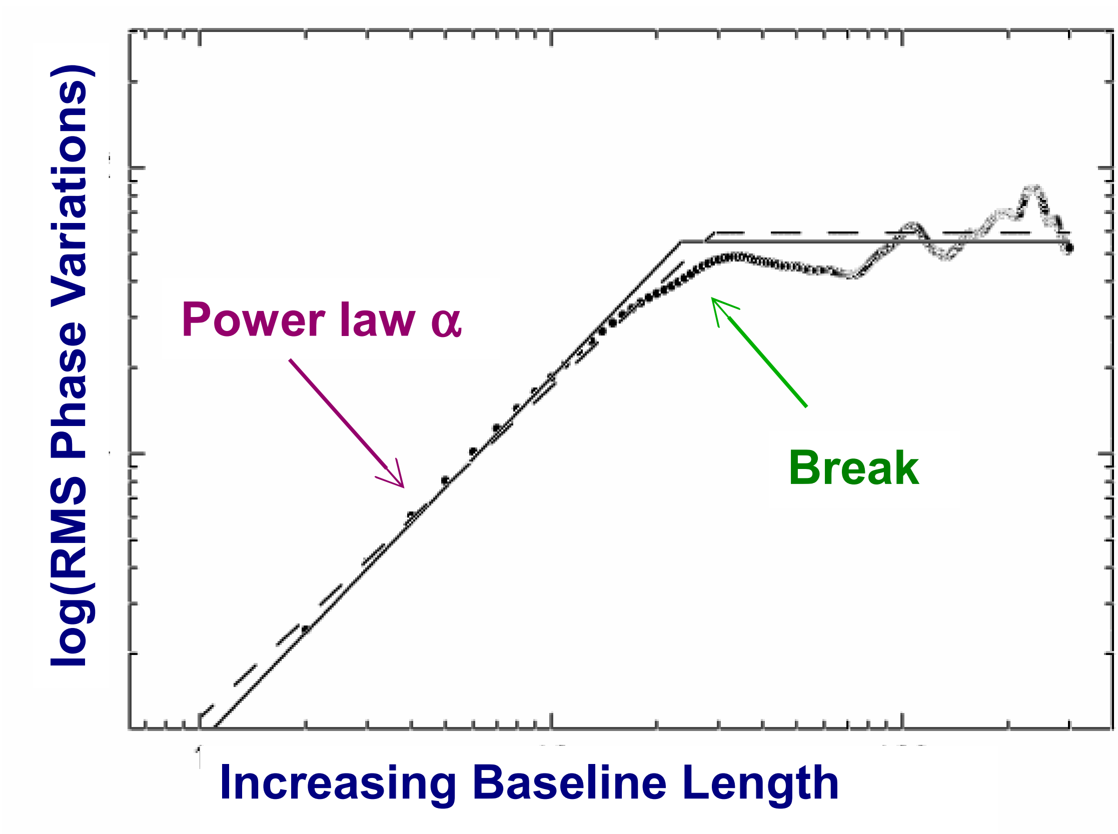
$$\varphi_e \approx \frac{12.6\pi}{\lambda} \cdot pwv$$

Hogg, Guiraud, & Decker, 1981

Peculiarities @ mm

Atmospheric phase fluctuations

Kolmogorov turbulence theory



Phase noise

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

b=baseline length (km)
α = 1/3 to 5/6 (thin or thick atmosphere)
λ = wavelength (mm)
K constant (~100 for ALMA)

The break is typically @ baseline lenghts few hundred meters to few km (scale of the turbulent layers)

Break and maximum are weather and wavelength dependent

Peculiarities @ mm

Atmospheric phase fluctuations → decorrelation

We loose integrated flux because visibility vectors partly cancel out

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

φ_{rms} = 1 radian → <V> = 0.60 V_0

In summary
Fluctuations in the line-of-sight pwv of an antenna
cause phase variations of the order of ~30 deg / sec at 90 GHz,
and scales linearly with frequency....

$$\varphi_e \approx \frac{12.6\pi}{\lambda} \cdot pwv$$

and the phase noise is worse at longer baselines...

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

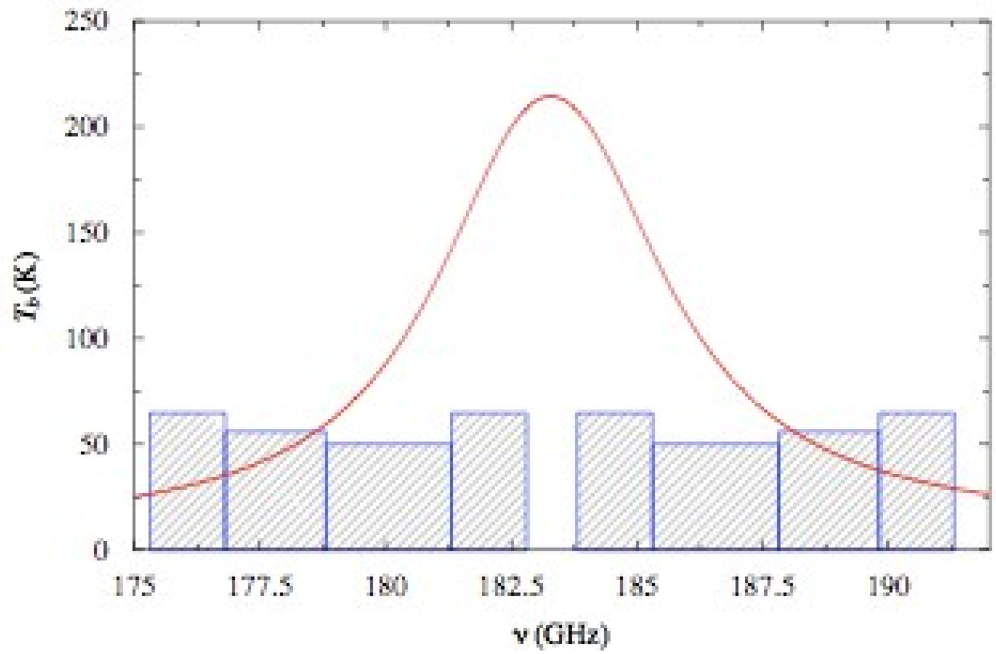
Peculiarities @ mm

WVR correction

Each ALMA 12 m antenna has a water **vapour radiometer**

Four “channels” flanking the peak of the 183 GHz water line

Data taken every second



Peculiarities @ mm

WVR correction

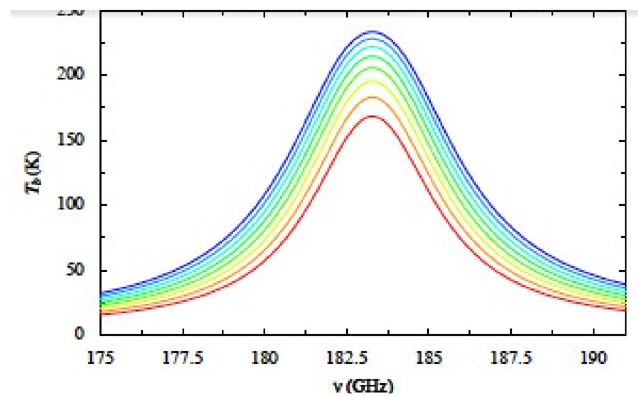
Each ALMA 12 m antenna has a water **vapour radiometer**

Four “channels” flanking the peak of the 183 GHz water line

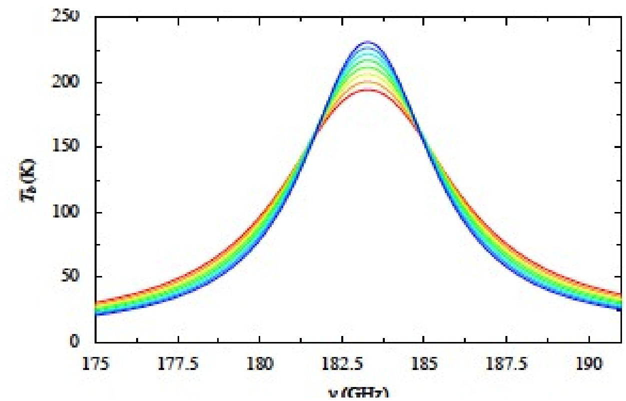
Data taken every second

Convert 183 GHZ brightness to PWV (wvrgcal):
model PWV, temperature and pressure
compare to the observed “spectrum”
compute the correction:

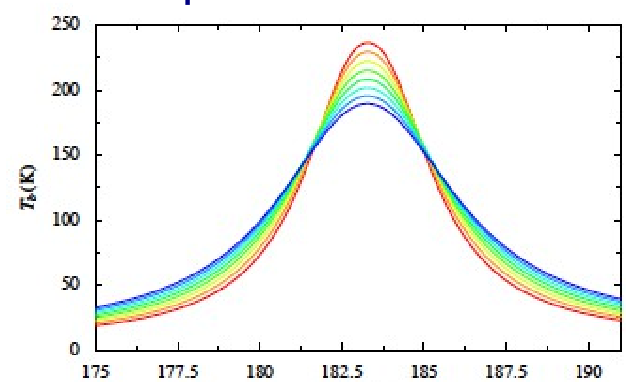
$$\varphi_e \approx \frac{12.6\pi}{\lambda} \cdot pwv$$



PWV from 0.6 to 1.3 mm



Temperature 230-300 K

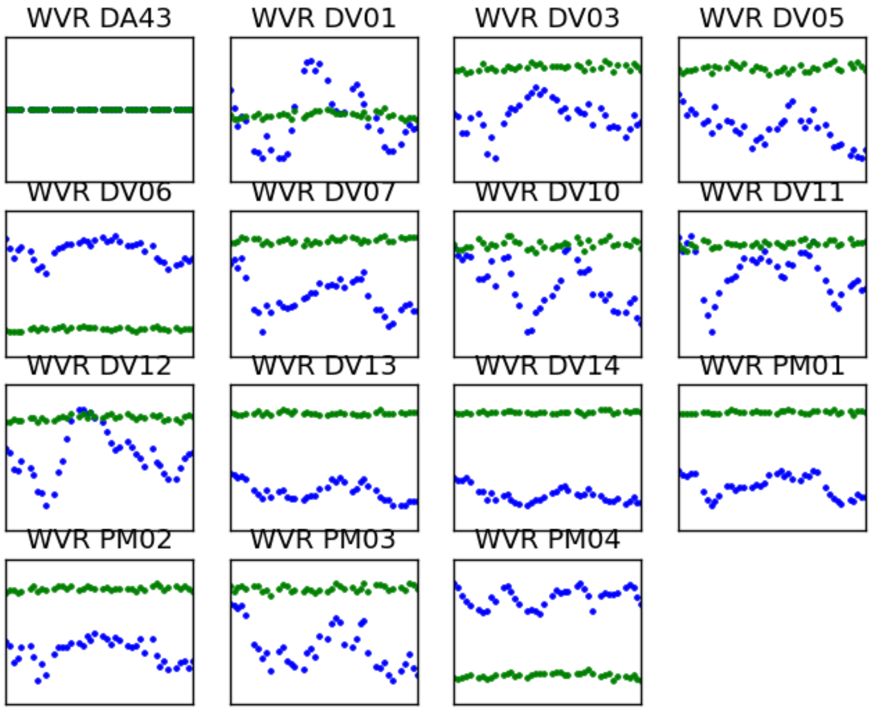


Pressure 400-750 mBar

Peculiarities @ mm

WVR correction

Band 6 (230 GHz)

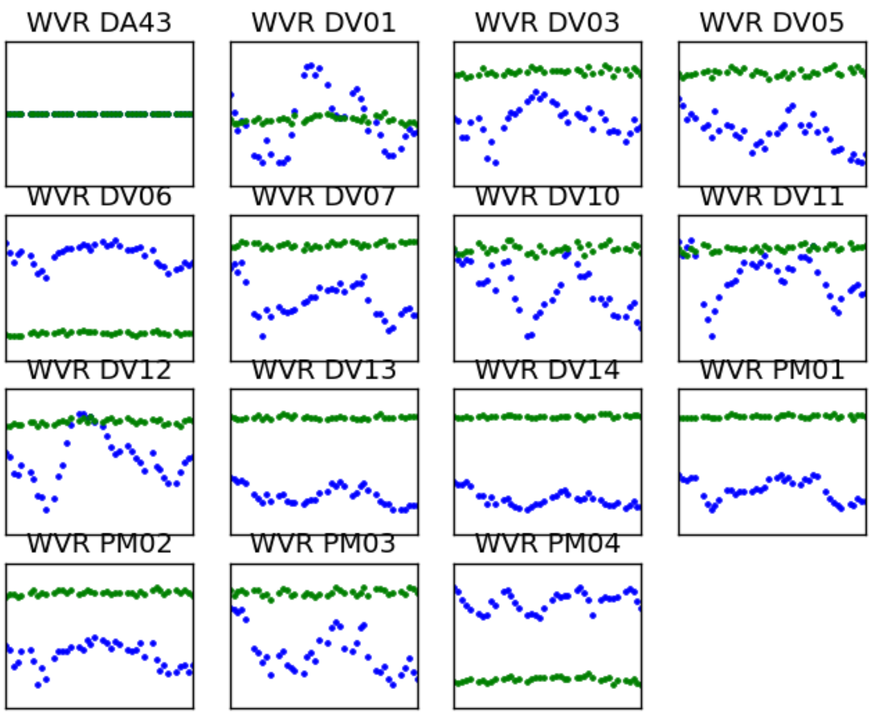


Raw phases & WVR corrected phases

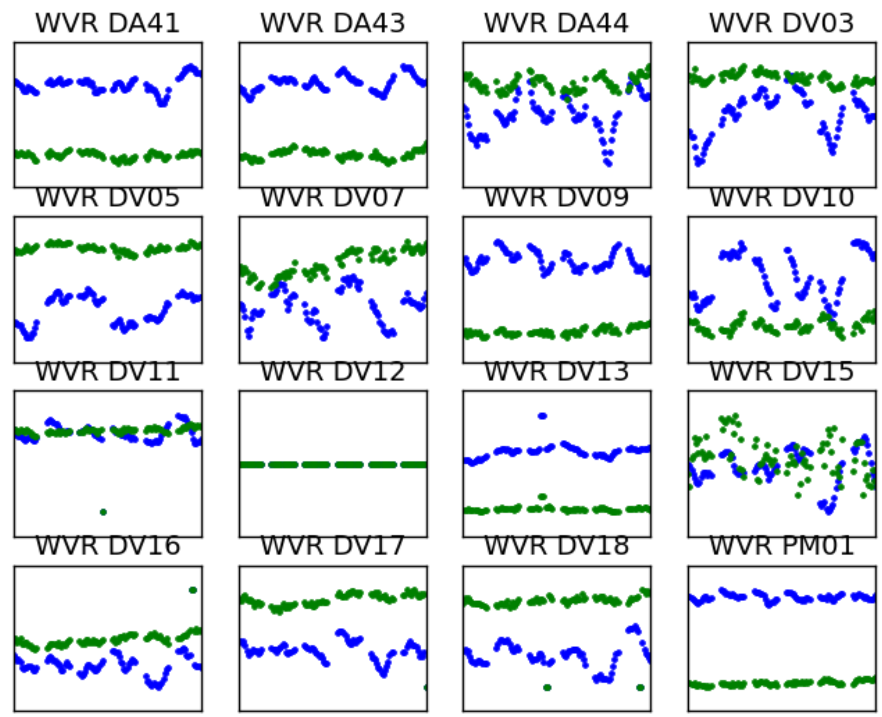
Peculiarities @ mm

WVR correction

Band 6 (230 GHz)



Band 7 (340 GHz)



Raw phases & WVR corrected phases

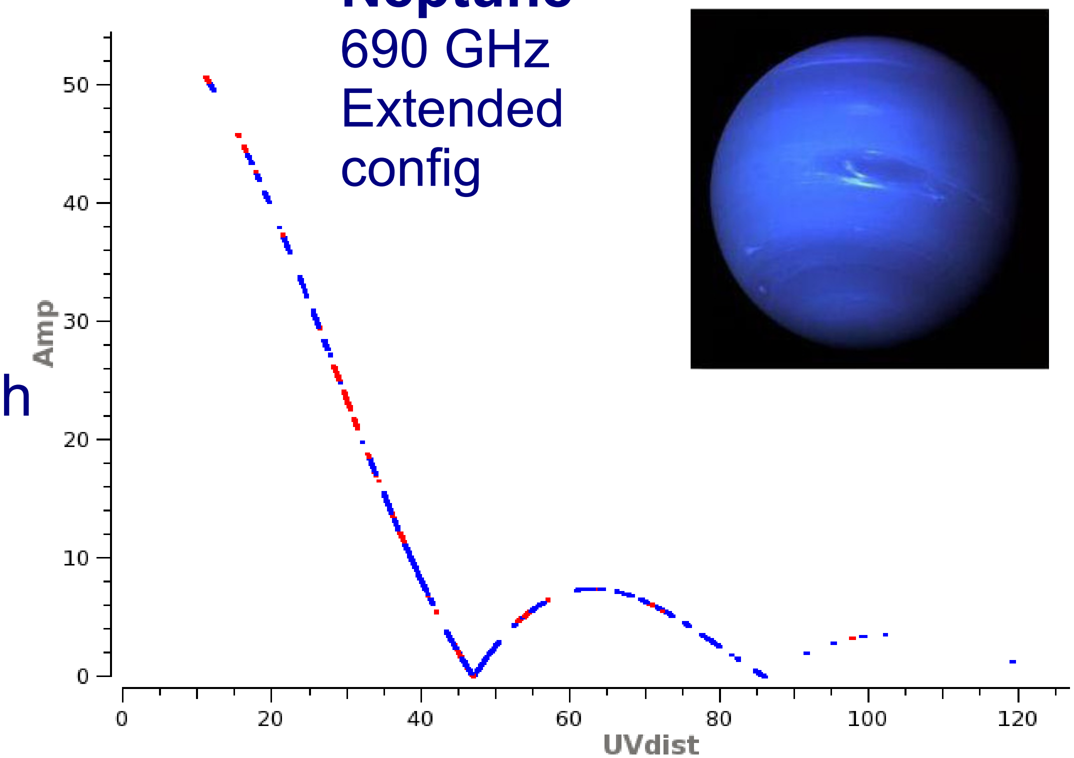
Peculiarities @ mm

Flux calibrators

- Quasars are strongly time-variable and good models do not exist at high frequencies

- Solar System bodies are used as primary flux calibrators (Neptune, Jovian moons, Titan, Ceres) but with many challenges:
  - **- all are resolved on long baselines**
  - **- brightness varies with distance from Sun and Earth**
  - **- line emission present → need models**

Neptune
690 GHz
Extended
config

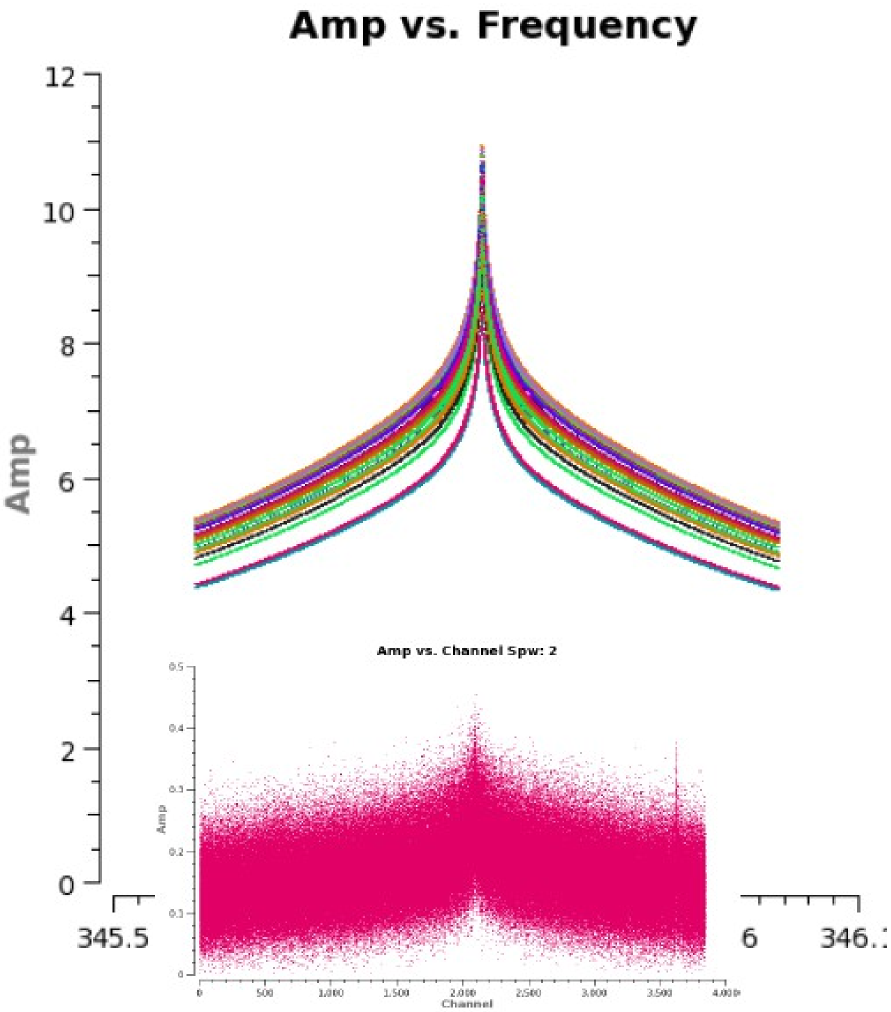


Other possibilities: asteroids,
red giant stars...
Monitoring of point-like quasars

Peculiarities @ mm

Flux calibrators

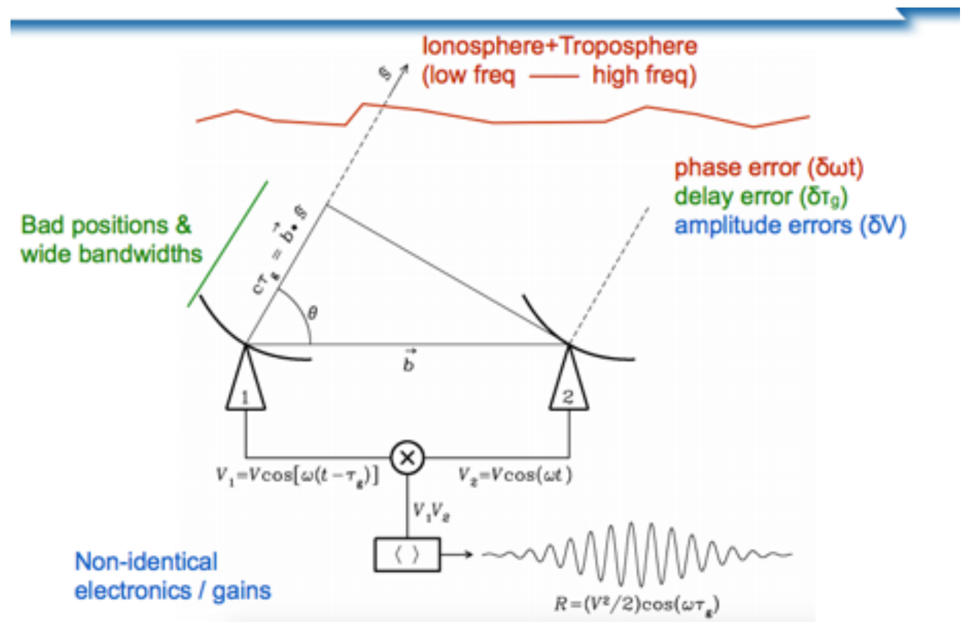
Model spetral lines: CO in Titan



Calibration in interferometry… why do we need to calibrate?

So far…

$$\mathcal{V}(u,v) = \iint \mathcal{A}(l,m) I(l,m) e^{-2\pi i(ul+vm)} dl dm.$$



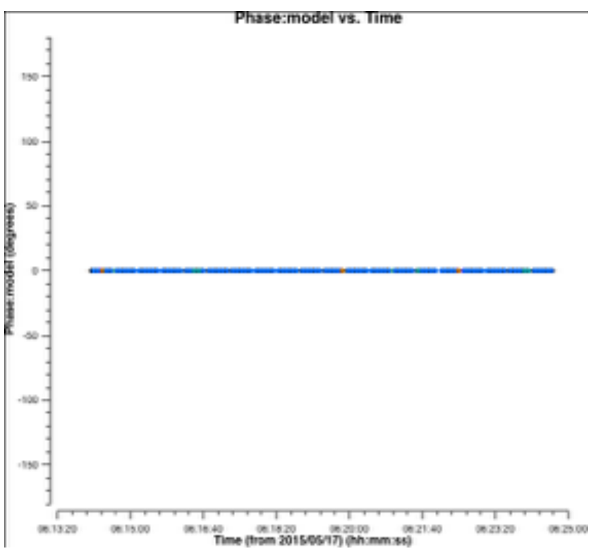
but…

- weather
- real antennas
- electronics
- correlators…

Calibration in interferometry…
why do we need to calibrate?

what do I expect for a point like source in visibility plane?

- Flat amps
- Flat phases at zero…



$$V(i,j)_{obs} = J(i,j)\ V(ij)_{true}$$

J_{ij} is a generalized operator characterizing the net effect of the observing process for antennas i and j on baseline ij.

It must be calibrated!

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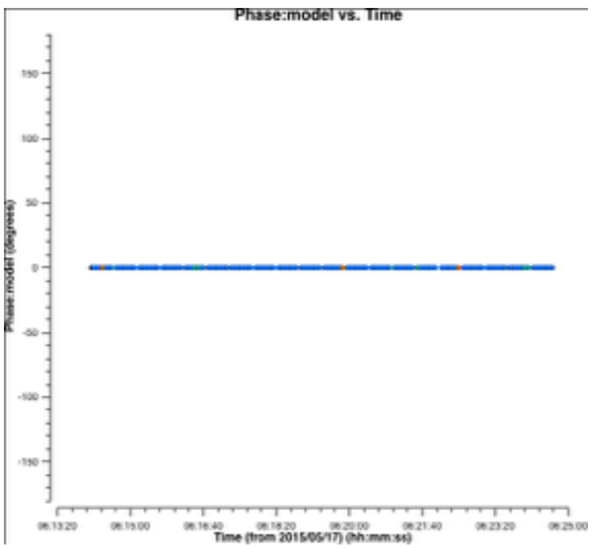
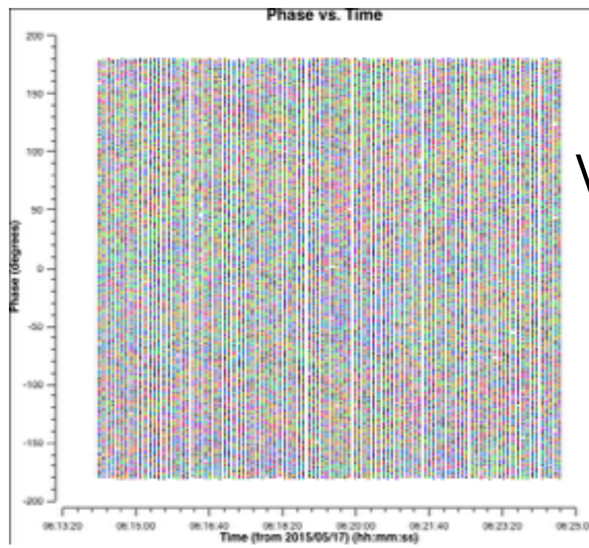




$V(i,j)_{obs} = J(i,j)\ V(ij)_{true}$

J_{ij} is a generalized operator characterizing the net effect of the observing process for antennas i and j on baseline ij.

It must be calibrated!

Calibration in interferometry… why do we need to calibrate?

Strategy:

- We need to observe some source which visibilities are known (calibrators). Thus:

$$J_{ij} = V_{obs}/V_{mod}$$

  - Observe strong astronomical sources near science (if necessary) target against which calibration (Jij) can be solved, and transfer solutions to target observations
  - Choose appropriate calibrators; usually point sources because we can easily predict their visibilities (Amp ~ constant, phase ~ 0)
  - Choose appropriate timescales for calibration

Calibration in interferometry…
why do we need to calibrate?

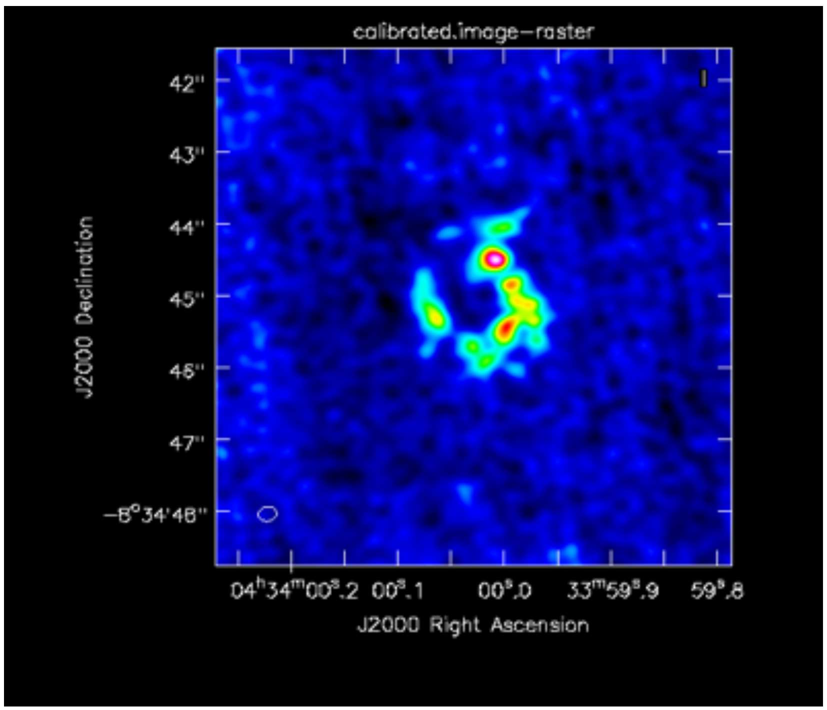
Assumptions:

- any information that can be factorized into antenna-based terms, could be antenna-based effects, and not source visibility
- different calibration terms are independent (v,t)

$$V_{ij}^{obs} = J_i J_j^* V_{ij}^{true} \quad \rightarrow \quad V_{ij}^{cor} = J_i^{-1} J_j^{*-1} V_{ij}^{obs}$$

Calibration in interferometry…
do we really need to calibrate?

what do I expect in the image plane?



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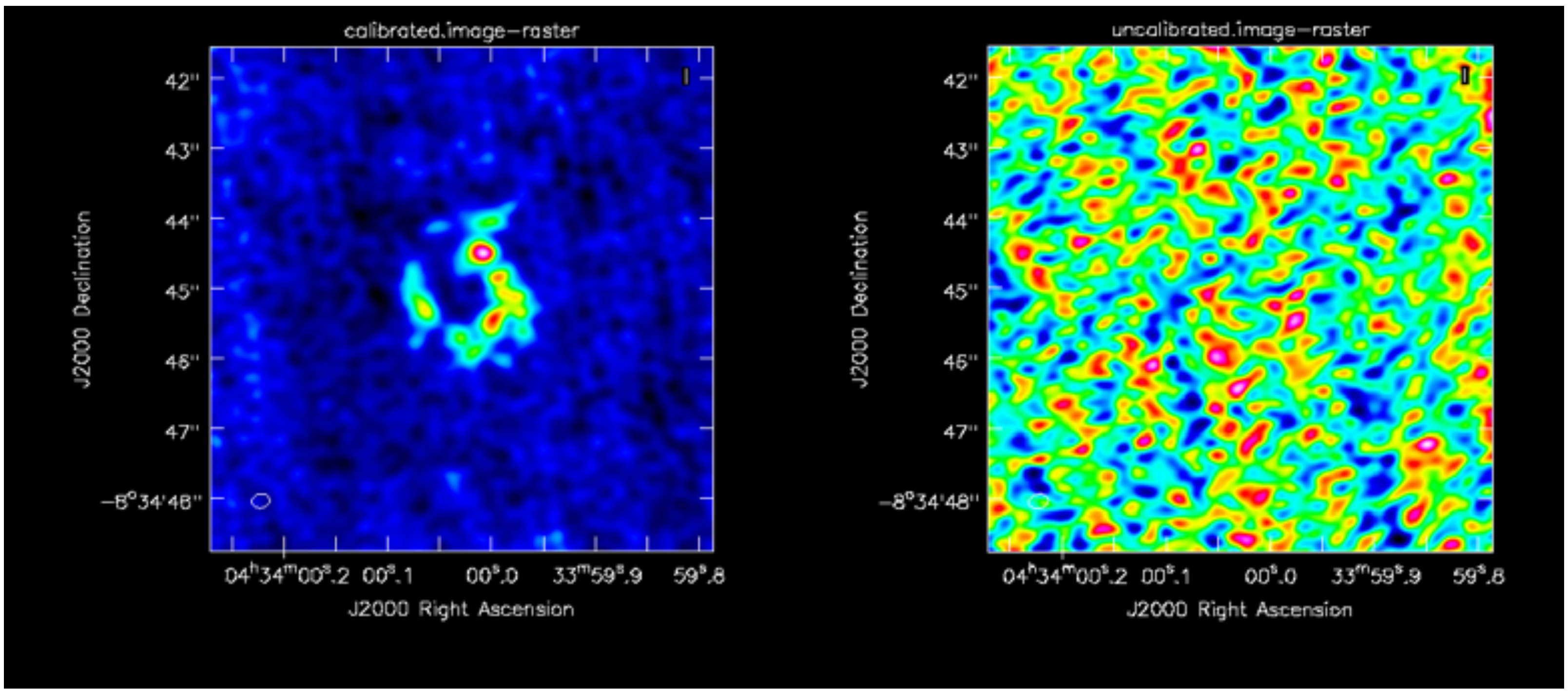

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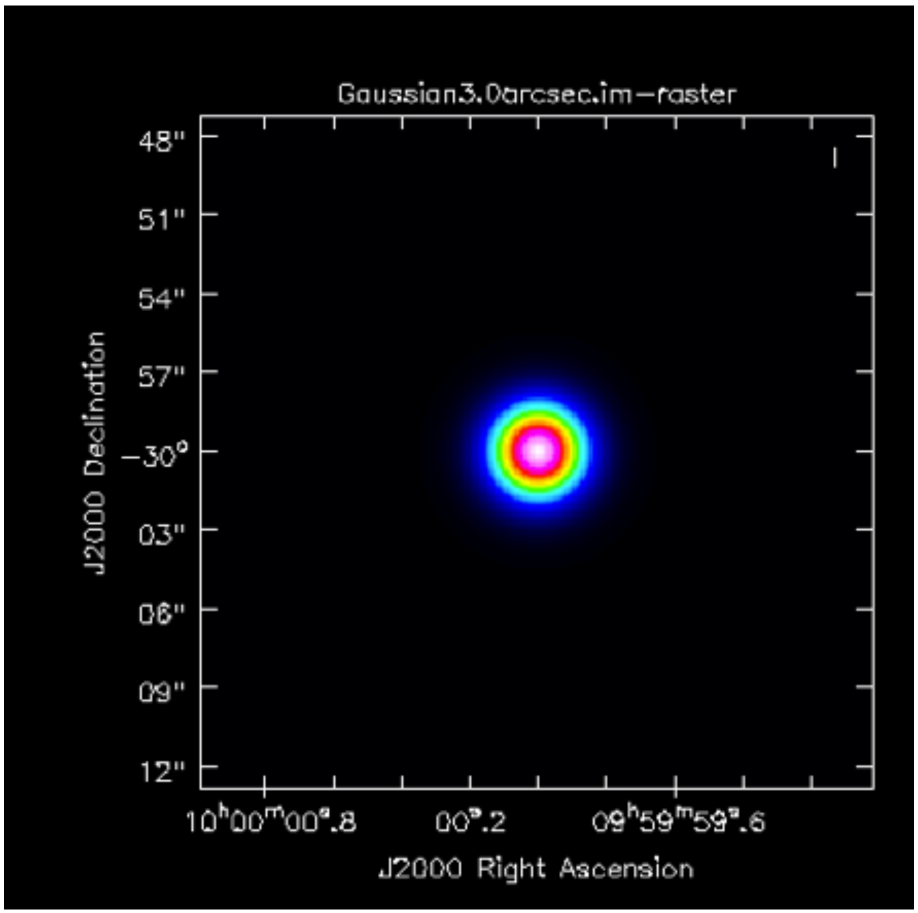

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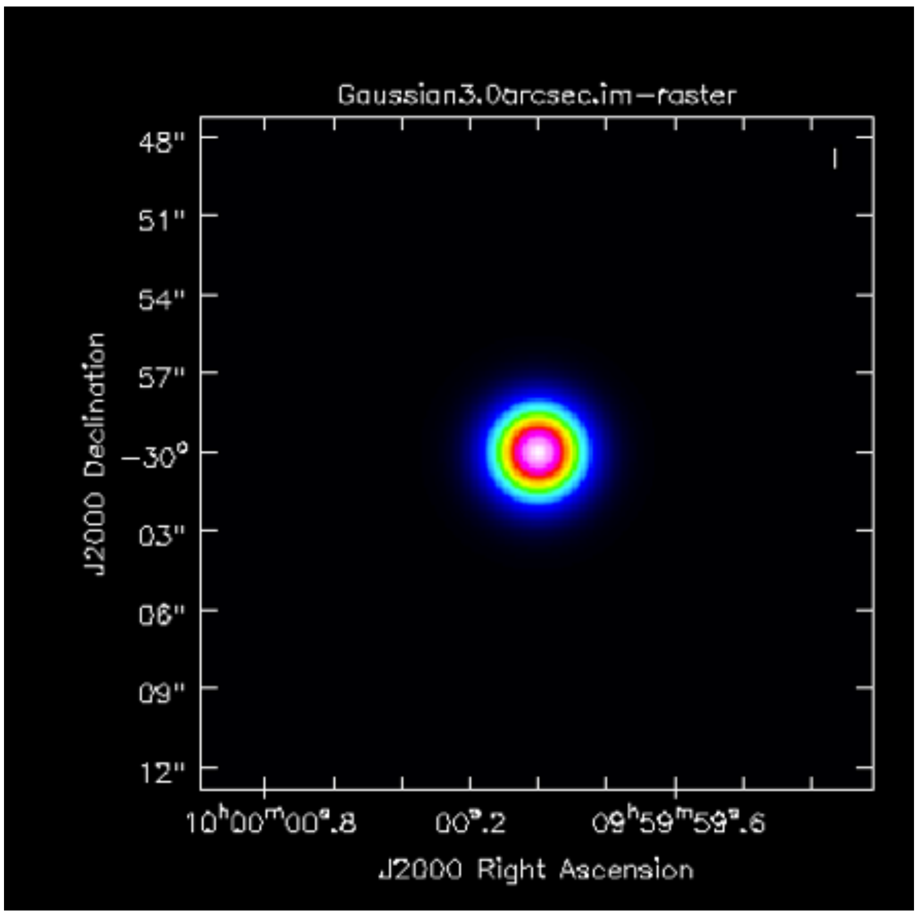
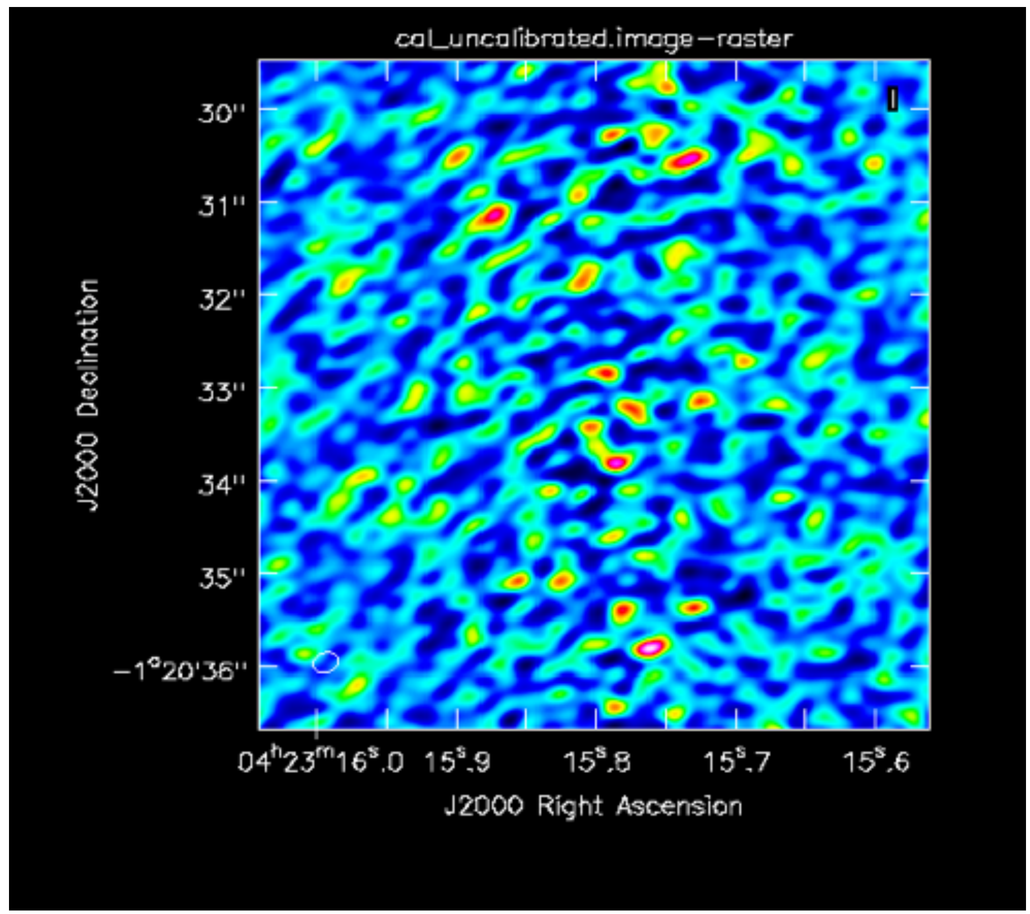


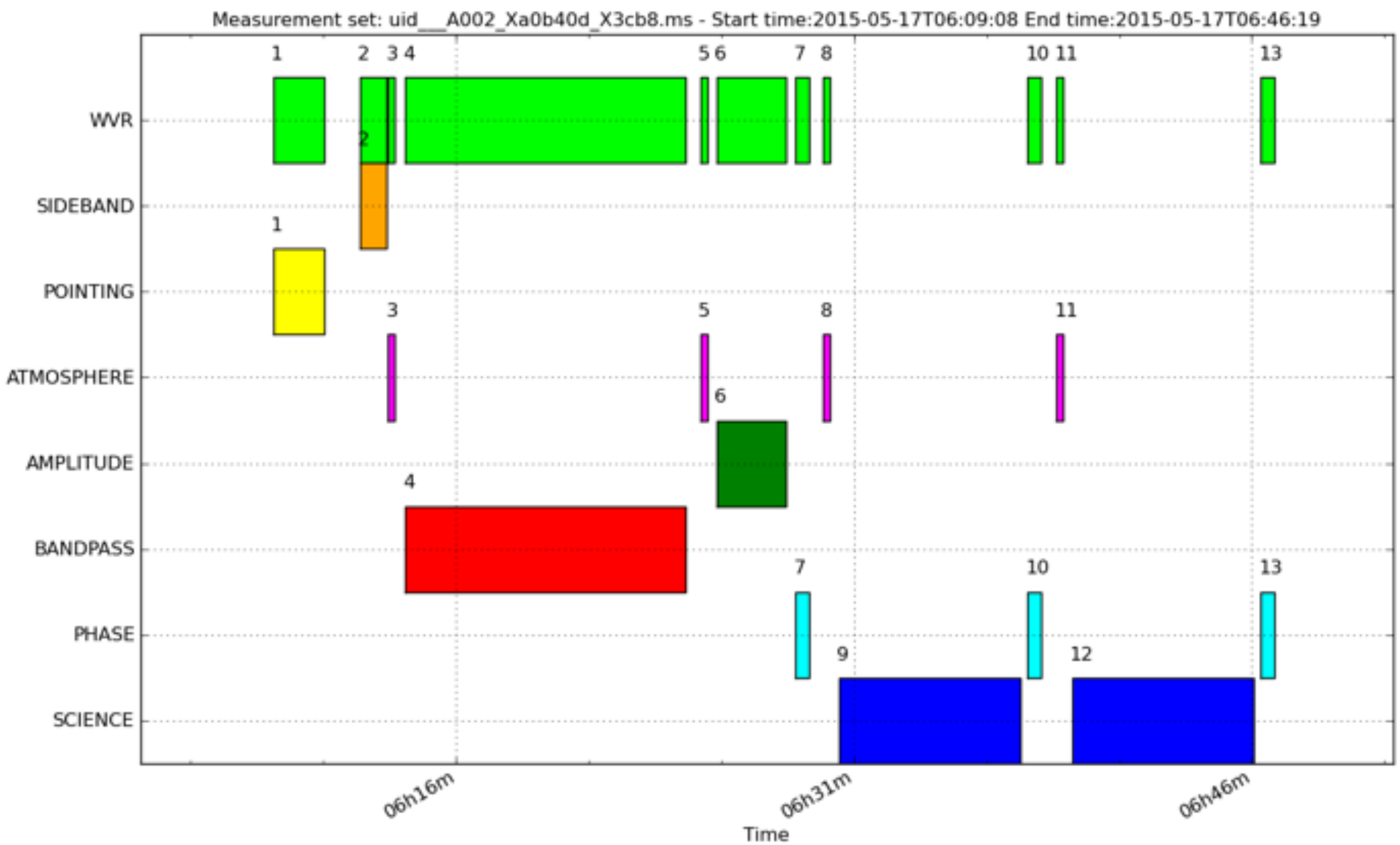


Calibration in interferometry…
CASA viewpoint

- Calibration Solutions in NEW TABLES (when calculated, MS doesn't change)
- Only when we apply to data, the MS is corrected/calibrated

MAIN	Model, e.g.:	Corrected data	Flags
Original visibility data	*FT of image made from MS* *FT of supplied model image* *FT of calibrator flux density*	*Copy of visibilities with calibration tables applied* (Used in imaging but not calibration)	(Edits are stored here first; backup tables can be made and used to modify)

Calibration in ALMA…
Observational Strategy



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Calibration in ALMA…
Observational Strategy (from the pipeline)

1. **hif_importdata**: Register measurement sets with the pipeline
2. **hifa_flagdata**: ALMA deterministic flagging
3. **hifa_fluxcalflag**: Flag spectral features in solar system flux calibrators
4. **hif_refant**: Select reference antennas
5. **hifa_tsyscal**: Calculate Tsys calibration
6. **hifa_tsysflag**: Flag Tsys calibration
7. **hifa_wvrgcalflag**: Calculate and flag WVR calibration
8. **hif_lowgainflag**: Flag antennas with low gain
9. **hif_setjy**: Set calibrator model visibilities
10. **hif_bandpass**: Bandpass calibration
11. **hif_bpflagchans**: Flag channels of bandpass calibration
12. **hifa_gfluxscale**: Transfer fluxscale from amplitude calibrator
13. **hifa_timegaincal**: Gain calibration

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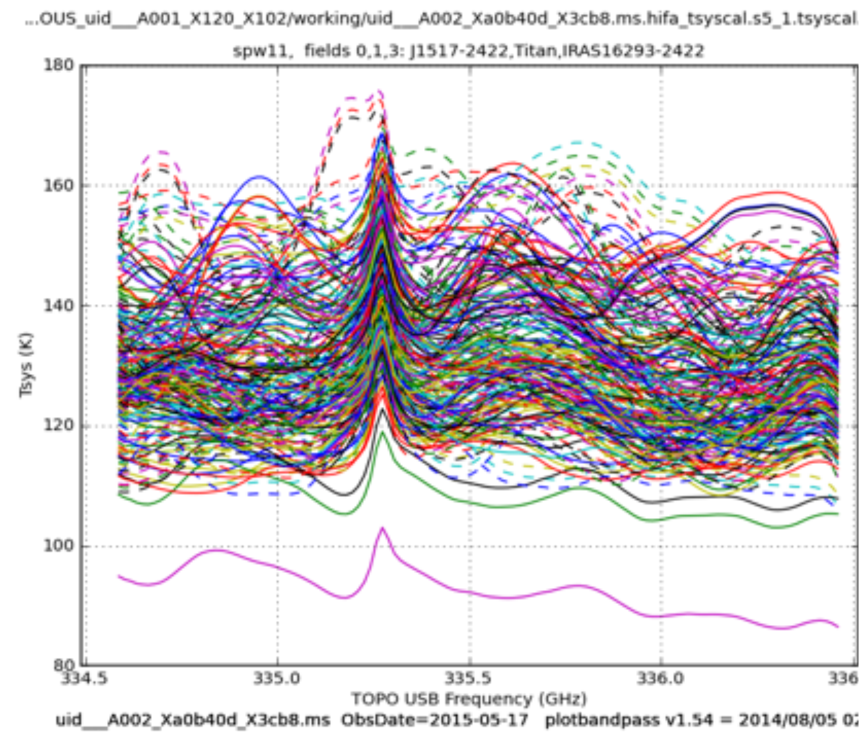
a priori calibration

Calibration in ALMA…
hifa-tsyscal

- System temperature (T_{sys}) refers to power available from the system noise
  - calibration gives a first-order correction for the atmospheric opacity as a function of time and frequency
  - @mm wavelengths, dominated by atmosphere

$$T_{sys}=T_{atm}\,(e^{\tau}-1)+T_{rx}e^{\tau}$$

  - Dependences:
    - opacity of atmosphere (τ)
    - T atmosphere (T_{atm})
    - T receiver (T_{rx})



The system Temperatures drops exponentially with τ

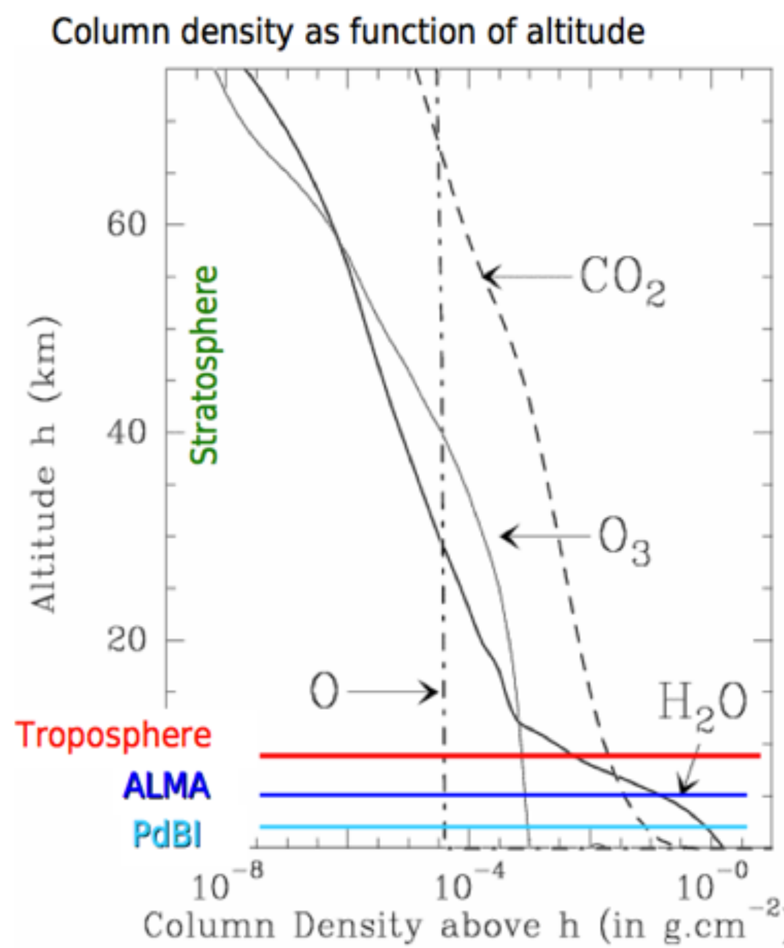
Calibration in ALMA… hifa-tsyscal

The role of troposphere

- ‘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



Calibration in ALMA…
hifa-tsyscal

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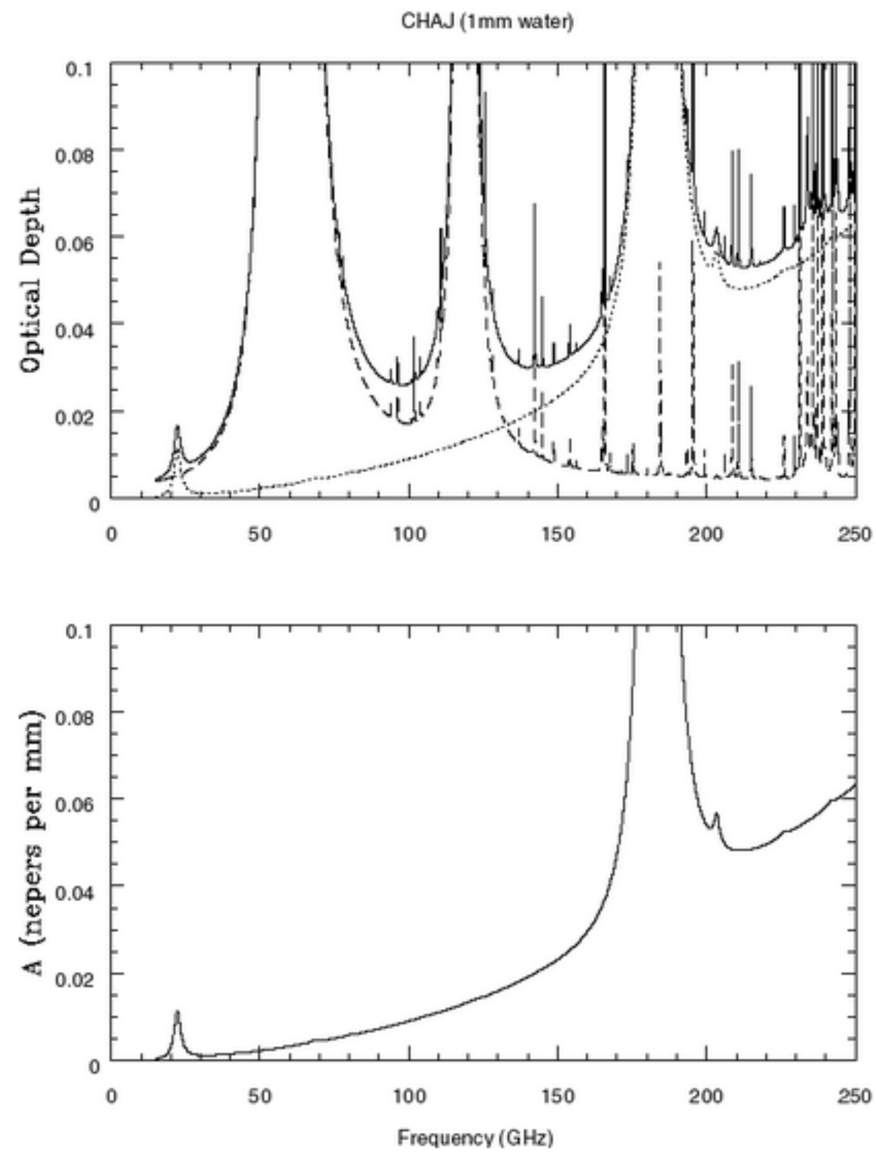
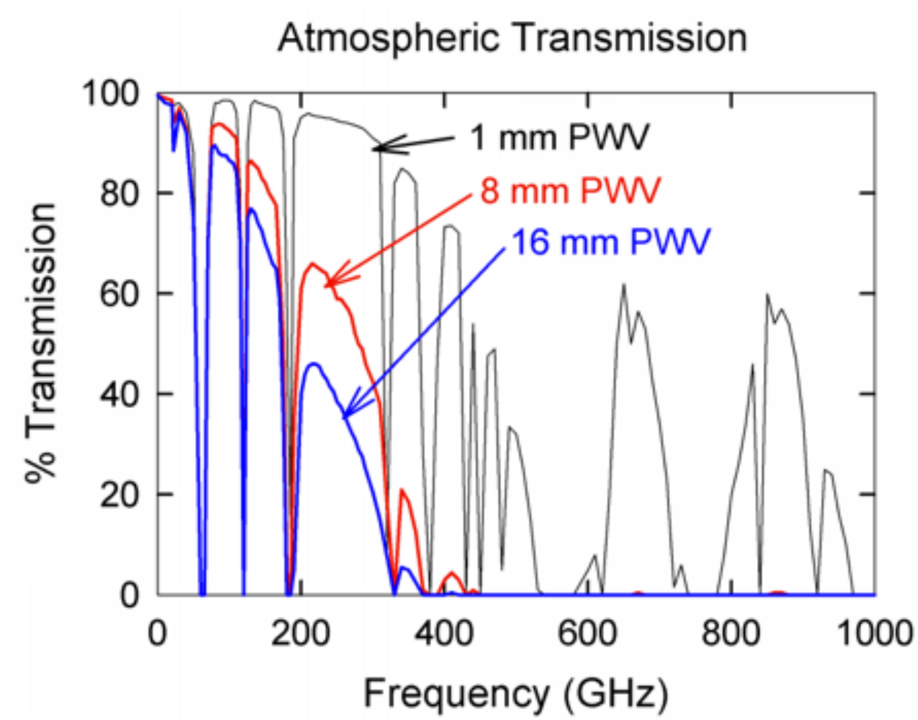
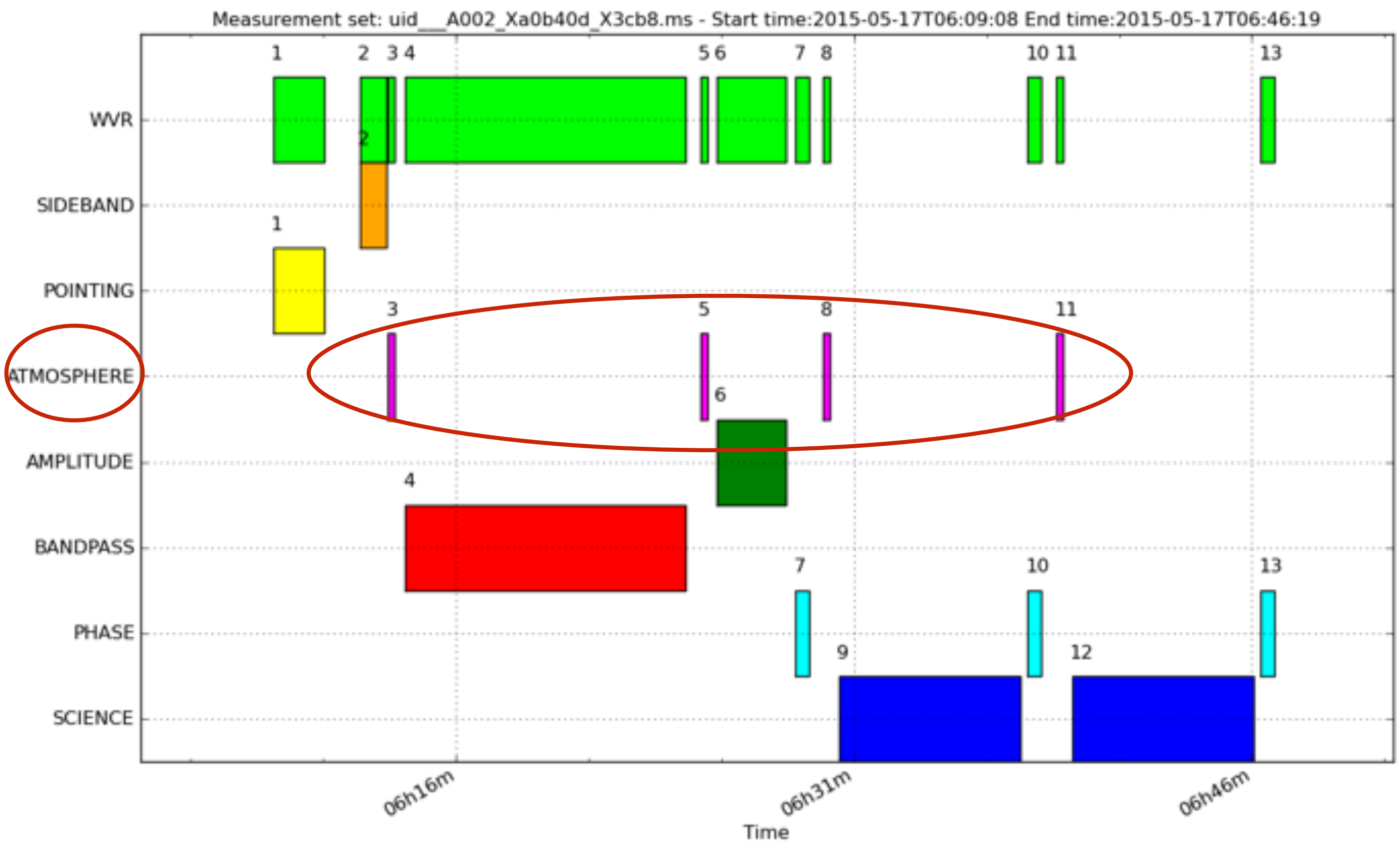


Calibration in ALMA…
hifa-tsyscal

- No need of any “calibrator” to correct for Tsys
  - Frequent “Single Dish” observation to measure atmosphere emissivity at the same position and frequency as for scientific observations
  - The Tsys drops exponentially with τ
  - Tsys determine visibility error/weigth $T_{sys}(i) * T_{sys}(j)$



Calibration in ALMA…
hifa-tsyscal



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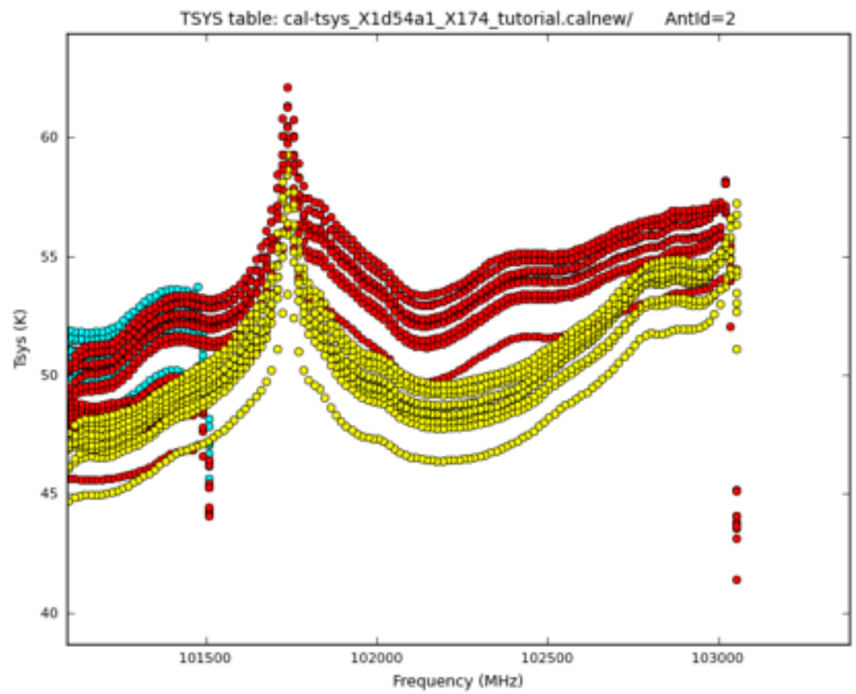
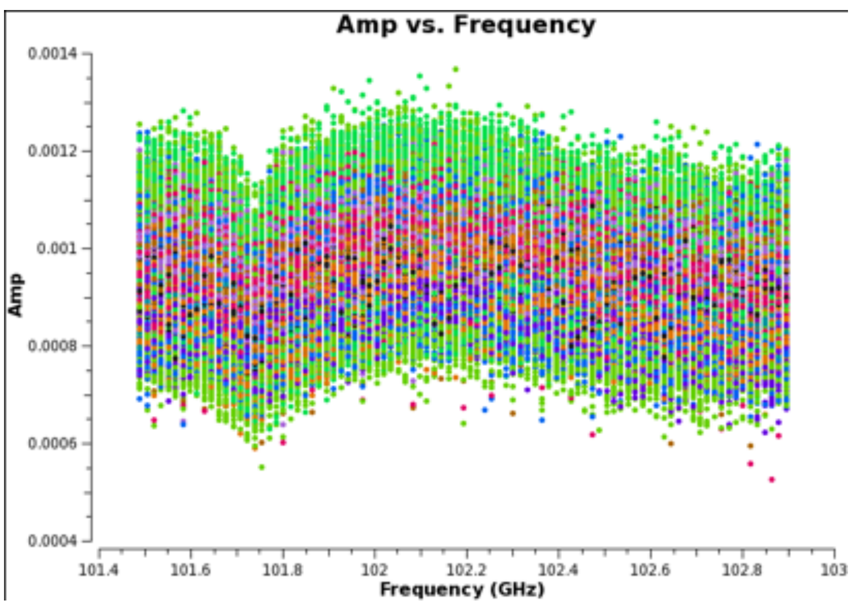
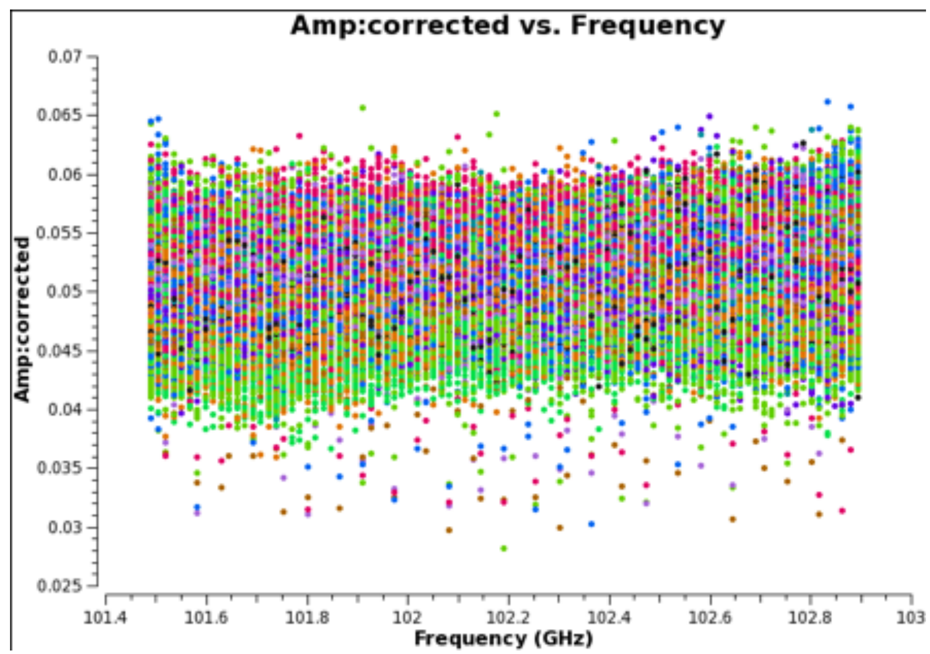
Calibration in ALMA… hifa-tsyscal

T_{sys} calibration "corrects" for atmosphere opacity (and for fake "line absorption" in spectra)



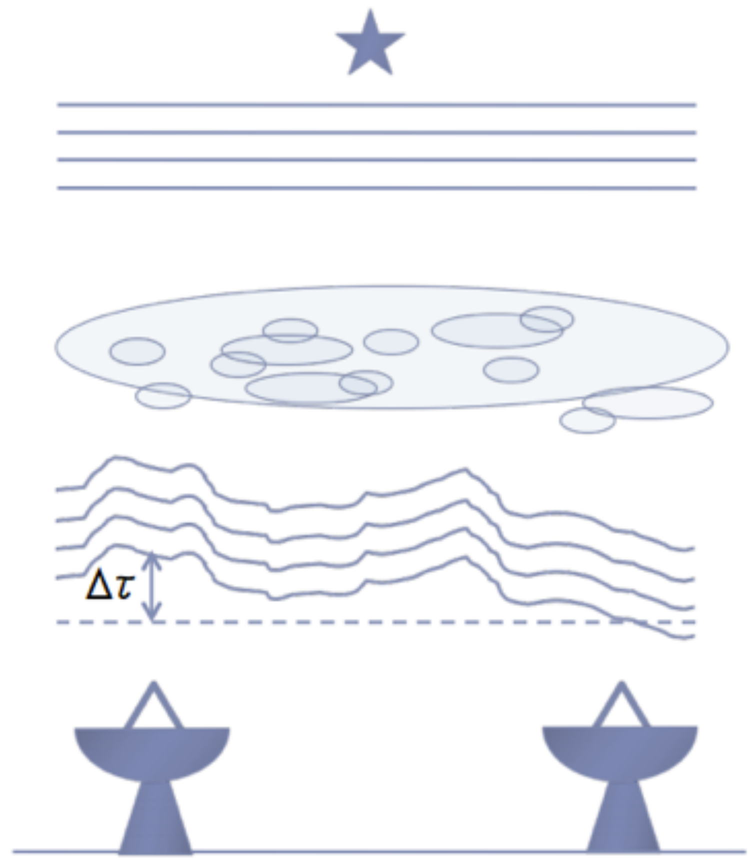




Calibration in ALMA…
hifa-wvrgcalflag

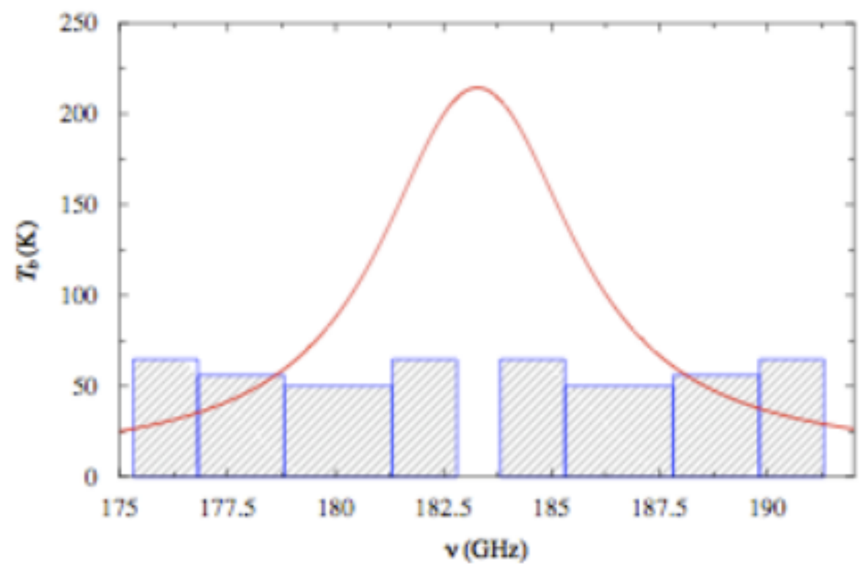
- Variations in the amount of PWV across the atmosphere cause random delay differences

$$\Delta\phi = 2\pi \cdot \nu \cdot \Delta\tau$$



Calibration in ALMA…
hifa-wvrgcalflag

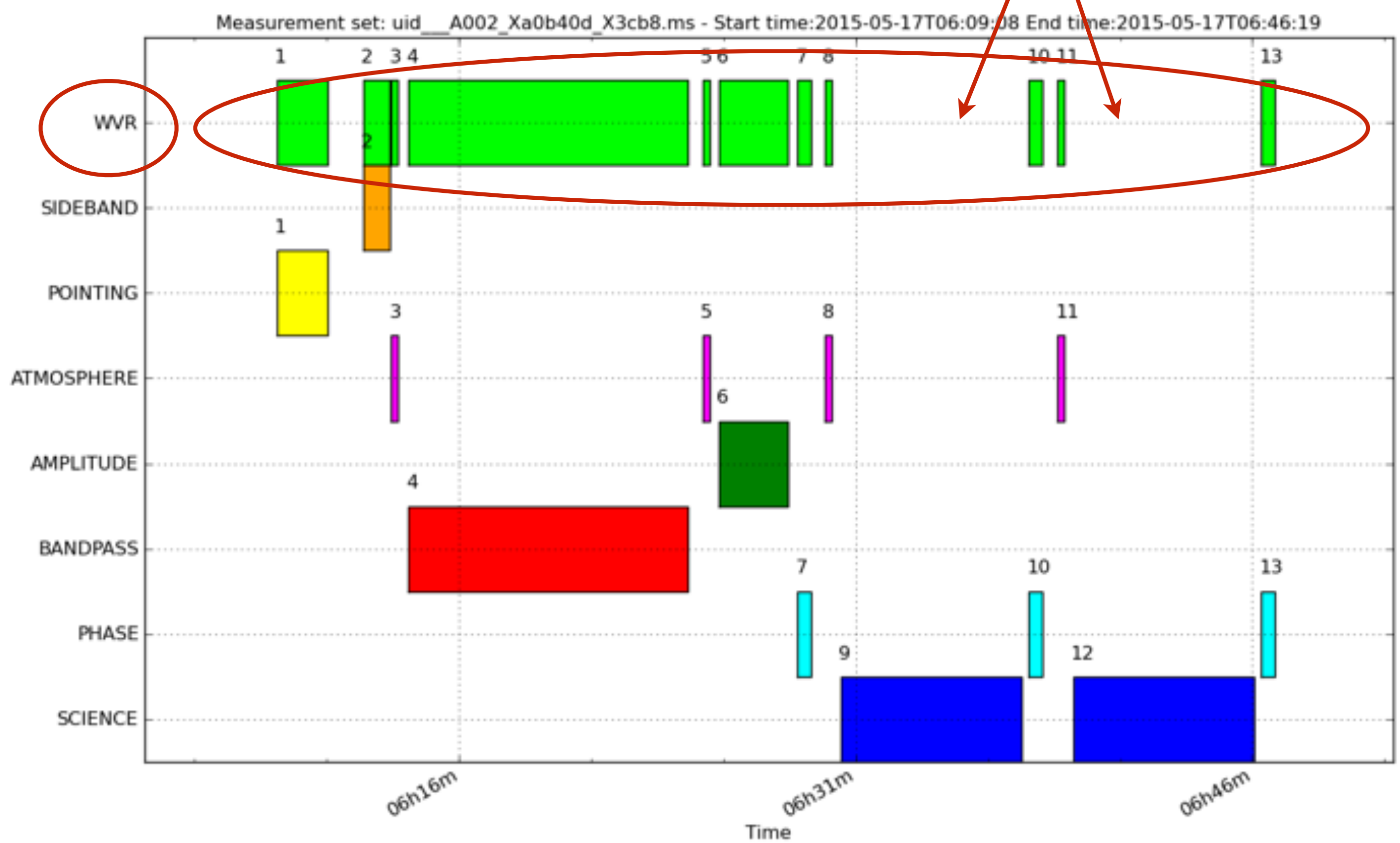
- Water Vapor Radiometry (WVR) Installed on every 12-m antenna :
  - measure (1sec) the rapid fluctuations of 182.5GHz H_2O line with a radiometer at each antenna
  - use these measurements to derive changes in water vapor column (Δw) and convert to phase corrections using:



$$\Delta\phi_e \approx 12.6\,\pi\,\Delta w / \lambda$$

Calibration in ALMA…
hifa-wvrgcalflag

measured also during target observations…



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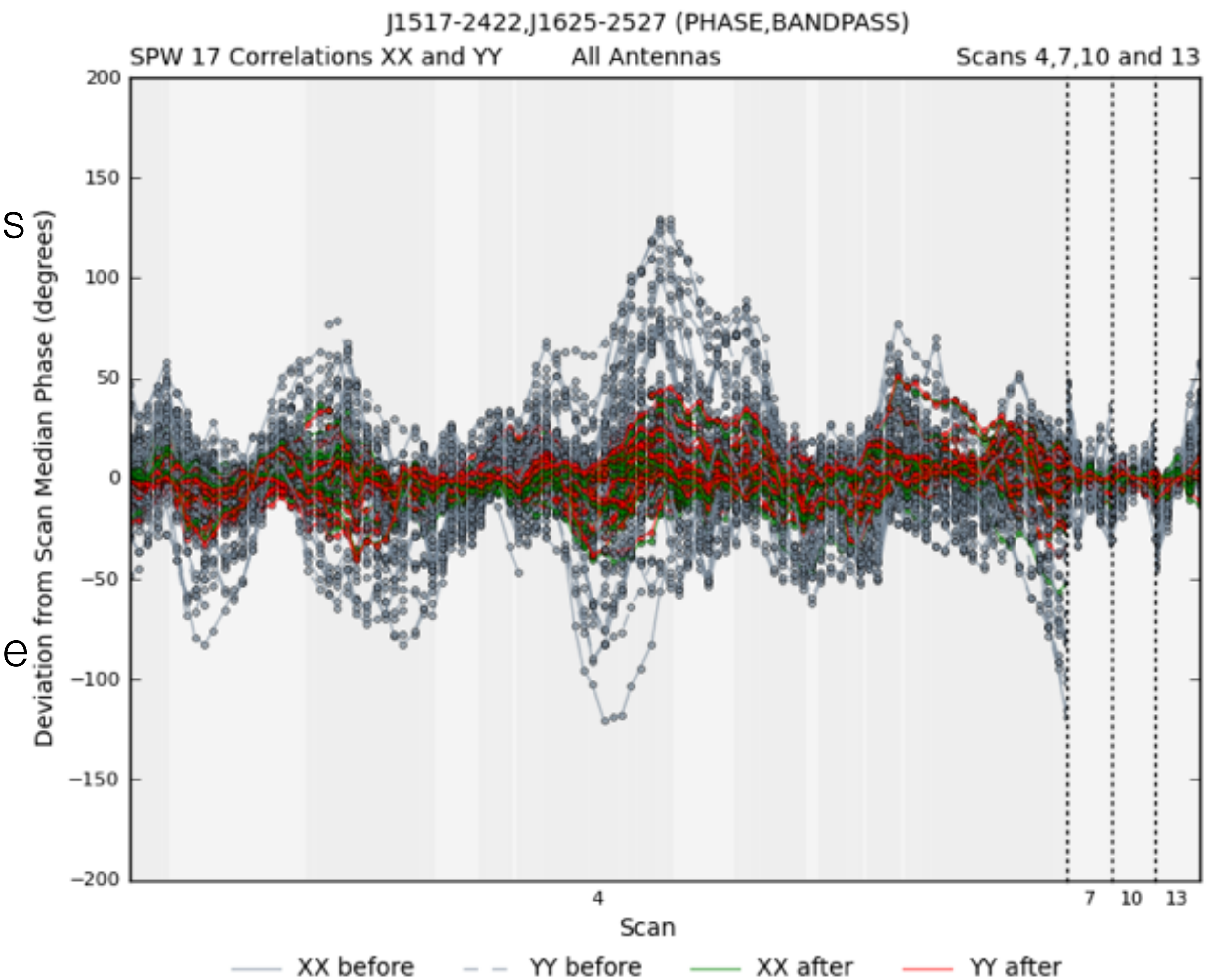
Calibration in ALMA…
hifa-wvrgcalflag

Before/After PWV corrections

- higher impact at high frequencies
- higher impact at long baseline
- Phases noise “should” decrease
    - if not improvement is seen, the pipeline will not apply the correction



Calibration in ALMA…
Observational Strategy (from the pipeline)

1. **hif_importdata:** Register measurement sets with the pipeline
2. **hifa_flagdata**: ALMA deterministic flagging
3. **hifa_fluxcalflag:** Flag spectral features in solar system flux calibrators
4. **hif_refant**: Select reference antennas
5. **hifa_tsyscal:** Calculate Tsys calibration
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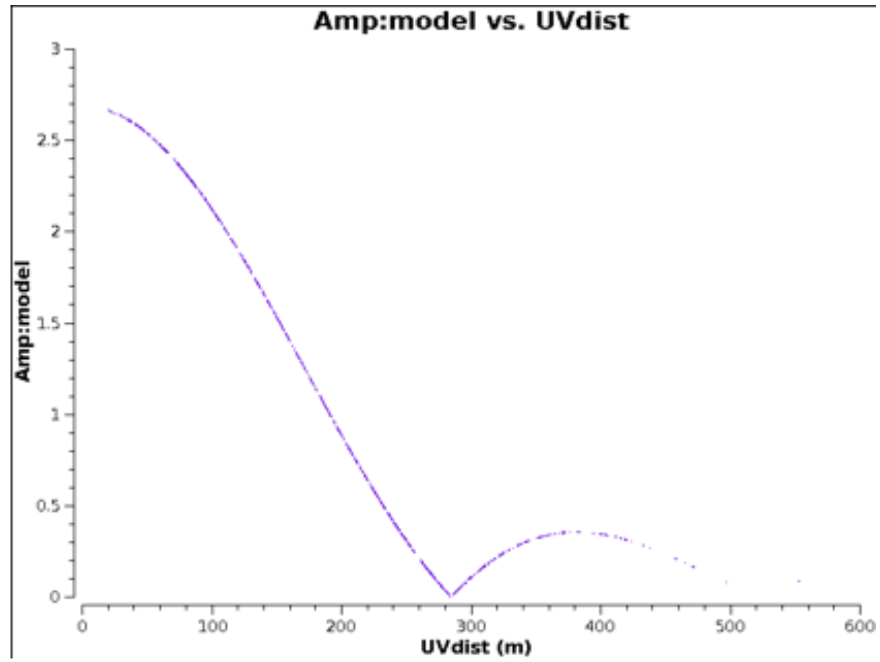
Calibration in ALMA…
hif-setJy

- Flux calibrators need to be modeled.
  - SetJy allows to calculate the model visibilities as observed by interferometer in the same (spatial and spectral) configuration as in our observations.
  - We fill the MODEL column
  - Problem with model libraries…

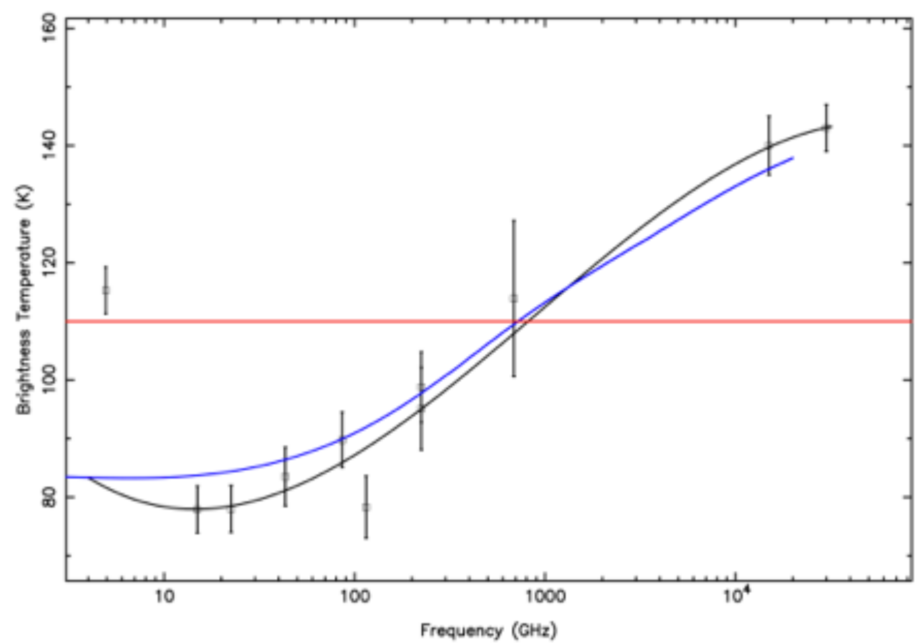


Titan visibilities

Calibration in ALMA…
hif-setJy

- Problems with model solar system bodies libraries…
    - By the end of 2012, new Butler-JPL-Horizons 2012 (2010)
    - significant change in flux estimation (in some cases by factors of ~20%)

Ganymede



https://science.nrao.edu/facilities/alma/aboutALMA/Technology/ALMA_Memo_Series/alma594/memo594.pdf

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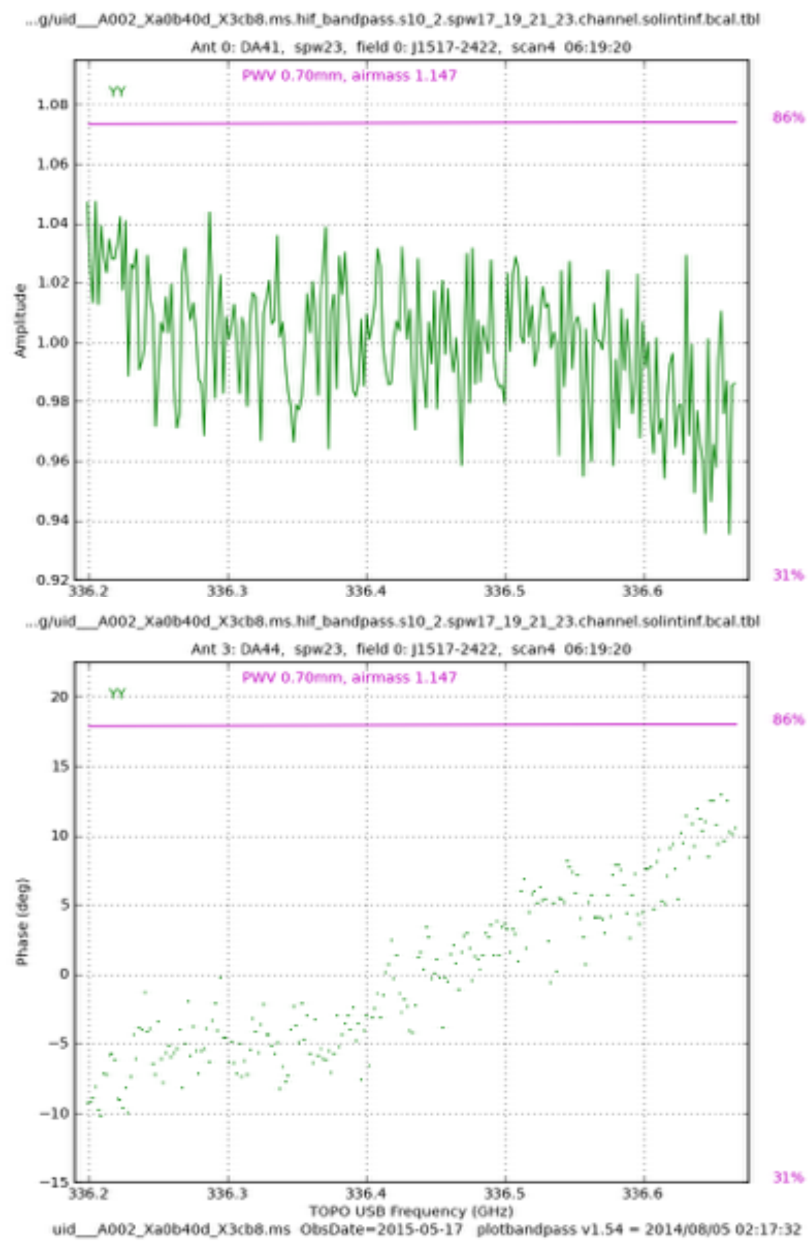
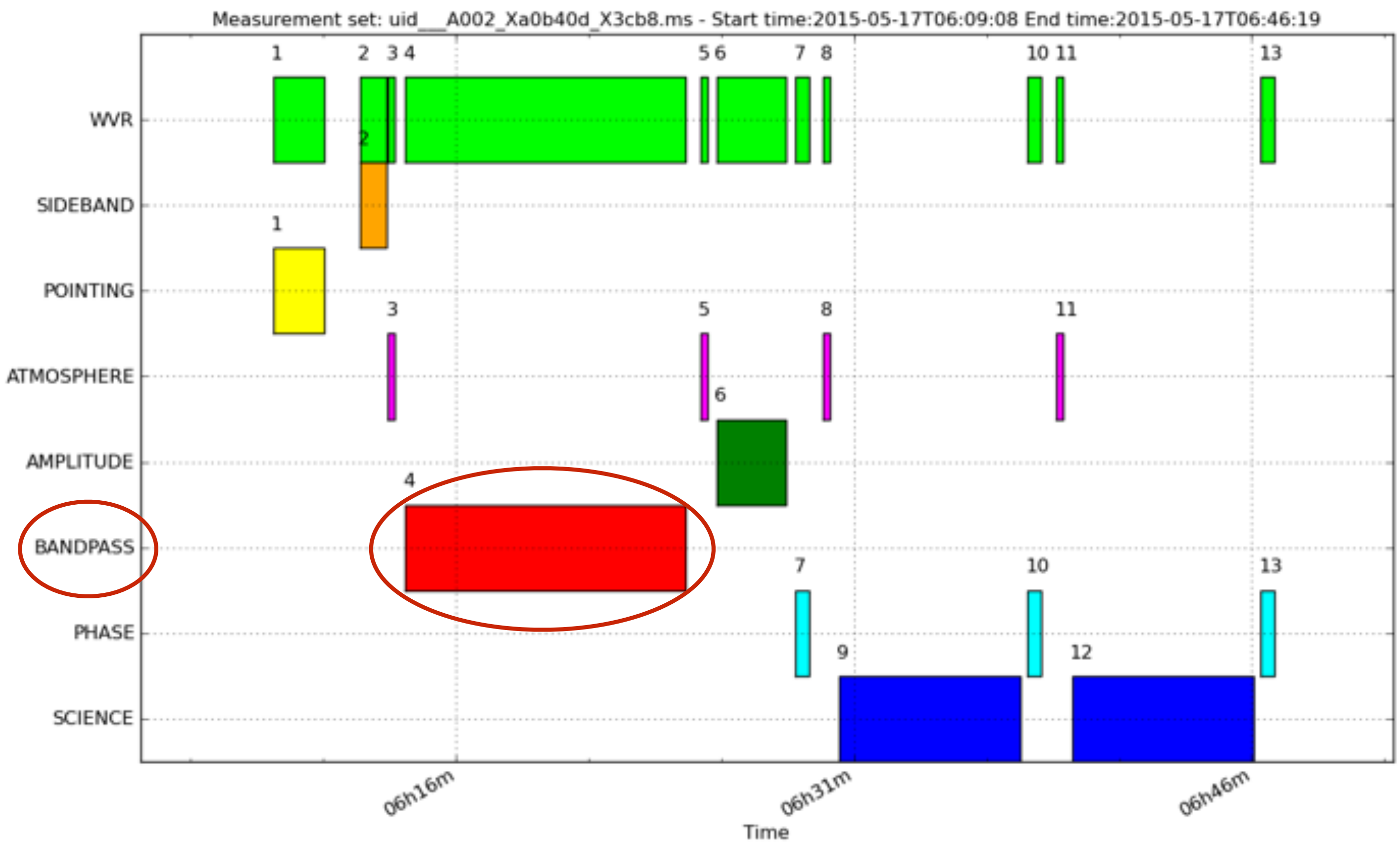
Calibration in ALMA…
hif-bandpass

- The spectral response of each antenna is calibrated.
    - basically, electronics
- how? observing a bright QSO in the sky, once during the run
    - typically at the beginning of the observations
    - no matter where the QSO is



Calibration in ALMA…
hif-bandpass



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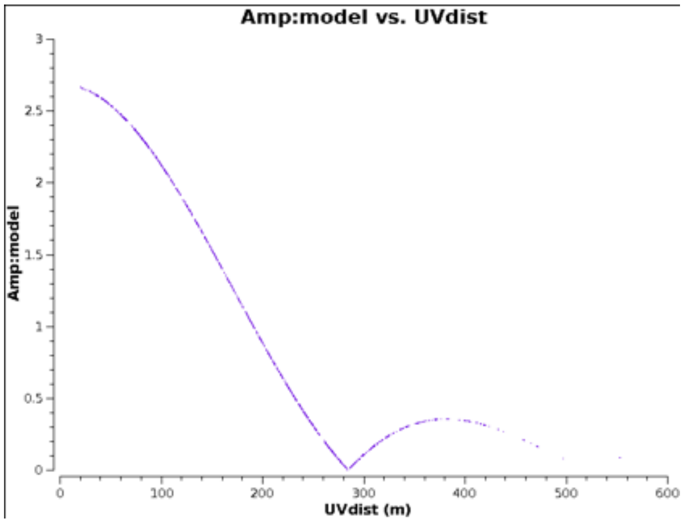
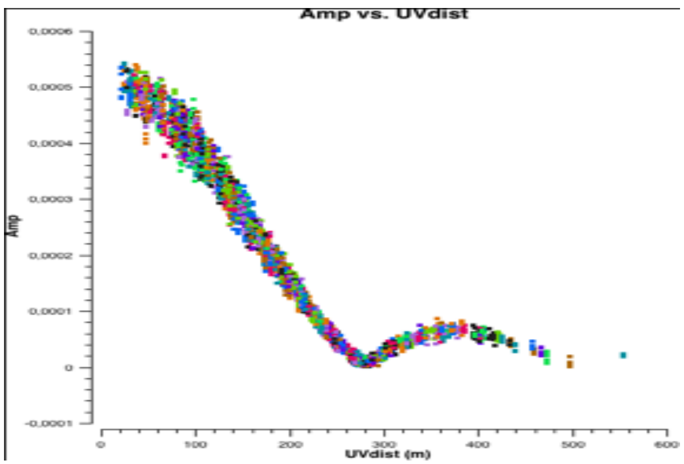
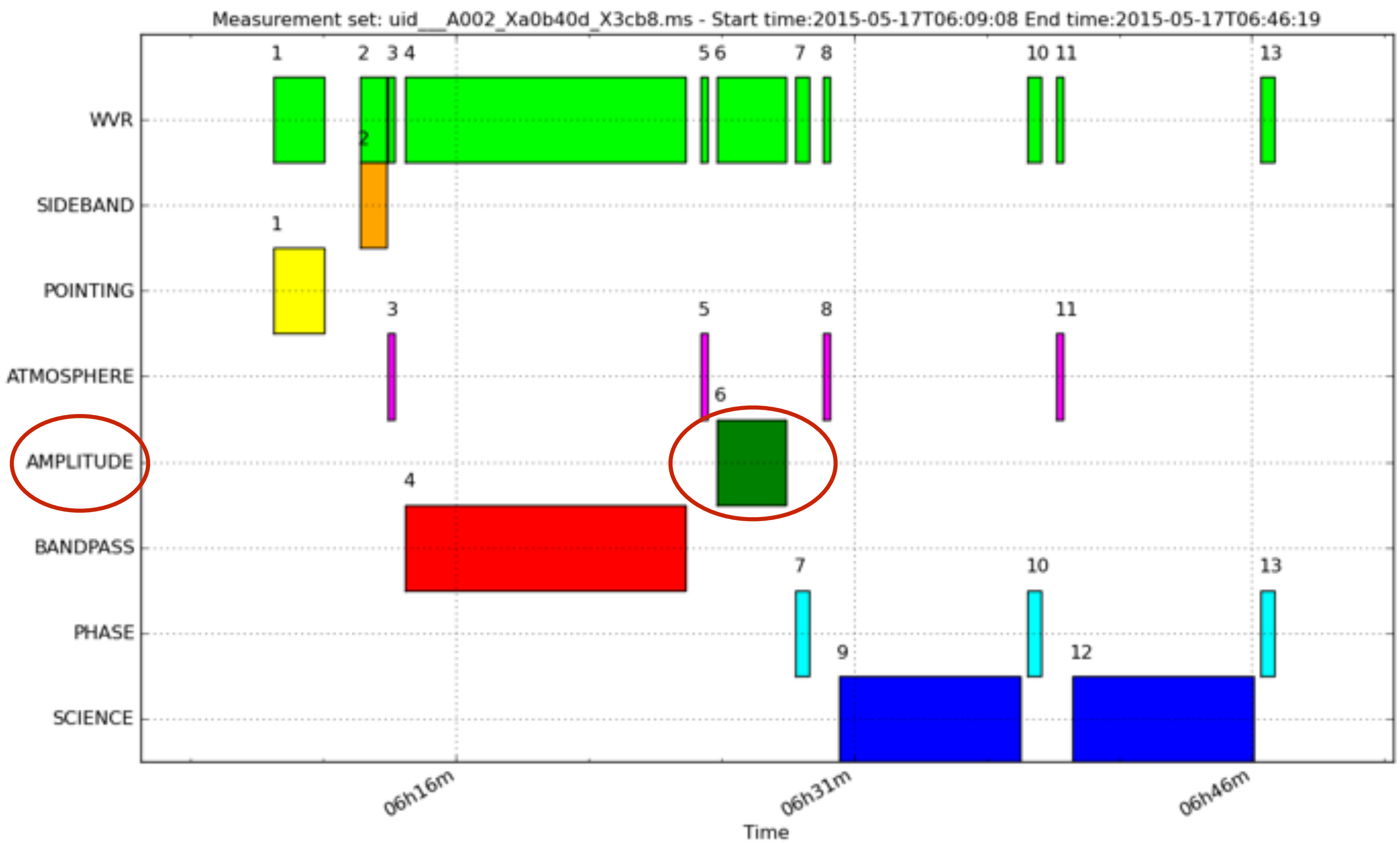
Calibration in ALMA…
hif-gfluxscale

- The Jy/K scale is calculated for flux calibrator (setJy) and transferred to BP, phase calibrators (10% error, anyway).
    - basically, antenna efficiency (approximately ~40Jy/K, once t_{sys} corrected)
- how? observing a known flux object in the sky
    - no variable objects: planets, moons, asteroids
    - typically at the beginning of the observations
    - no matter where in the sky





Calibration in ALMA…
hif-gfluxscale



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Calibration in ALMA…
hif-gfluxscale

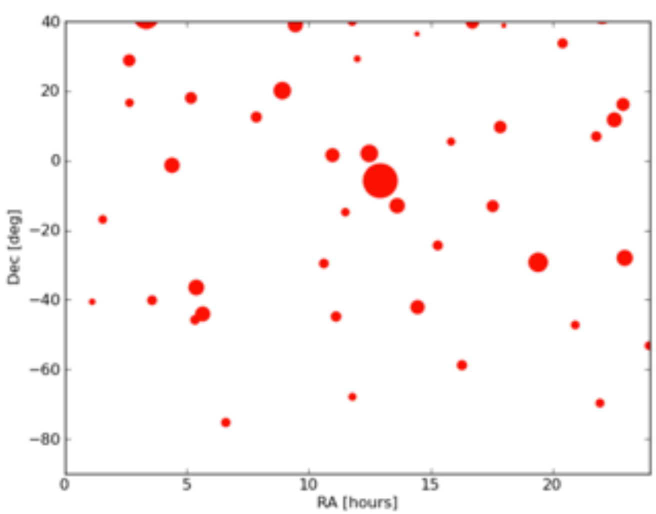
- Flux calibration is one of the most critical in the calibration process…
  - model libraries, sources extended, variability
  - good to check transferred fluxes in alma calibrator database (https://almascience.eso.org/sc/)

Computed Flux Densities

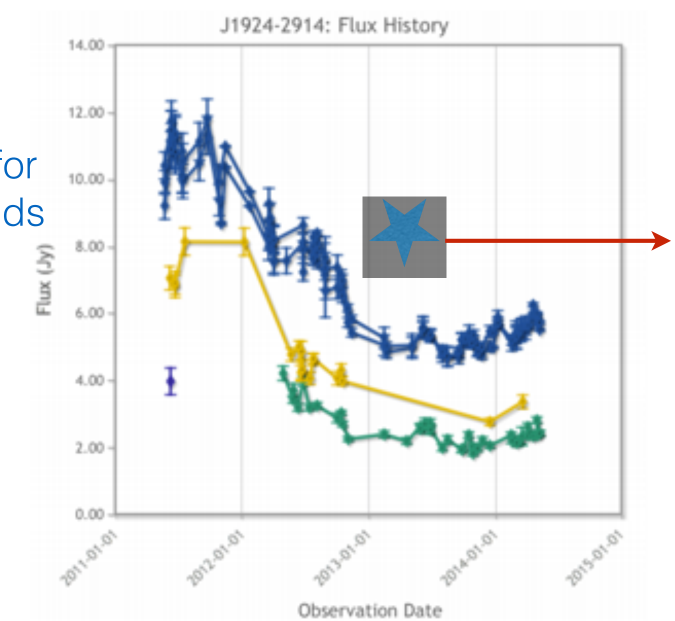
The following flux densities were set in the measurement set model column and recorded in the pipeline context:

Measurement Set	Field	SpW	Flux Density			
			I	Q	U	V
uid___A002_Xa0b40d_X3cb8.ms	J1517-2422 (#0)	17	1.142 Jy ± 3.968 mJy (0.3%)	0.000 Jy	0.000 Jy	0.000 Jy
		19	1.149 Jy ± 5.600 mJy (0.5%)			
		21	1.145 Jy ± 13.350 mJy (1.2%)			
		23	1.136 Jy ± 4.577 mJy (0.4%)			
	J1625-2527 (#2)	17	686.225 mJy ± 3.385 mJy (0.5%)			
		19	685.805 mJy ± 4.784 mJy (0.7%)			
		21	684.340 mJy ± 10.235 mJy (1.5%)			
		23	678.322 mJy ± 3.097 mJy (0.5%)			

sample of 45 Bright QSO, frequently monitored
—> used as BP, Flux



Calibrator flux monitoring in time for different ALMA bands (different colors)



my point here? something wrong!

http://library.nrao.edu/public/memos/alma/memo599.pdf

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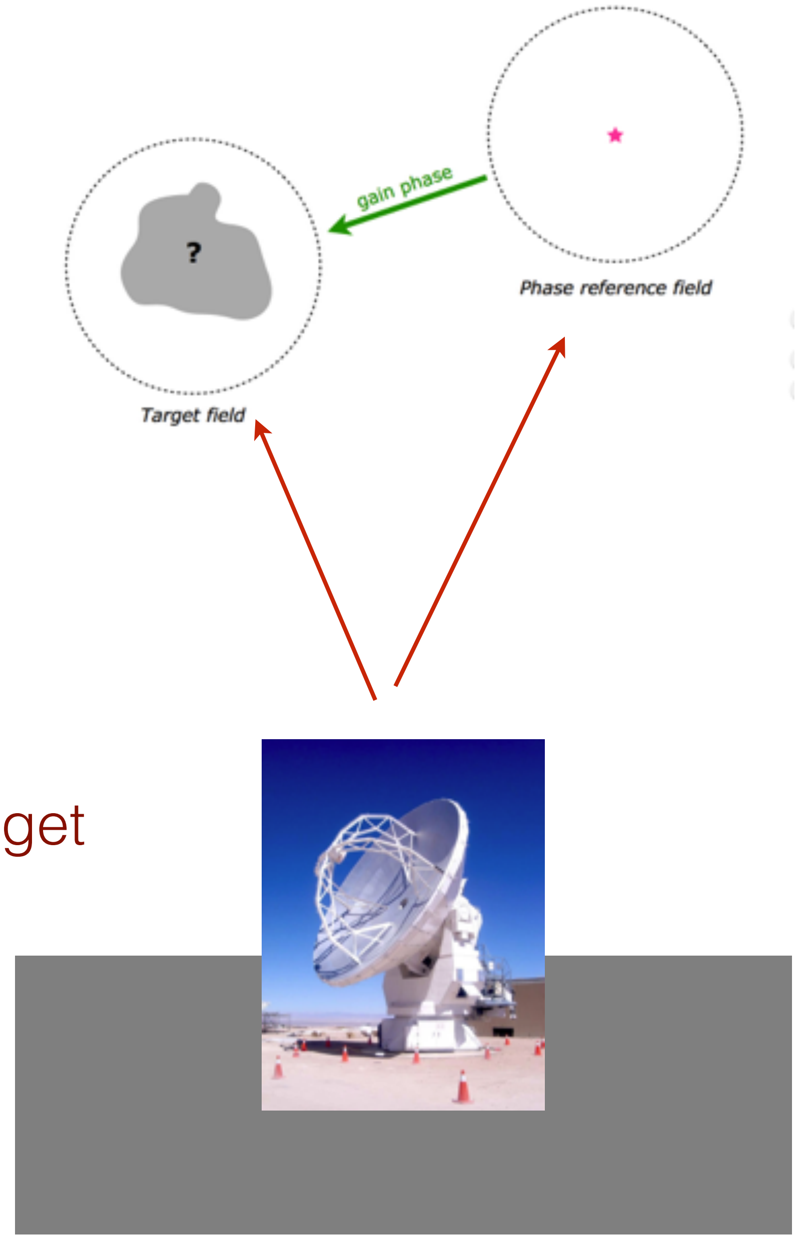
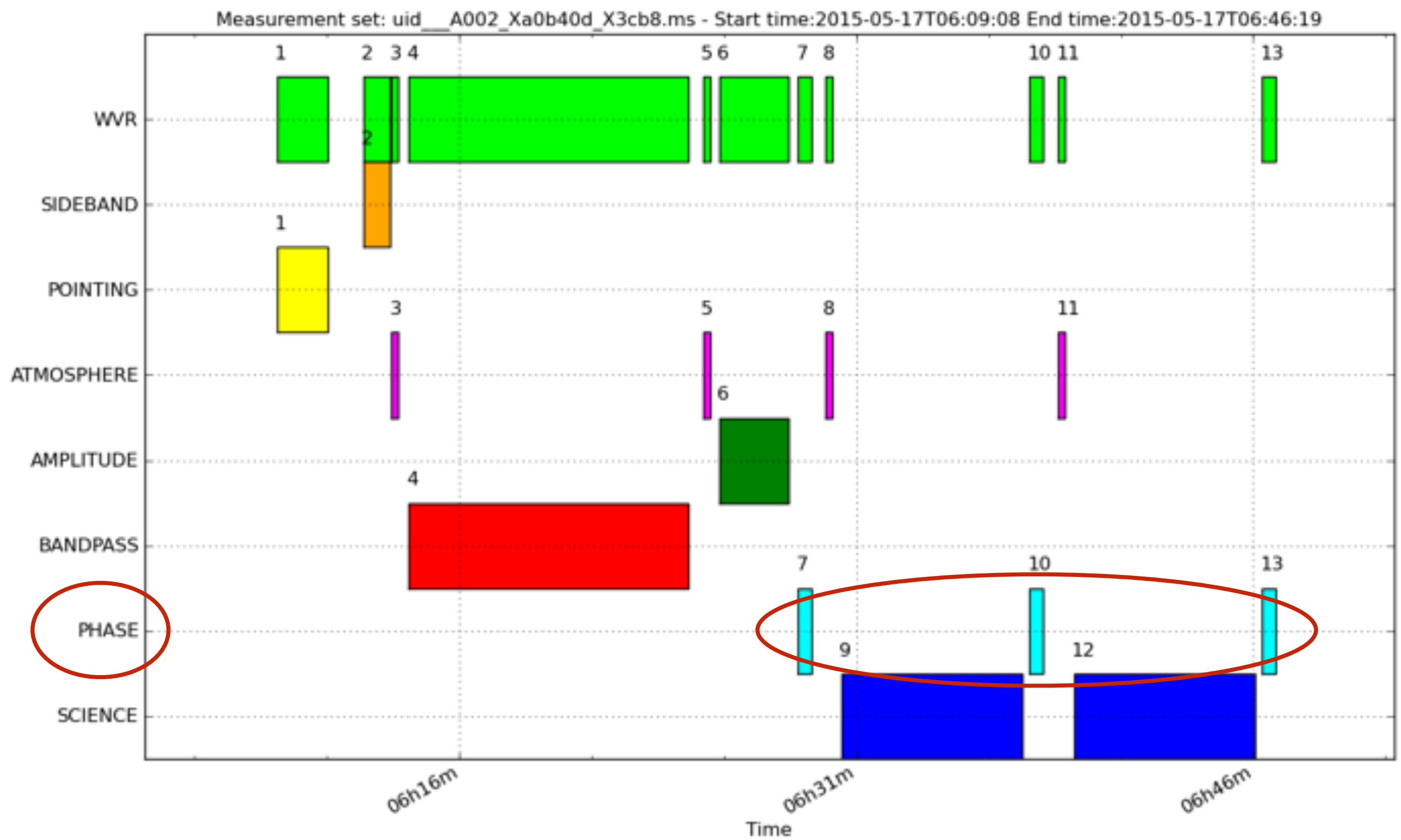
Calibration in ALMA… hif-timegaincal

- The long time scale dependent response of each antenna is calibrated.
  - basically, atmosphere
- how? observing a point like source (QSO) in the sky
  - regularly (freq, configuration dependent) observed with the target
  - closest possible to the target



Calibration in ALMA…
hif-timegaincal



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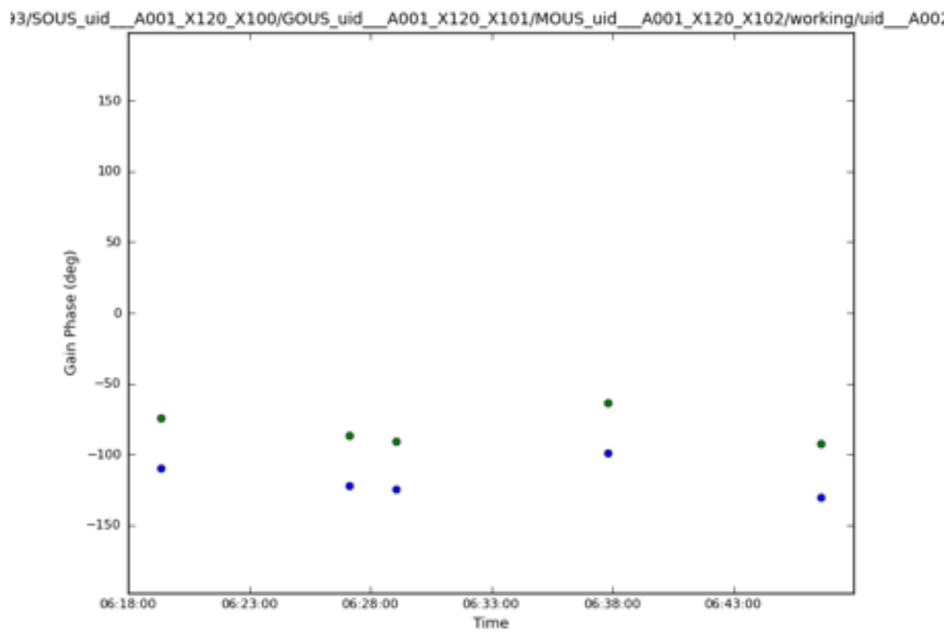
Calibration in ALMA…
hif-timegaincal

Errors larger than what expected

$$\sigma^2_J = \frac{\sigma_b^2}{(N-3)S^2}$$



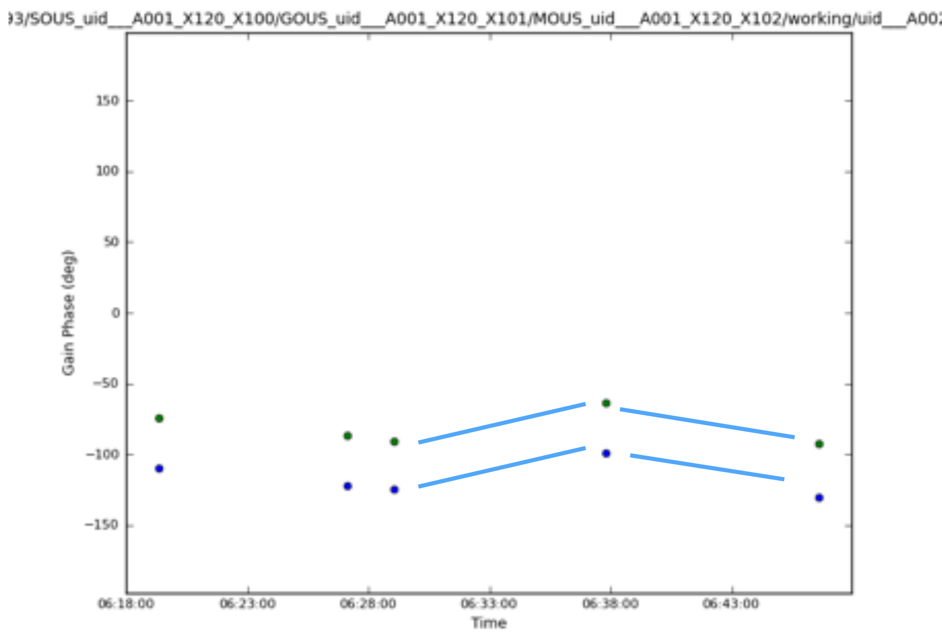
- phase calibrator close to the target position

- linear interpolation…

Calibration in ALMA…
hif-timegaincal

Errors larger than what expected

$$\sigma^2_{\mathrm{J}} = \frac{\sigma_b^2}{(N-3)S^2}$$



- phase calibrator close to the target position

- linear interpolation…

Calibration in ALMA…
hif-timegaincal

Errors larger than what expected

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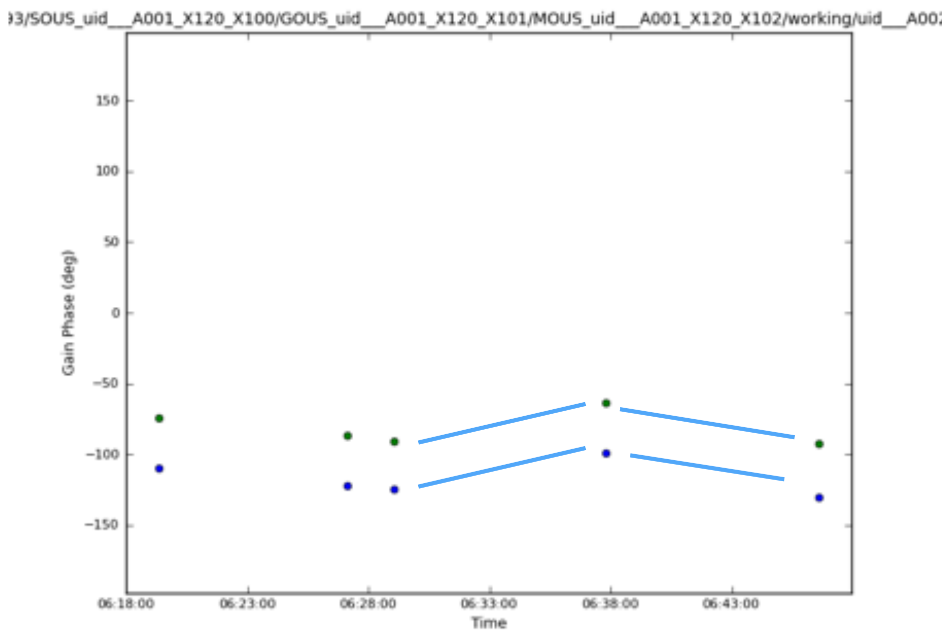

- phase calibrator close to the target position

- linear interpolation…

go for self-calibration!

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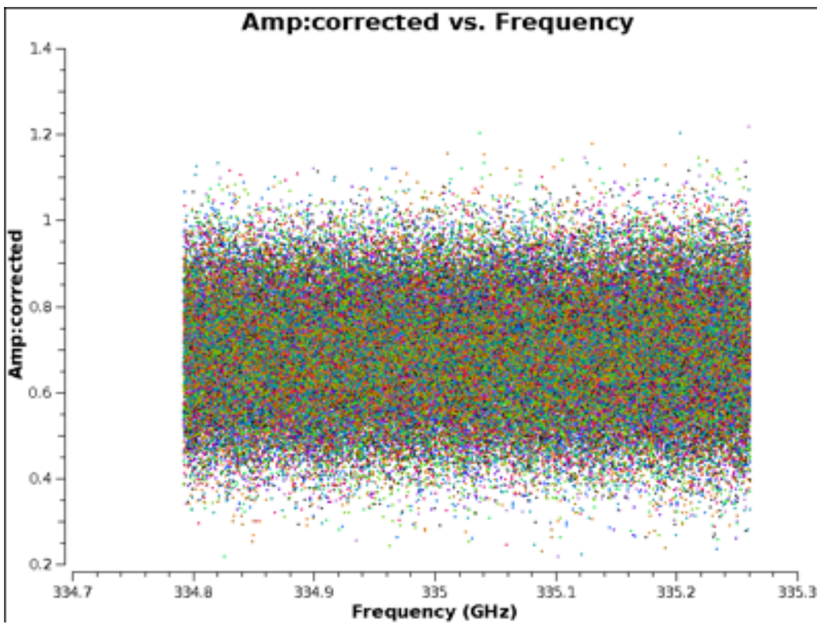
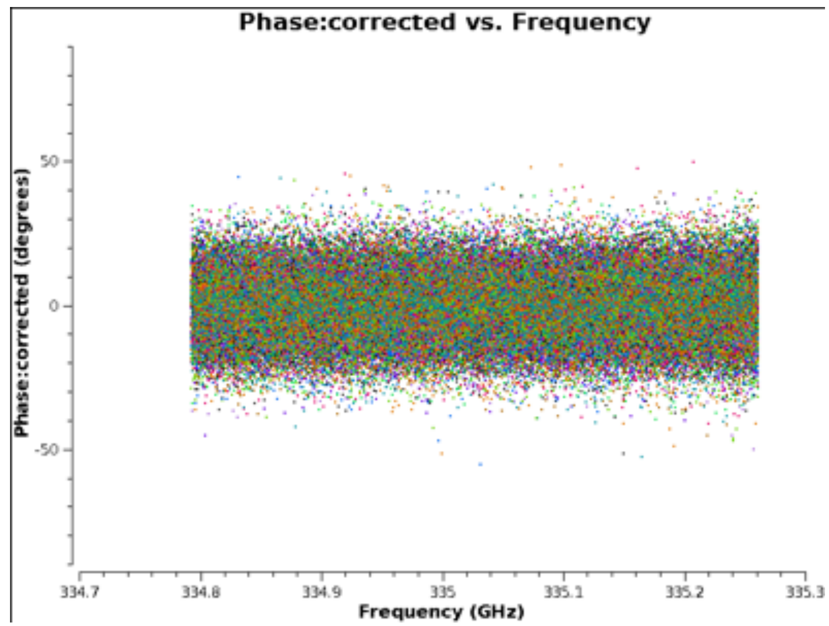
14. **hif_applycal:** Apply calibrations from context

Calibration in ALMA…
hif-applycal

- Apply all the solutions found (Tsys, wvr, BP, gaincal….) to:
    - calibrator themselves (we should reproduce model visiblities)
    - science target





A,ϕ vs frequency

Calibration in ALMA…
hif-applycal

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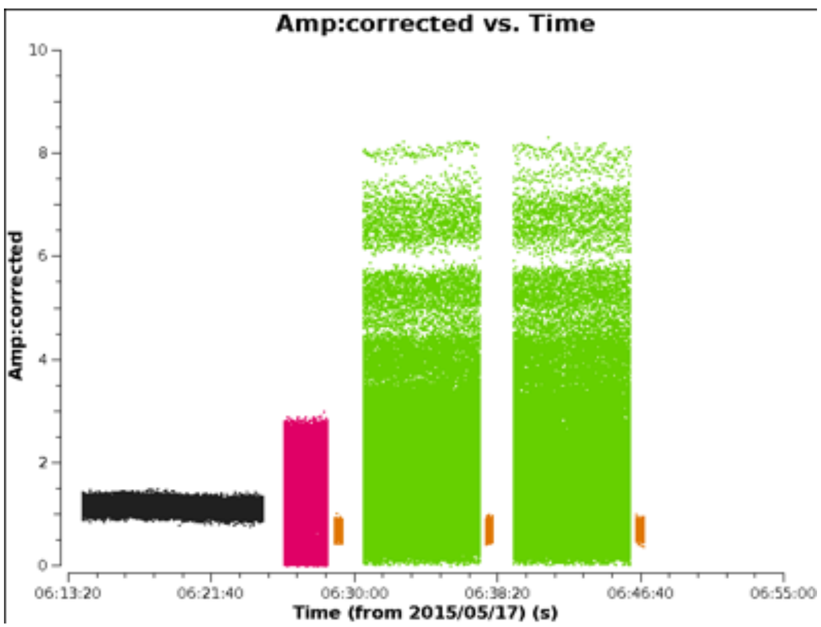

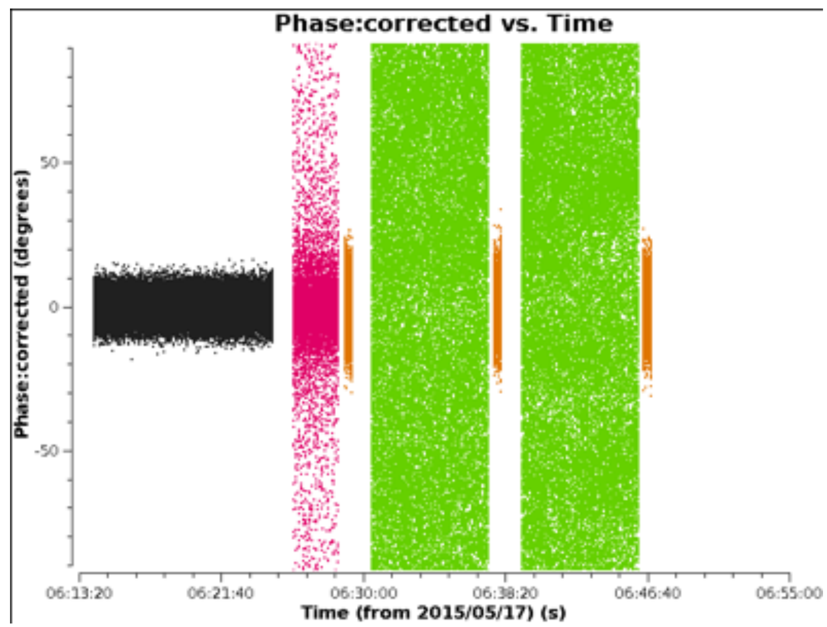

A,ϕ vs time

Caveat

- should I re-do the calibration when dealing with ALMA archive data?

  - YES if Cycle 0 data

  https://help.almascience.org/index.php?/Knowledgebase/Article/View/161/0/how-can-i-update-cycle-0-absolute-fluxes-to-the-butler-jpl-horizons-2012-model-standards

  - NO if Cycle >0