Short intro to interferometry calibration

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Outline

- Calibration Theory (the basics)

- Calibration Observational Strategy
  - A priori calibration
  - Standard calibration

- Check calibration results

AIM: not to learn calibration in detail, but to show how to check what is done by pipeline

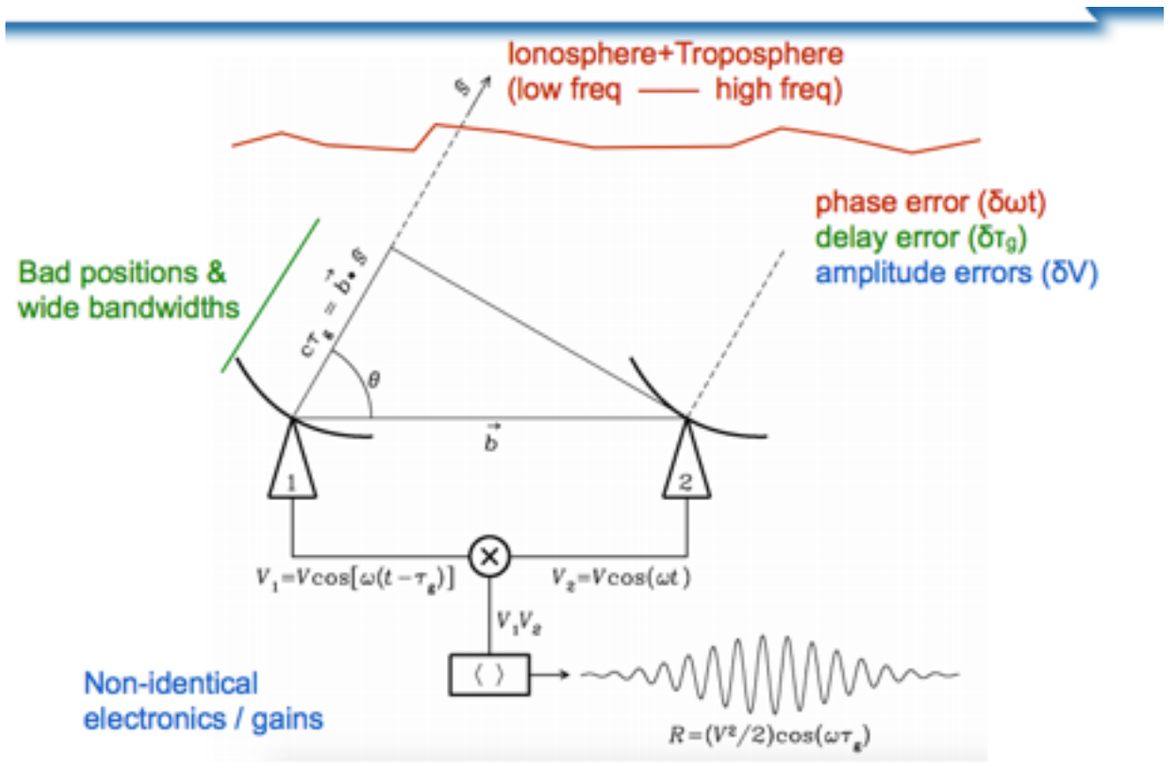
Calibration in interferometry… why do we need to calibrate?

So far…

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

but…

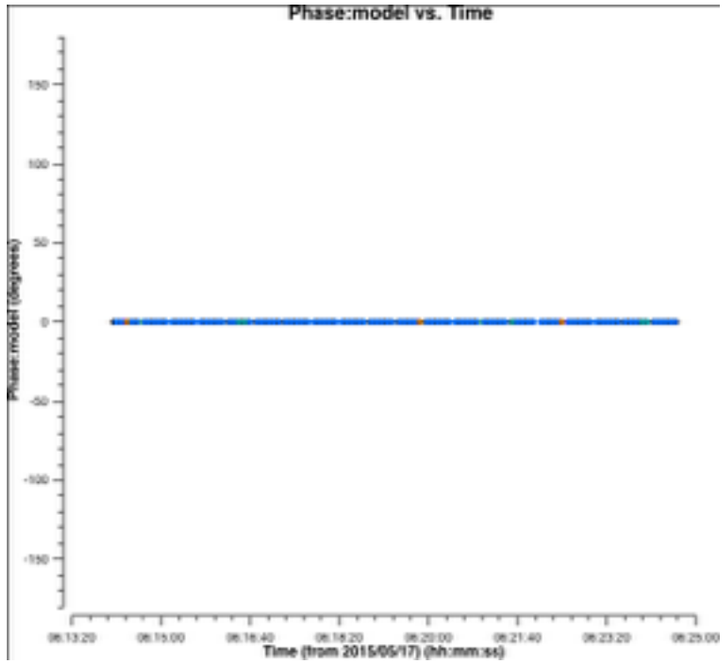
- weather
- real antennas
- electronics
- correlators…



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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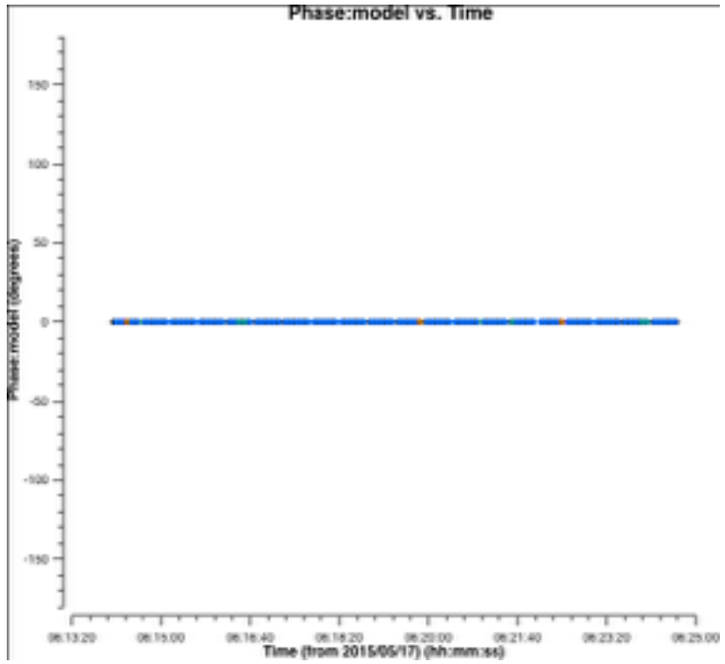

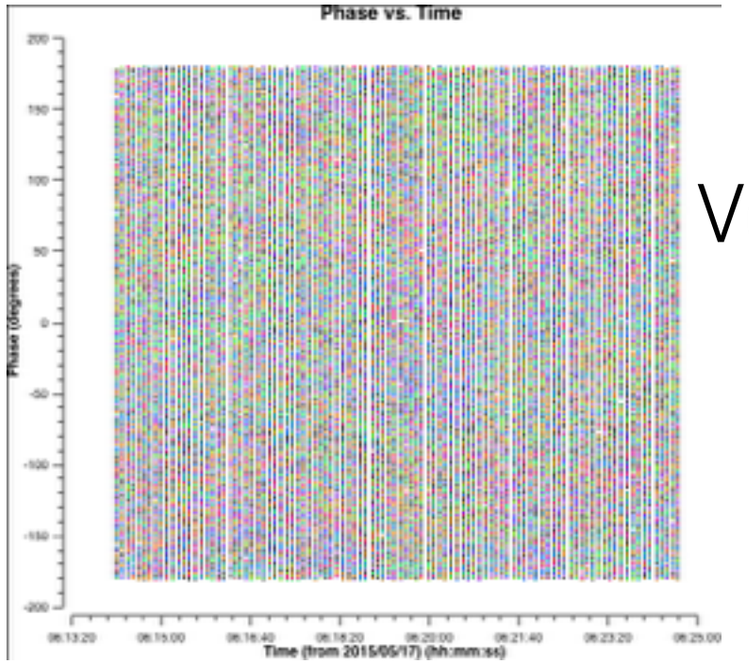

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Calibration in interferometry… why do we need to calibrate?

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?

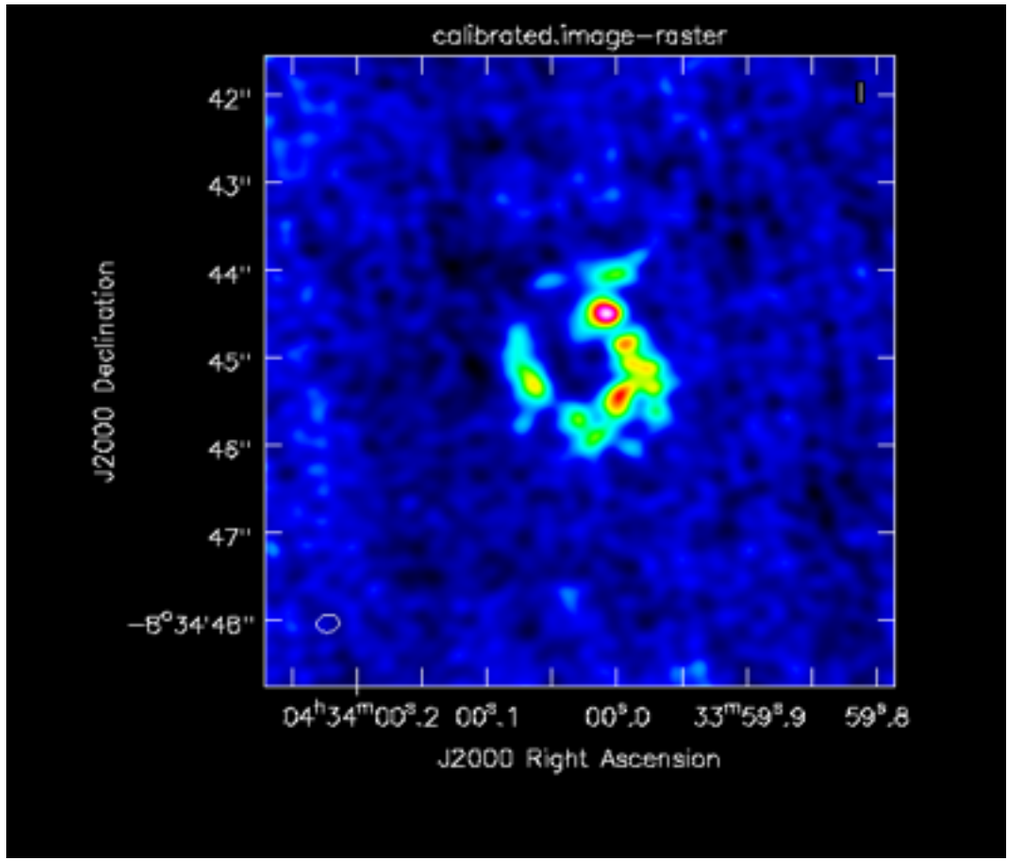
Assumptions:

- 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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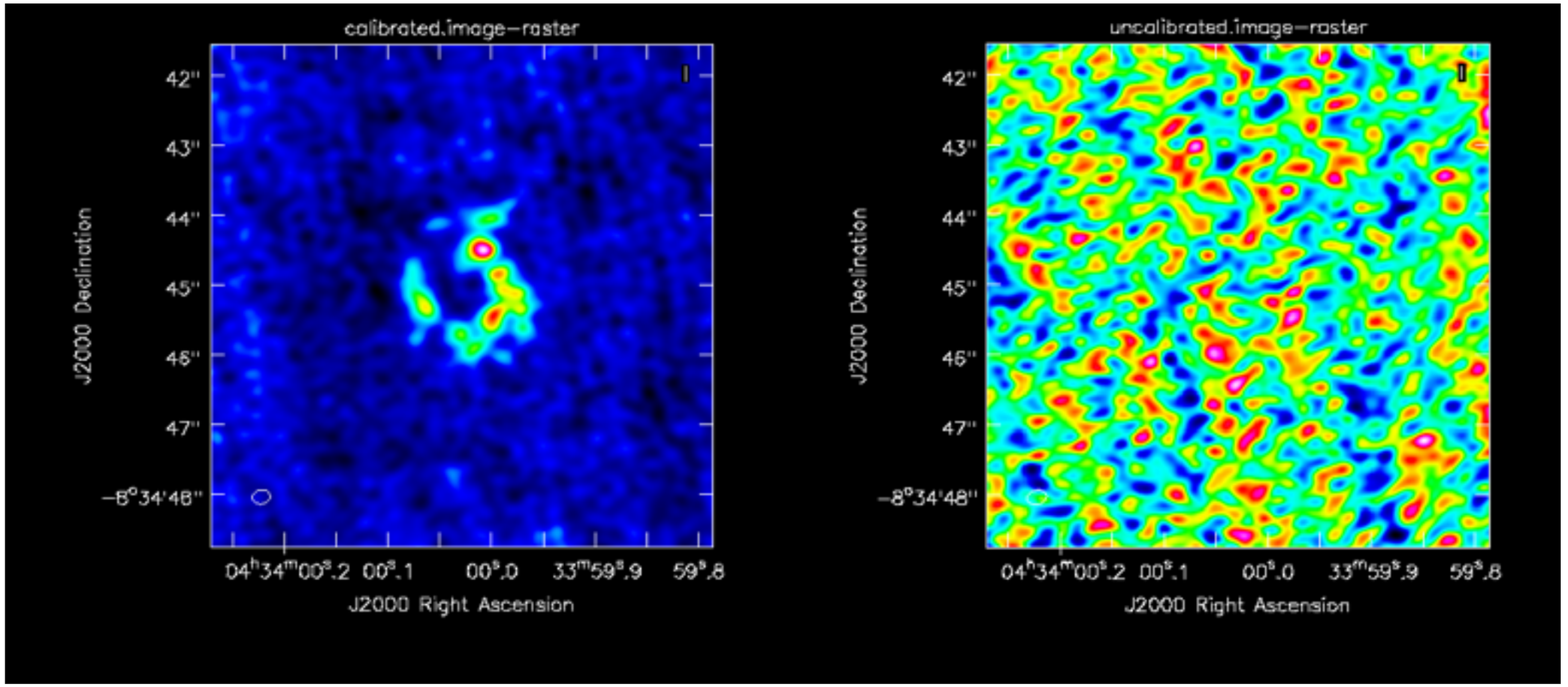

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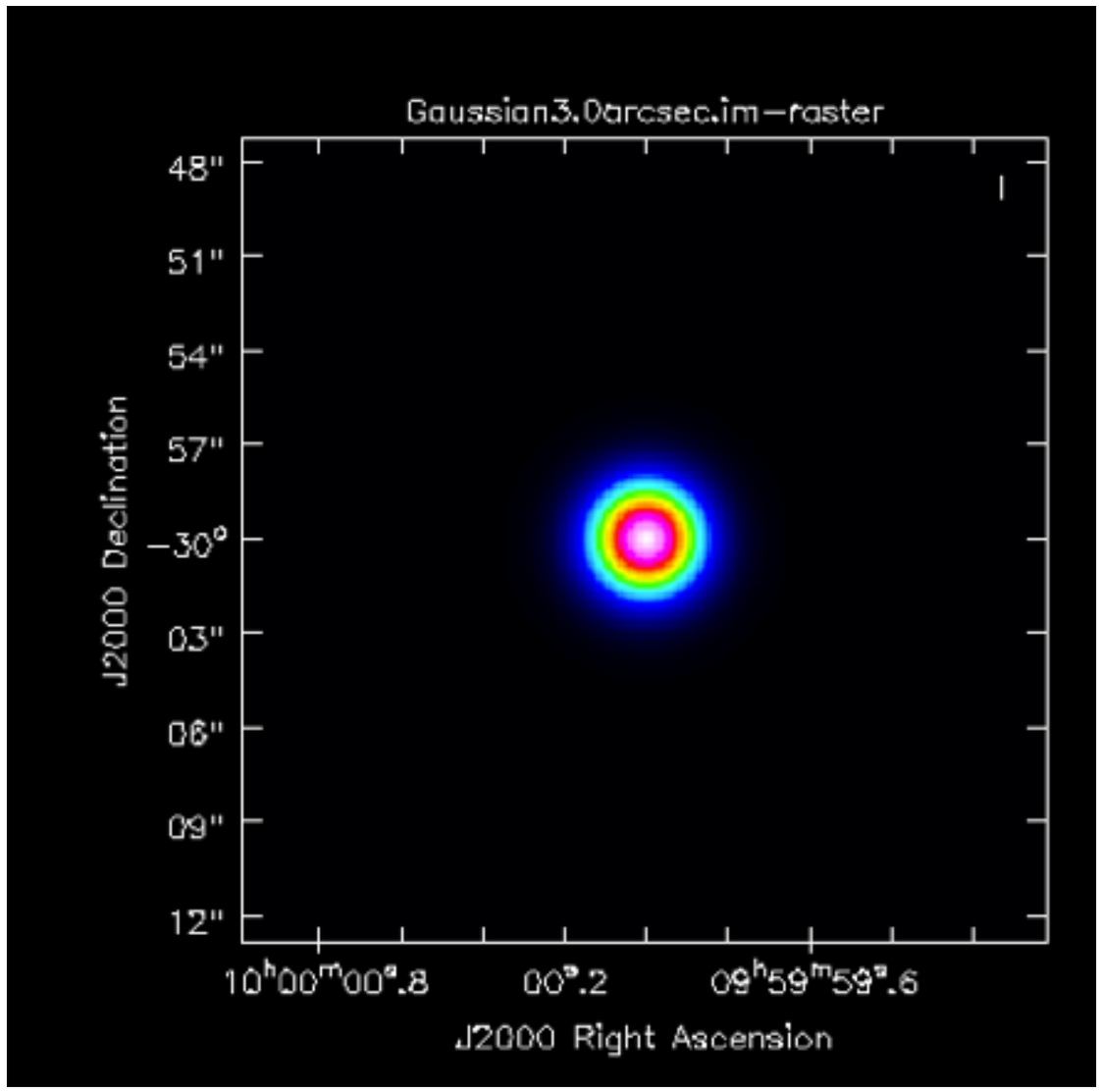

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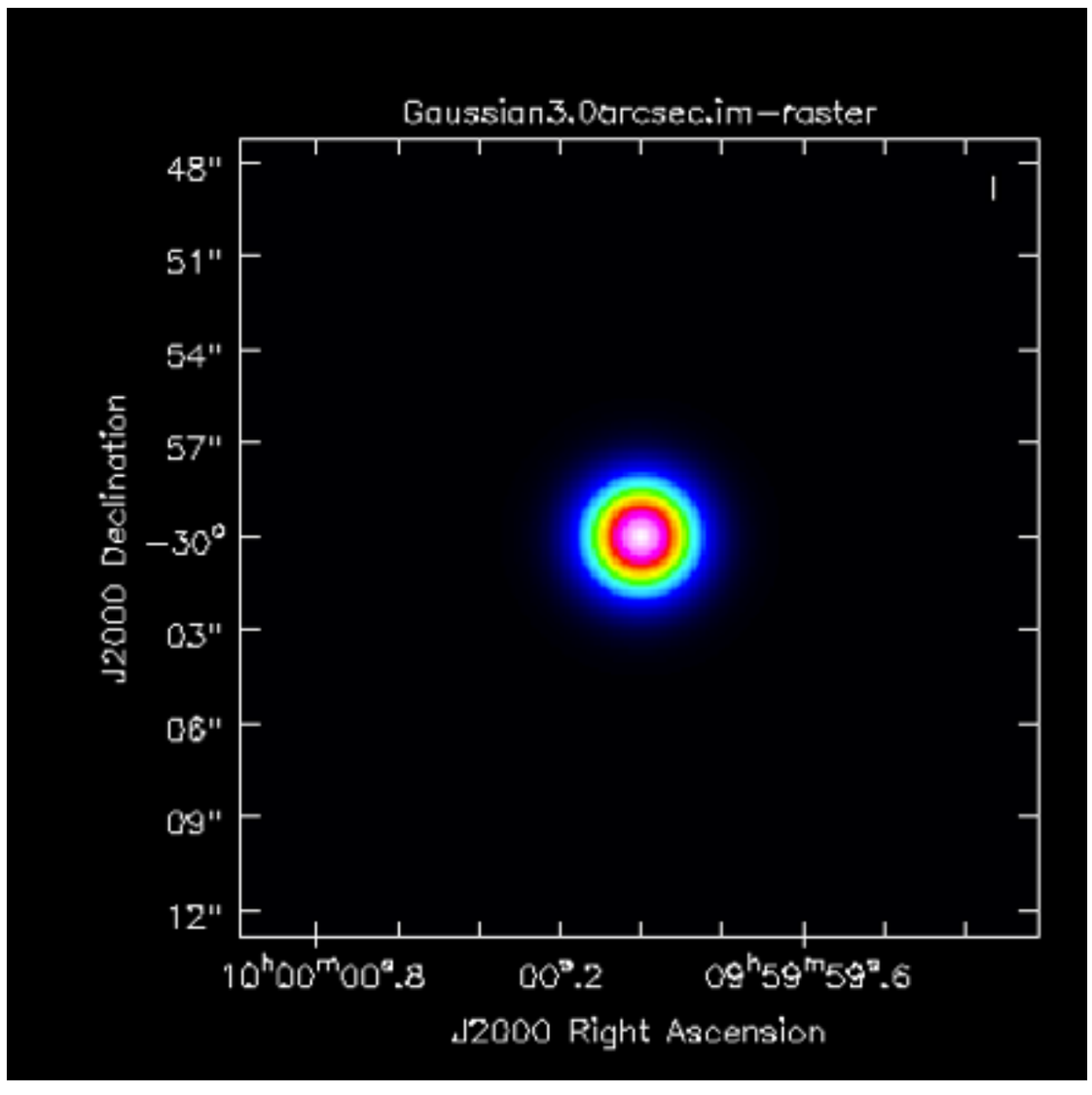
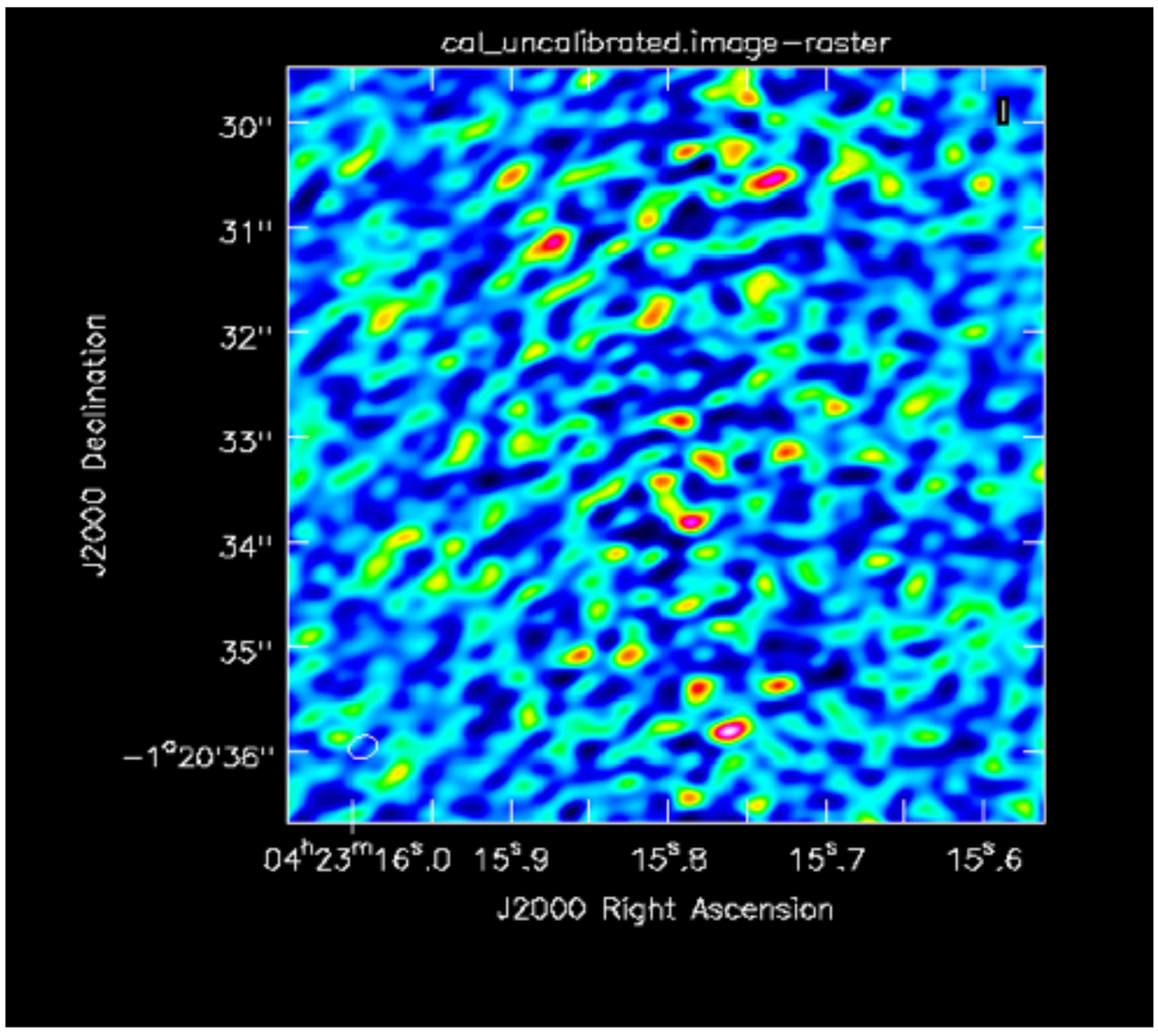


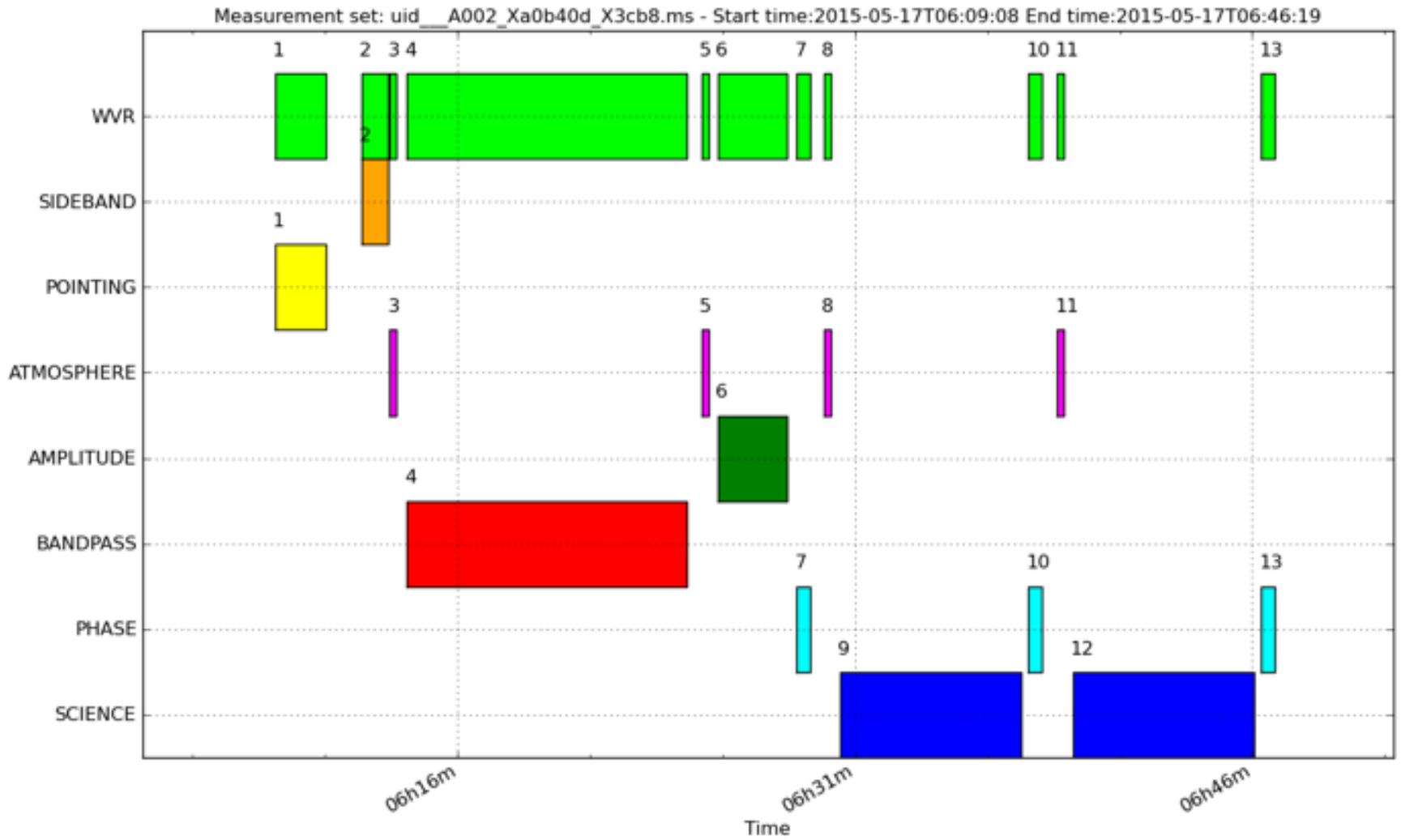


Calibration in interferometry… CASA viewpoint

- 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
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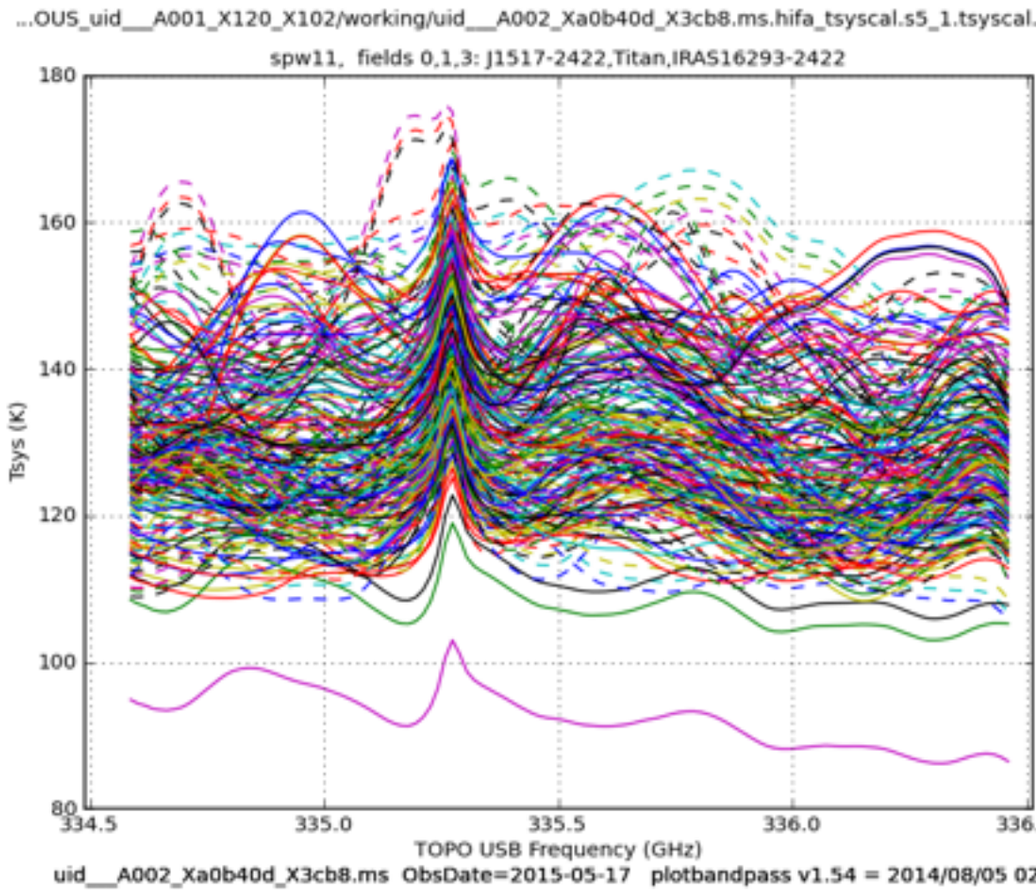
a priori calibration

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})

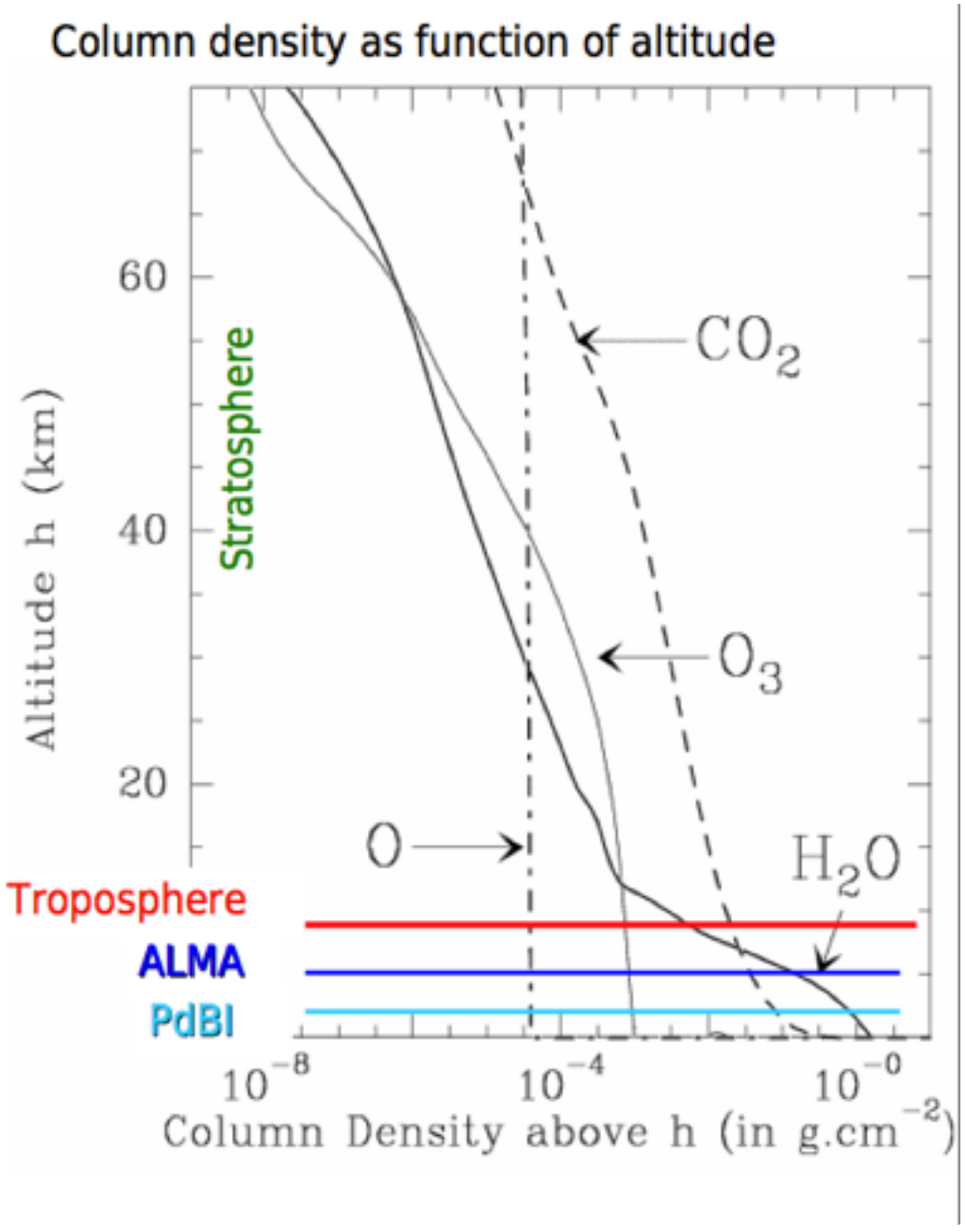


The system Temperatures drops exponentially with τ

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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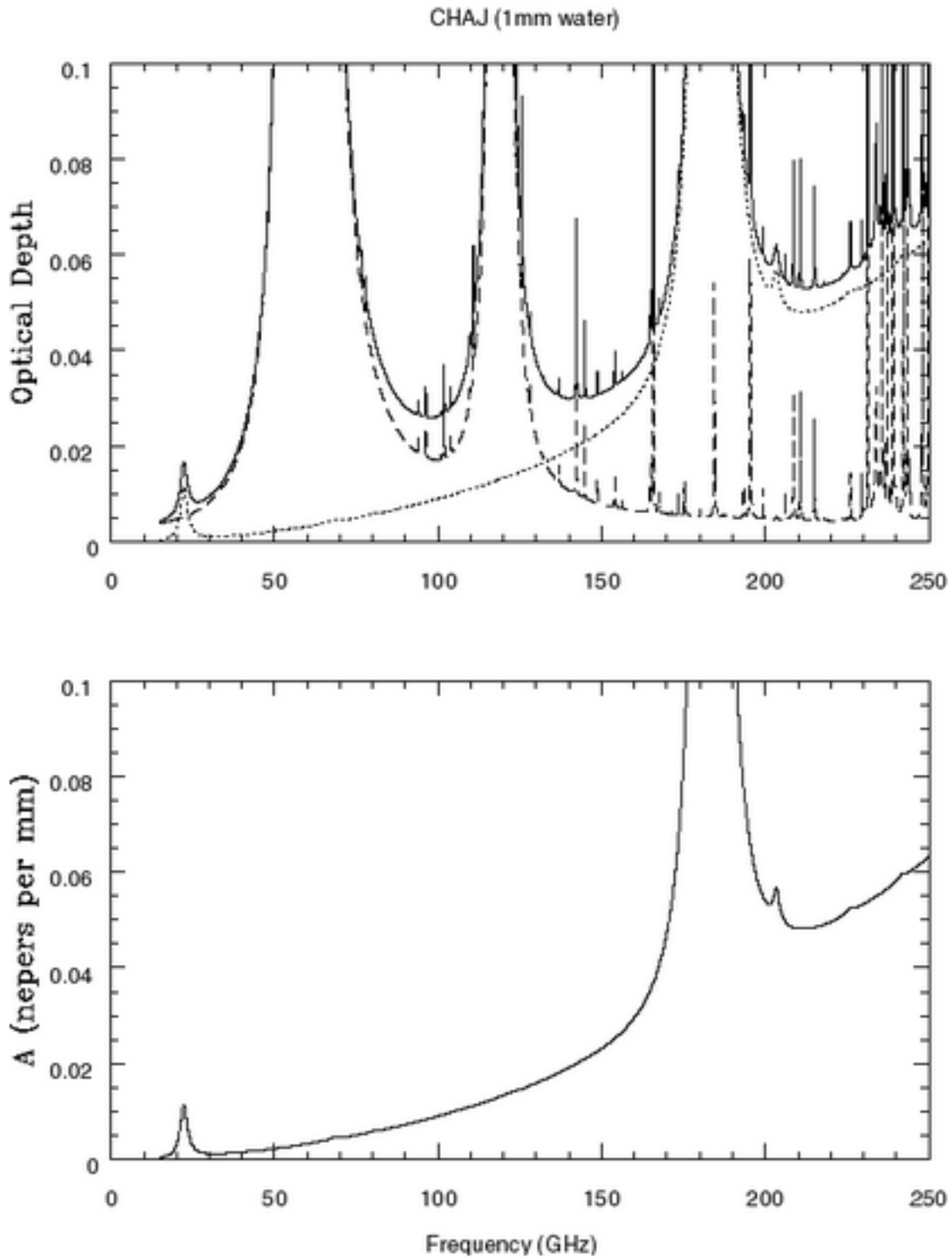
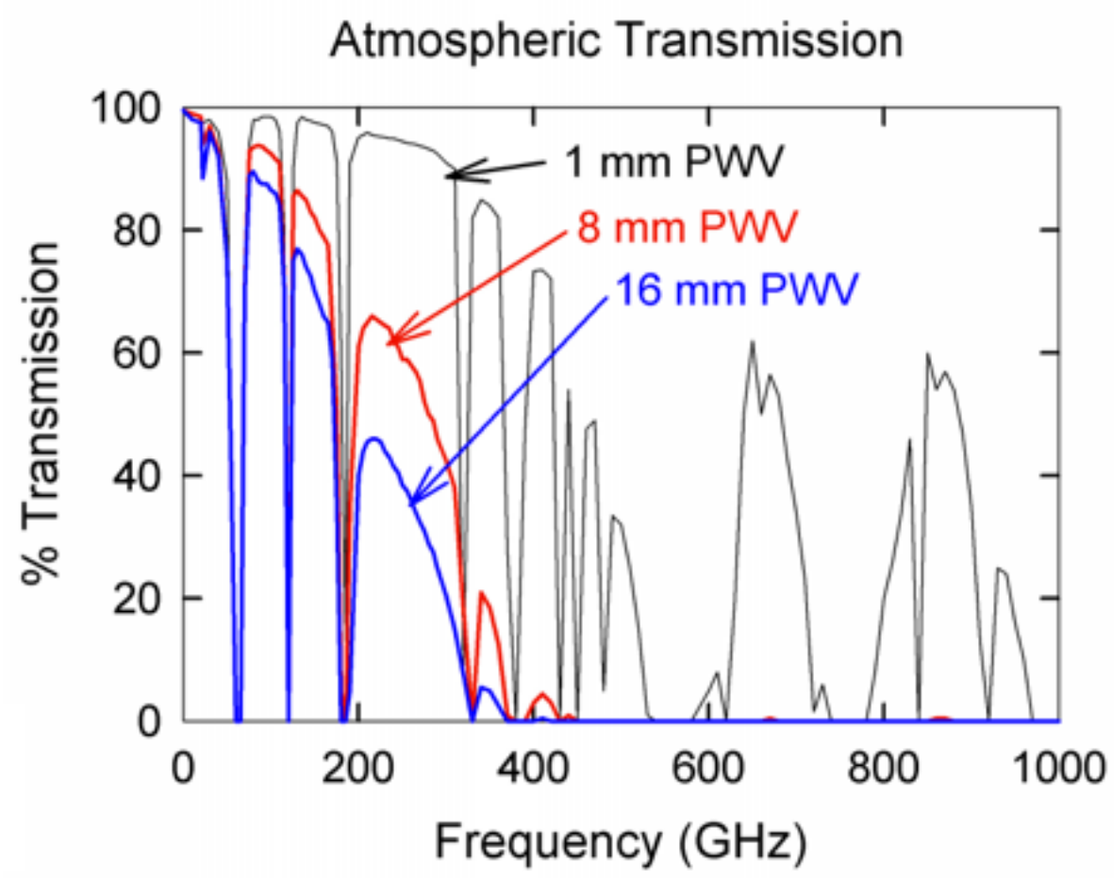
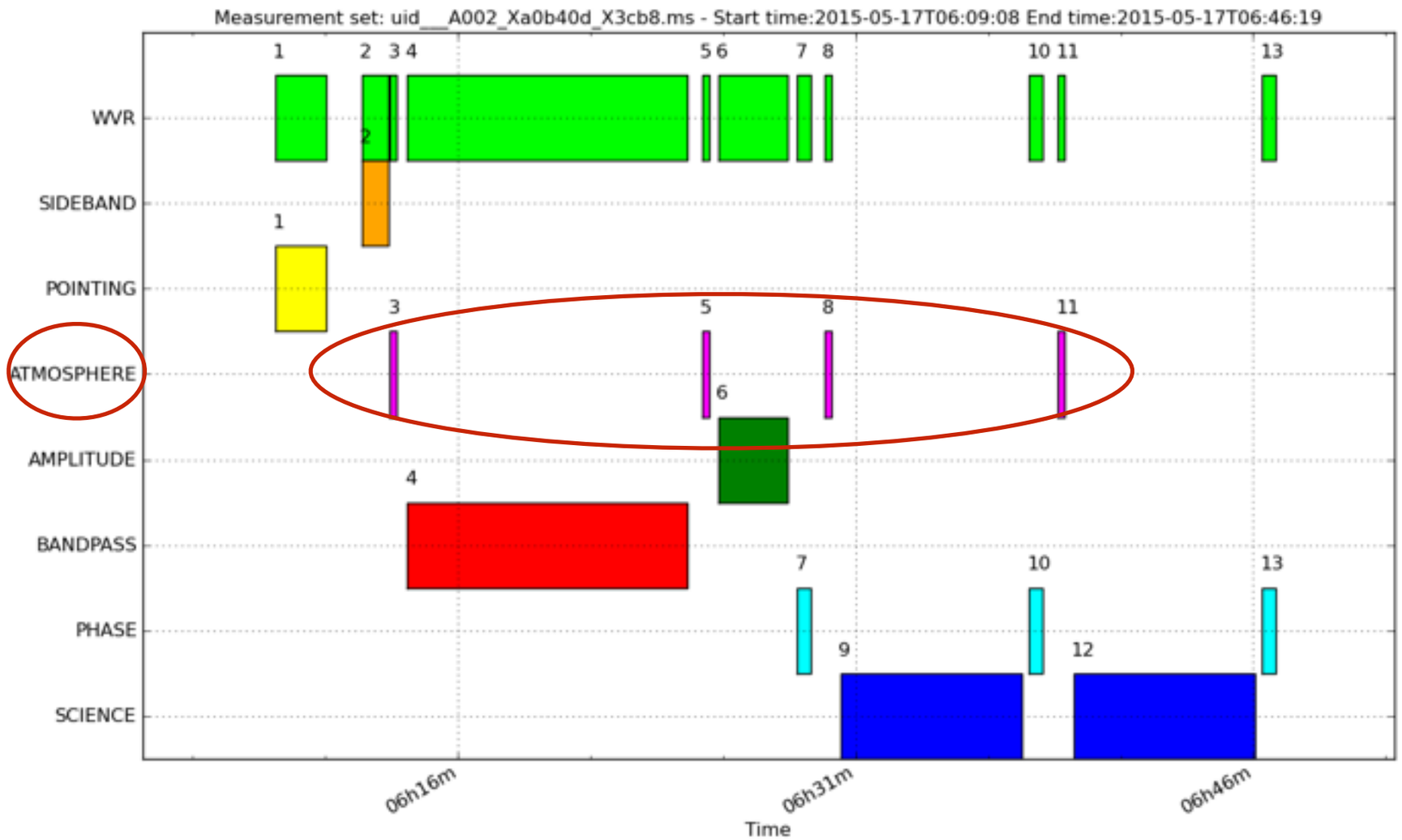


Calibration in ALMA… hifa-tsyscal

- 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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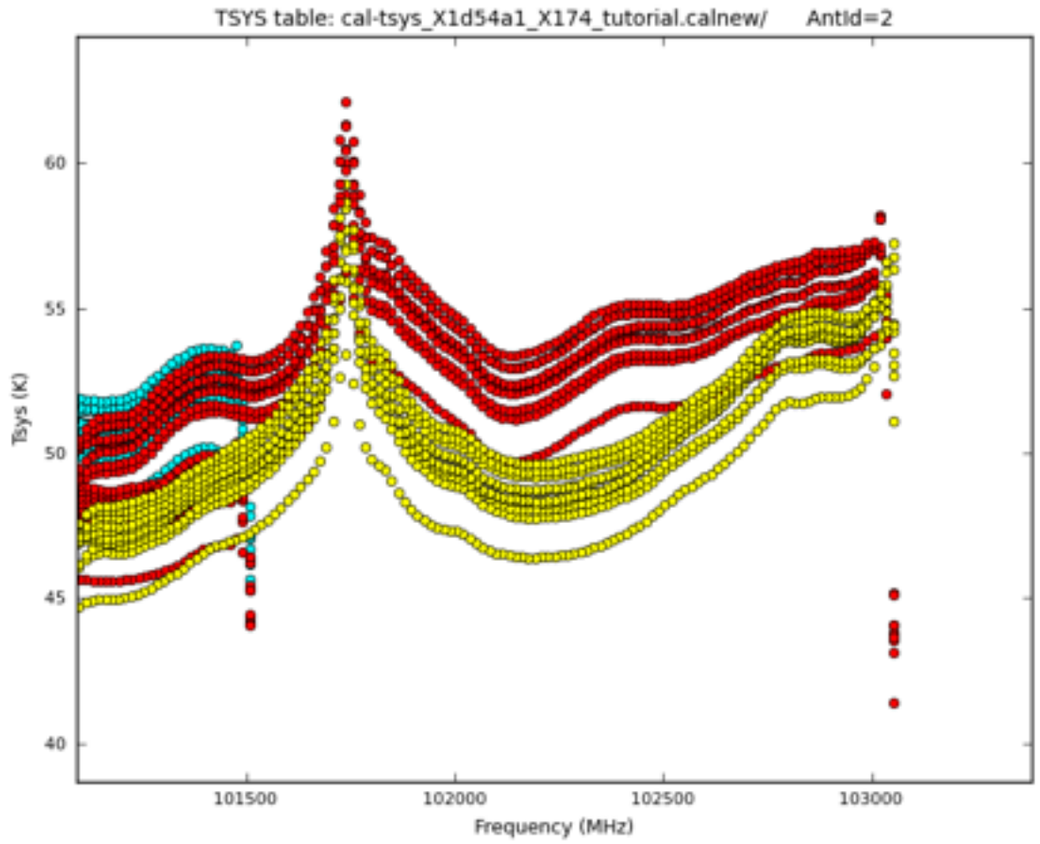
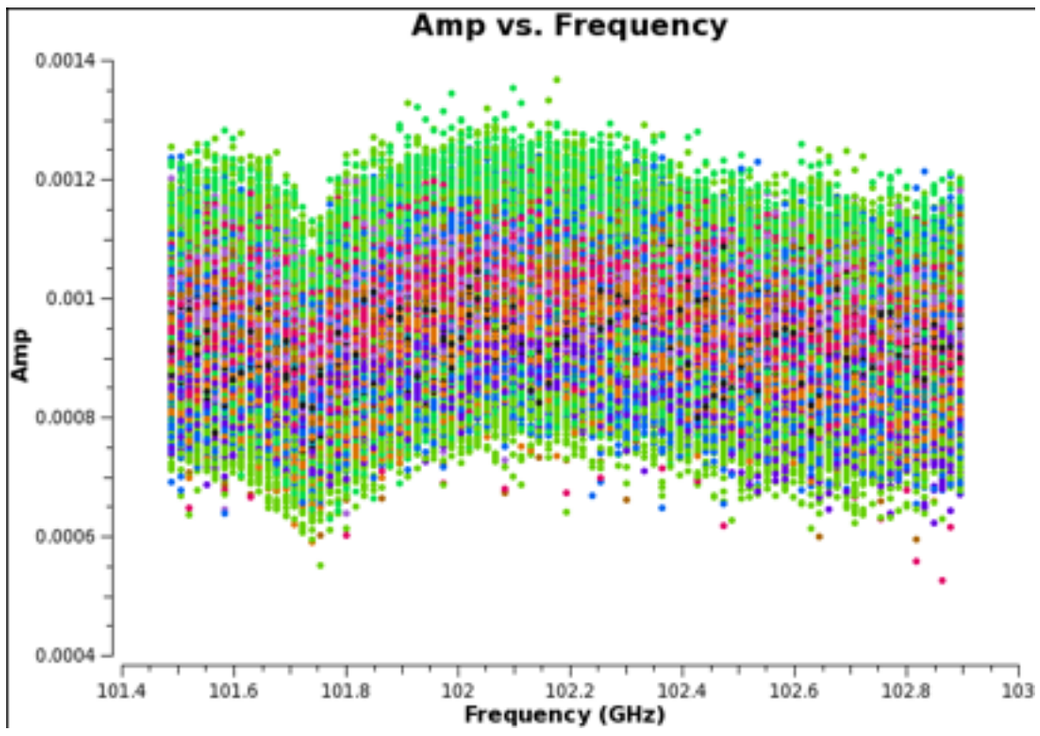
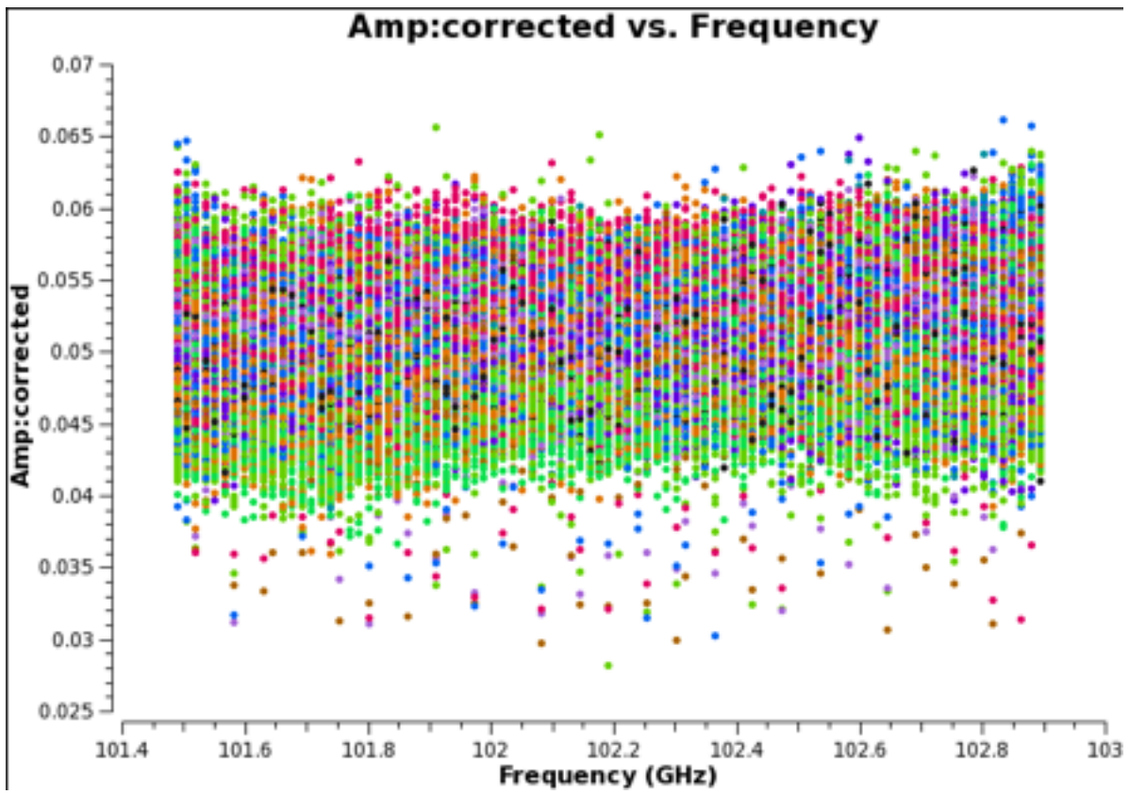
Calibration in ALMA… hifa-tsyscal

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

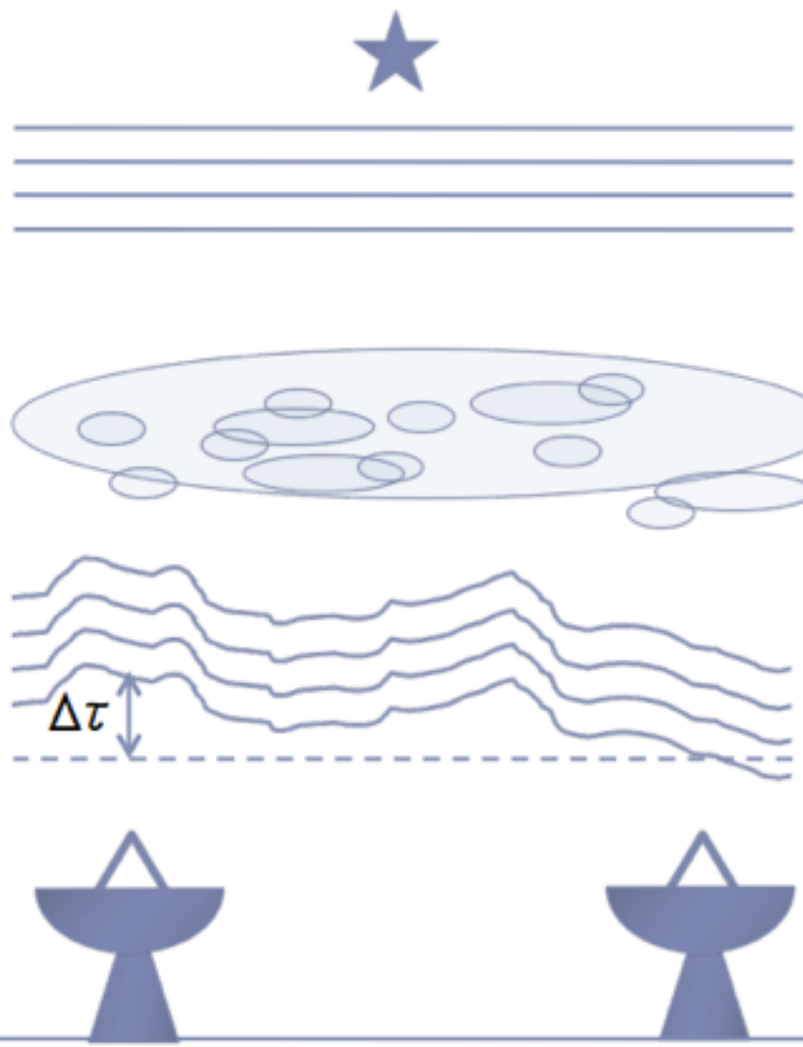






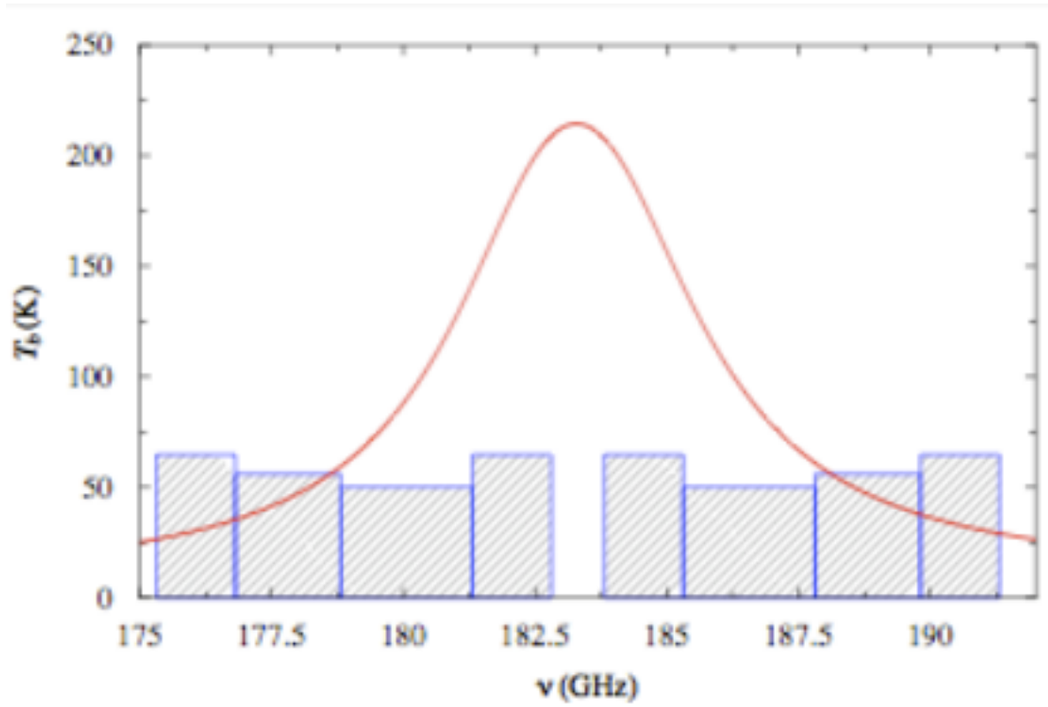
Calibration in ALMA… hifa-wvrgcalflag

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



Calibration in ALMA… hifa-wvrgcalflag

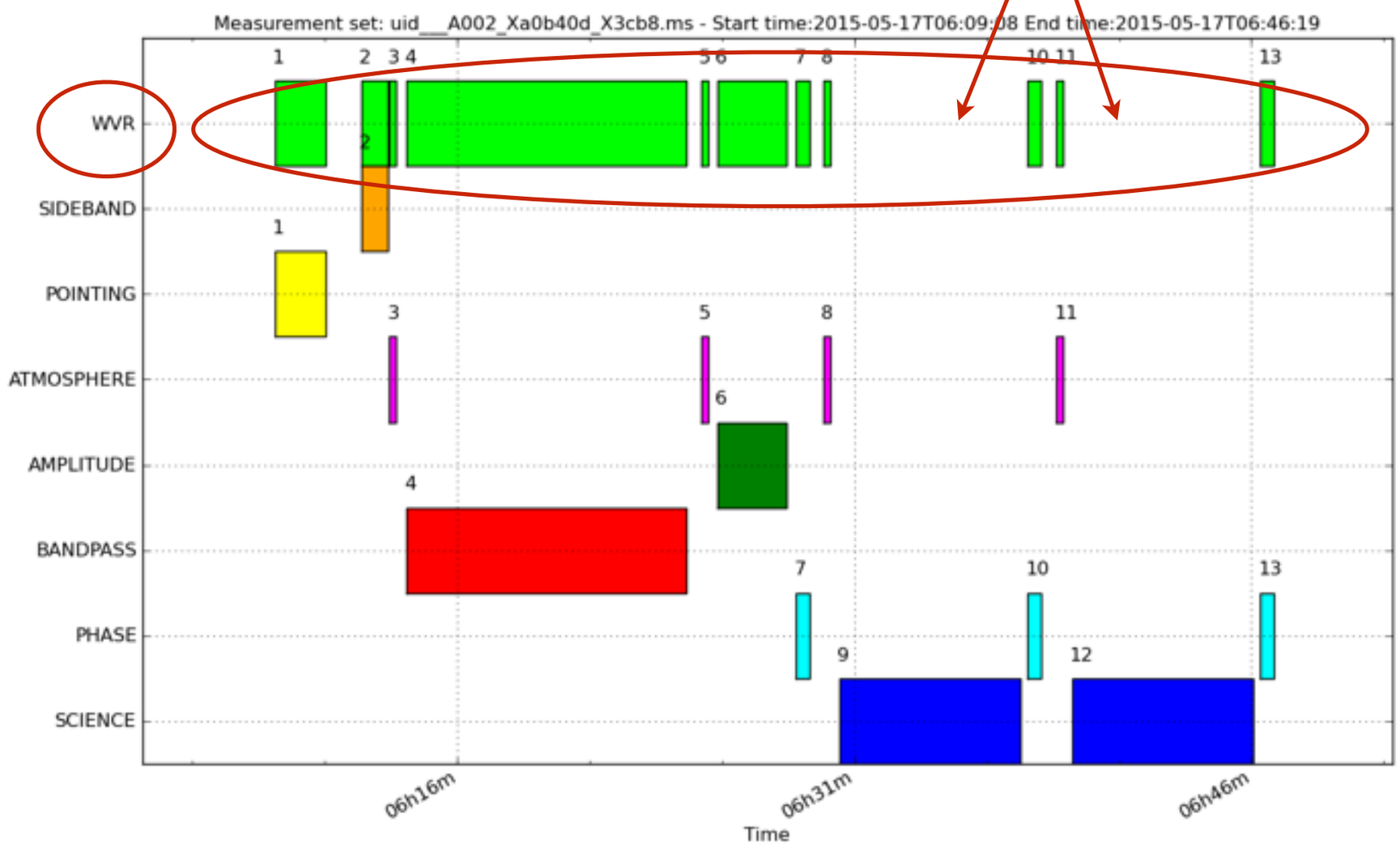
- Water Vapor Radiometry (WVR) Installed on every 12-m antenna :
  - measure (1sec) the rapid fluctuations of 182.5GHz H_2O line with a radiometer at each antenna
  - use these measurements to derive changes in water vapor column (Δw) and convert to phase corrections using:



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

Calibration in ALMA…
hifa-wvrgcalflag

measured also during target observations…



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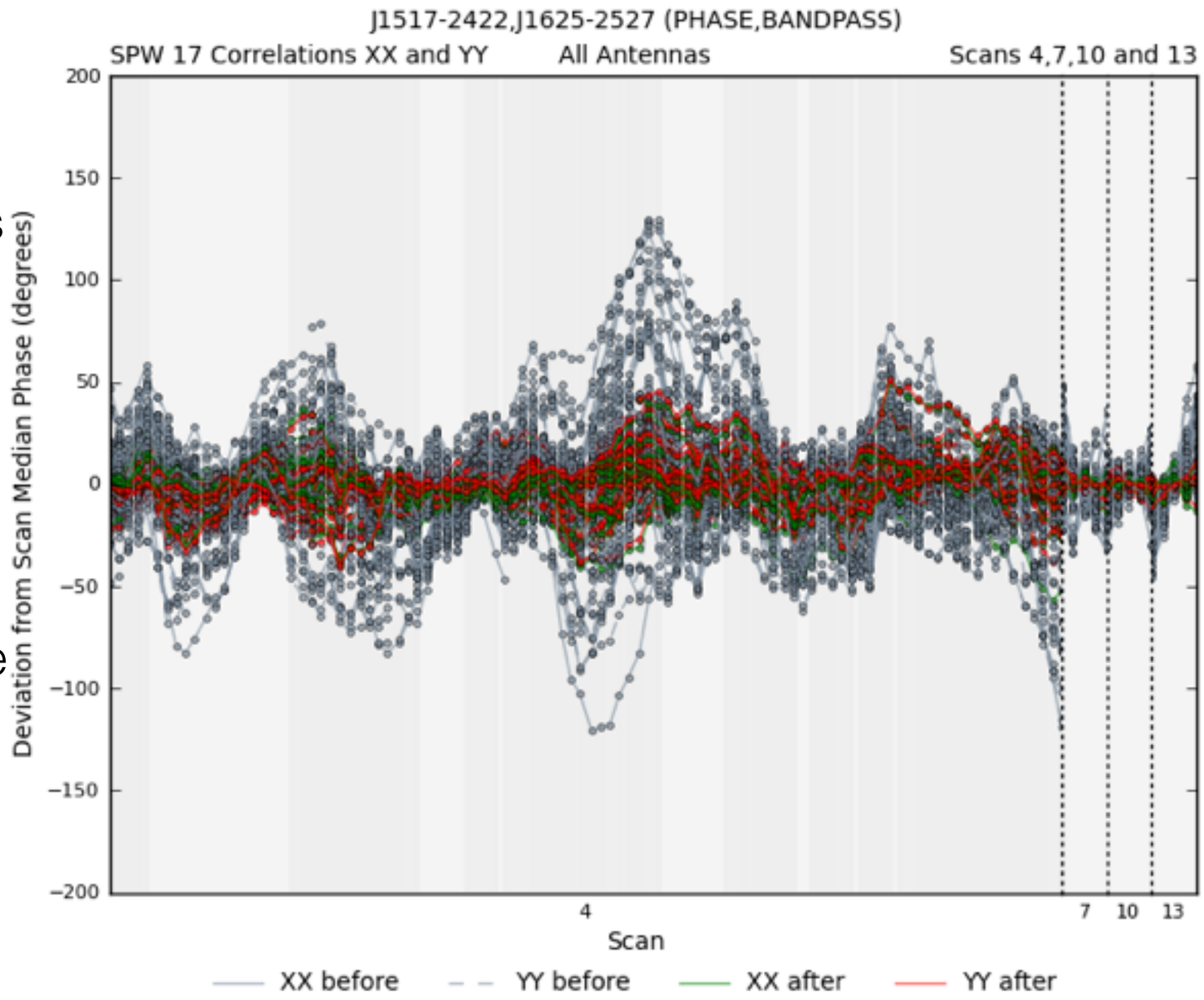
Calibration in ALMA… hifa-wvrgcalflag

- 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

Before/After PWV corrections



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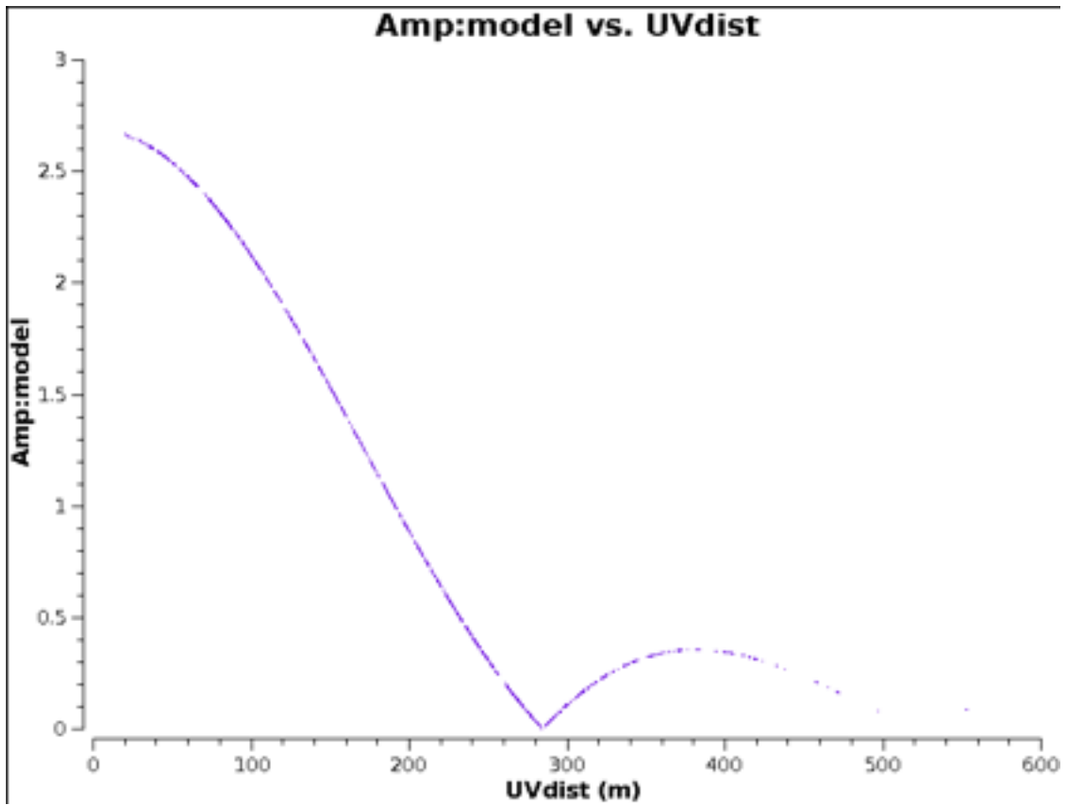
Calibration in ALMA… hif-setJy

- 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…

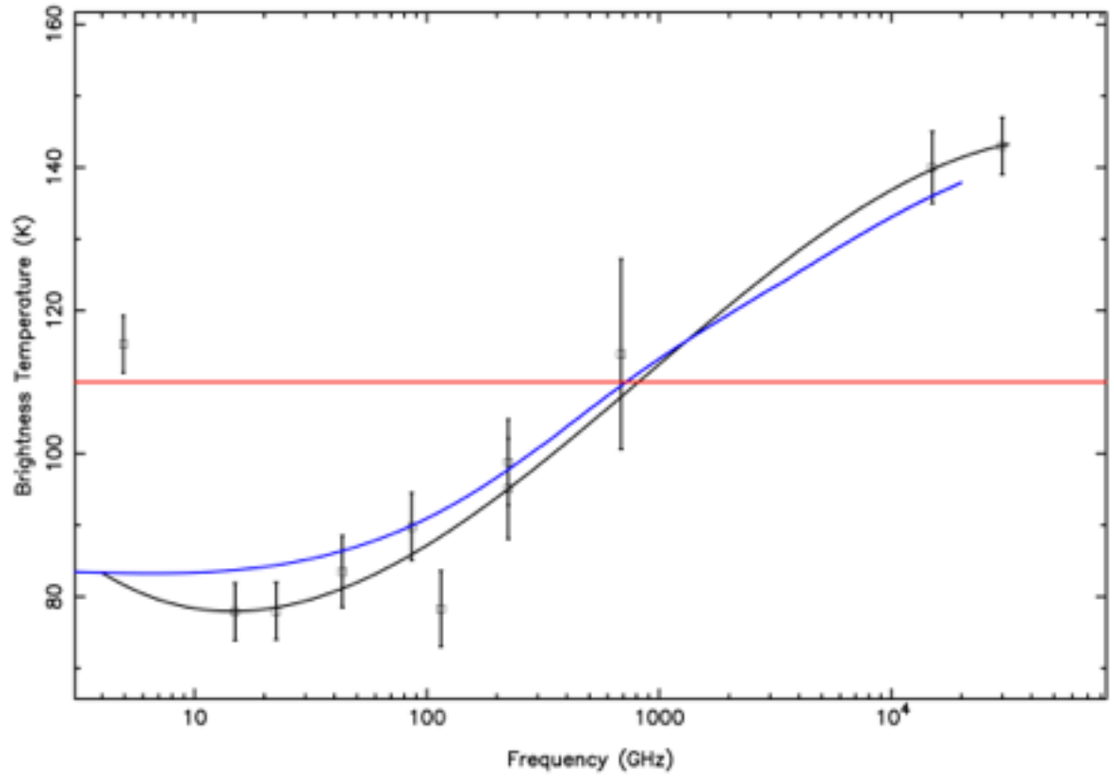


Titan visibilities

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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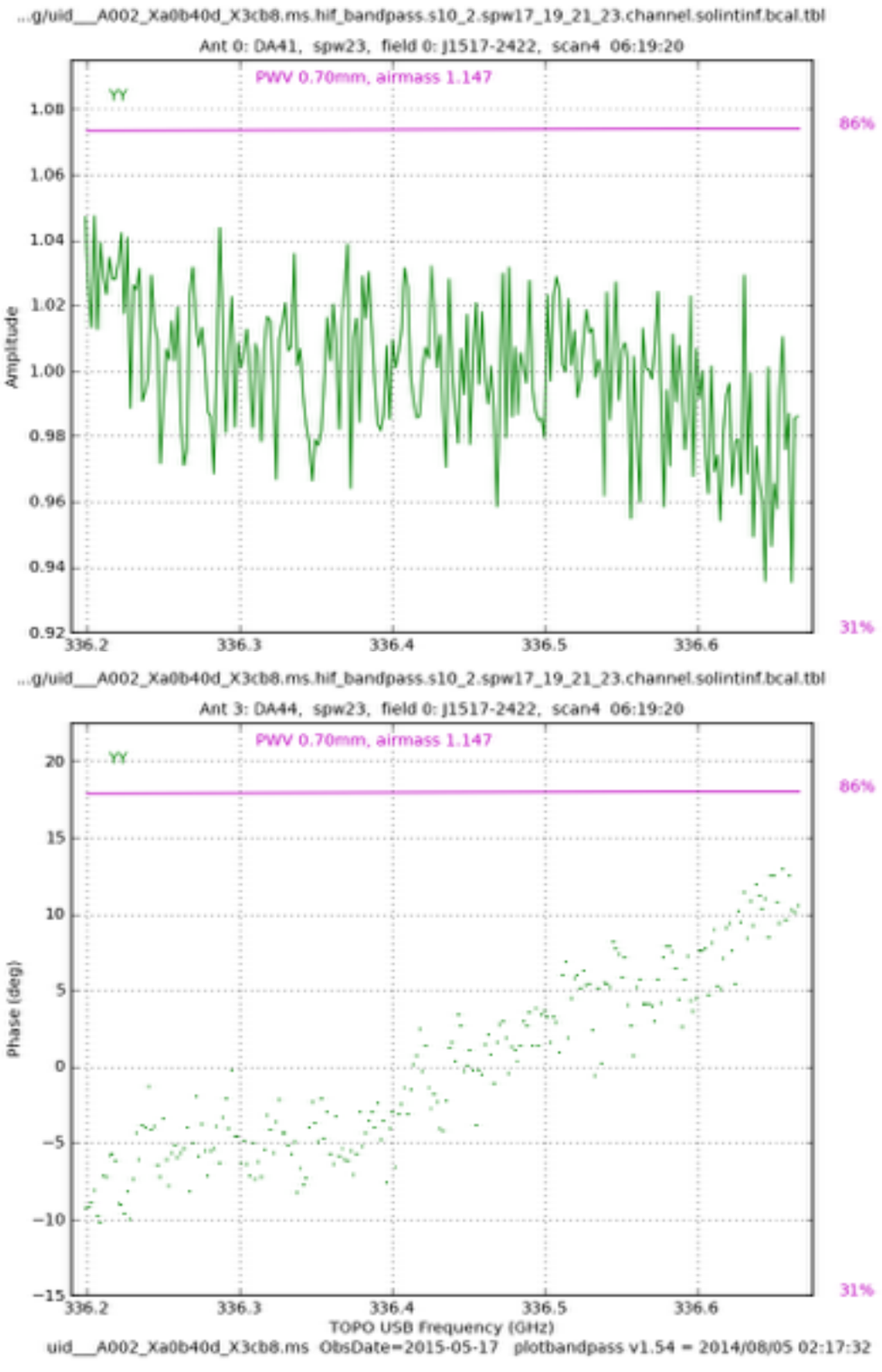
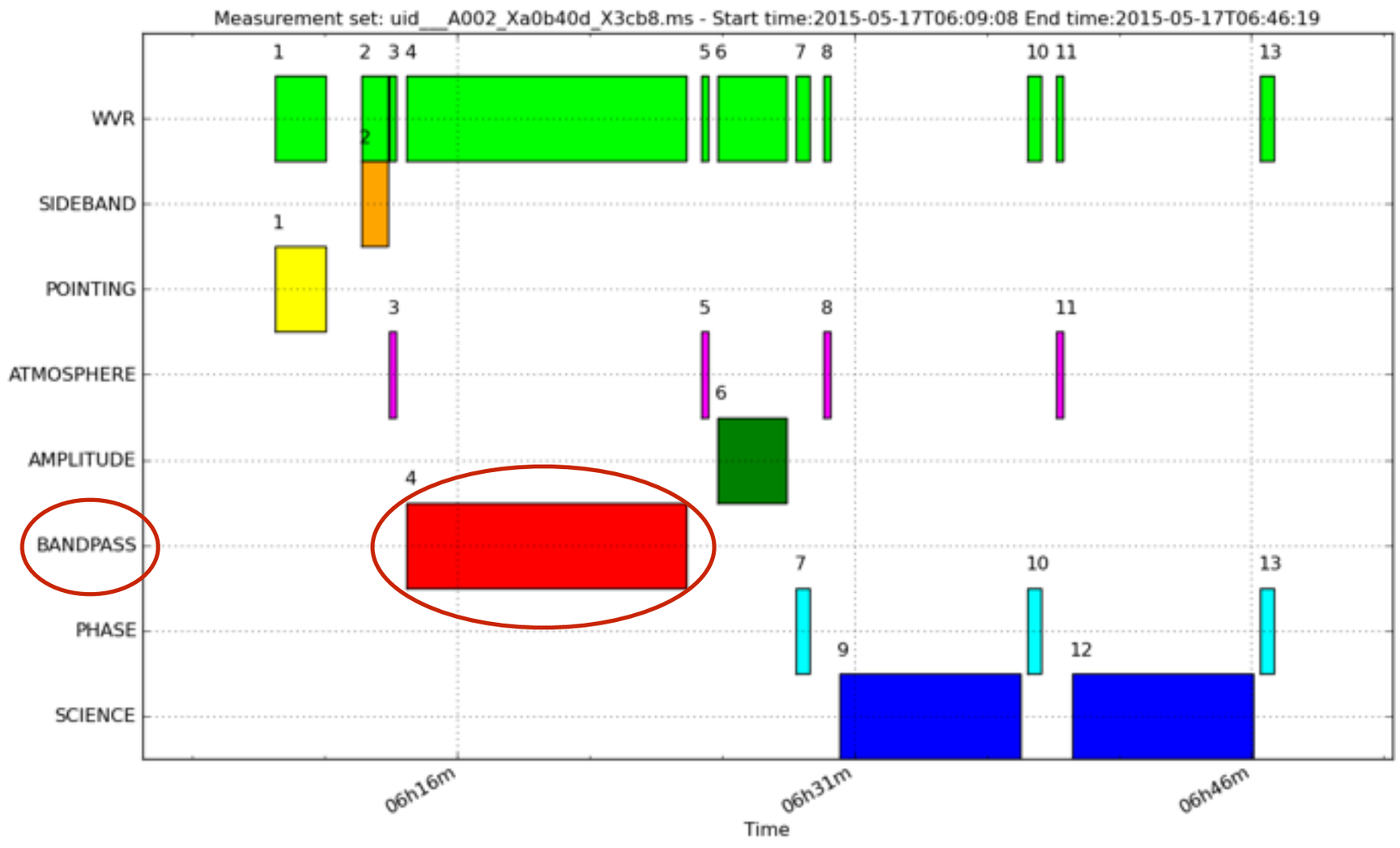
Calibration in ALMA… hif-bandpass

- 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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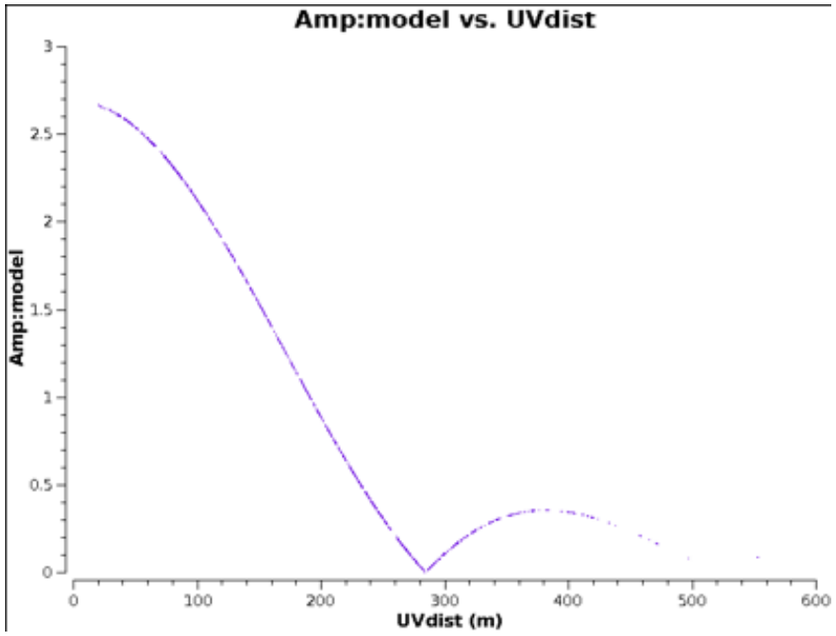
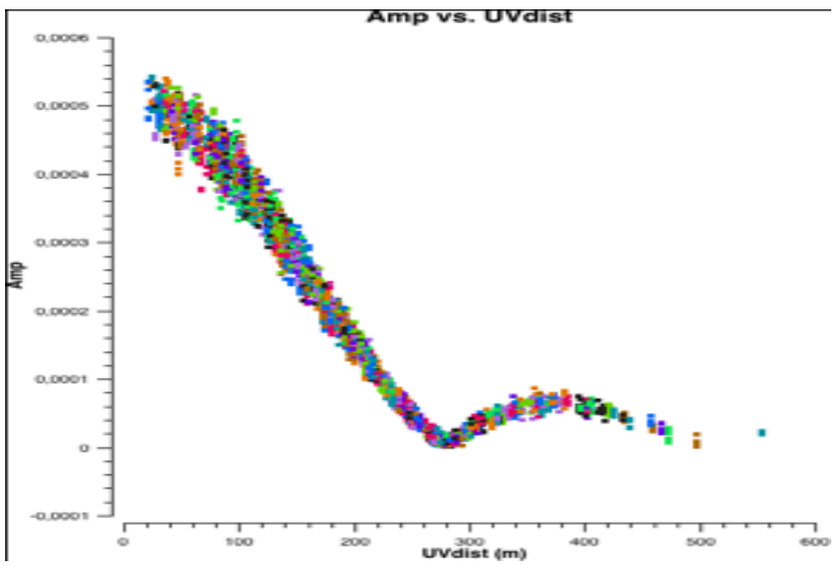
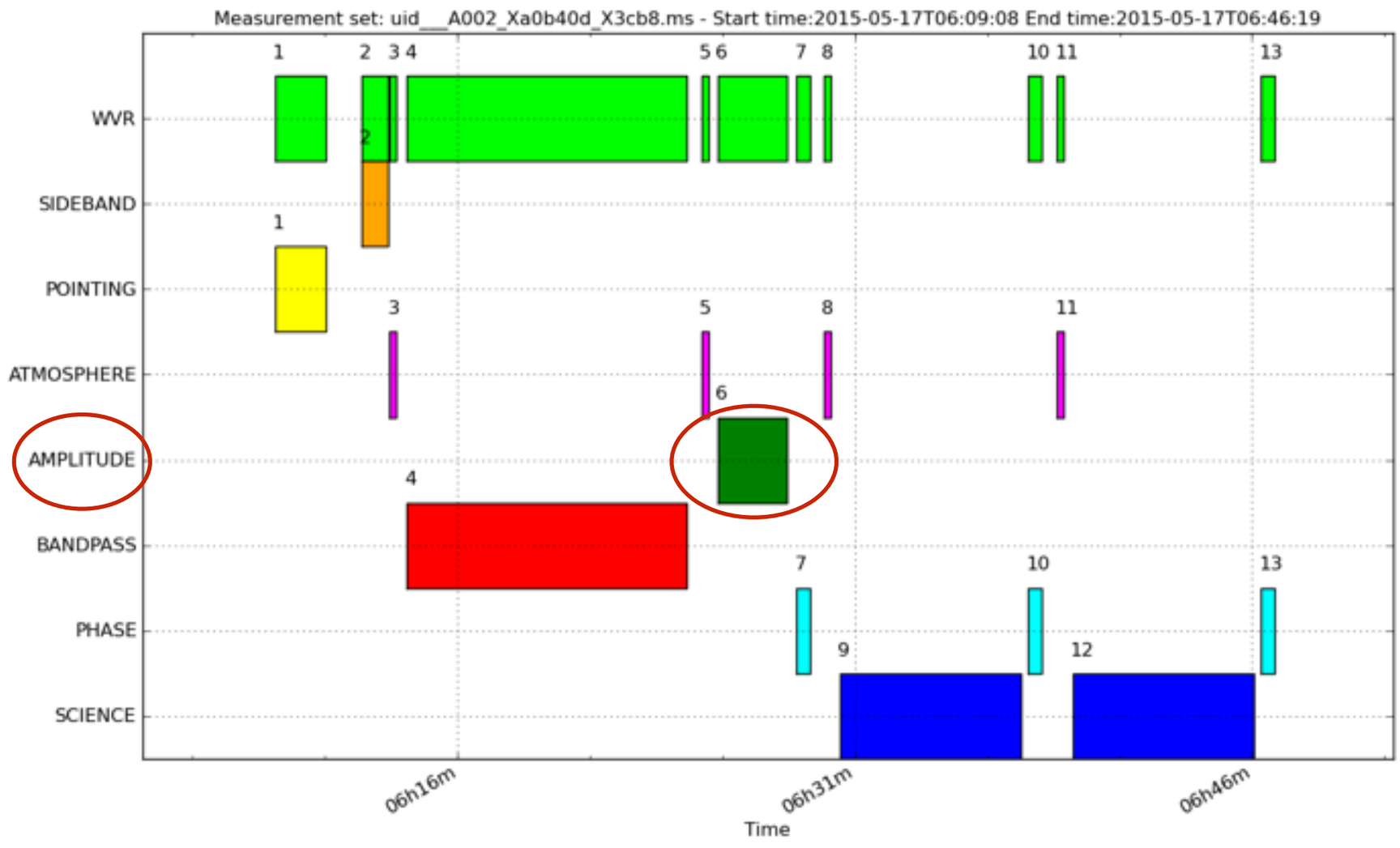
Calibration in ALMA… hif-gfluxscale

- 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

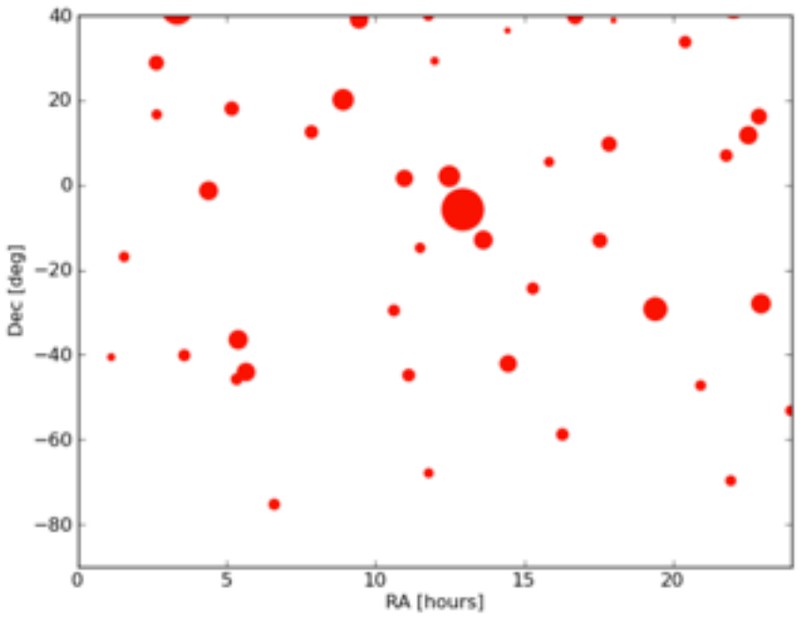
- Flux calibration is one of the most critical in the calibration process…
  - model libraries, sources extended, variability
  - good to check transferred fluxes in alma calibrator database (https://almascience.eso.org/sc/)

Computed Flux Densities

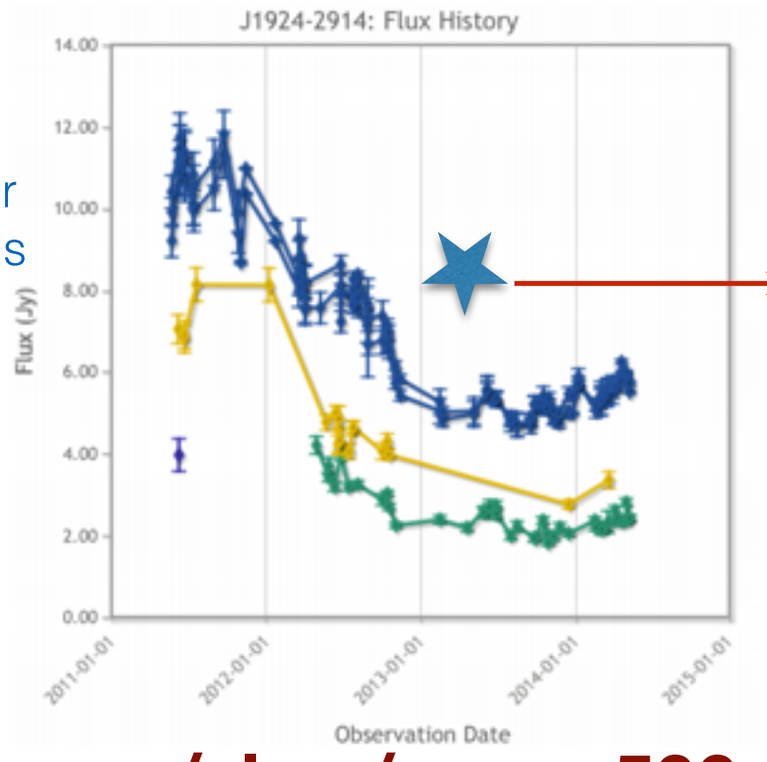
The following flux densities were set in the measurement set model column and recorded in the pipeline context:

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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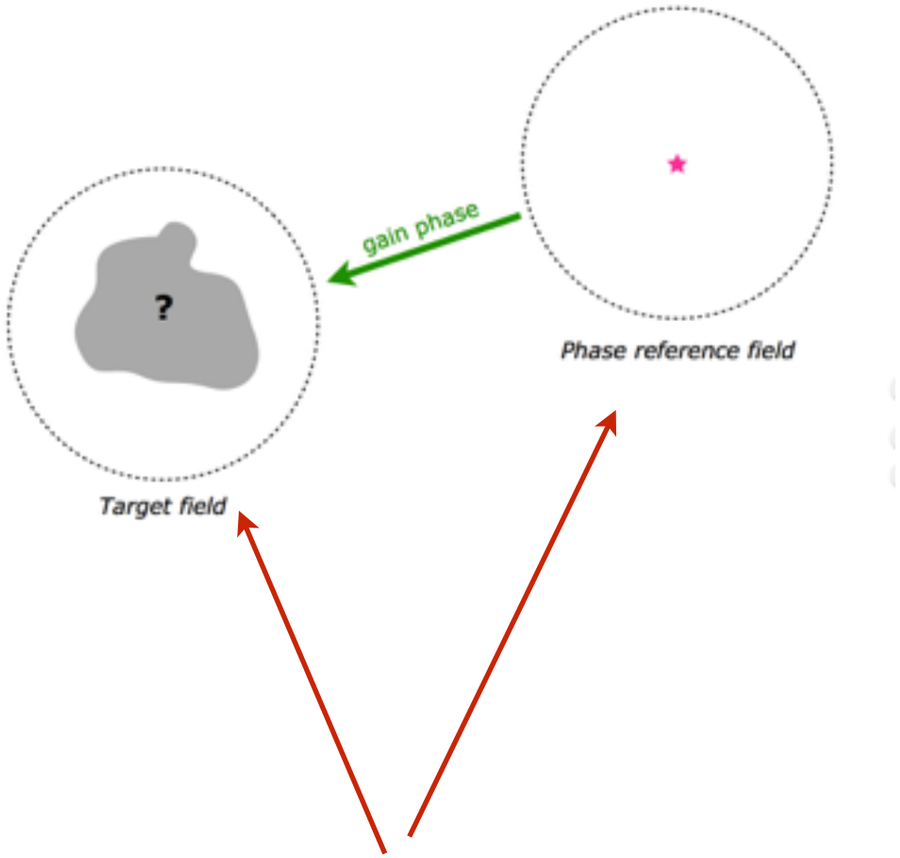
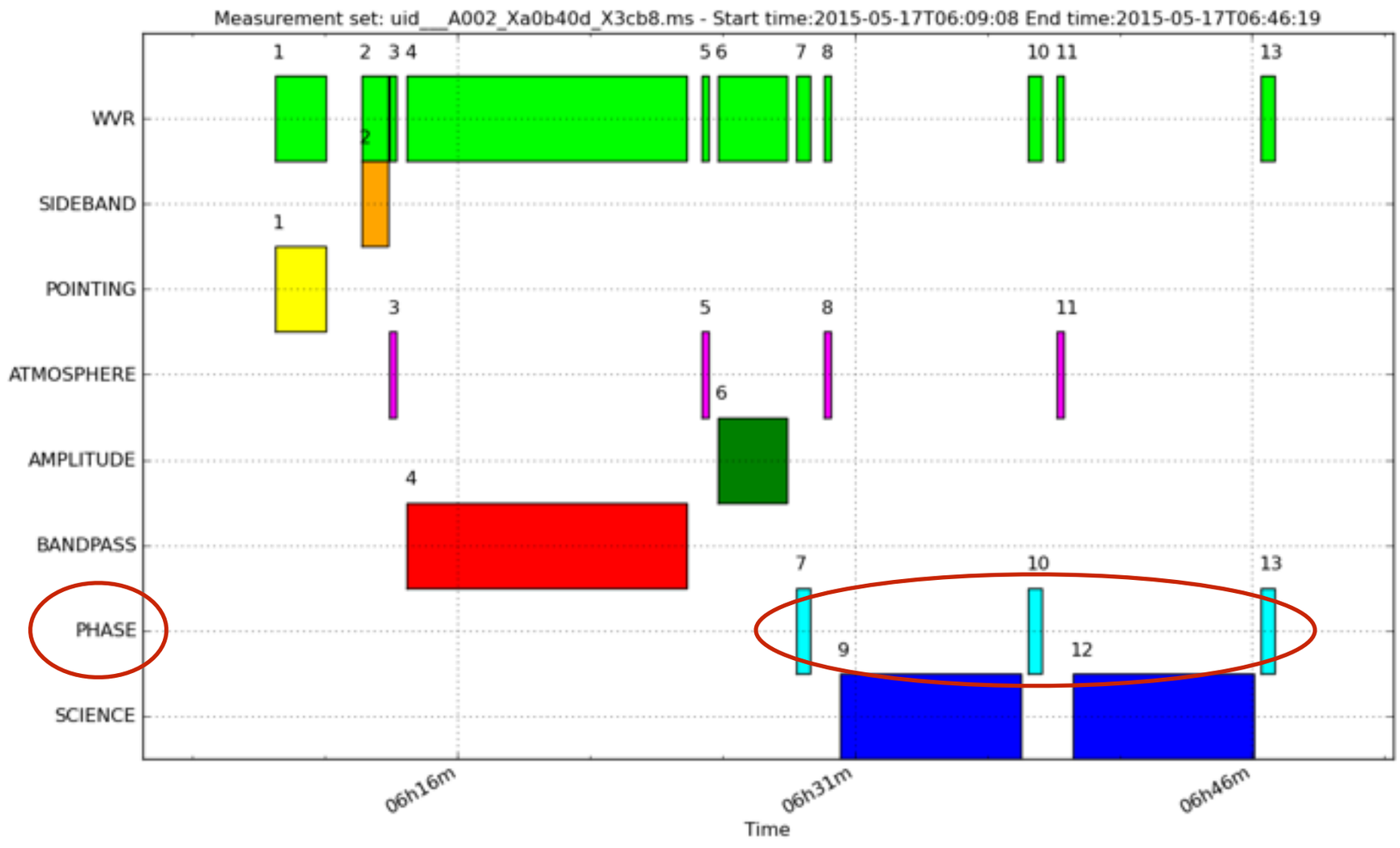
Calibration in ALMA… hif-timegaincal

- 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

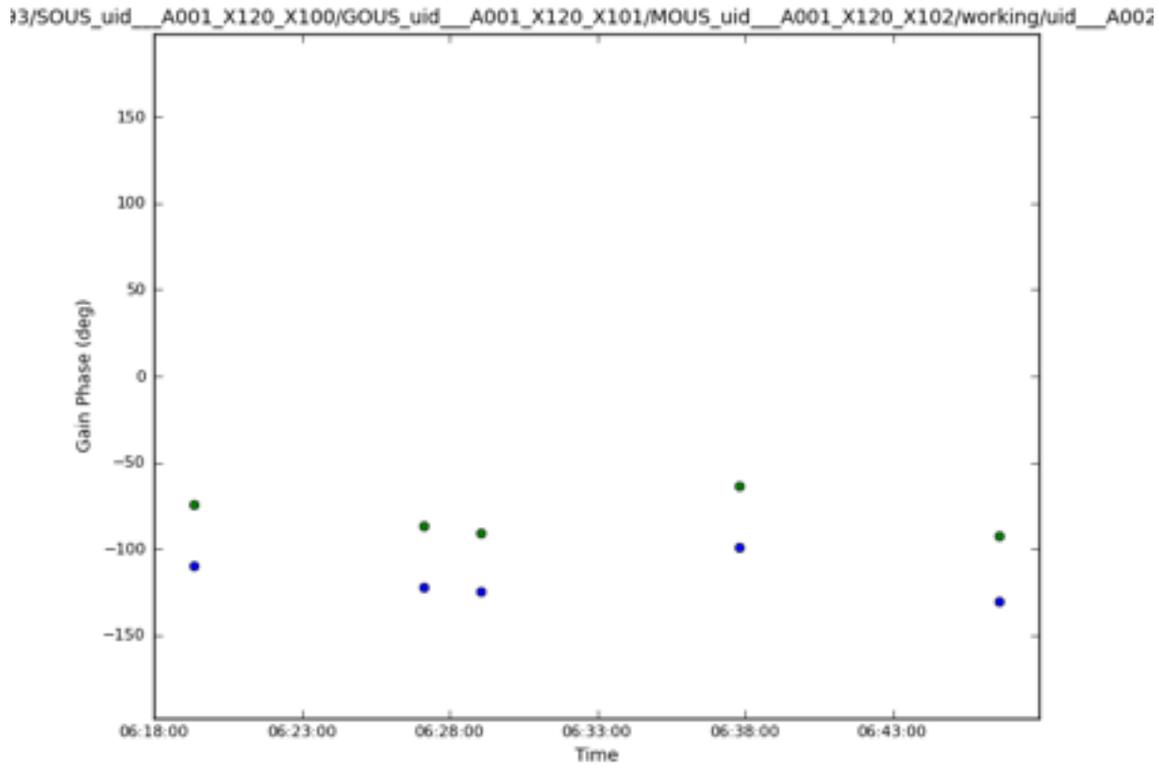


weblog

Calibration in ALMA… hif-timegaincal

Errors larger than what expected

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



- phase calibrator close to the target position
- linear interpolation…

Calibration in ALMA… hif-timegaincal

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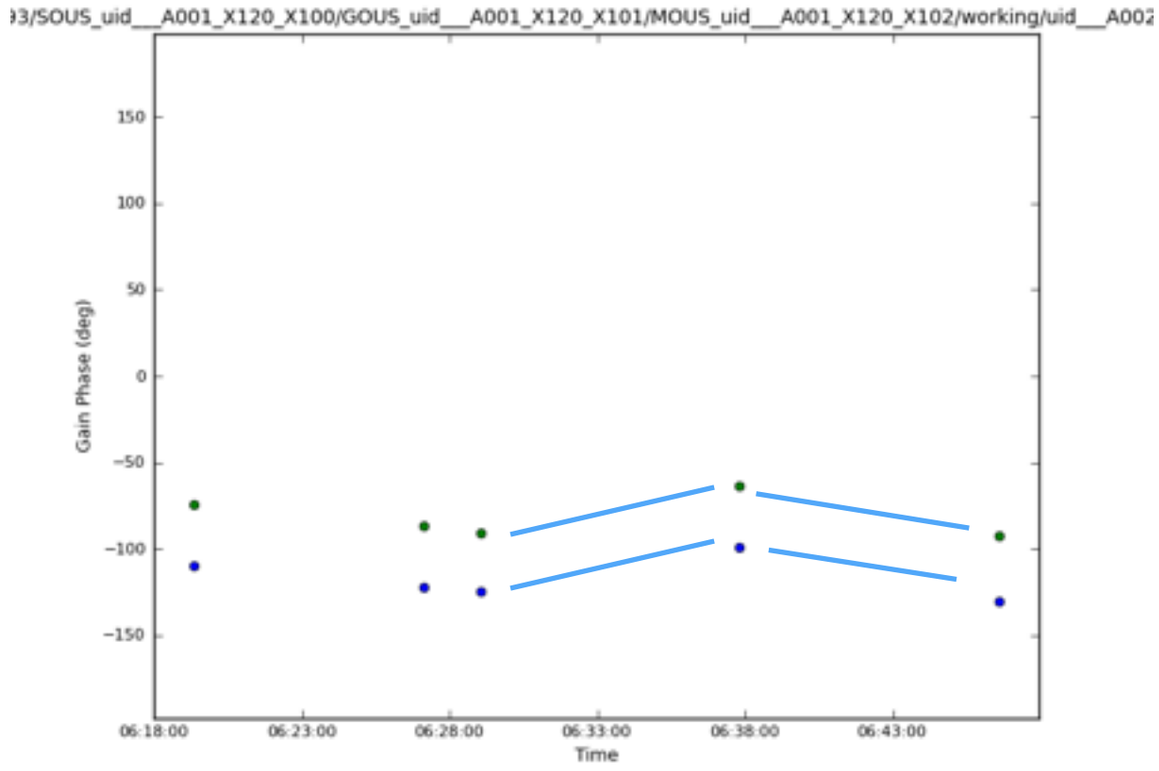

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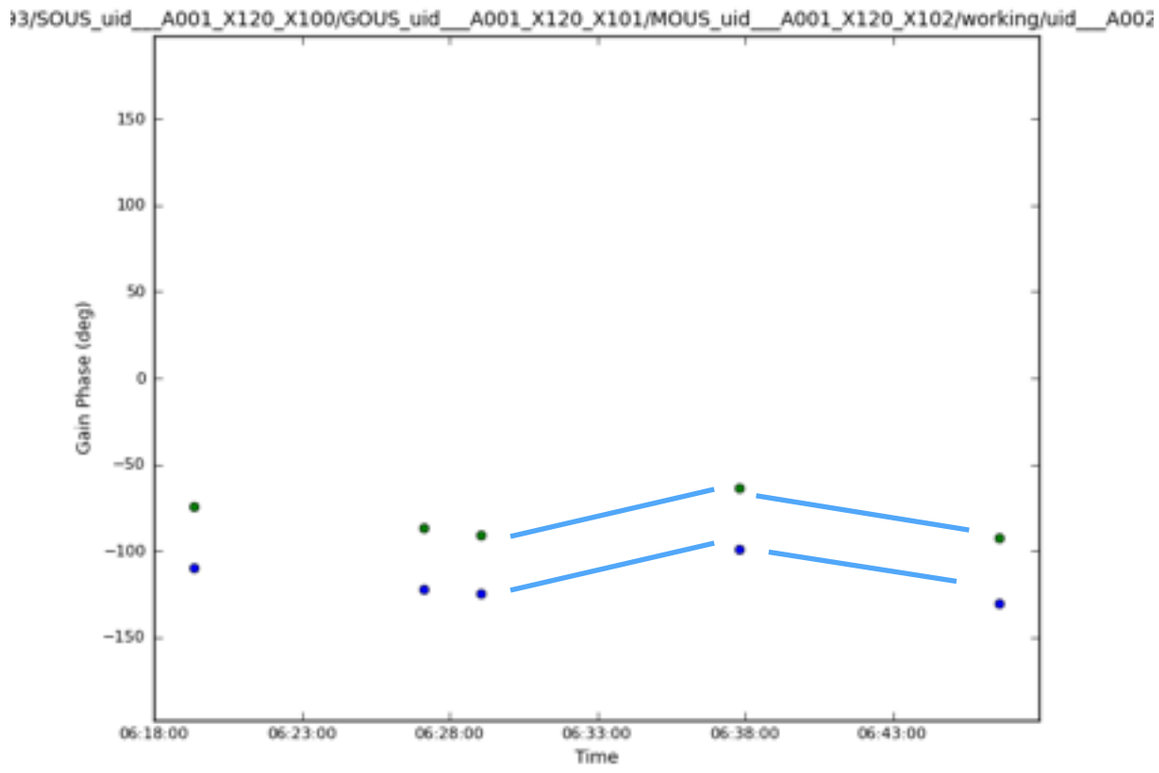


- phase calibrator close to the target position
- linear interpolation…

go for self-calibration!

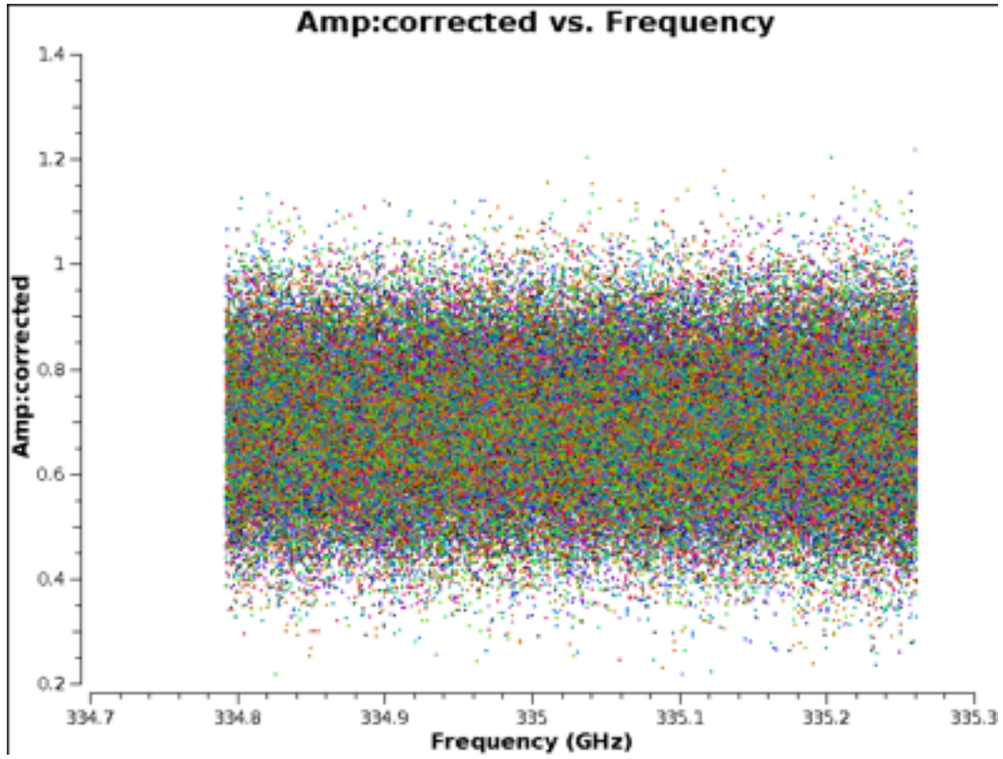
Calibration in ALMA…
Observational Strategy (from the pipeline)

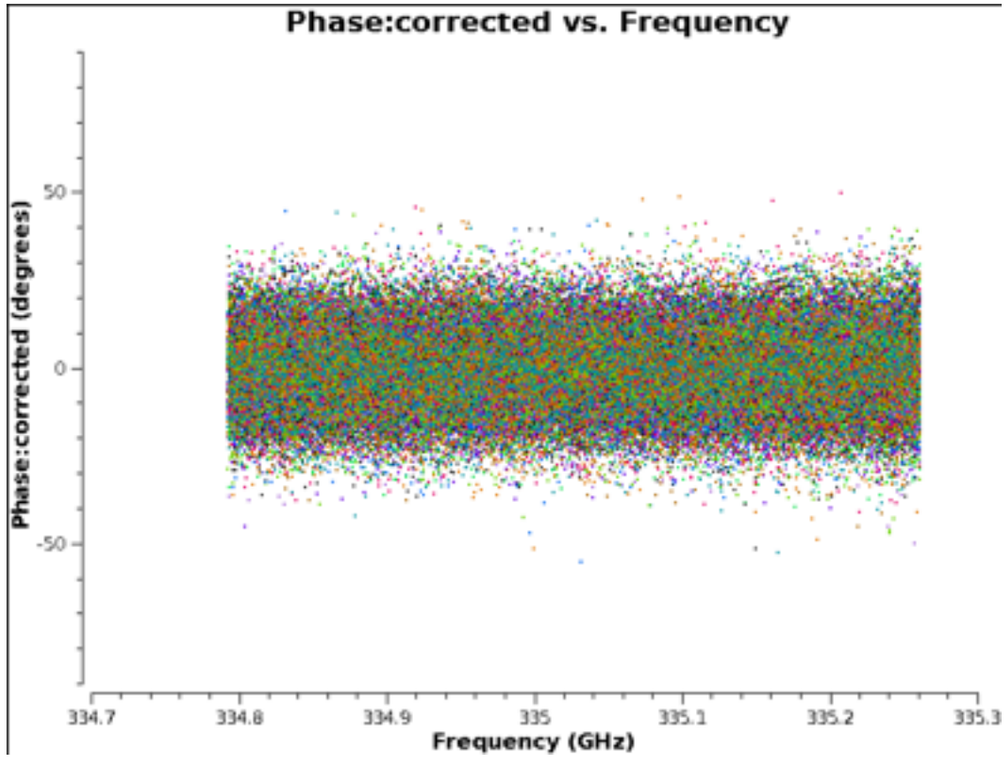
1. **hif_importdata:** Register measurement sets with the pipeline
2. **hifa_flagdata:** ALMA deterministic flagging
3. **hifa_fluxcalflag:** Flag spectral features in solar system flux calibrators
4. **hif_refant:** Select reference antennas
5. **hifa_tsyscal:** Calculate Tsys calibration
6. **hifa_tsysflag:**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

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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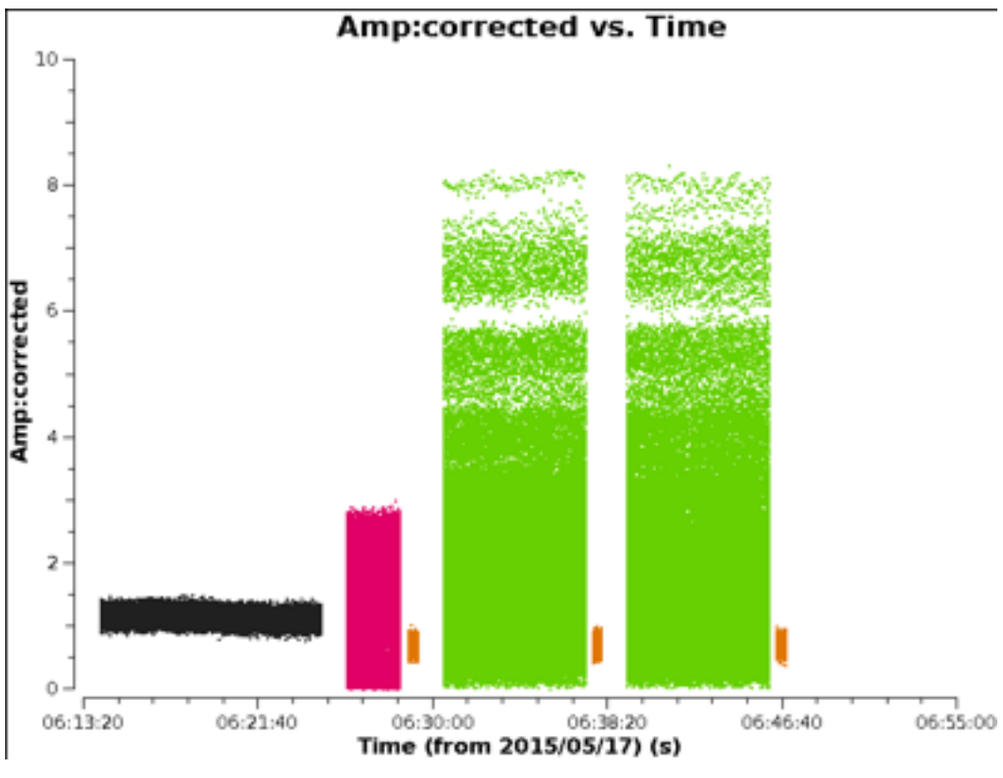

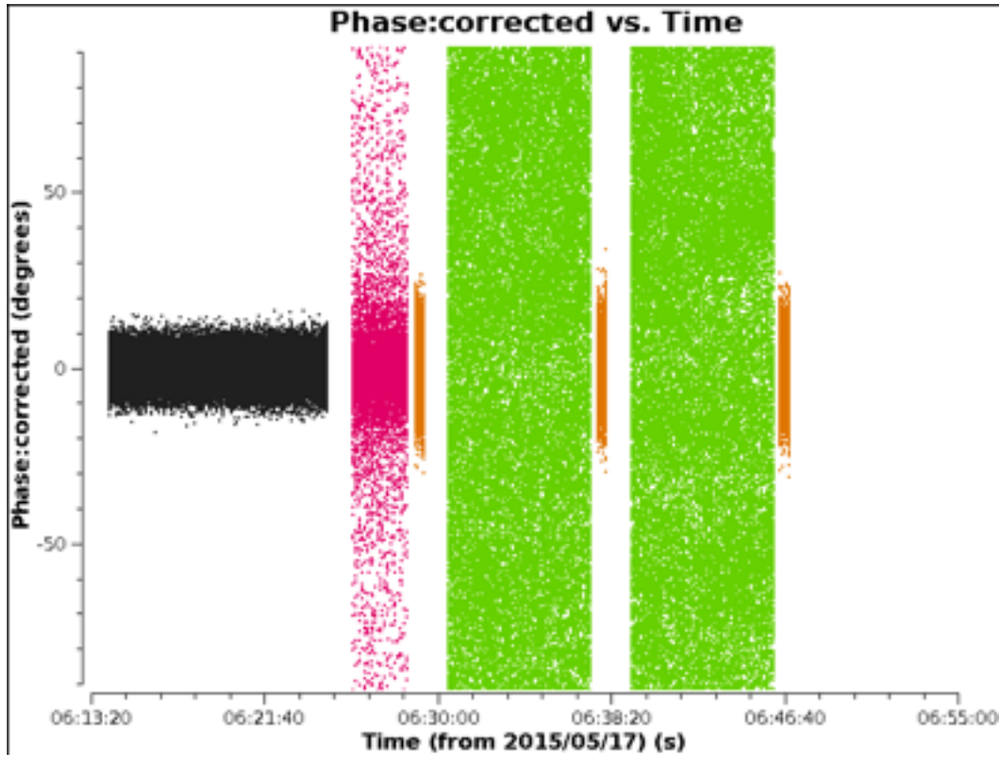

A,ϕ vs time

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