Advanced Calibration Topics

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Eighteenth Synthesis Imaging Workshop

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Outline

- Origin of Atmospheric Opacity
- Effect of Atmosphere on Phase
- Phase Correction Techniques
    - Water Vapor Radiometer
    - Fast-switching
    - Band to Band Phase Transfer
    - Self-calibration

Additional topics if there is time:

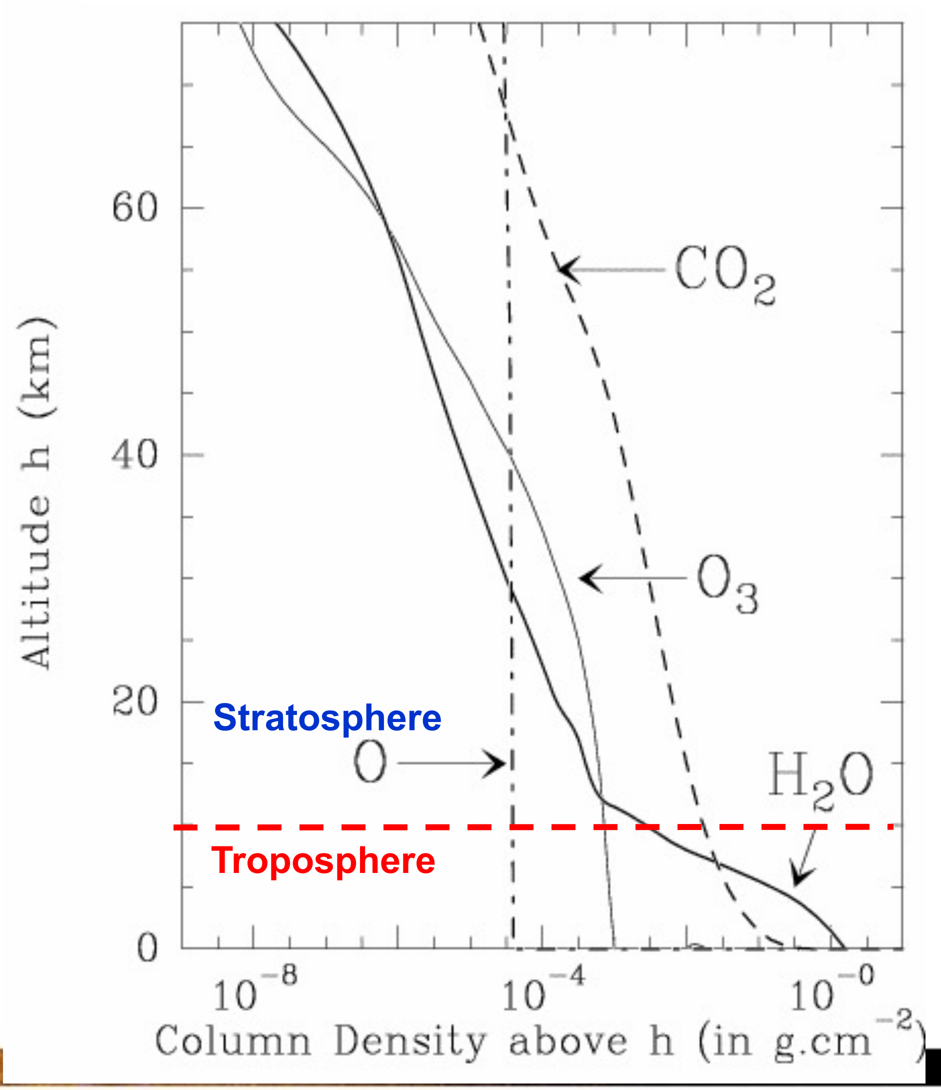
- Atmospheric Opacity Correction (Tsys)
- Absolute Flux Calibration

Atmospheric Opacity

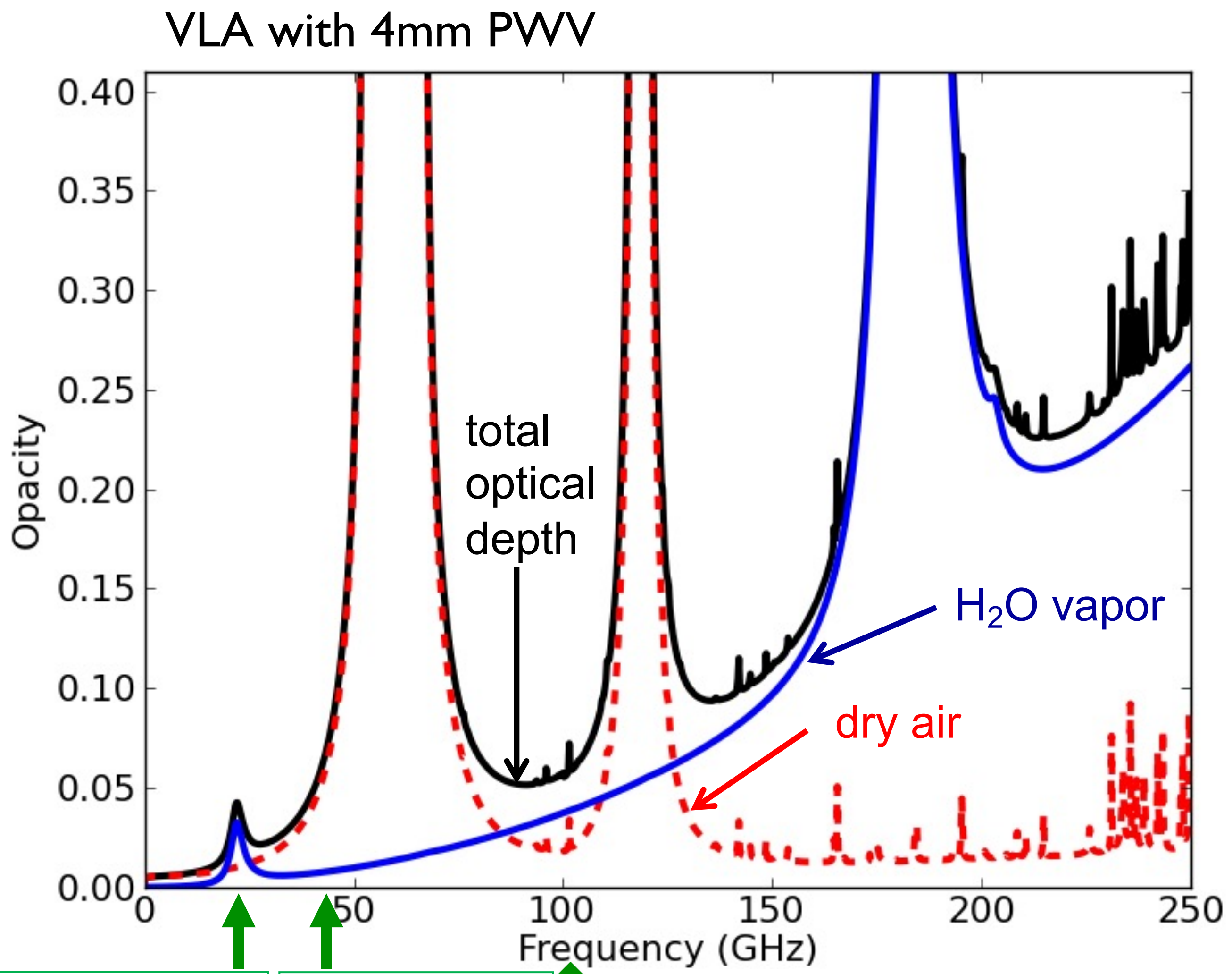
Constituents of Atmospheric Opacity

- Due to the troposphere (lowest layer of atmosphere): $h \lesssim 10$ km
- Temperature ↓ with ↑ altitude: clouds & convection can be significant
- "Dry" Constituents of the troposphere:, O_2, O_3, CO_2, Ne, He, Ar, Kr, CH_4, N_2, H_2
- H_2O: abundance is highly variable but is < 1% in mass, mostly in the form of water vapor

Column Density as a Function of Altitude



Optical Depth as a Function of Frequency



22 GHz 1.3cm

VLA K-band

43 GHz 7mm

VLA Q-band
ALMA Band 1

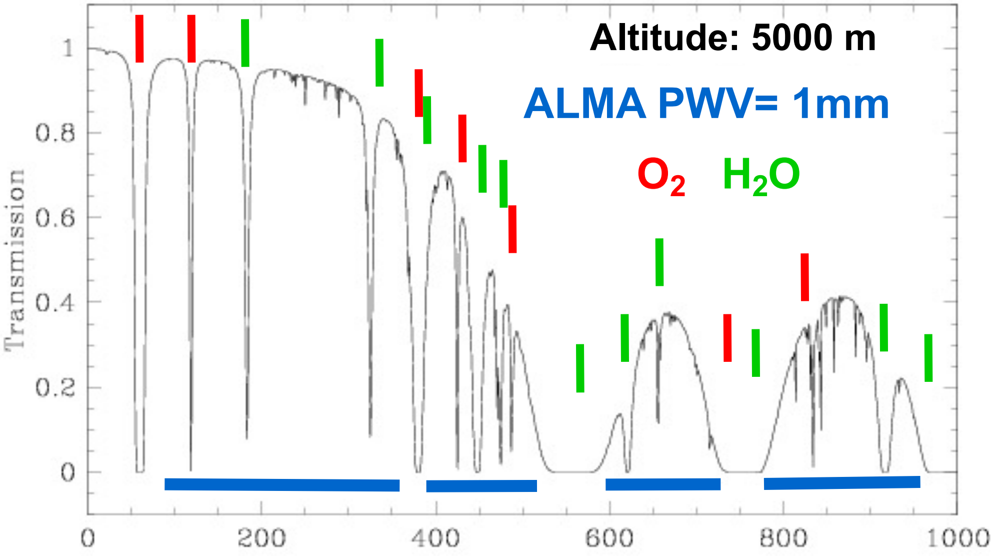
100 GHz 3mm

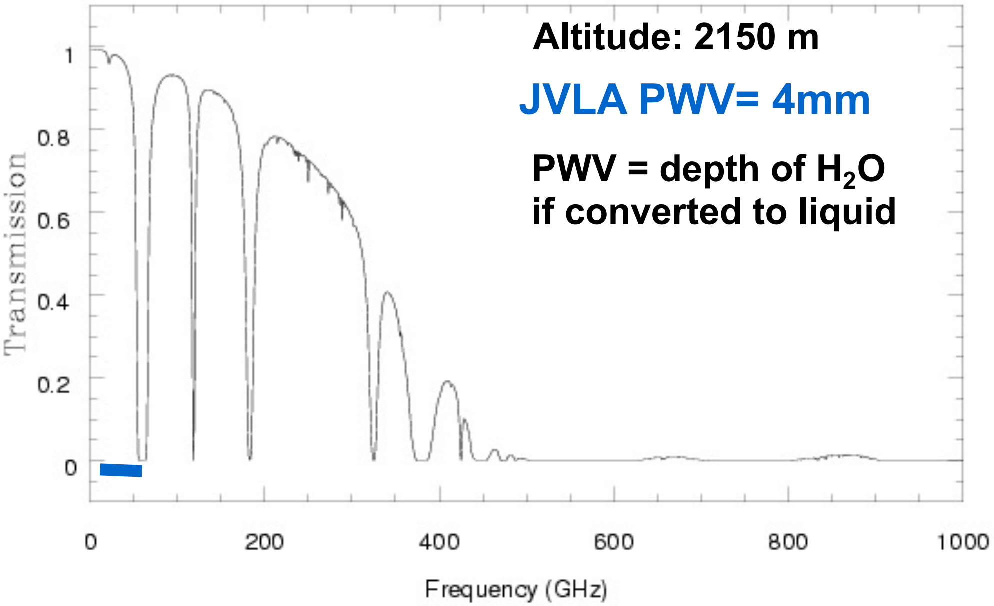
ALMA Bands 2 & 3

Future ngVLA

- At 1.3cm most opacity comes from H_2O vapor
- At 7mm biggest contribution from “dry” constituents
- At 3mm both components are significant
- “hydrosols” i.e. water droplets (i.e. clouds, not shown) can also add significantly to the opacity

Tropospheric Opacity Depends on Altitude:



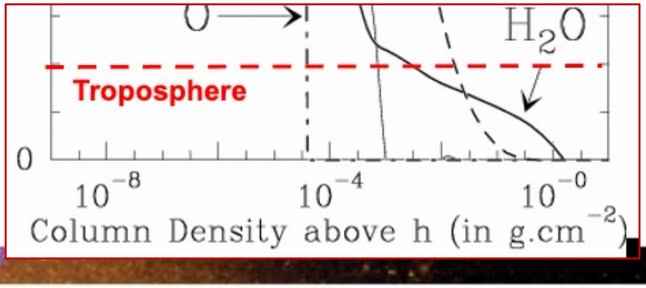


PWV = depth of H_2O if converted to liquid

- Transmission is inverse of opacity
- Models of atmospheric transmission from 0 to 1000 GHz for the ALMA site in Chile, and for the VLA site in New Mexico

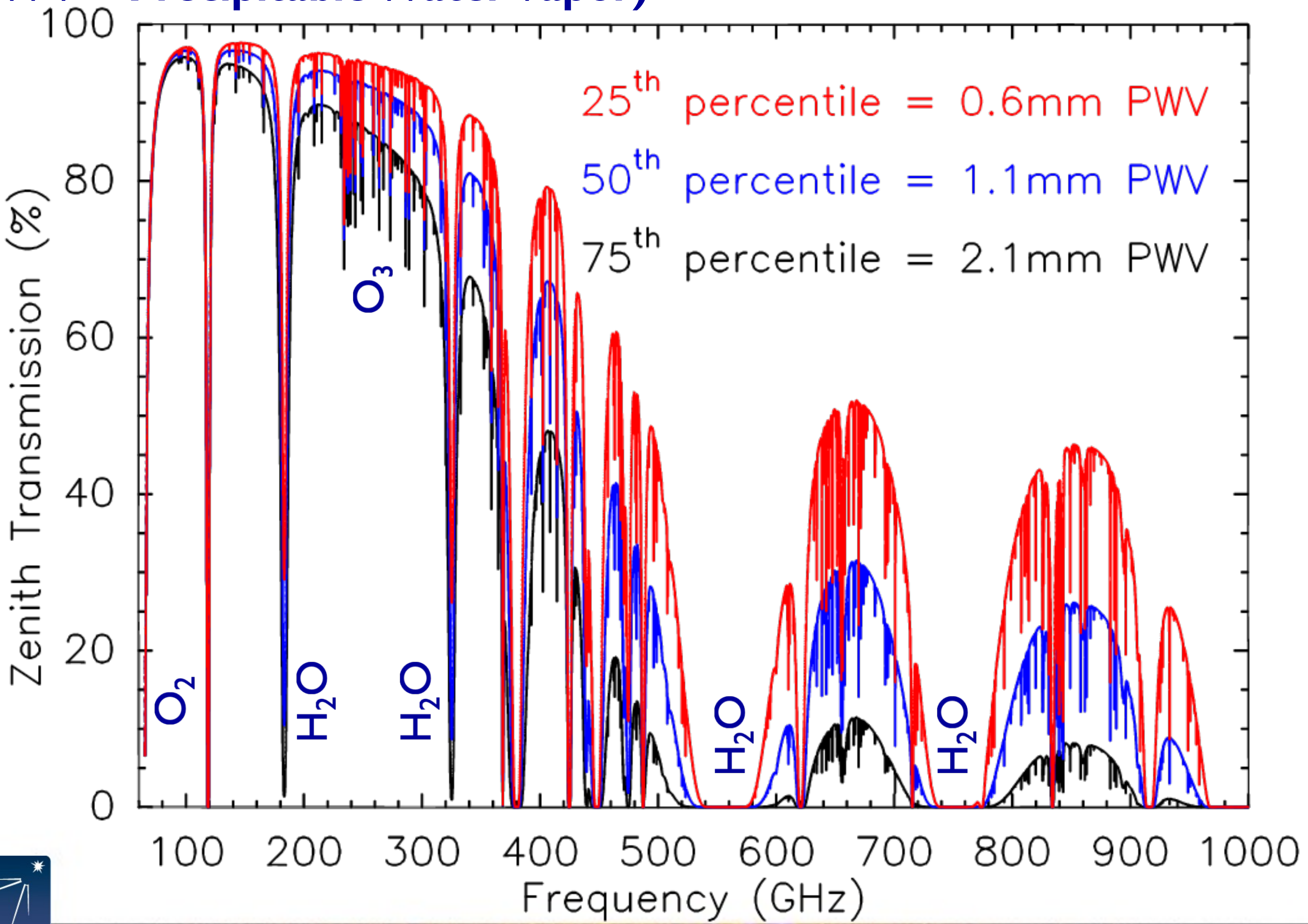
⇒ Atmospheric transmission not a problem for $\lambda > 1$ cm (30 GHz; i.e. most VLA bands), serious problem for ALMA Bands $\lambda < 1$ mm (300 GHz).

- Differences are due primarily to the elevation difference versus scale height of significant water vapor (<10 km), not the "dryness" of these sites.



Atmospheric Opacity at ALMA

(PWV = Precipitable Water Vapor)



Effect of Atmosphere on Phase

Mean Effect of Atmosphere on Phase

- Since the refractive index (n) of the atmosphere ≠1, an electromagnetic wave propagating through it will have a phase change (i.e. Snell's law)
- The phase change is related to the refractive index of the air, *n*, and the distance traveled, *D*, by

$$\varphi_e = \frac{2\pi}{\lambda} \; n \; D$$

$N = (n - 1)\times 10^6$ is typically separated into "dry" air and water vapor components

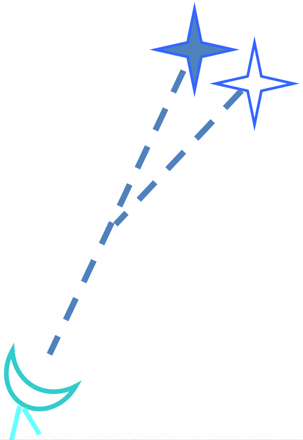
$N_d = 2.2\text{x}10^5\,\rho_{tot}$ ρ_{tot} ~ 1000-700 g m^{-3}

$N_{wv} = 1.7\text{x}10^9\,\frac{\rho_{wv}}{T_{\ atm}}$ ρ_{wv} ~ 0.01-0.001 x ρ_{tot} and T_{atm} ~270 K

Dry air dominates the total refraction correction by ~order of magnitude but the water component is much more time-variable.

$$\varphi_e \approx 6.3\;\frac{2\pi}{\lambda}\;W$$

at T_{atm} ~270 K, where *W* is the precipitable water vapor (PWV) column



Refraction causes:

- Pointing off-sets, $\Delta\theta \approx 2.5\text{x}10^{-4}$ x $\tan(z)$ (radians)
  @ zenith angle z=45° typical offset is ~1 arcmin
- Delay (time of arrival) offsets

⇨ These "mean" effects are generally removed by the online system

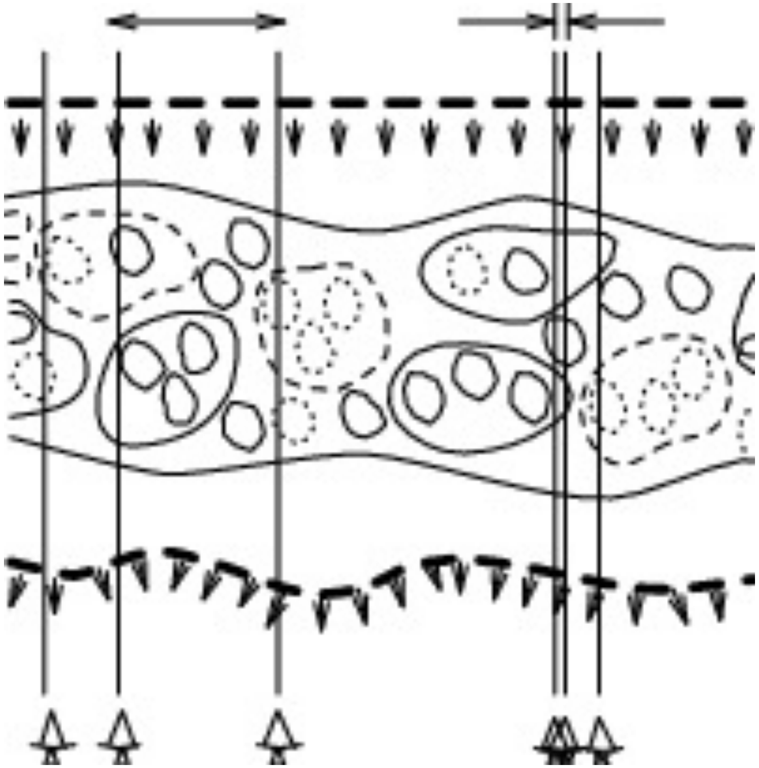
For more info see Thompson, Moran, & Swenson (2017, on-line version)

Atmospheric phase fluctuations

- Spatial and temporal variations in the amount of precipitable water vapor (PWV) cause phase fluctuations, which are worse at shorter wavelengths (higher frequencies), and result in:
  - Loss of coherence (loss of Signal)
  - Radio "seeing", typically 0.1-1″ at 1 mm
  - Anomalous pointing offsets
  - Anomalous delay offsets

You can observe in apparently excellent submm weather (in terms of transparency, i.e. low PWV) and still have terrible "seeing" i.e. phase stability.

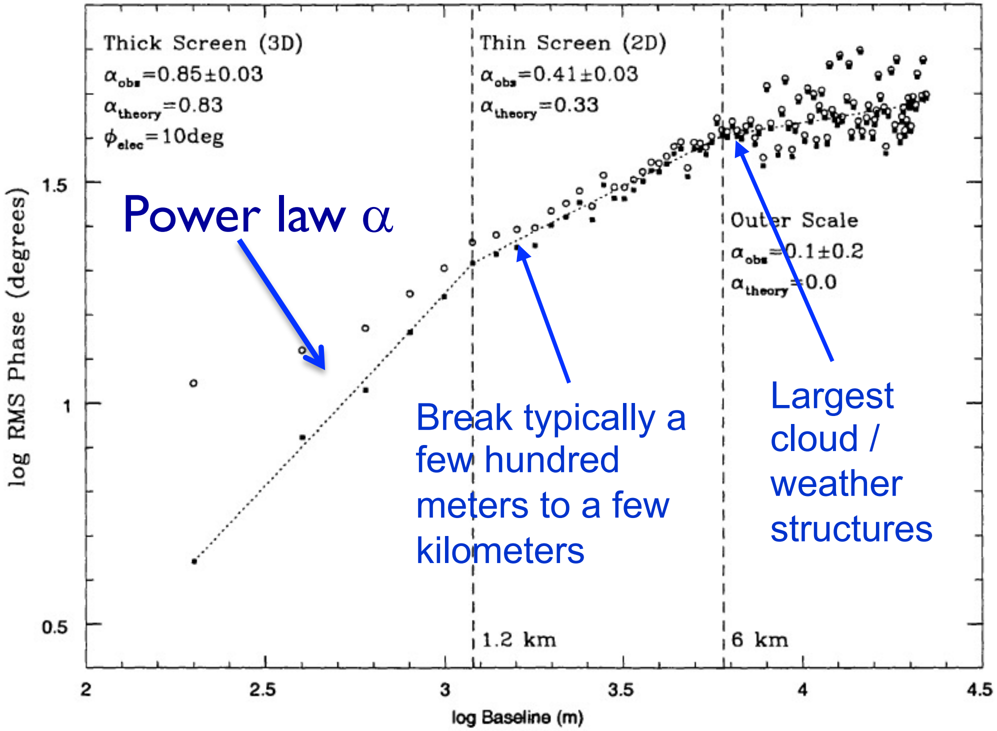
Due to turbulence in a water vapor layer about 1 km thick, with sizescales ranging from tiny to the size of clouds and even weather systems



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

Atmospheric phase fluctuations, continued…

VLA phase variations as function of baseline length at 13 mm



Power law α

Break typically a few hundred meters to a few kilometers

Largest cloud / weather structures

- “Root phase structure function” (Carilli, Carlstrom, Holdaway 1999)
- RMS phase fluctuations grow as a function of increasing baseline length until break when baseline length ≈ thickness of turbulent layer
- The position of the break and the maximum phase variation are weather, wavelength, and site dependent

RMS phase of fluctuations given by Kolmogorov turbulence theory

ϕ_{rms} = $K\, b^{\alpha} / \lambda$ [deg]

b = baseline length (km)

α = 1/3 to 5/6 (thick 3D atmosphere to thin 2D atmosphere)

λ= wavelength (mm)

K = constant (~100 for ALMA, 300 for VLA)

For ALMA Matsushita et al. (2016) found:

For b< 1 km α =0.6-0.65

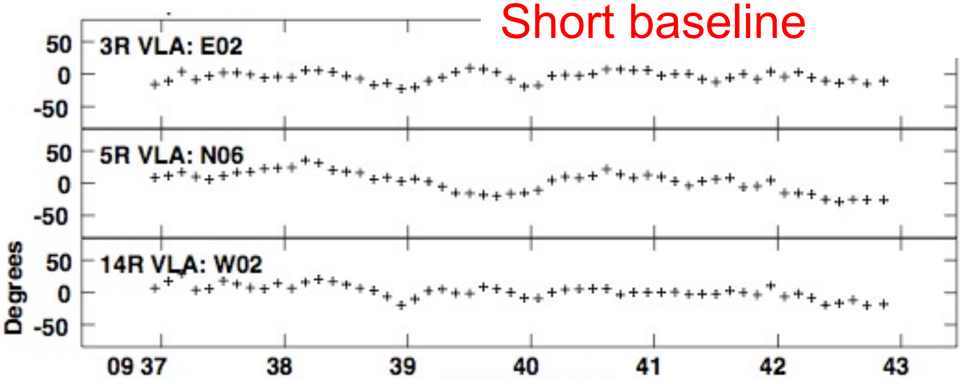
For b> 1 km α = 0.17-0.31

Residual Phase and Decorrelation

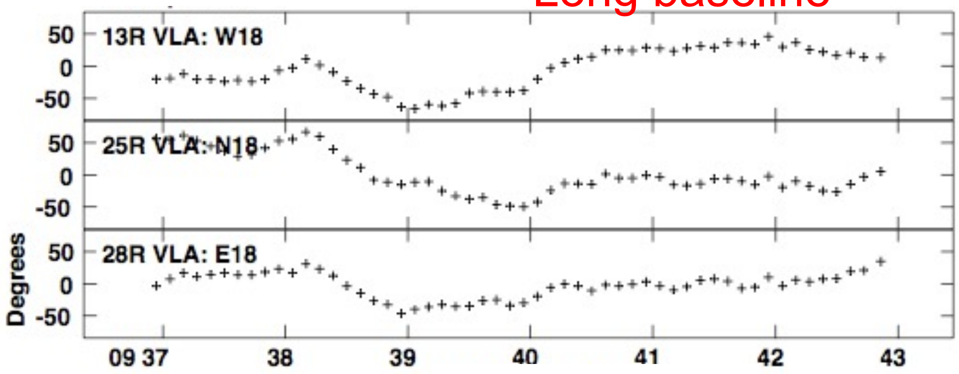
Q-band (7mm) VLA C-config. data from “good” day

An average phase has been removed from absolute flux calibrator 3C286

Short baseline



Long baseline



(minutes)

⇨ Residual phase on long baselines have larger excursions, than short baselines

Coherence = (vector average/true visibility amplitude) = $\langle V \rangle / V_0$

Where, $V = V_0 e^{i\phi}$

The effect of phase noise, $\phi_{\mathbf{rms}}$, on the measured visibility amplitude :

$$\langle V \rangle = V_0 \ \langle e^{i\phi} \rangle = V_0 \ e^{-\phi^2_{\text{rms}}/2}$$

(Gaussian phase fluctuations)

Example: if $\phi_{\mathbf{rms}}$ = 1 radian (~60 deg), coherence = $\underline{\langle V \rangle}$ = $0.60V_0$

=> Decoherence does not manifest in rms noise

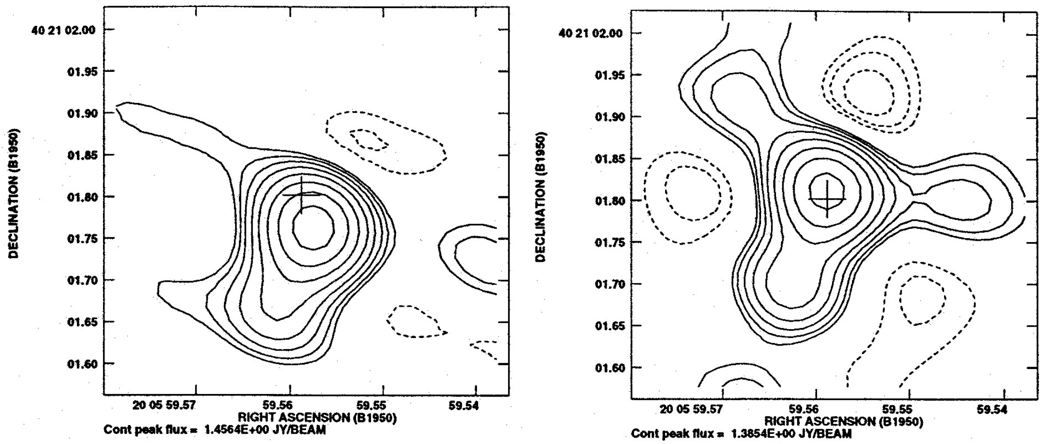
For these data, the residual rms phase (5-20 degrees) from applying an average phase solution produces a 7% error in the flux scale

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

resolution of 0.1” (Max baseline 30 km)

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

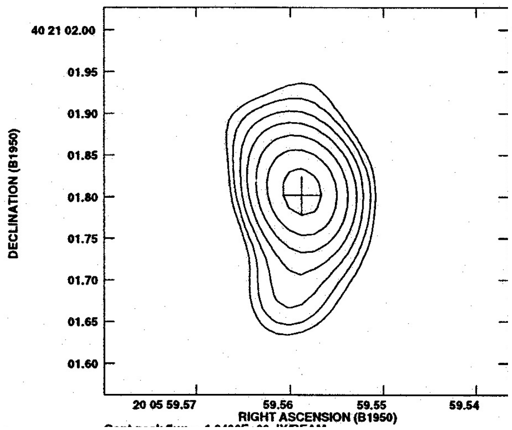
Position offsets due to large scale structures that are correlated ⇨ phase gradient across array



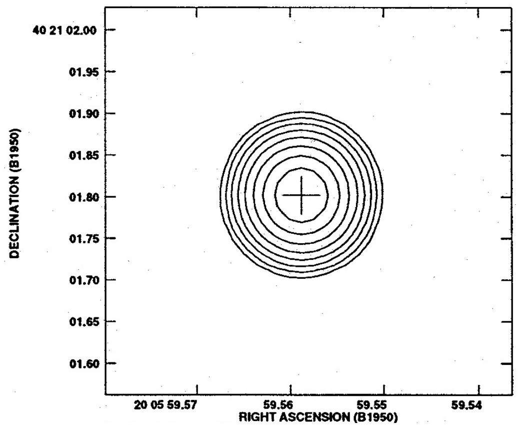
Sidelobe pattern shows signature of antenna based phase errors ⇨ small scale variations that are uncorrelated

All Data: Corrections 30min:

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



Corrections 30sec:



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

⇨ Uncorrelated phase variations degrades and decorrelates image

⇨ Correlated phase variations = position shift

Phase Correction Techniques

Phase fluctuation correction methods (often used in combination)

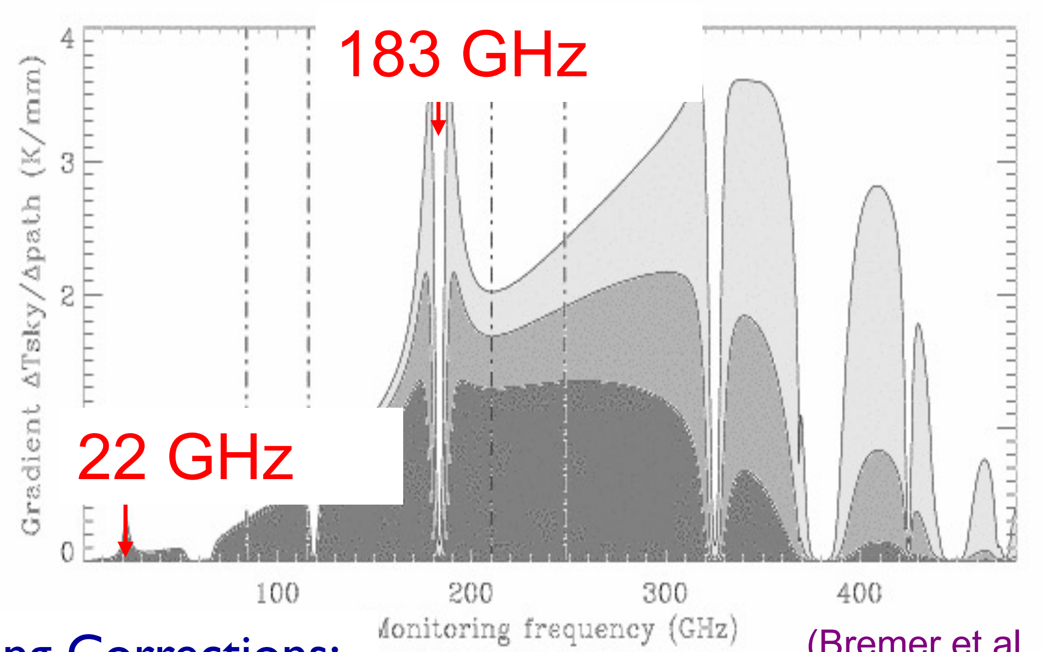
- Radiometer (Observing Strategy): Monitor PWV changes with special dedicated receivers. Requires modeling the atmosphere. Used by ALMA.
- Fast switching (Observing strategy): used at the VLA and ALMA for higher frequencies and longer baselines. Choose fast switching cycle time, t_{cyc}, short enough to reduce Φ_{rms} to an acceptable level. Calibrate in the normal way.
- Phase transfer (Band-2-Band; Observing Strategy): transfer scaled phase solutions from low to high frequency. Requires well characterized system due to differing electronics at the frequencies of interest. Will be employed for select projects in ALMA Cycle 9.
- Self-calibration (Assess after the fact): Requires adequate antenna-based S/N and a decent starting image/model.
- Paired array calibration (Observing Strategy): divide array into two separate arrays, one for observing the source, and another for observing a nearby calibrator.
  - Will not remove fluctuations caused by electronics
  - Can only work for arrays with large numbers of antennas (was used by CARMA)

Radiometers (an observing strategy):

- Radiometry: 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

$$\varphi_e \approx 6.3 \frac{2\,\pi}{\lambda} \Delta W$$

W=precipitable water vapor (PWV) column



183 GHz

22 GHz

(Bremer et al. 1997)

Facilities Applying Corrections:

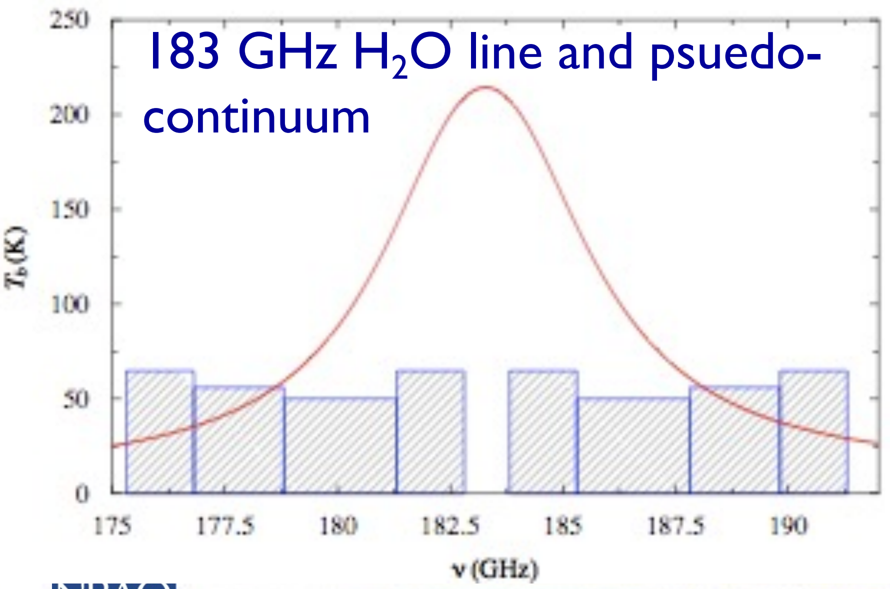
183 GHz H_2O line (ALMA)

22 GHz H_2O line (NOEMA)

ngVLA under consideration

ALMA's particular need for WVR correction:

- Observations at 300 microns (Band 10) require a path error less than 25 microns to keep the phase fluctuations < 30 degrees
- 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 5) 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


183 GHz H_2O line and psuedo-continuum

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

Modeling the Path Change

Challenge: Convert changes in 183 GHz brightness to changes in path length

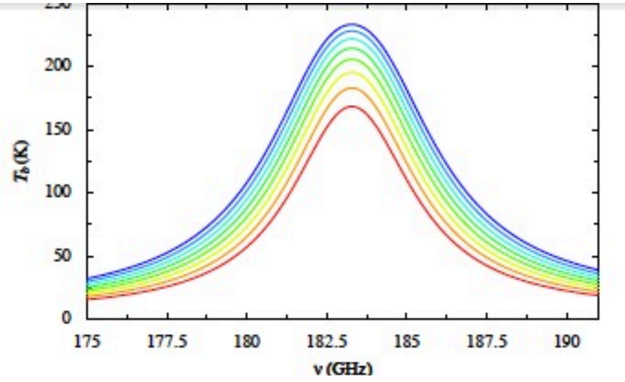
Implementation offline: wvrgcal

- 3 unknowns: PWV, temperature, pressure (in water vapor layer) in a simple plane parallel, thin layer model
- 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:

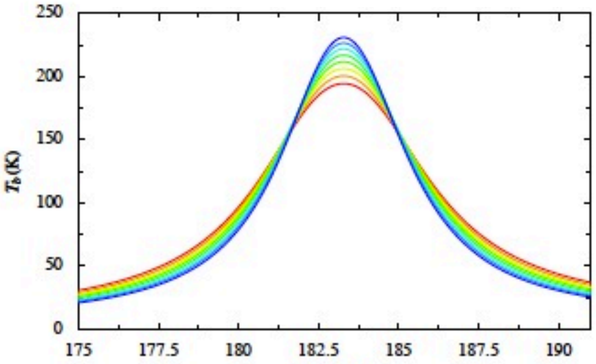
  $$\Delta(\text{path}) = \Delta(\text{PWV}) * 1741/T(\text{H2O layer})$$

- The path change is converted to phase for the mean frequency of each "science" spectral window

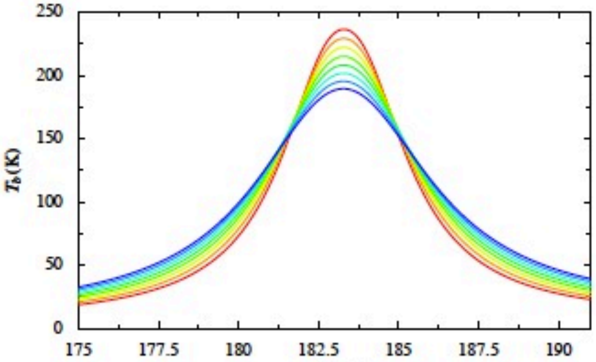
For a more complete description ALMA Memo 587



PWV from 0.6 to 1.3mm



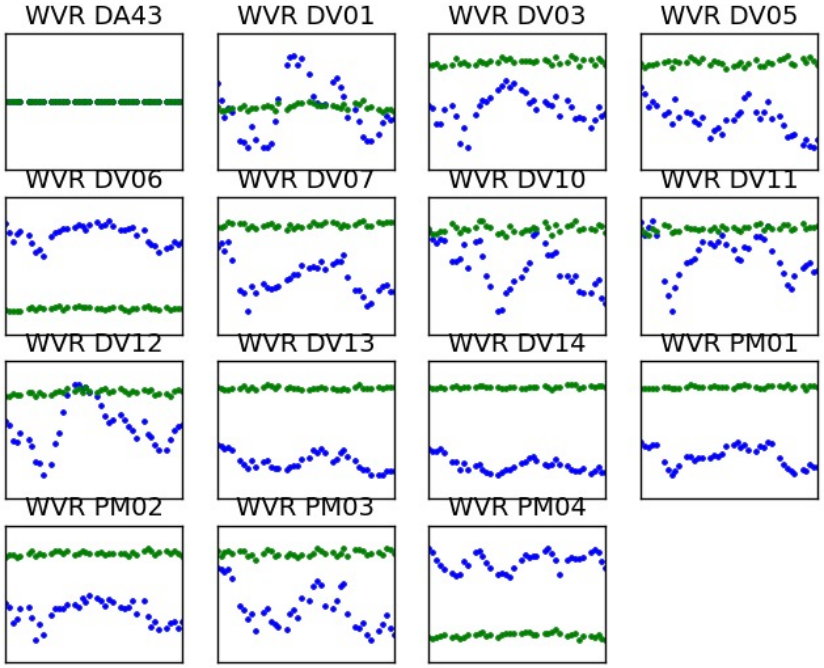
Temperature from 230 to 300 K



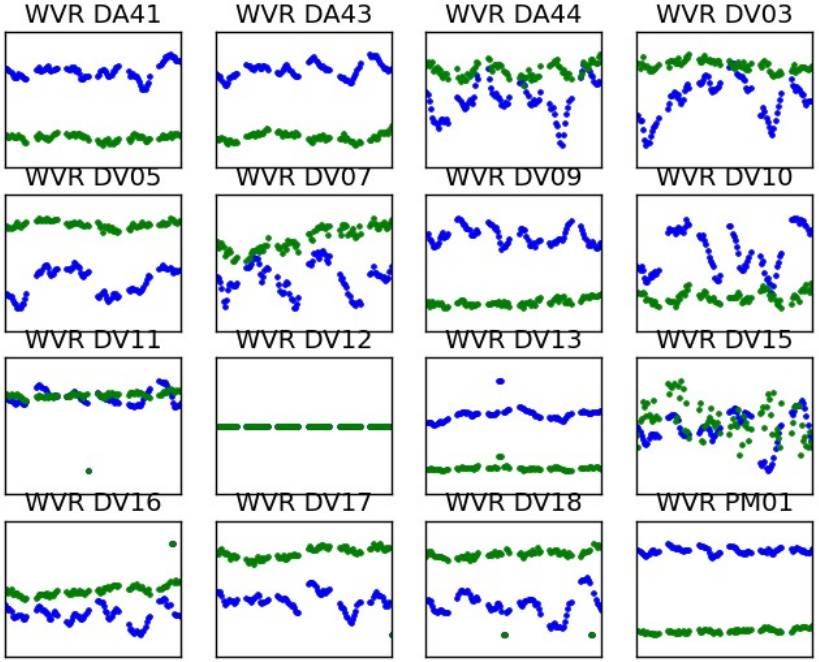
Pressure from 400 to 750 mBar

ALMA WVR Phase Correction - Examples

Band 6 (230 GHz) Compact config



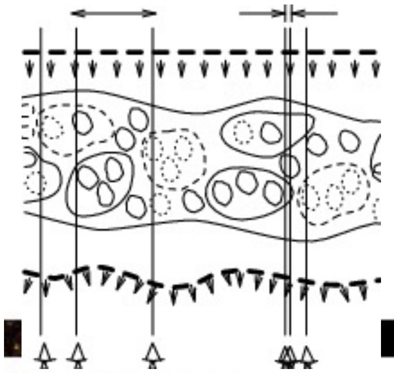
Band 7 (340 GHz) Extended config



Raw phase & **WVR corrected phase**

(from gaincal solutions)

- Works well to remove “bulk” or common mode variations in typical conditions
- Due to necessary simplicity of atmospheric model not all fluctuations removed, fast switching at long baselines & self-calibration still typically needed for high dynamic range observations
  - Cannot fix directional calibration issues (phase referencing, antenna position errors
  - Little improvement in very dry conditions, or when there are noticeable clouds



Fast Switching (an observing strategy)

Fast switching can remove tropospheric phase variations with size scales larger than an effective baseline length:

$$b_{eff} \sim d + \frac{V_a t_{cyc}}{2} \text{ (m)}$$

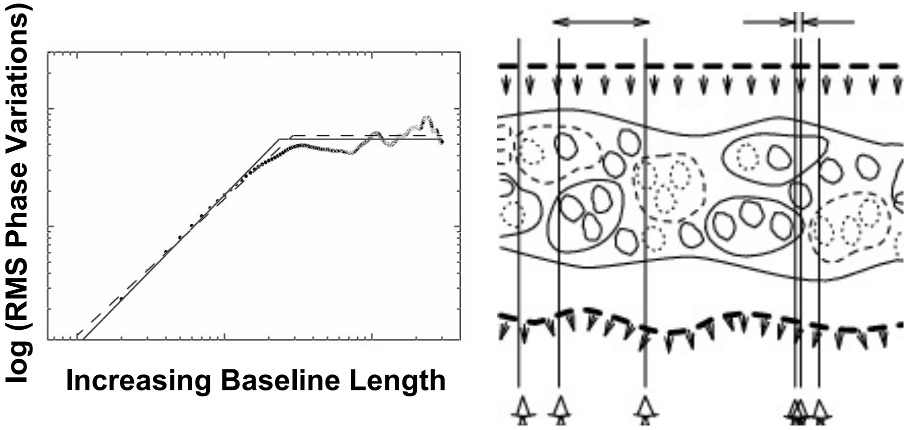
b_{eff}: effective baseline length in m
V_a: velocity of the winds aloft in m/s (~10 m/s)
t_{cyc}: phasecal / target cycle time in seconds (~20 to 200 sec)
d: geometric distance between calibrator and target at altitude of turbulent layer (a term often ignored, but see next slide)

To track largest phase variations, need cycle time < the baseline distance at which the phase structure function goes from steeply increasing to nearly flat (typically ~ 1 km), sometimes called the "corner time".

$$t_{cycle} < 200 \left(\frac{\phi_{rms}(deg)\lambda(mm)}{K}\right)^{1/\alpha} (s)$$

K = constant (~100 for ALMA, ~300 for VLA)

Note that a 90 degree phase rms can easily wipe out a source.



VLA Phase monitor: https://webtest.aoc.nrao.edu/cgi-bin/thunter/apipg.cgi
Also see: Carilli & Holdaway (1999), TMS (2017), Maud et al. (2022)

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$$b_{eff} \sim d + \frac{V_a t_{cyc}}{2} \ (\mathrm{m})$$

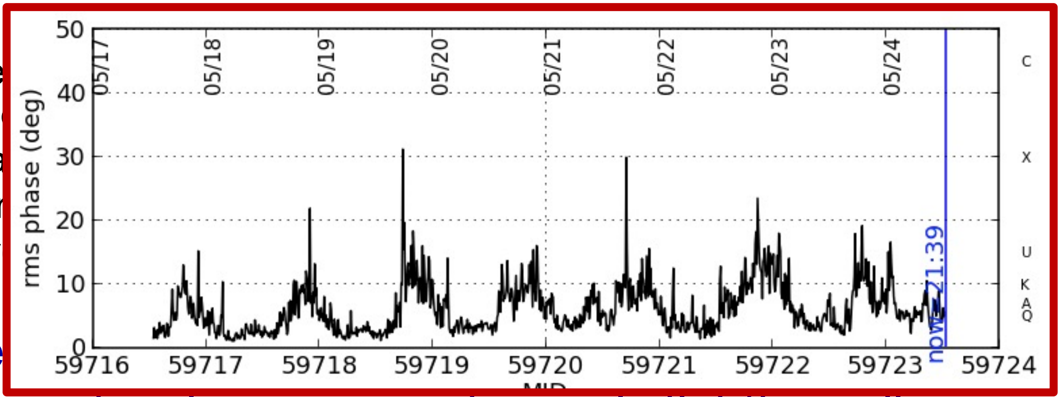
b_{eff}: effective

V_a: velocity

t_{cyc}: phaseca

d: geometr

turbulent lay



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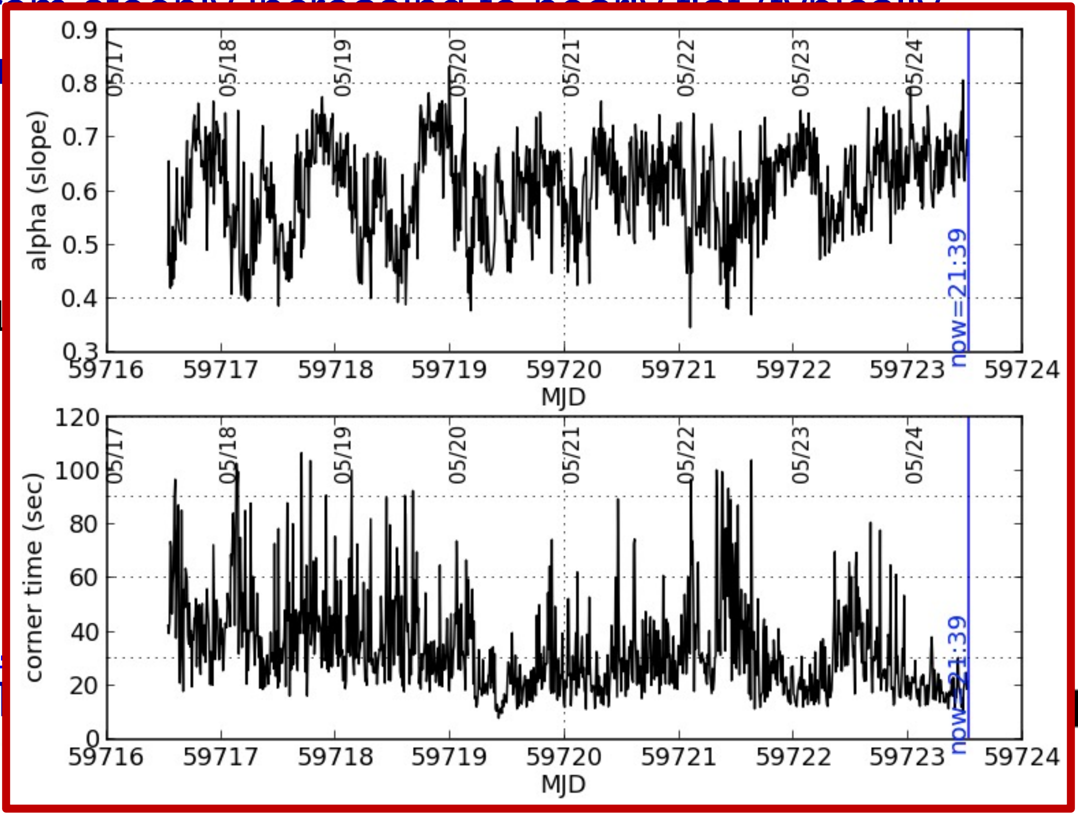

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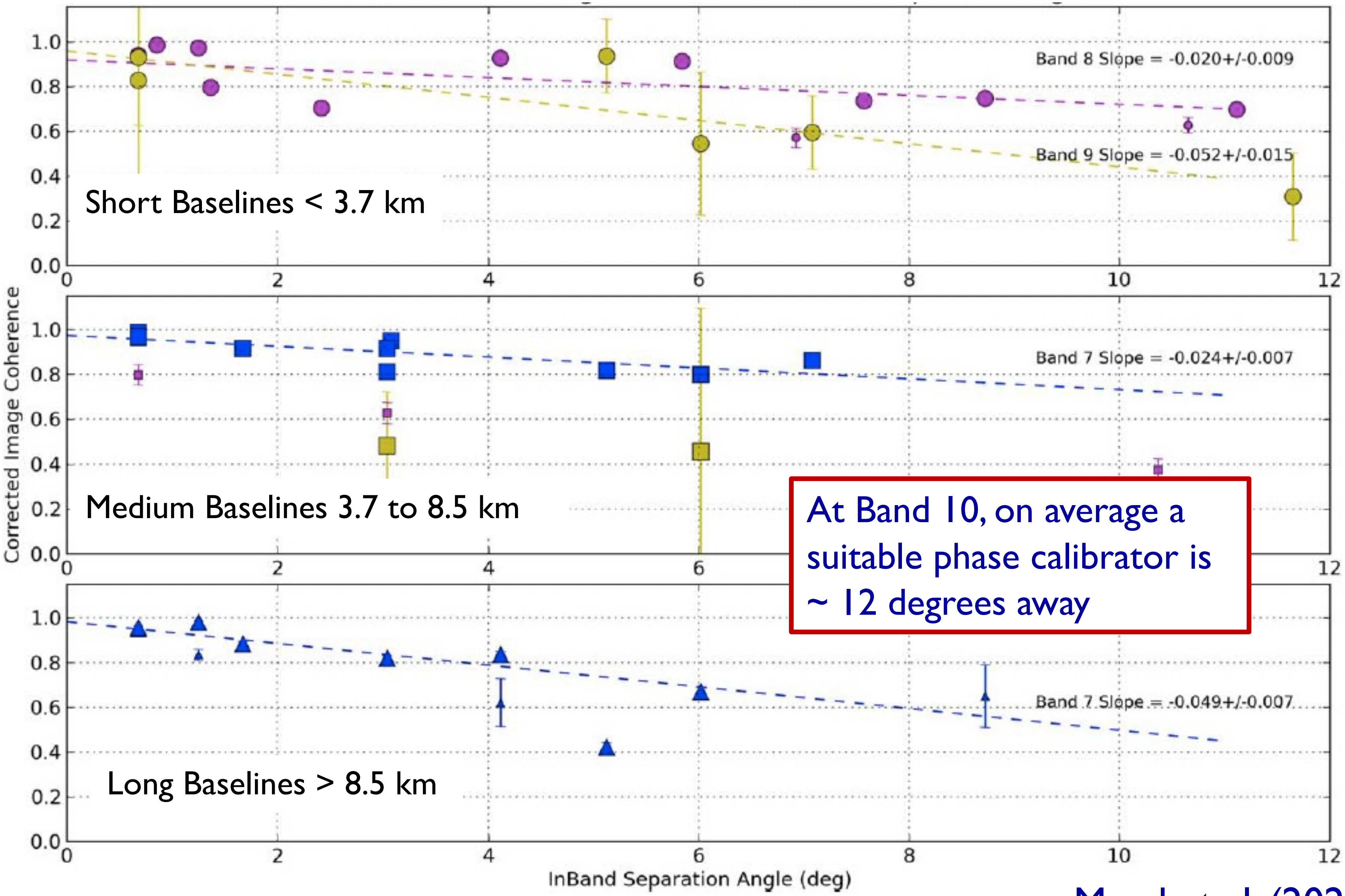
VLA Phase monitor: https://webtest.

Also see: Carilli & Holdaway (1999), T

Decorrelation due to Phase Calibrator Separation

(even with 24s Fast Switching on ALMA)

Colors = Band 7 Band 8 Band 9



At Band 10, on average a suitable phase calibrator is ~ 12 degrees away

Maud et al. (2020)

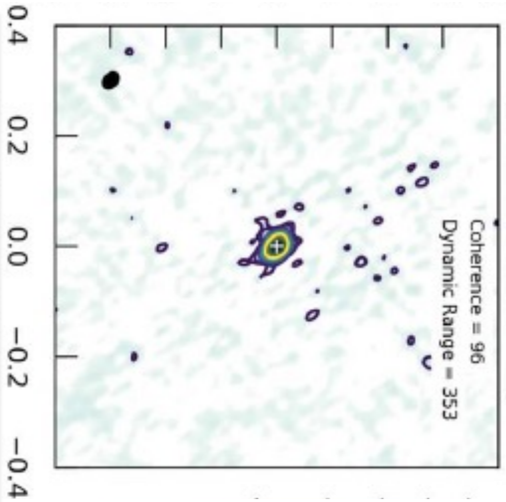
High frequency & no suitable nearby calibrator = Band to Band (B2B)

Recall $\varphi_e \approx 6.3 \; \frac{2\pi}{\lambda} \; W$ for T_{atm} = 270 K, W=precipitable water vapor (PWV)

- In principle, a simple linear relationship between the phase at one frequency versus another => <u>observe phase calibrator at lower frequency where one can usually be found that is both brighter and closer to science target</u>
  - Instrumental effects on phase must be stable with time, measured and removed => high S/N observation of differential gain and bandpass calibrators (must be bright at both frequencies)
    - ➢ Still requires high frequency weather conditions
  - Level of dispersive atmospheric effects (wavelength dependent) & non-water vapor atmospheric components can limit accuracy

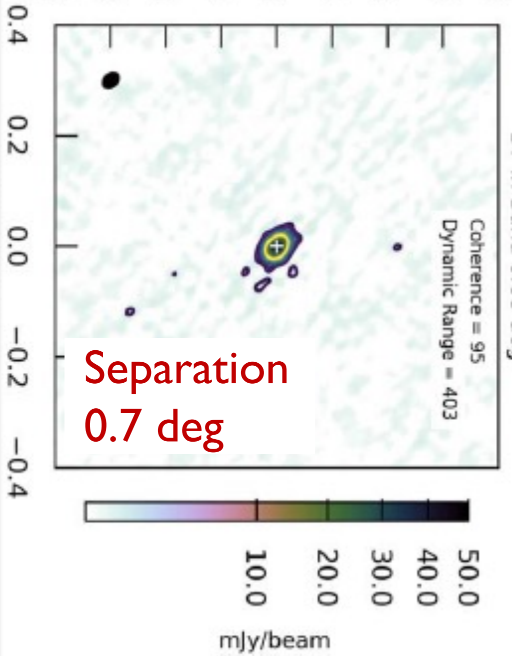
➢ Will be employed for science data in Cycle 9 for select longer baseline, higher frequency projects with no suitable in-band calibrator

High frequency & no suitable nearby calibrator = Band to Band (B2B)



Band 3 to 7 B2B calibration

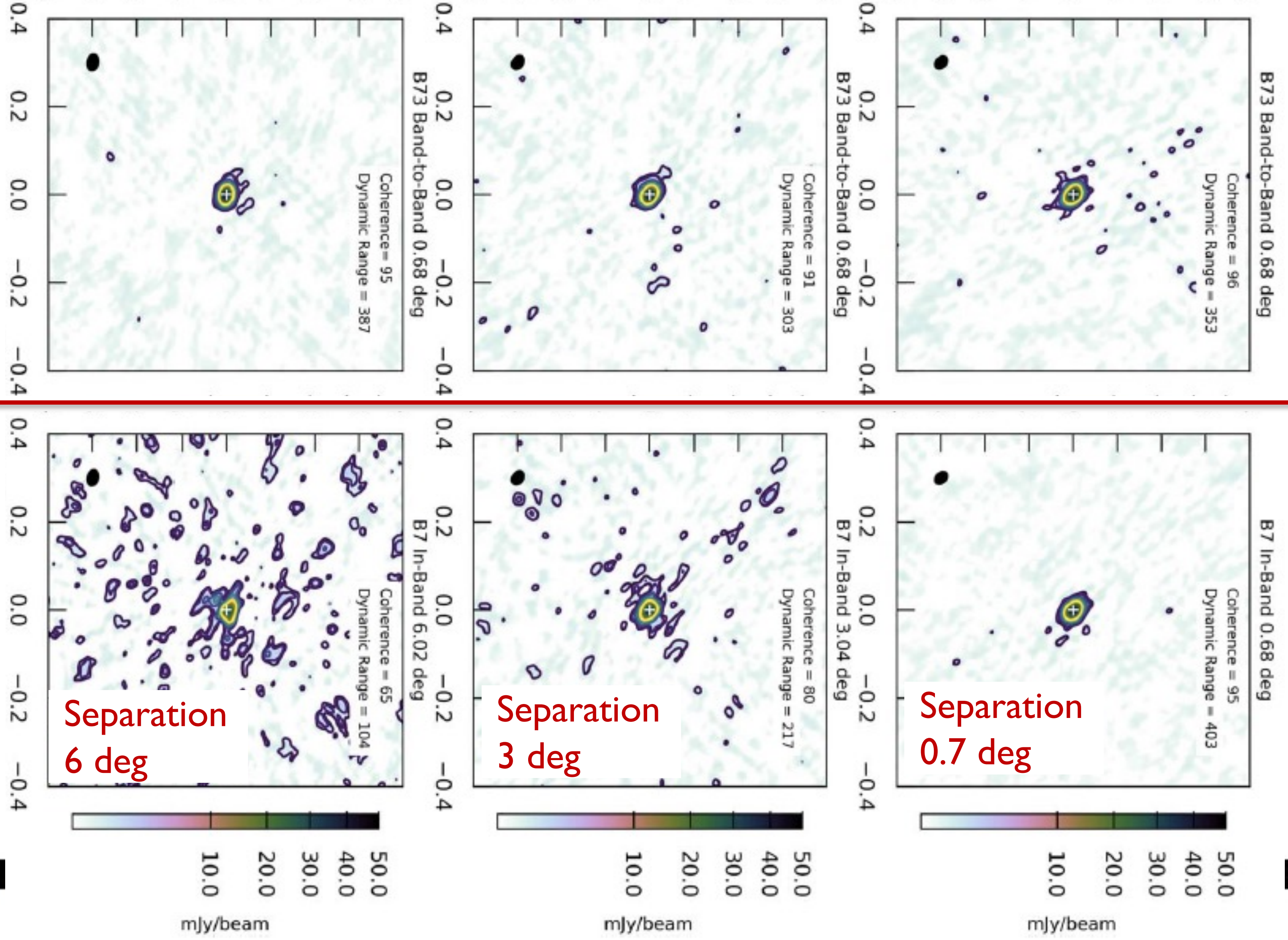
Separation 0.7 deg



Separation 0.7 deg

Band 7 in-band calibration

High frequency & no suitable nearby calibrator = Band to Band (B2B)



Separation 6 deg

Separation 3 deg

Separation 0.7 deg

Band 3 to 7 B2B calibration

Separation 0.7 deg

Band 7 in-band calibration

Self-Calibration: Motivation

VLA and ALMA have impressive sensitivity! But what you achieve is often limited by residual calibration errors

Many objects will have enough Signal-to-Noise (S/N) so they can be used to better calibrate ***themselves*** to obtain a more accurate image. This is called self-calibration and it really works, if you are careful! Sometimes, the increase in effective sensitivity may be an order of magnitude.

It is not a circular trick to produce the image that you want. It works because the number of baselines is much larger than the number of antennas so that an approximate source image does not stop you from determining a better antenna-based temporal gain calibration which leads to a better source image.

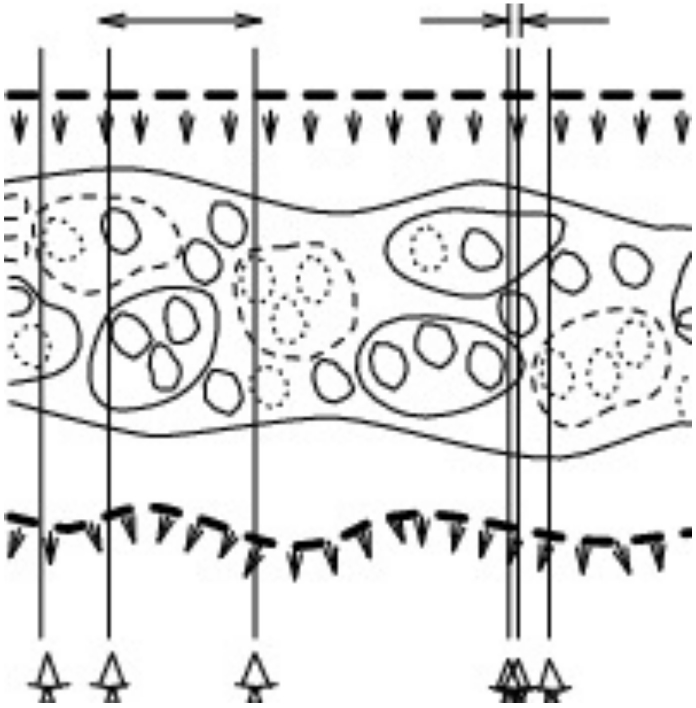
Data Corruption Types

The true visibility is corrupted by many effects:

- Atmospheric attenuation
- Radio "seeing"
- Variable pointing offsets
- Variable delay offsets
- Electronic gain changes
- Electronic delay changes
- Electronic phase changes
- Radiometer noise
- Correlator mal-functions
- Most Interference signals

Antenna-based

baseline



Antenna-based Calibration- I

- The most important corruptions are associated with antennas
- Basic Calibration Equation

$$\widetilde{V}_{ij}(t) = g_i(t)g_j^*(t)G_{ij}(t)V_{ij}(t) + \varepsilon_{ij}(t) + \epsilon_{ij}(t)$$

$g_i(t)g_j^*(t)$	Factorable (antenna-based) complex gains
$G_{ij}(t)$	Non-factorable complex gains (not Antenna based and typically small)
$V_{ij}(t)$ -	True Visibility
$\varepsilon_{ij}(t)$	Additive offset (not antenna based and typically small)
$\epsilon_{ij}(t)$	Thermal noise

- Can be reduced to (approximately)

$$\widetilde{V}_{ij}(t) = g_i(t)g_j^*(t)V_{ij}(t) + \epsilon_{ij}(t)$$

Antenna-based Calibration-II

- For N antennas, [(N-1)*N]/2 visibilities are measured, but only N amplitude and (N-1) phase gains fully describe the complete Antenna-based calibration. This redundancy is used for antenna gain calibration
- Basic gain (phase and amplitude) calibration involves observing unresolved (point like) "calibrators" of known position with visibility $M_{i,j}$ ($t_{k,}$ ν)
- Determine complex gain corrections, g, that minimizes S_k for each time stamp t_k where

$$S_k = \sum_k \sum_{i,j}^{i \neq j} w_{i,j} \; |g_i(t_k) g_j^*(t_k) V^o_{i,j}(t_k) - M_{i,j}(t_k)|^2$$

Data Weights

Complex Gains

Complex Visibilities

Fourier transform of model image

The solution interval, $\mathbf{t}_k$, is the data averaging time used to obtain the values of g, (i.e. solint='int' or 'inf'). The apriori weight of each data point is $w_{i,j}$.

- This IS a form of Self-calibration, only we assume a Model (Mij) that has constant amplitude and zero phase, i.e. a point source
- The transfer of these solutions to another position on the sky at a different time (i.e. your science target) will be imperfect, but the same redundancy can be used with a **model image of the science target** for Self-calibration

Sensitivities for Self-Calibration-I

- **For phase only self-cal:** Need to detect the target in a solution time (**solint$_{\text{self}}$**) < the time for significant phase variations with only the baselines to **a single antenna** with a S/N$_{\text{self}}$ $\gtrsim$ 3. For 25 antennas, S/N$_{\text{Self}}$ > 3 will lead to < 15 deg error.

- Make an initial image, cleaning it conservatively
  - Measure rms in emission free region of image
  - rms$_{\text{Ant}}$ = rms x $\sqrt{N-3}$ where N is # of antennas
  - rms$_{\text{self}}$ = rms$_{\text{Ant}}$ x $\sqrt{Time\_on\_source/solintself}$
  - Measure Peak flux density = Signal
  - If S/N$_{\text{self}}$ = Peak/rms$_{\text{Self}}$ >3 try phase only self-cal

Rule of thumb:

For an array with ~25 antennas, if S/N in image >20 its worth trying phase-only self-cal

- CAVEAT 1: If dominated by extended emission, estimate what the flux will be on the longer baselines (by plotting the uv-data) instead of using the image
  - If the majority of the baselines in the array cannot "see" the majority of emission in the target field (i.e. emission is resolved out) at a S/N of about 3, the self-cal will fail in extreme cases (though bootstrapping from short to longer baselines is possible, it can be tricky).

- CAVEAT 2: If severely dynamic range limited (poor uv-coverage), it can also be helpful to estimate the rms noise from uv-plots

Sensitivities for Self-Calibration-II

- **For amplitude self-cal:** Need to detect the target with only the baselines to a single antenna with a $S/N_{self} \gtrsim 10$, in a solution time ($solint_{self}$) < the time for significant amplitude variations. For 25 antennas, an antenna based S/N > 10 will lead to a 10% amplitude error.
  - Amplitude corrections are more subject to deficiencies in the model image, check results carefully!
  - For example, if clean model is missing significant flux compared to uv-data, restrict uvrange for amplitude solution that excludes short baselines

Additional S/N for self-cal can be obtained by:

- Increase solint (solution interval)
  - Errors that are directional, rather than time dependent can yield surprising improvement even if the solint spans the whole observation = antenna position (aka baseline) errors are a good example
- gaintype= 'T' to average polarizations
  - Phase **differences** between polarizations are generally well calibrated
- Combine = 'spw' to average spw's (assumes prior removal of spw to spw offsets)
  - Caveat: If source spectral index/morphology changes significantly across the band, do not combine spws, especially for amplitude self-cal unless you use mtmfs
- Combine = 'fields' to average fields in a mosaic (use with caution, only fields with strong signal)

Self-calibration Example:

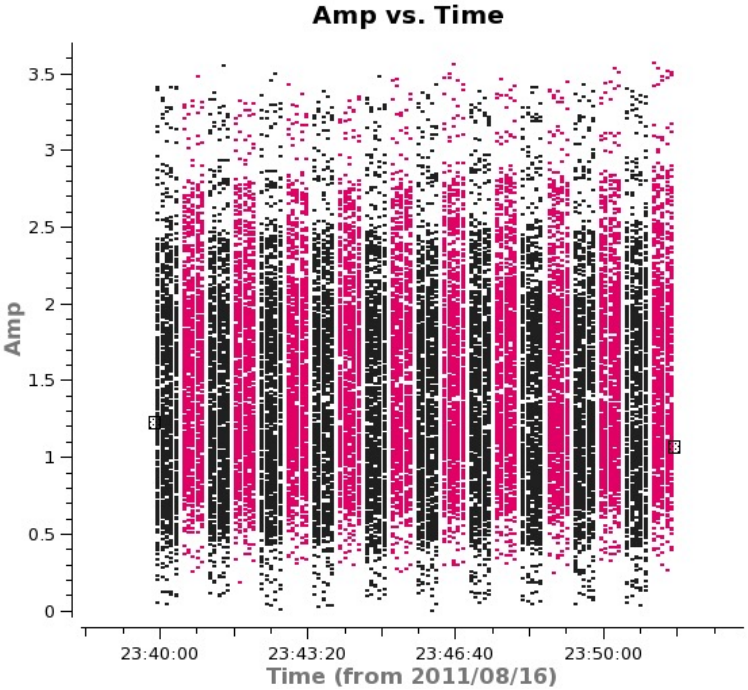
ALMA SV Data for IRAS16293 Band 6 (Ia)

Step 1 – Determine basic setup of data:

- 2 pointing mosaic
- Integration = 6.048 sec; subscans ~ 30sec
- Scan= 11min 30s (split between two fields)

Step 2 – What is the expected rms noise?

- Use actual final total time and # of antennas on science target(s) from this stage and sensitivity calculator.
- Be sure to include the actual average weather conditions for the observations in question and the bandwidth you plan to make the image from
- 54 min per field with 16 antennas and average Tsys ~ 80 K, 9.67 MHz BW; rms= 1 mJy/beam
- Inner part of mosaic will be about 1.6 x better due to overlap of mosaic pointings



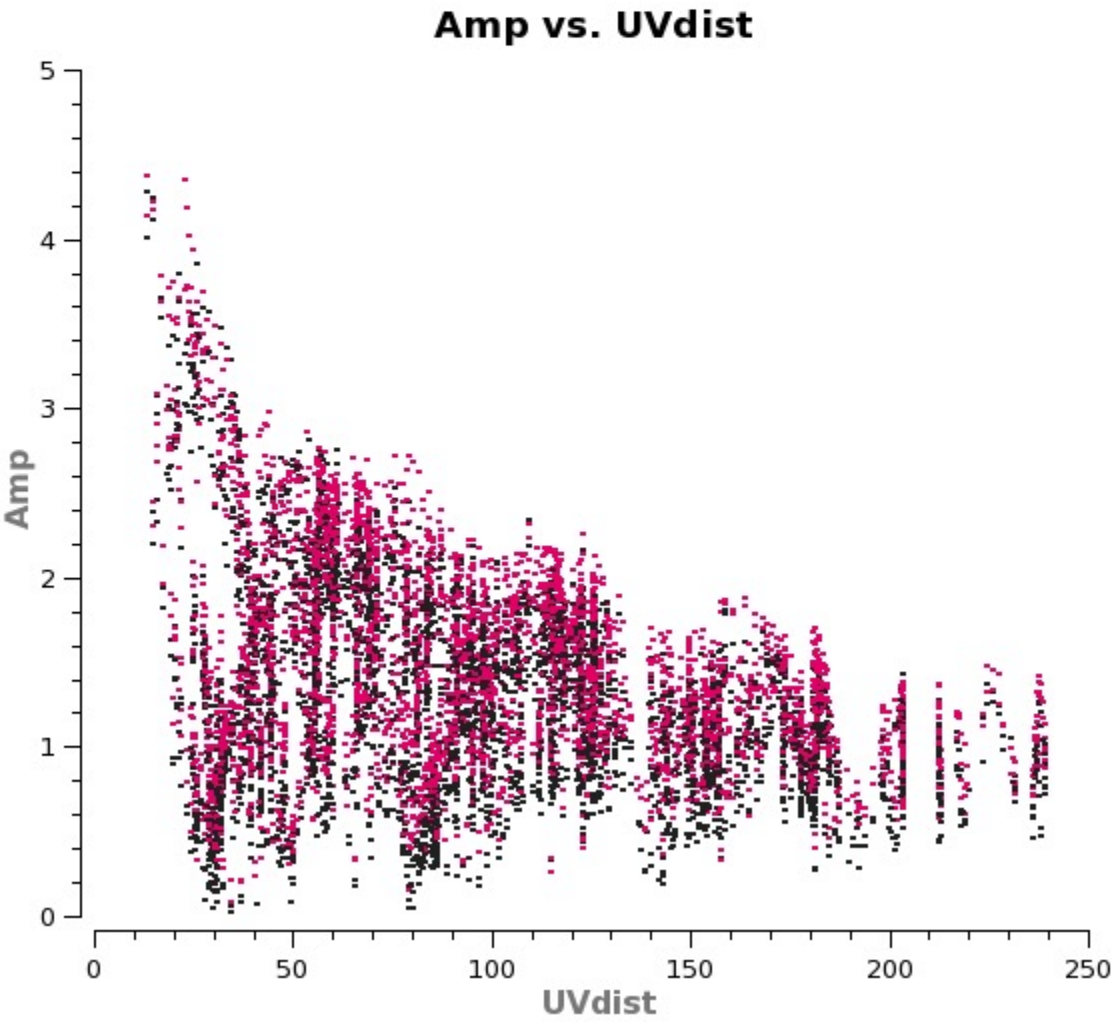
- ALMA mosaic: alternates fields in "subscan" this picture = 1 scan
- EVLA mosaic: alternates fields in scans
- Subscans are transparent to CASA (and AIPS)

Self-calibration Example:

ALMA SV Data for IRAS16293 Band 6 (Ib)

Step 3 – What does the amplitude vs uv-distance of your source look like?

- Does it have large scale structure? i.e. increasing flux on short baselines.
- What is the flux density on short baselines?
- Keep this 4 Jy peak in mind while cleaning. What is the total cleaned flux you are achieving?

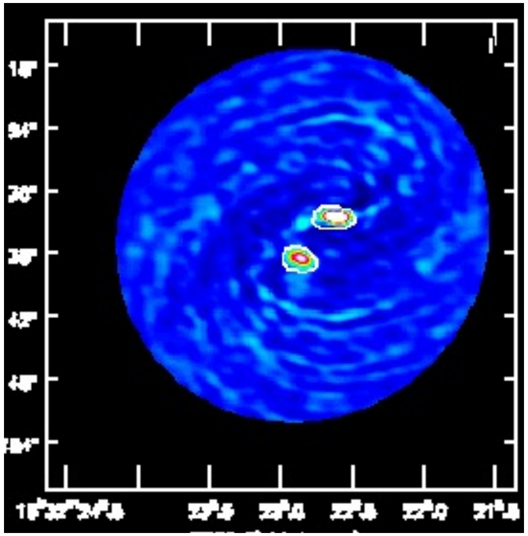


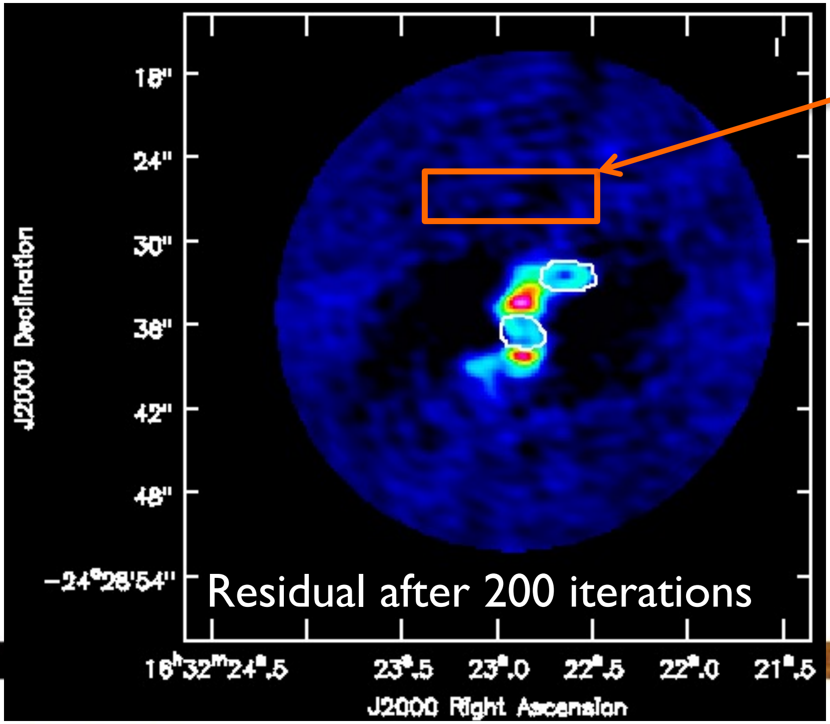
Self-calibration Example:

ALMA SV Data for IRAS16293 Band 6 (II)

Step 4 – What is the S/N in a conservatively cleaned image?

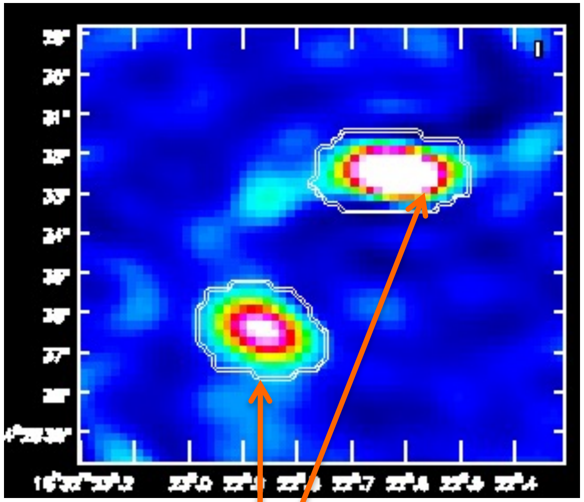
- What is this “conservative” of which you speak
- Rms~ 15 mJy/beam; Peak ~ 1 Jy/beam ➔ S/N ~ 67
- Rms > expected and S/N > 20 ➔ self-cal!





Residual after 200 iterations

Stop clean, and get rms and peak from image, avoiding negative bowls and emission



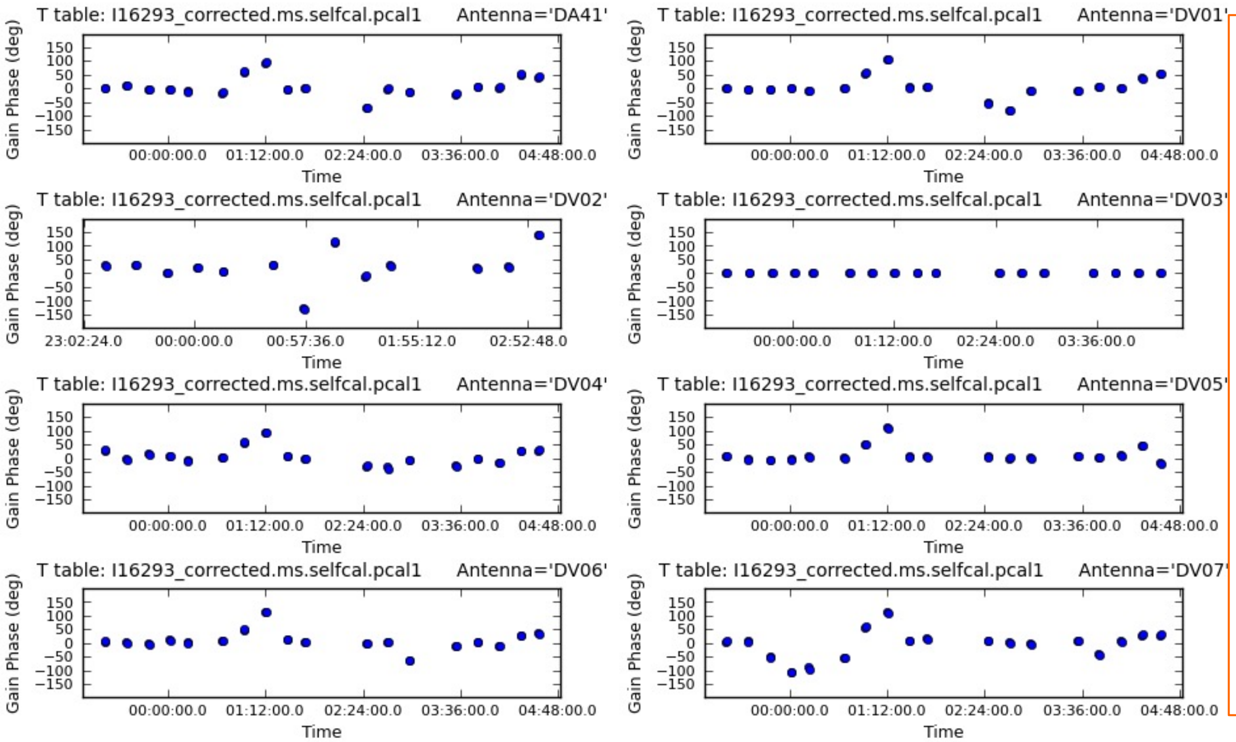
Clean boxes only around emission you are SURE are real at this stage

Self-calibration Example:

ALMA SV Data for IRAS16293 Band 6 (III)

Step 5: Decide on an time interval for initial phase-only self-cal

- A good choice is often the scan length (in this case about 5 minutes per field)
    - Exercise for reader: show that $S/N_{self} \sim 5.4$
- In CASA you can just set solint='inf' (i.e. infinity) and as long as combine ≠ 'scan' AND ≠ 'field' you will get one solution per scan, per field.
- Use 'T' solution to combine polarizations

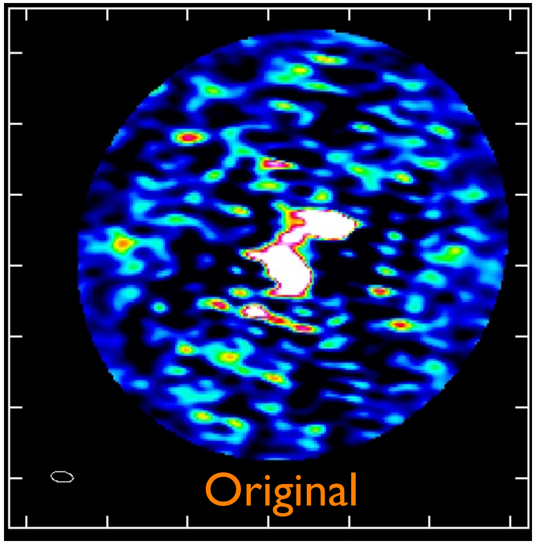


What to look for:

- Lot of failed solutions on most antennas? if so, go back and try to increase S/N of solution = more averaging of some kind
- Do the phases appear smoothly varying with time (as opposed to noise like)

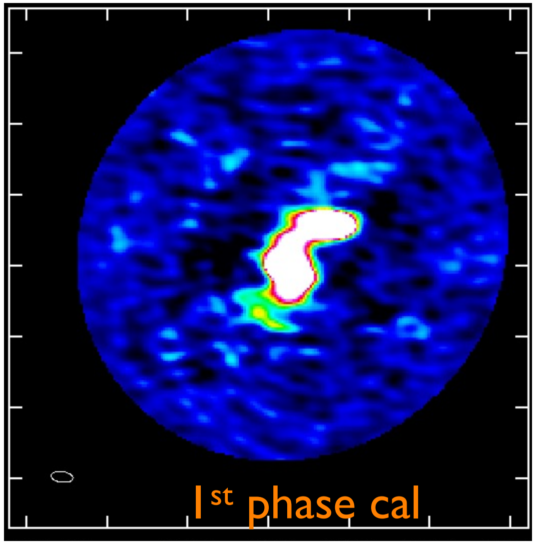
Self-calibration Example:

ALMA SV Data for IRAS16293 Band 6 (IV)



Step 6: Apply solutions and re-clean

- Incorporate more emission into clean box if it looks real
- Stop when residuals become noise-like but still be a bit conservative, ESPESCIALLY for weak features that you are very interested in
    - You **cannot** get rid of real emission by not boxing it
    - You can create features by boxing noise



Step 7: Compare Original clean image with 1st phase-only self-cal image

- Original:

  Rms~ 15 mJy/beam; Peak ~ 1 Jy/beam ➔ S/N ~ 67
- 1st phase-only:

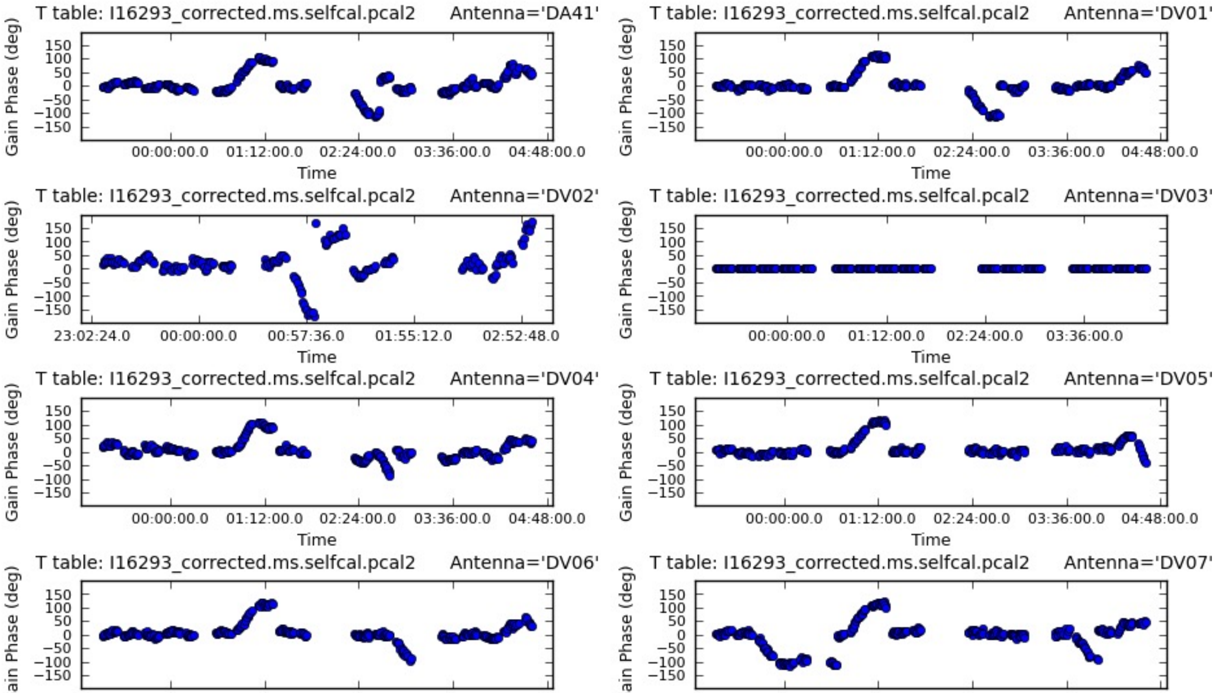
  Rms~ 6 mJy/beam; Peak ~ 1.25 Jy/beam ➔ S/N ~ 208
- Did it improve? If, yes, continue. If no, something has gone wrong or you need a shorter solint to make a difference, go back to Step 4 or stop.

Self-calibration Example:

ALMA SV Data for IRAS16293 Band 6 (V)

Step 8: Try shorter solint for 2nd phase-only self-cal

- In this case we'll try the subscan length of 30sec
- I did NOT apply the 1st self-cal while solving for the 2nd. i.e. incremental tables can be easier to interpret but you can also "build in" errors in first model by doing this if the data are especially noisy. Opinions on this do differ…



What to look for:

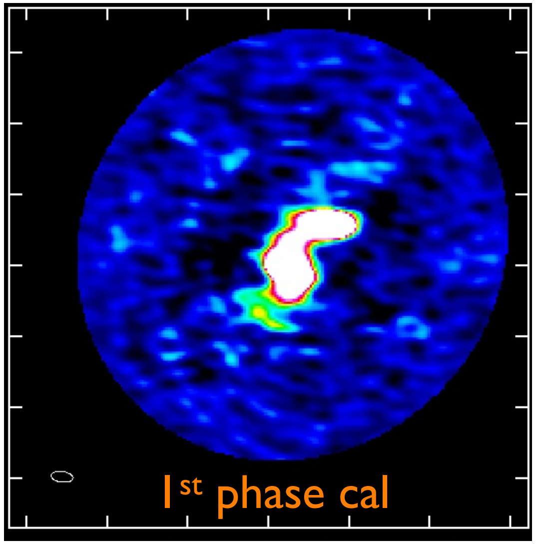
- Still smoothly varying?
- If this looks noisy, go back and try with longer solint solution
- IF this improves things a lot, could try going to even shorter solint

Self-calibration Example:

ALMA SV Data for IRAS16293 Band 6 (VI)

Step 9: Apply solutions and re-clean

- Incorporate more emission into clean box if it looks real
- Stop when residuals become noise-like but still be a bit conservative, ESPECIALLY for weak features that you are very interested in
  - You **cannot** get rid of real emission by not boxing it
  - You can create features by boxing noise

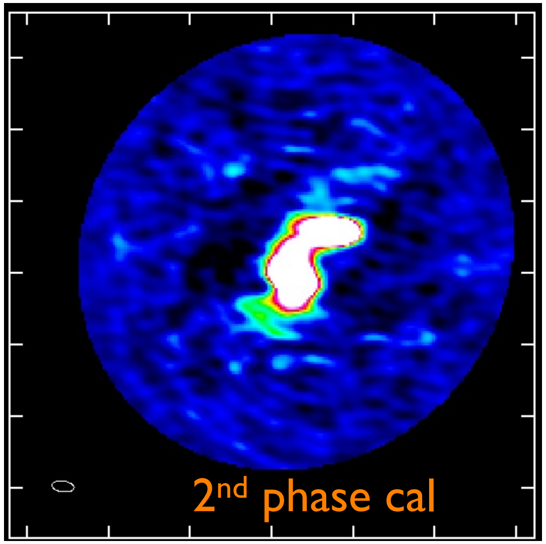


Step 10: Compare 1st and 2nd phase-only self-cal images

- 1st phase-only:

  Rms~ 6 mJy/beam; Peak ~ 1.25 Jy/beam → S/N ~ 208
- 2nd phase-only:

  Rms~ 5.6 mJy/beam; Peak ~ 1.30 Jy/beam → S/N ~ 228
- Did it improve? Not much, so going to shorter solint probably won't either, so we'll try an amplitude self-cal next

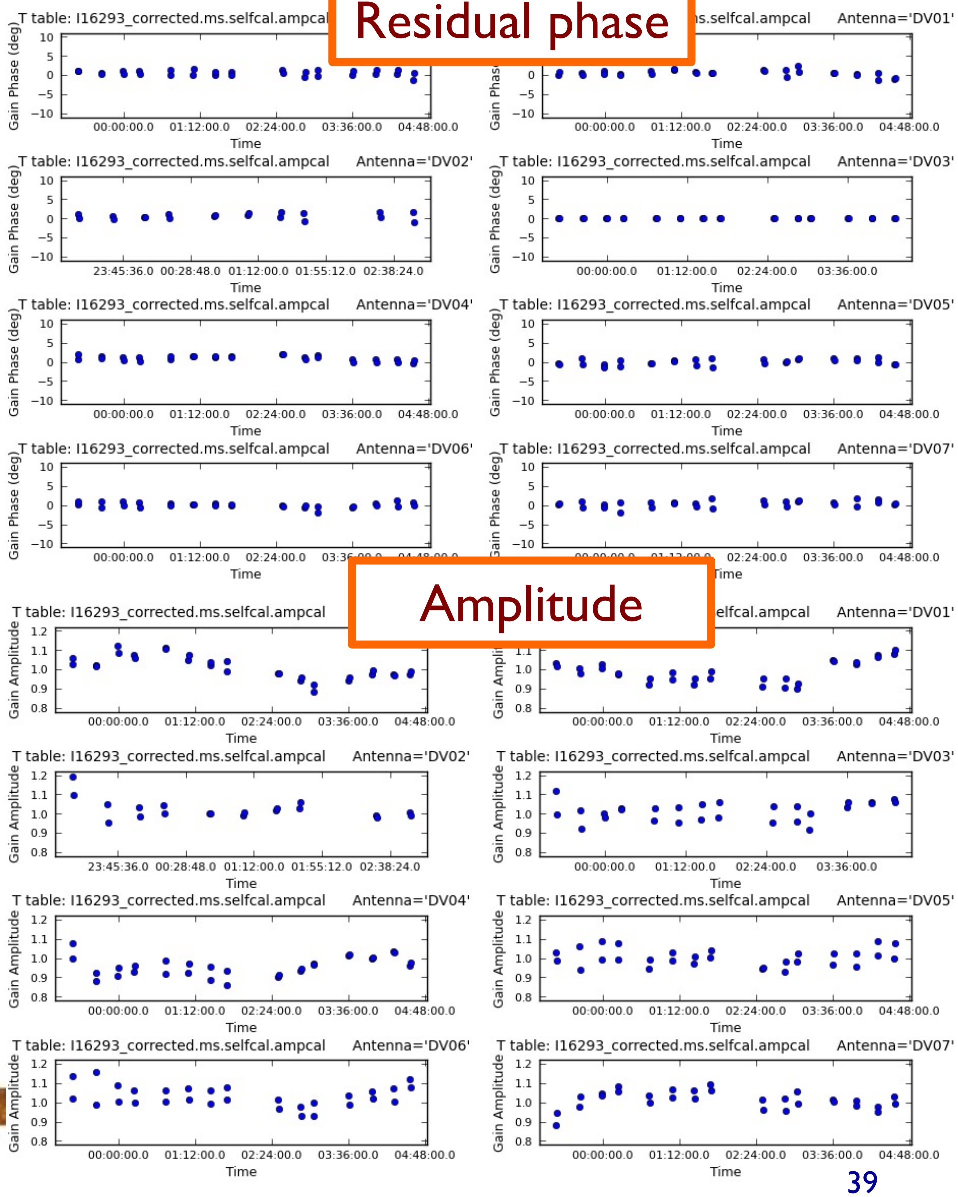


Self-calibration Example:

ALMA SV Data for IRAS16293 Band 6 (VII)

Step 11: Try amplitude self-cal

- Amplitude tends to vary more slowly than phase. It's also less constrained, so solints are typically longer. Lets try two scans worth or 23 minutes
- Essential to apply the best phase only self-cal when solving for amplitude. Also a good idea to use mode='ap' rather than just 'a' to check that residual phase solutions are close to zero.
- Again make sure mostly good solutions, and a smoothly varying pattern.



Residual phase

Amplitude

Scale +/- 10 degrees

Scale 0.8 to 1.0

Self-calibration Example:

ALMA SV Data for IRAS16293 Band 6 (VIII)

Step 12: Apply solutions

- Apply both 2nd phase and amp cal tables
- Inspect uv-plot of corrected data to
    - Check for any new outliers, if so flag and go back to Step 9.
    - Make sure model is good match to data.
    - Confirm that flux hasn't decreased significantly after applying solutions

Original

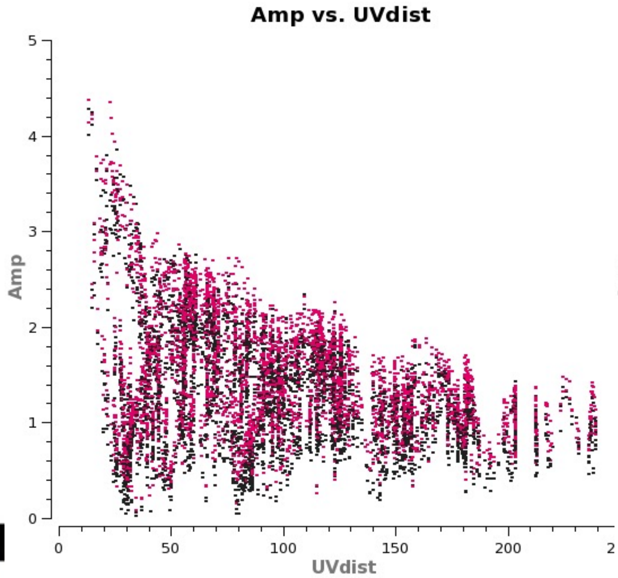
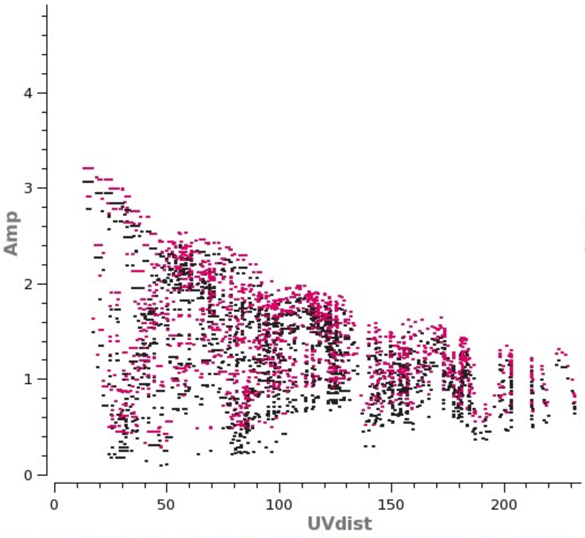
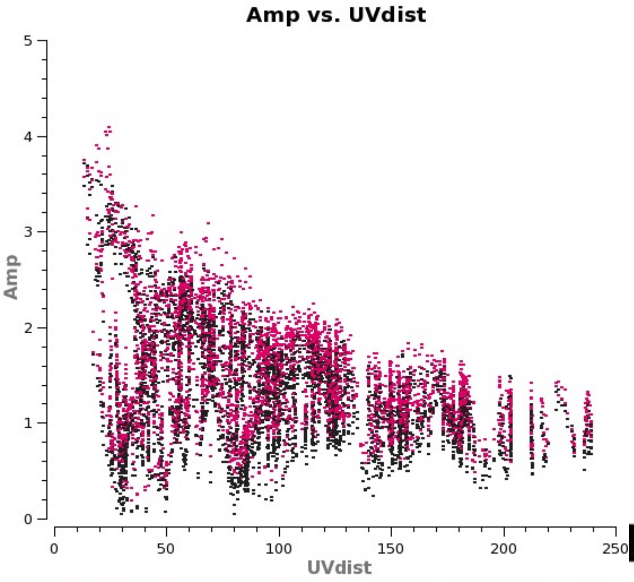


Image Model

(total cleaned flux = 3.4 Jy)

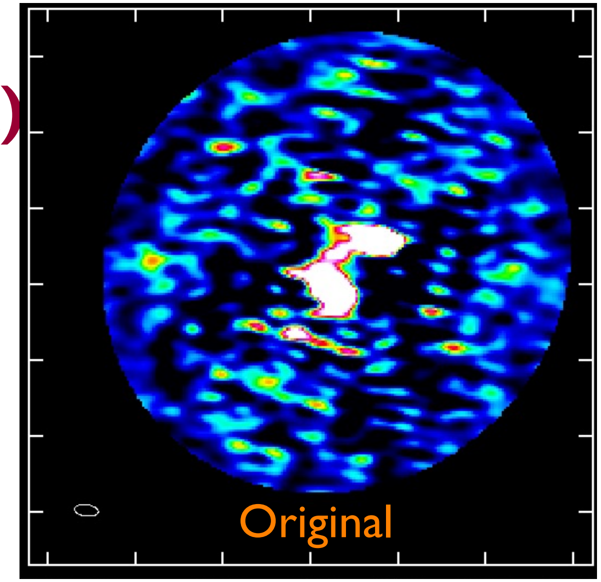


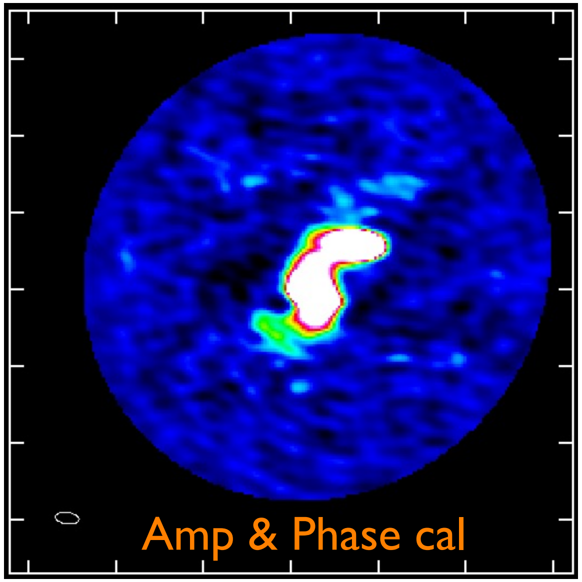
Amp & Phase applied



Self-calibration Example:

ALMA SV Data for IRAS16293 Band 6 (IX)





Step 13: Re-clean

- Incorporate more emission into clean box
- Stop when residuals become noise-like – clean everything you think is real

Step 14: Compare 2nd phase-only and amp+phase self-cal images

- 2nd phase-only:

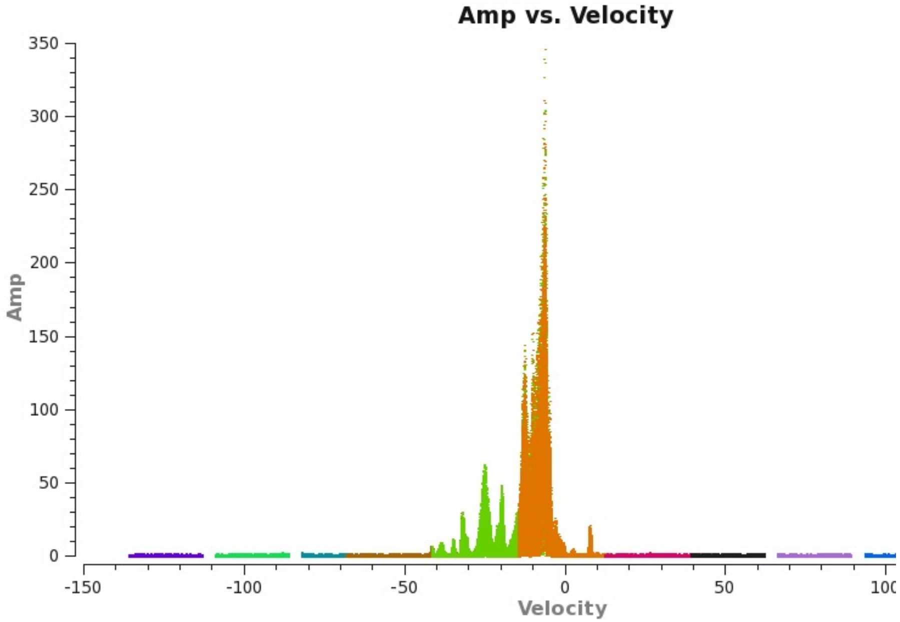
  Rms~ 5.6 mJy/beam; Peak ~ 1.30 Jy/beam ➔ S/N ~ 228
- Amp & Phase:

  Rms~4.6 mJy/beam; Peak~1.30 Jy/beam ➔ S/N ~283
- Did it improve? ➔ Done!

Final: S/N=67 vs 283!

But not as good as theoretical = dynamic range limit

Self-Calibration example 2: VLA Water Masers (I)



uv-spectrum after standard calibrator-based calibration for bandpass and antenna gains

There are 16 spectral windows, 8 each in two basebands (colors in the plot)

Some colors overlap because the basebands were offset in frequency by ½ the width of an spw in order to get good sensitivity across whole range.

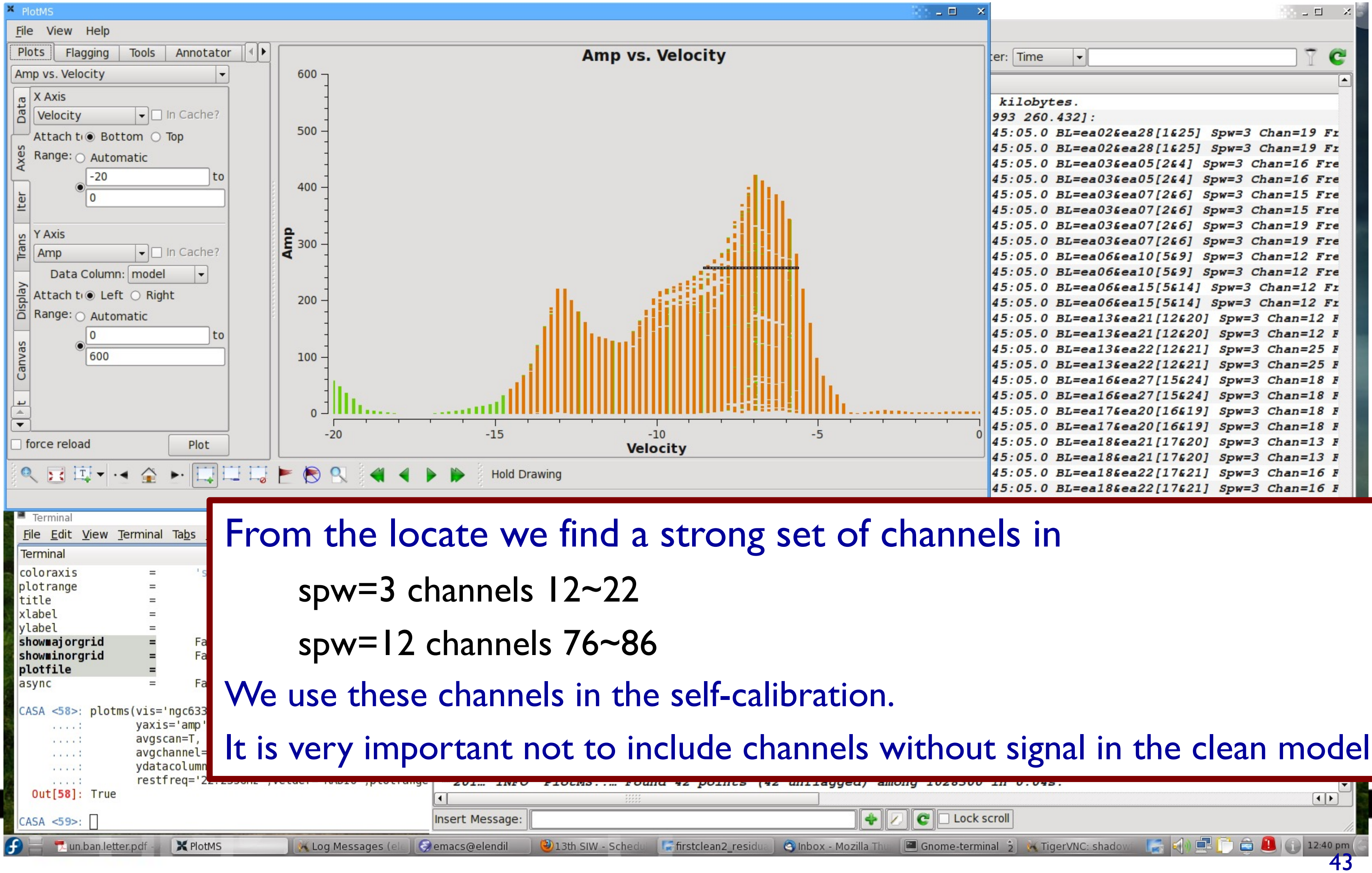
The continuum of this source is weak. How do you self-cal this?

- In general DATA CHANNEL NUMBER ≠ IMAGE CHANNEL NUMBER due to Doppler Shift, also LSB windows will have negative channel width, i.e. data and image channel numbers going in opposite directions (as of CASA 5.1)
- Suggest running CVEL using the rest frequency of the line at the same velocity resolution that you want for the final cube – this will give you a uv-dataset with the same channelization as the cube you want DATA CHANNEL NUMBER = IMAGE CHANNEL NUMBER

Self-Calibration example 2: VLA Water Masers (III)

Need to know the SPWs and the CHANNELs with strong emission in the model:

plotms of the MODEL (no CVEL, so data channels ≠ image channels) with locate can help



X Axis: Velocity

Range: -20 to 0

Y Axis: Amp

Data Column: model

Range: 0 to 600

```
 kilobytes.
993 260.432]:
45:05.0 BL=ea02&ea28[1&25] Spw=3 Chan=19 Fr
45:05.0 BL=ea02&ea28[1&25] Spw=3 Chan=19 Fr
45:05.0 BL=ea03&ea05[2&4] Spw=3 Chan=16 Fre
45:05.0 BL=ea03&ea05[2&4] Spw=3 Chan=16 Fre
45:05.0 BL=ea03&ea07[2&6] Spw=3 Chan=15 Fre
45:05.0 BL=ea03&ea07[2&6] Spw=3 Chan=15 Fre
45:05.0 BL=ea03&ea07[2&6] Spw=3 Chan=19 Fre
45:05.0 BL=ea03&ea07[2&6] Spw=3 Chan=19 Fre
45:05.0 BL=ea06&ea10[5&9] Spw=3 Chan=12 Fre
45:05.0 BL=ea06&ea10[5&9] Spw=3 Chan=12 Fre
45:05.0 BL=ea06&ea15[5&14] Spw=3 Chan=12 Fr
45:05.0 BL=ea06&ea15[5&14] Spw=3 Chan=12 Fr
45:05.0 BL=ea13&ea21[12&20] Spw=3 Chan=12 F
45:05.0 BL=ea13&ea21[12&20] Spw=3 Chan=12 F
45:05.0 BL=ea13&ea22[12&21] Spw=3 Chan=25 F
45:05.0 BL=ea13&ea22[12&21] Spw=3 Chan=25 F
45:05.0 BL=ea16&ea27[15&24] Spw=3 Chan=18 F
45:05.0 BL=ea16&ea27[15&24] Spw=3 Chan=18 F
45:05.0 BL=ea17&ea20[16&19] Spw=3 Chan=18 F
45:05.0 BL=ea17&ea20[16&19] Spw=3 Chan=18 F
45:05.0 BL=ea18&ea21[17&20] Spw=3 Chan=13 F
45:05.0 BL=ea18&ea21[17&20] Spw=3 Chan=13 F
45:05.0 BL=ea18&ea22[17&21] Spw=3 Chan=16 F
45:05.0 BL=ea18&ea22[17&21] Spw=3 Chan=16 F
```

```
coloraxis          =     's
plotrange          =
title              =
xlabel             =
ylabel             =
showmajorgrid      =     Fa
showminorgrid      =     Fa
plotfile           =
async              =     Fa

CASA <58>: plotms(vis='ngc633
     ....:          yaxis='amp'
     ....:          avgscan=T,
     ....:          avgchannel=
     ....:          ydatacolumn
     ....:          restfreq='2
  Out[58]: True

CASA <59>: 
```

From the locate we find a strong set of channels in

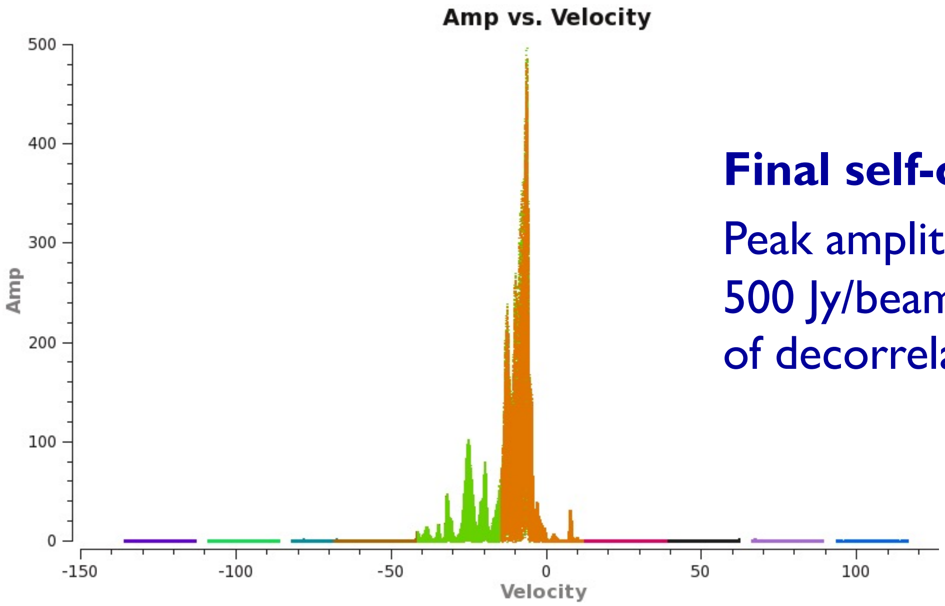
spw=3 channels 12~22

spw=12 channels 76~86

We use these channels in the self-calibration.

It is very important not to include channels without signal in the clean model!

Self-Calibration example 2: VLA Water Masers (III)



Final self-calibrated spectrum

Peak amplitude increased from 350 Jy/beam to 500 Jy/beam (a 40% increase) due to correction of decorrelation

- One remaining trickiness: calibration solutions are only for spw=3 and 12. The spwmap parameter can be used to map calibration from one spectral window to another in applycal. There must be an entry for all spws (16 in this case):

  spwmap=[3,3,3,3,3,3,3,3,12,12,12,12,12,12,12,12]

  In other words apply the spw=3 calibration to the 8 spectral windows in the lower baseband and the calibration from spw=12 to the 8 spws in the upper baseband
- Beyond this everything is the same as previous example.

Summary (Part 1)

- Spatial and temporal variations in the amount of precipital water vapor in the troposphere cause phase fluctuations but there are a wide range of options for corrections: observing techniques and post-processing
  - Fast switching
  - WVRs
  - Self-calibration
  - If no close calibrator (higher frequencies), Band to Band phase transfer
- Self-calibration is not so hard and can make a big difference
  - Make sure your model is a good representation of the data
  - Make sure the data you put into solver, is a good match to the model
  - If you are lacking a little in S/N try one of the "S/N increase techniques"
  - If you really don't have enough S/N don't keep what you try!
- For more self-calibration examples, tips, tricks, and advice see https://arxiv.org/abs/1805.05266

Advanced Gain Calibration Techniques in Radio Interferometry

Crystal L. Brogan, Todd R. Hunter, Ed B. Fomalont

Atmospheric Opacity Correction Techniques

Sensitivity: System noise temperature

In addition to receiver noise, at millimeter wavelengths the atmosphere has a significant brightness temperature (T_{sky}):

For a perfect antenna, ignoring spillover and efficiencies

$$T_{noise} \approx T_{rx} + T_{sky}$$

$$where\ T_{sky} = T_{atm}\,(1 - e^{-\tau}) + T_{bg} e^{-\tau}$$

$$T_{noise} \approx \underset{\substack{\uparrow \\ \textbf{Receiver temperature}}}{T_{rx}} + \underset{\substack{\uparrow \\ \textbf{Emission from atmosphere}}}{T_{atm}(1\text{-}e^{-\tau})}$$

T_{atm} = temperature of the atmosphere ≈ 300 K

T_{bg} = 3 K cosmic background

Before entering atmosphere the source signal $S = T_{source}$

After attenuation by atmosphere the signal becomes $S = T_{source}\, e^{-\tau}$

Consider the signal-to-noise ratio:

$$S / N = (T_{source}\, e^{-\tau}) / T_{noise} = T_{source} / (T_{noise}\, e^{\tau})$$

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

⇨The system sensitivity drops rapidly (exponentially) as opacity increases

Impact of Atmospheric Noise

Assuming T_{atm} = 300 K, elevation=40 degrees, ignoring antenna efficiencies

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

$$\boxed{\tau = \frac{\tau_{zenith}}{\sin(elevation)}}$$

τ_{40} = opacity at a observing elevation of 40 degrees

JVLA Qband (43 GHz)

- typical winter PWV = 5 mm ➔ τ_{zenith}=0.074 ➔ τ_{40}= 0.115
- typical Trx=35 K
- Tsys = 76 K

ALMA Band 6 (230 GHz)

- typical PWV = 1.8 mm ➔ τ_{zenith}=0.096 ➔ τ_{40}= 0.149
- typical Trx=50 K
- Tsys= 106 K

ALMA Band 9 (690 GHz)

- typical PWV = 0.7 mm ➔ τ_{zenith}=0.87 ➔ τ_{40}= 1.35
- typical Trx= 150 K (DSB)
- Tsys= 1435 K

Measurement of T_{sys} in the Sub(millimeter)

- How do we measure $T_{sys} = T_{atm}(e^{\tau}-1) + T_{rx}e^{\tau}$ without constantly measuring T_{rx} and the opacity?
- The "chopper wheel" method: putting an ambient temperature load (T_{load}) in front of the receiver and measuring the resulting power compared to power when observing sky T_{atm} (Penzias & Burrus 1973).

Load in

$$V_{in} = G\,T_{in} = G\,[T_{rx} + T_{load}]$$

Load out

$$V_{out} = G\,T_{out} = G\,[T_{rx} + T_{atm}(1-e^{-\tau}) + T_{bg}e^{-\tau} + T_{source}e^{-\tau}\,]$$

assume $T_{atm} \approx T_{load}$

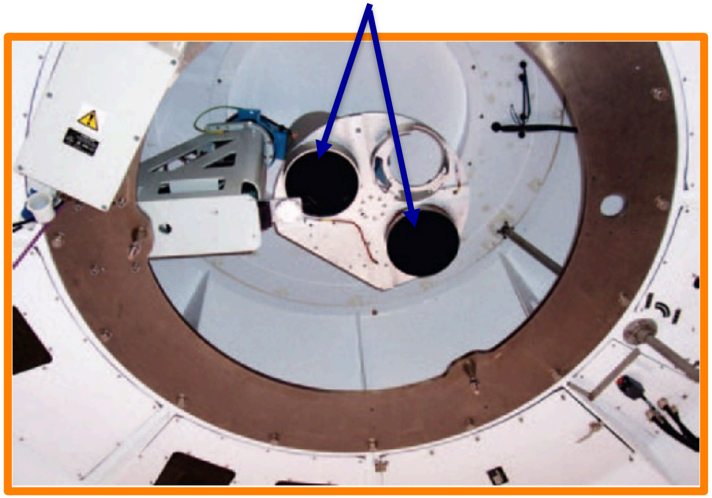
Comparing in and out

$$\frac{V_{in} - V_{out}}{V_{out}} = \frac{T_{load}}{T_{sys}}$$

$$\boxed{T_{sys} = T_{load} * T_{out} / (T_{in} - T_{out})}$$

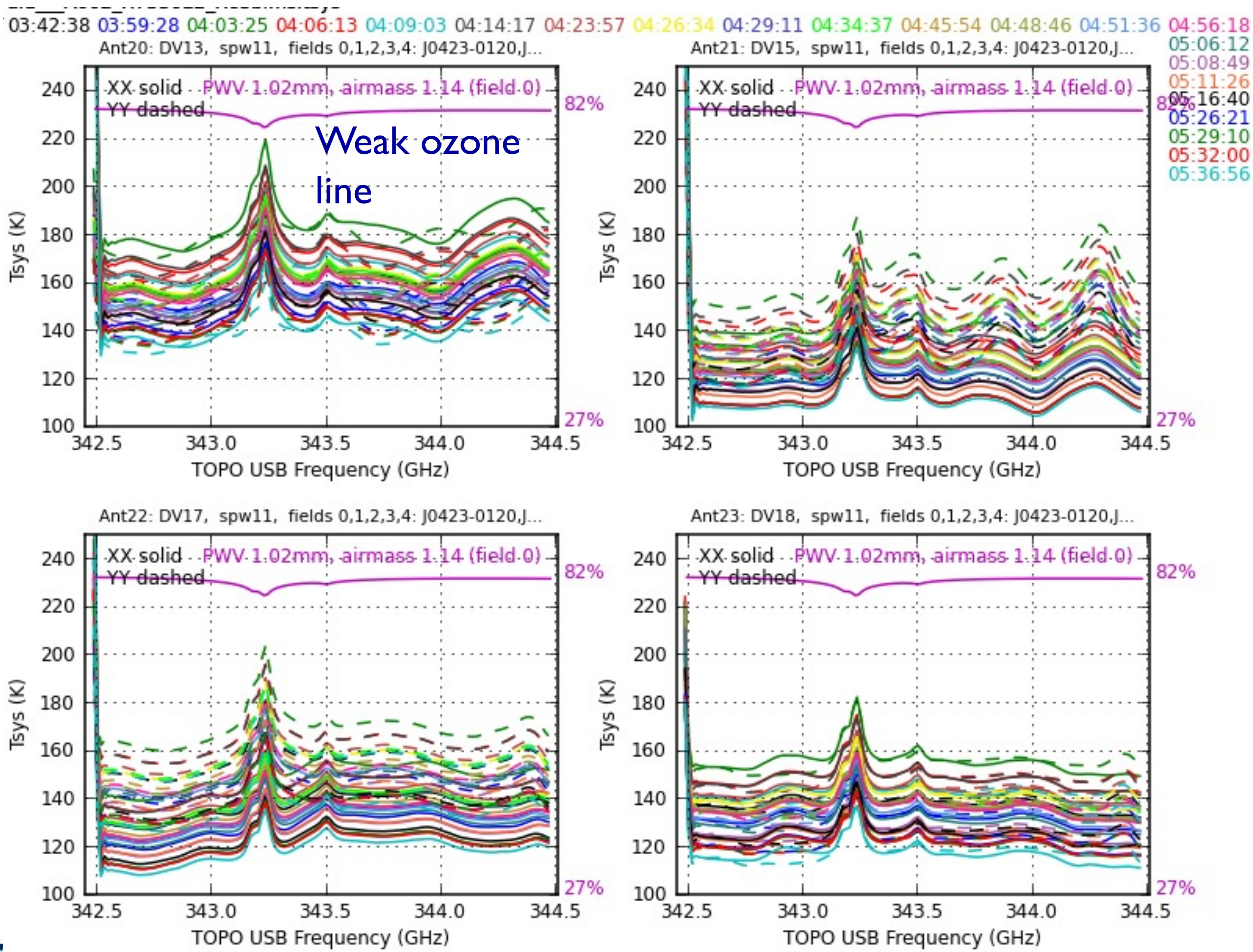
Power is really observed but is $\propto$ T in the R-J limit

ALMA two-load Tsys system also gives measure of Trx



- ➢ IF T_{sys} is measured often, changes in mean atmospheric absorption are corrected

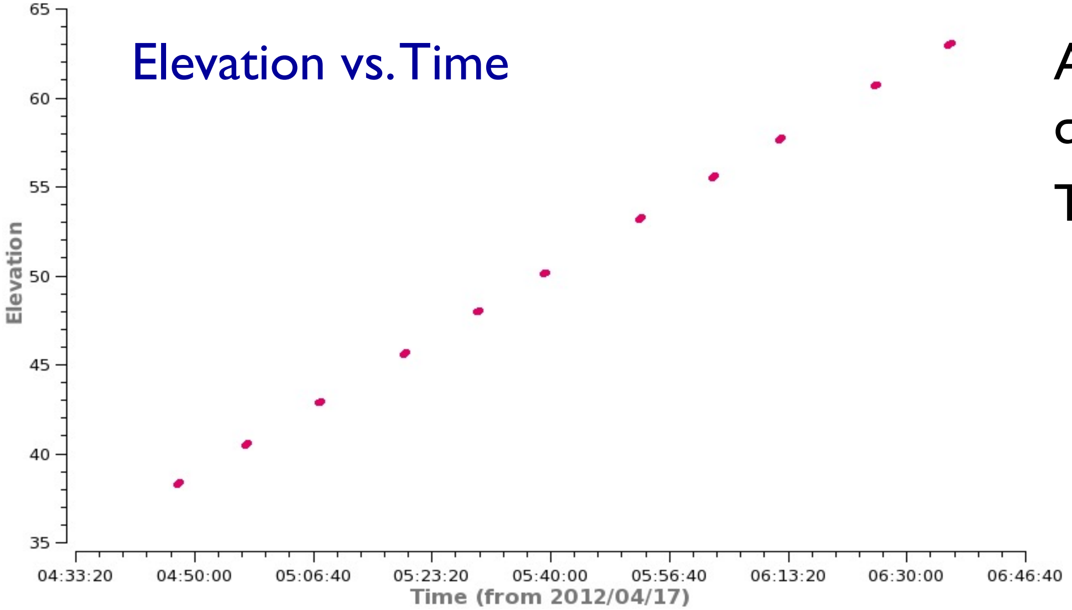
ALMA Spectral Tsys: 4 Antennas Band 6 (230 GHz)



Weak ozone line

Colors show changes with time (and sometimes source)

ALMA System Temperature: Example-1

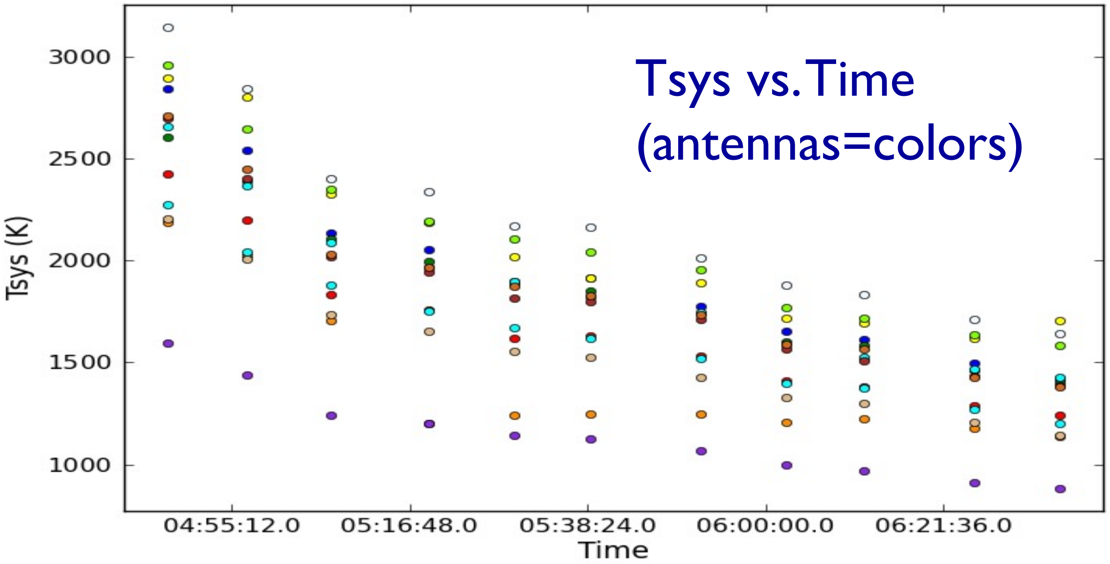


ALMA Band 9 Test Data on the quasar NRAO530

Tsys measured every ~16 min

Notice:

- Inverse relationship between elevation and Tsys

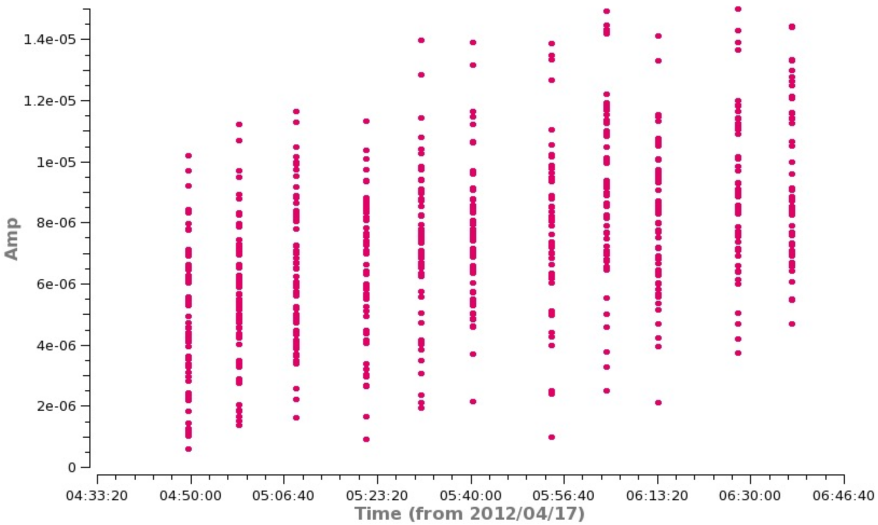


- Large variation of Tsys among the antennas

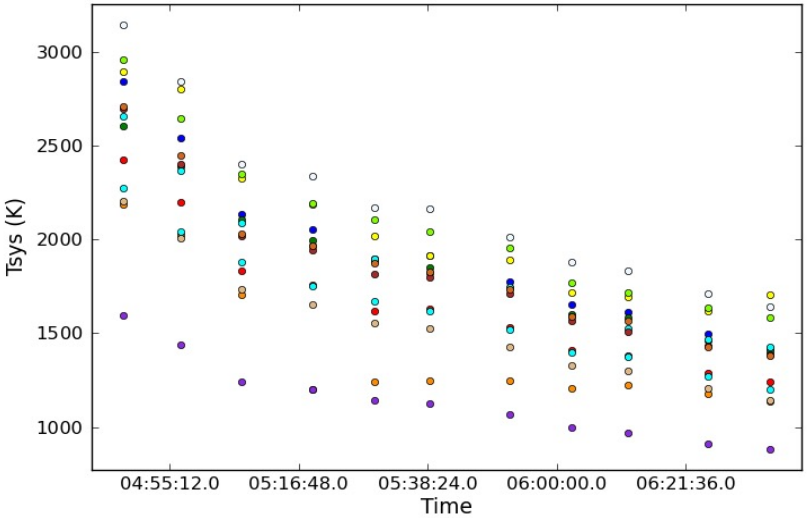
$$VisibilityWeight \propto \frac{1}{T_{sys}(i)T_{sys}(j)}$$

ALMA System Temperature: Example-2

Raw Amplitude vs. Time

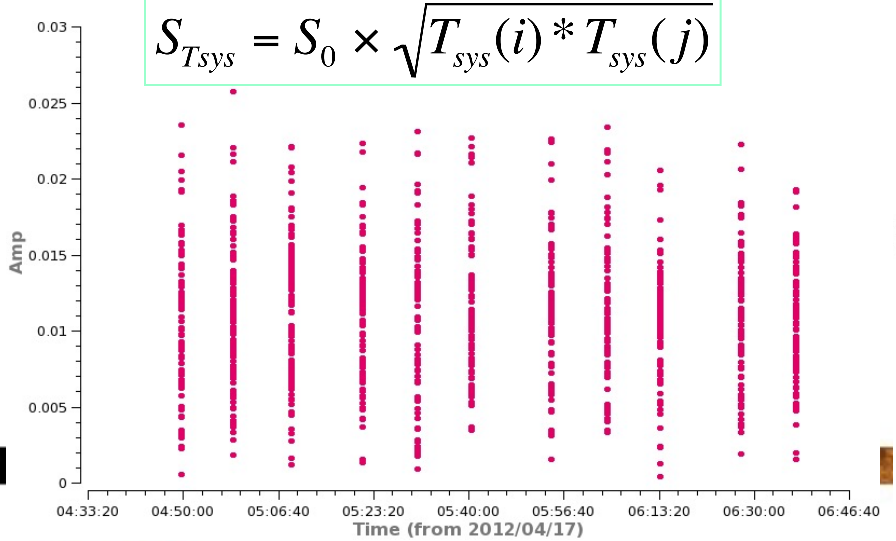


Tsys vs. Time (all antennas)



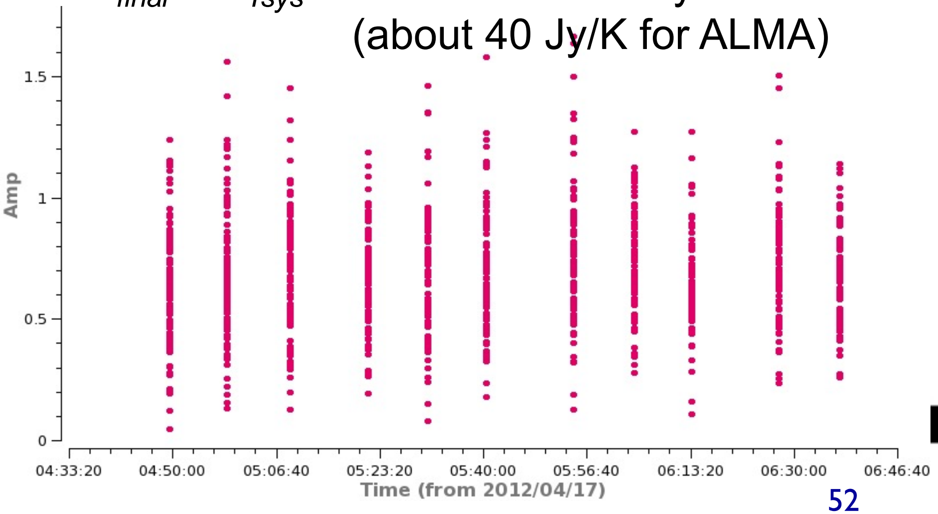
Amplitude Corrected for Tsys

$$S_{Tsys} = S_0 \times \sqrt{T_{sys}(i) * T_{sys}(j)}$$



Fully Calibrated using flux reference

$S_{final} \sim S_{Tsys}$ * Antenna Efficiency Factor (about 40 Jy/K for ALMA)

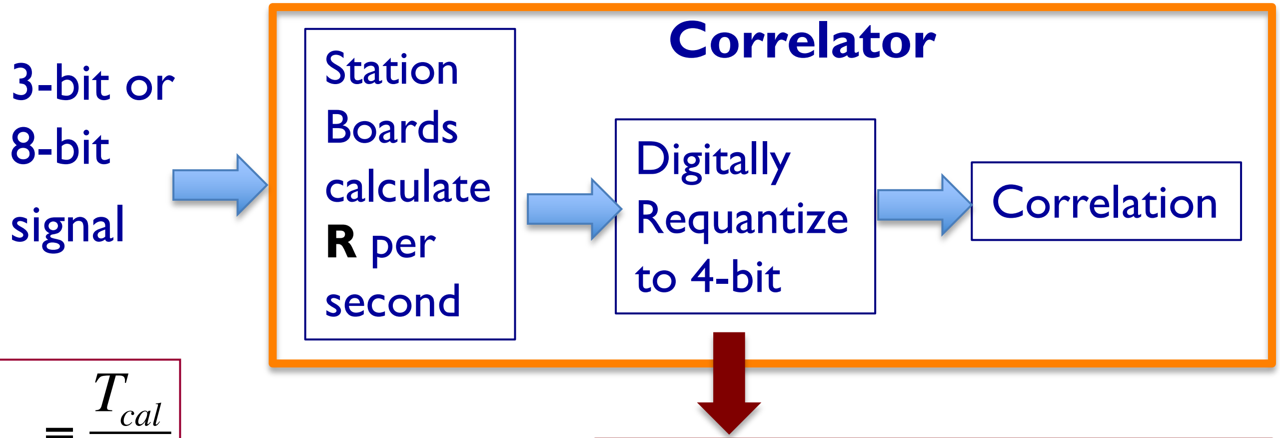


VLA Switched Power

$$VisibilityWeight \propto \frac{1}{T_{sys}(i)T_{sys}(j)}$$

Alternative to a mechanical load system is a switched "calibration diode"

- Broad band, stable noise (Tcal~3K) is injected into receiver at ~20 Hz
- Synchronous detector downstream gives sum & difference powers



3-bit or 8-bit signal

Correlator

Station Boards calculate **R** per second

Digitally Requantize to 4-bit

Correlation

$$R = \frac{2(P_{on} - P_{off})}{P_{on} + P_{off}}$$

$$T_{sys} = \frac{T_{cal}}{R}$$

This produces an additional gain change that should be applied for 3-bit data now, and eventually 8-bit. This gain is also stored in the "switched power" table

Advantages

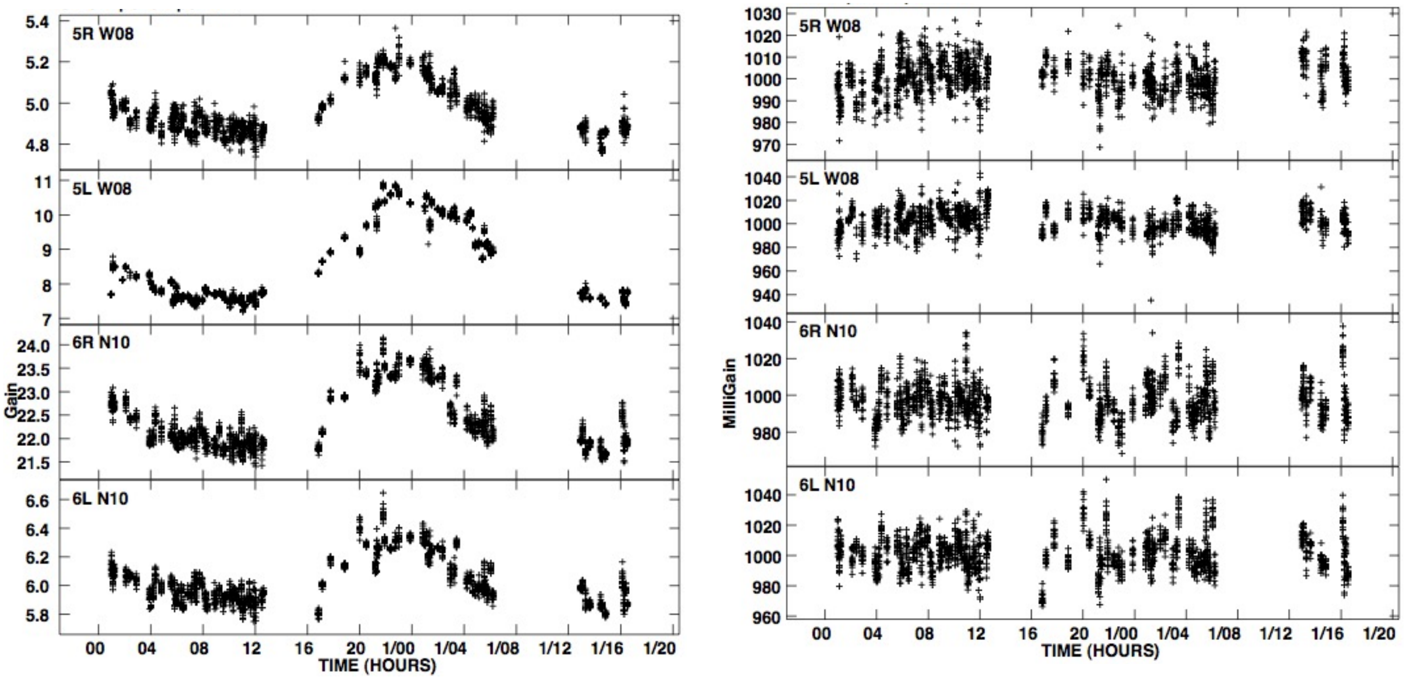
- Removes gain variations due to electronics between the diode and correlator on 1 second timescales
- Puts data on absolute temperature scale

Caveats:

- Does not account for opacity effects
- Does not account for antenna gain curve

VLA Switched Power Example

Antenna Gain as a function of time



Gain solutions from calibrator-based calibration; all the sources are strong calibrators

This is what you get if you apply switched power first, large variations with time are removed

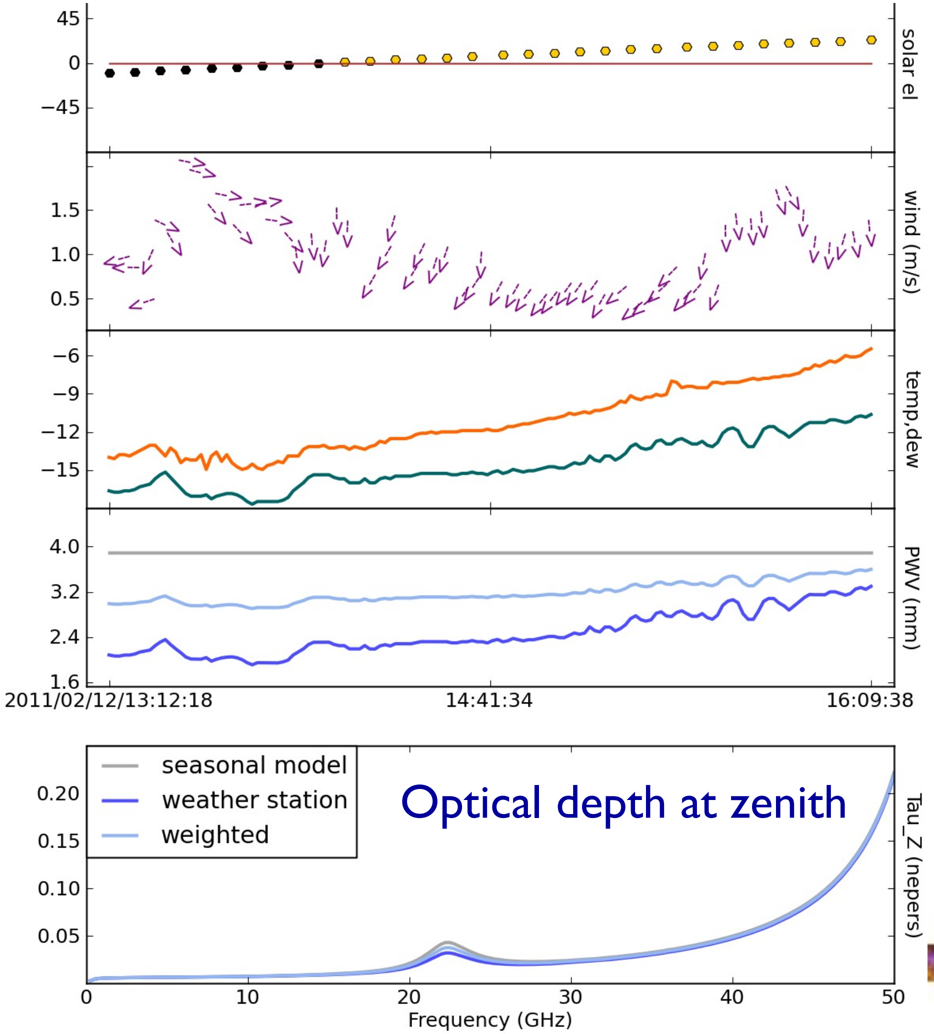
A science source will have similar gain variations with time, and only if you switch frequently to a strong calibrator for gain solutions can you TRY to take out these variations.

This calibration takes out electronic but not ionospheric or tropospheric gain variations. The latter would still need to be taken out by calibrator observations.

VLA Atmospheric Correction

- For VLA, still need to account for atmospheric opacity and antenna gain variations with elevation (i.e. antenna gain curves)

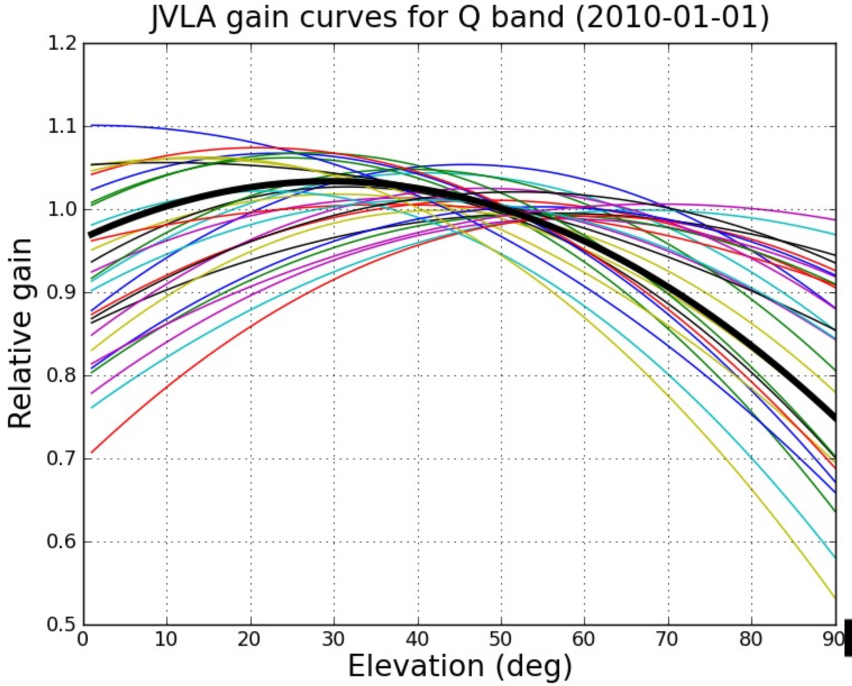
plotweather task available in CASA



Optical depth at zenith

$$\tau = \frac{\tau_{zenith}}{\sin(elevation)}$$

Hopefully in the future a "tipper" that directly monitors the atmospheric opacity will provide more accurate estimates


JVLA gain curves for Q band (2010-01-01)

Absolute Flux Calibration

Absolute Flux Calibration

Goal:

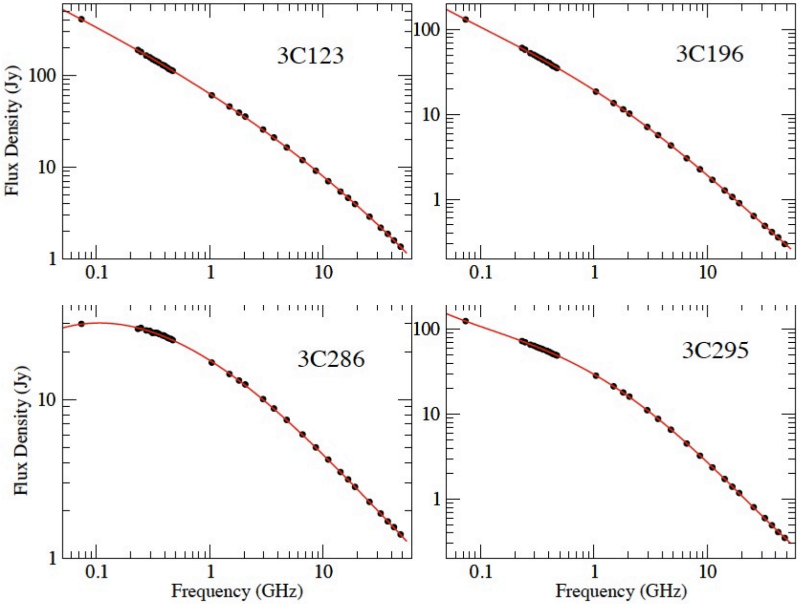
- Observe a source of known flux density and spectral index, that is a point source on all observed scales (and thus constant phase and amplitude) and has no spectral line emission in the observing band
- Measure ratio of known flux density to observed mean amplitude (corrected for Tsys, phase, and amplitude with time variations)
- Transfer that ratio to gain calibrator (which in turn will correct science target)

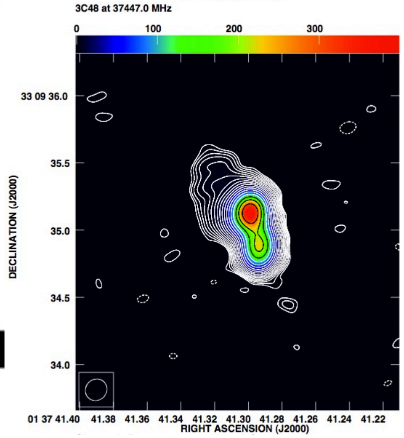
Reality -- there are no perfect absolute flux calibrators

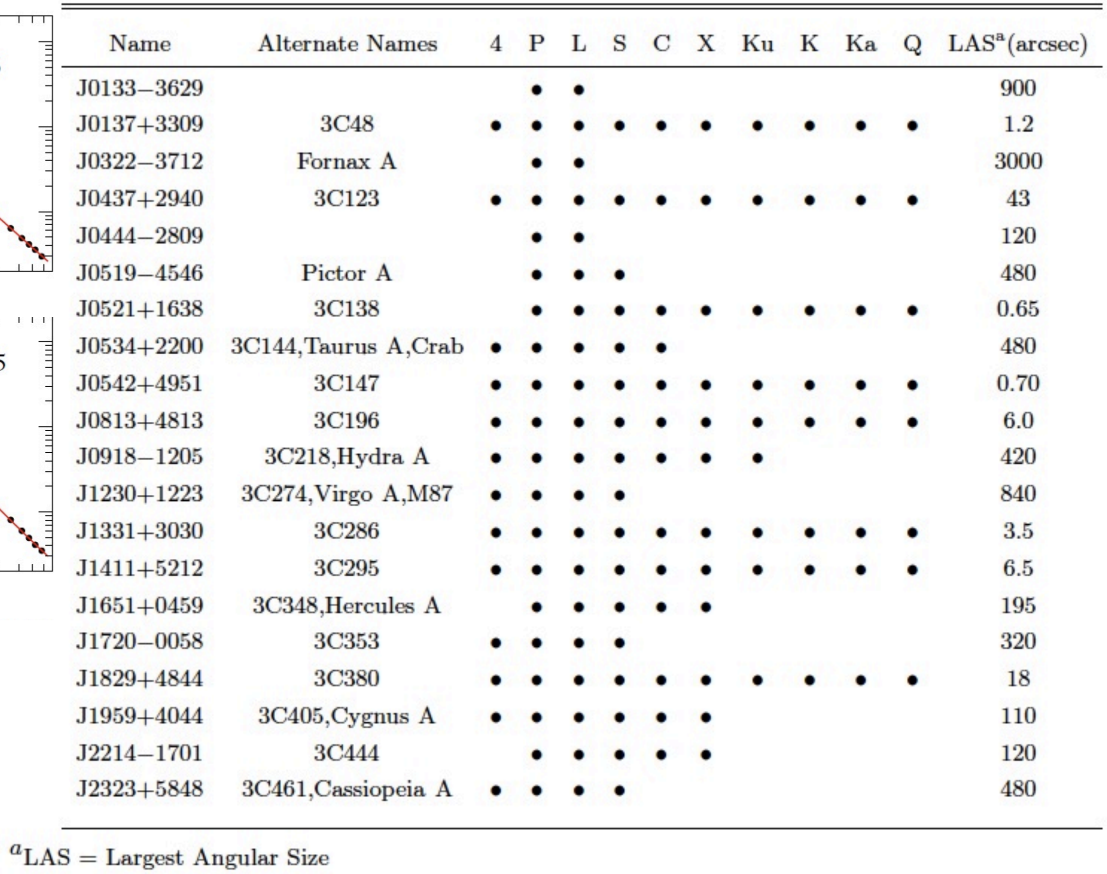
- In the centimeter regime there are a few good approximations
- In the (sub)mm the situation is harder
- In general the key is to derive accurate models and / or high cadence flux monitoring

VLA Quasar Flux Standards

- Only four quasars have been observed to vary by less than 1% over 20 years, and four others that are relatively stable that can be used across the full VLA frequency range







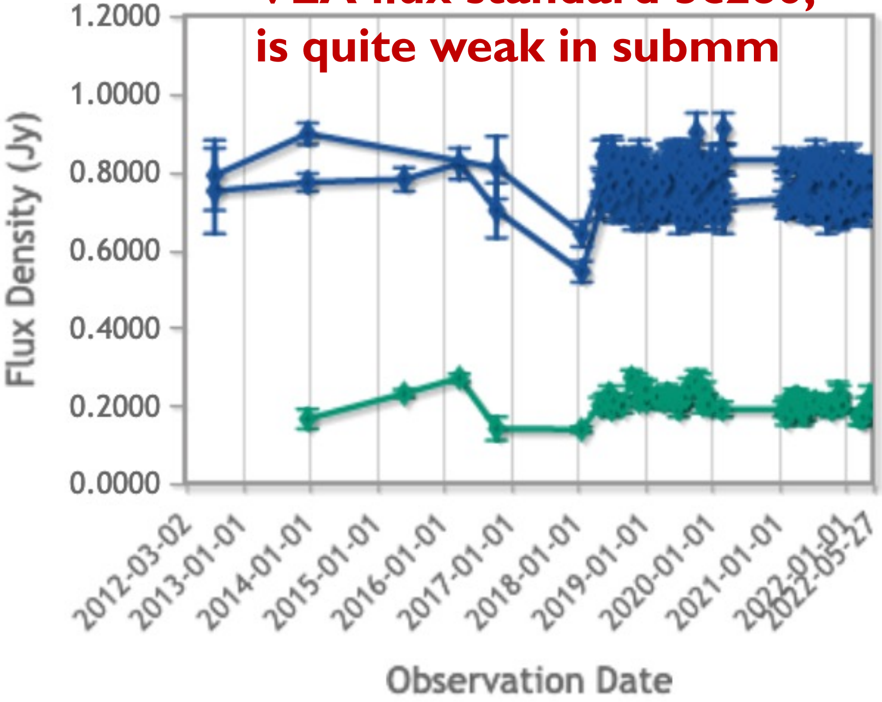
Name	Alternate Names	4	P	L	S	C	X	Ku	K	Ka	Q	LAS[a] (arcsec)
J0133−3629			•	•								900
J0137+3309	3C48	•	•	•	•	•	•	•	•	•	•	1.2
J0322−3712	Fornax A		•	•								3000
J0437+2940	3C123	•	•	•	•	•	•	•	•	•	•	43
J0444−2809			•	•								120
J0519−4546	Pictor A		•	•	•							480
J0521+1638	3C138		•	•	•	•	•	•	•	•	•	0.65
J0534+2200	3C144,Taurus A,Crab	•	•	•	•	•						480
J0542+4951	3C147	•	•	•	•	•	•	•	•	•	•	0.70
J0813+4813	3C196	•	•	•	•	•	•	•	•	•	•	6.0
J0918−1205	3C218,Hydra A	•	•	•	•	•	•	•				420
J1230+1223	3C274,Virgo A,M87	•	•	•	•							840
J1331+3030	3C286	•	•	•	•	•	•	•	•	•	•	3.5
J1411+5212	3C295	•	•	•	•	•	•	•	•	•	•	6.5
J1651+0459	3C348,Hercules A		•	•	•	•	•					195
J1720−0058	3C353	•	•	•	•							320
J1829+4844	3C380	•	•	•	•	•	•	•	•	•	•	18
J1959+4044	3C405,Cygnus A	•	•	•	•	•	•					110
J2214−1701	3C444		•	•	•	•	•					120
J2323+5848	3C461,Cassiopeia A	•	•	•	•							480

[a] LAS = Largest Angular Size

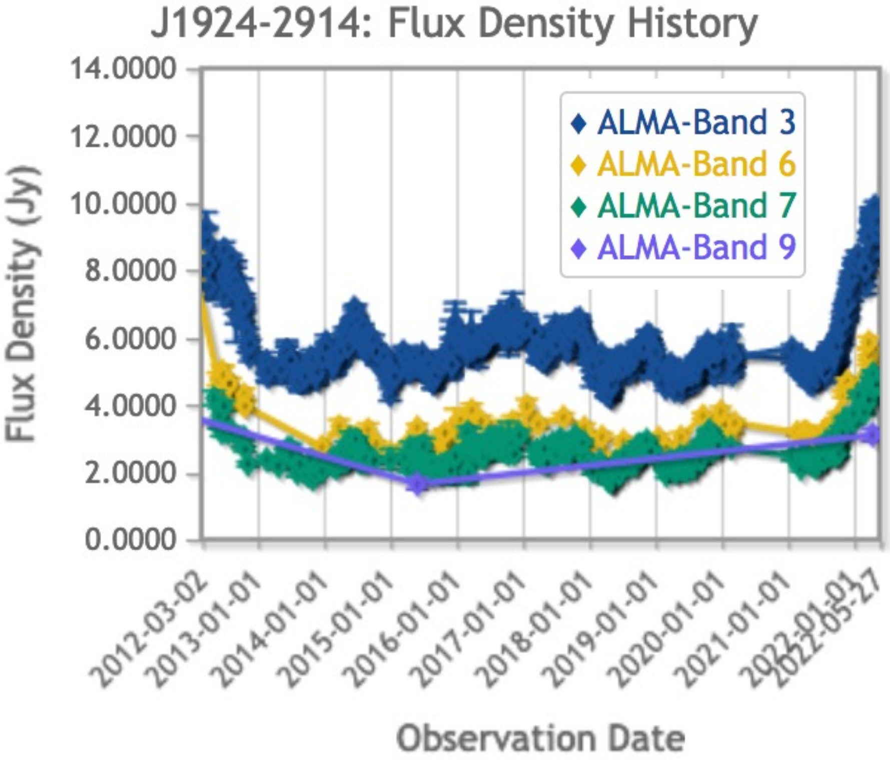
Perley, R.A., & Butler, B.J. 2017, ApJS, 230, 7

(sub)mm ALMA Quasar Monitoring

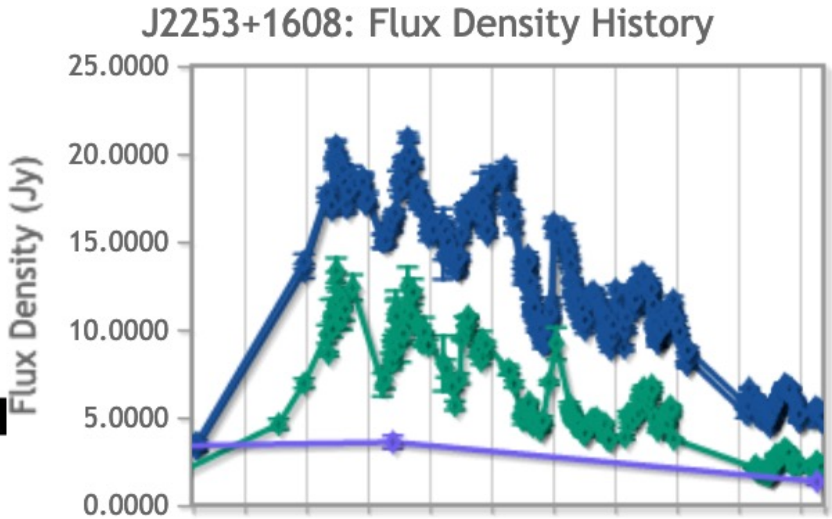
https://almascience.nrao.edu/sc/



VLA flux standard 3c286, is quite weak in submm



J1924-2914: Flux Density History



J2253+1608: Flux Density History

- Strong quasars in the submm tend to be highly time-variable
- Aim to monitor at minimum every two weeks, Bands 3 & 7
  - Interpolation or extrapolation for other bands based on derived spectral index

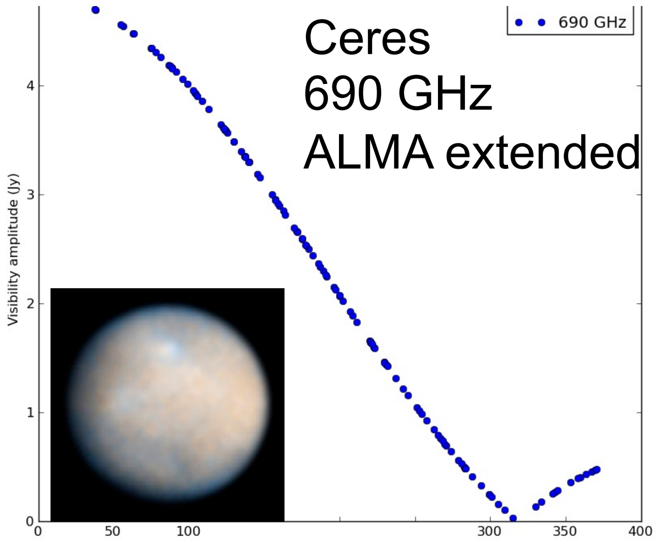
Flux calibrators – ALMA

- Solar system bodies can be used as primary flux calibrators (Neptune, Jovian moons, Titan, Ceres) but with many challenges:
  - Resolved on long ALMA baselines
  - Brightness varies with distance from Sun and Earth
  - Line emission (Neptune, Titan)

- ALMA primarily uses regular monitoring of a small grid (~20) of point-like quasars bootstrapped with Solar System objects

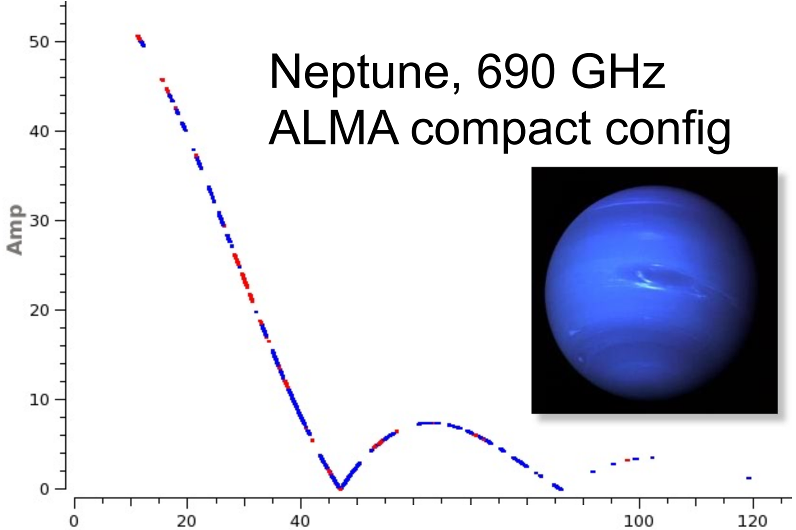
Other options:

- More asteroids? modeling is needed because they are not round!
- Red giant stars?



Ceres
690 GHz
ALMA extended

UV distance



Neptune, 690 GHz
ALMA compact config

UV distance

"SEFD" (System Equivalent Flux Density) Method

For one visibility, one pol (one baseline between antennas i, j) the noise is:

$$\sigma(i,j) = \underbrace{\frac{2K_B}{\eta_q\eta_c}\sqrt{\frac{1}{A_{eff}(i)\,Ae_{ff}(j)}}}_{\text{Jy/K}}\;\underbrace{\sqrt{\frac{T_{sys}(i)T_{sys}(j)}{2\,\Delta\nu\,t_{ij}}}}_{\text{K}} \times 10^{26}\,\text{Jy} \quad = \quad \frac{SEFD}{\sqrt{2\,\Delta\nu\,t_{ij}}}$$

Relatively constant → Jy/K

Antenna / Correlator properties (gain^{-1})

K

Atmosphere / Receiver and observing setup

Using mean values:

VLA 6 cm ~ 8 Jy/K

ALMA (12m) 1.3mm ~ 35 Jy/K

- K_B : Boltzmann's constant
- $\eta_q\eta_c$: digitizer quantization efficiency and correlator efficiency, respectively (0.96 and 0.88 for ALMA BLC)
- A_{eff}: antenna effective area = $\eta_a\,\pi r^2$ where η_a is the aperture efficiency which depends on the antenna surface accuracy (which depends on elevation, ambient temperature, and frequency), blockage, etc, slightly different for every antenna
- $T_{sys}(i)$: system temperature for antenna i
- $\Delta\nu\ t_{ij}$: observing bandwidth and integration time, respectively

ALMA is exploring SEFD via look-up table as an absolute flux calibration method