Advanced Calibration Techniques

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2015 NRAO NAASC Interferometry School

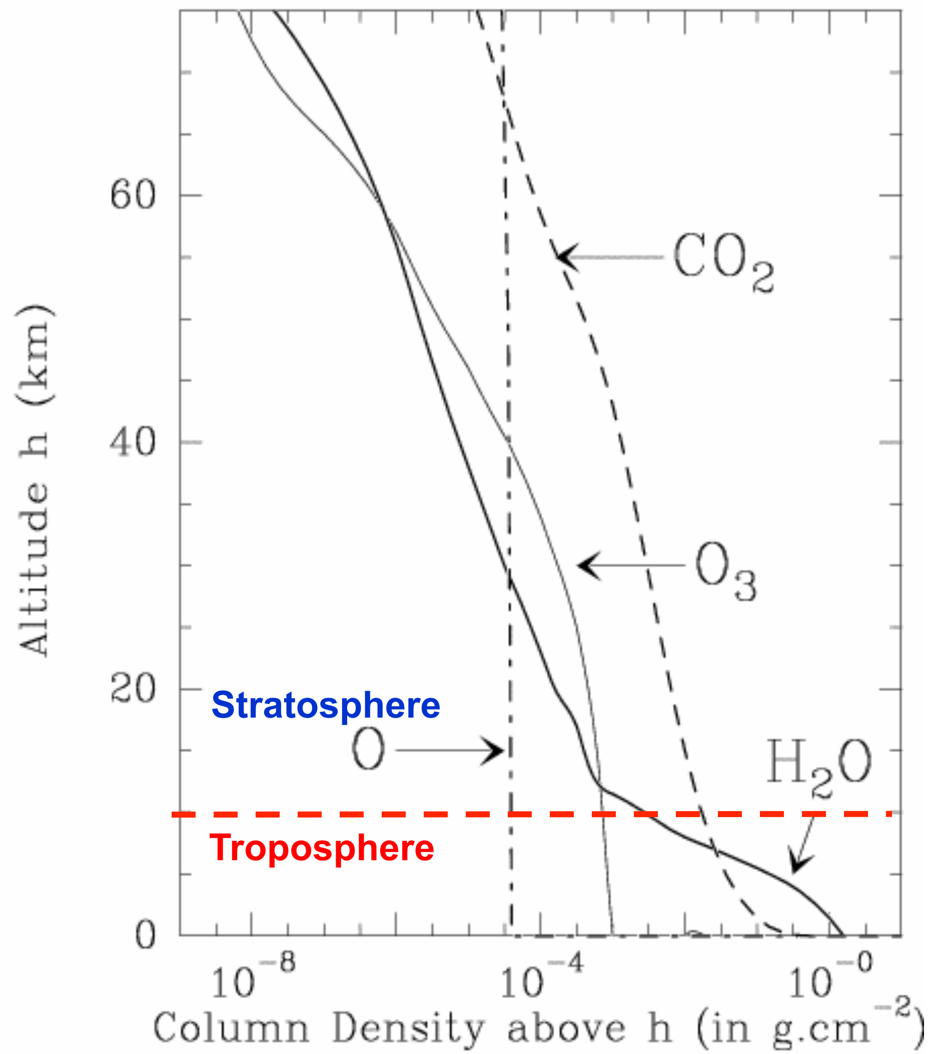
Outline: ~~Advanced Calibration Techniques~~ Improving Calibration, Especially at Higher Frequencies

- The Troposphere
  - Mean effect
  - Correcting for atmospheric noise and attenuation
  - Phase Fluctuations / Decorrelation
- Phase Correction Techniques
  - Techniques
  - Fast Switching
  - Water Vapor Radiometers
  - Self-calibration
- Absolute Flux Calibration

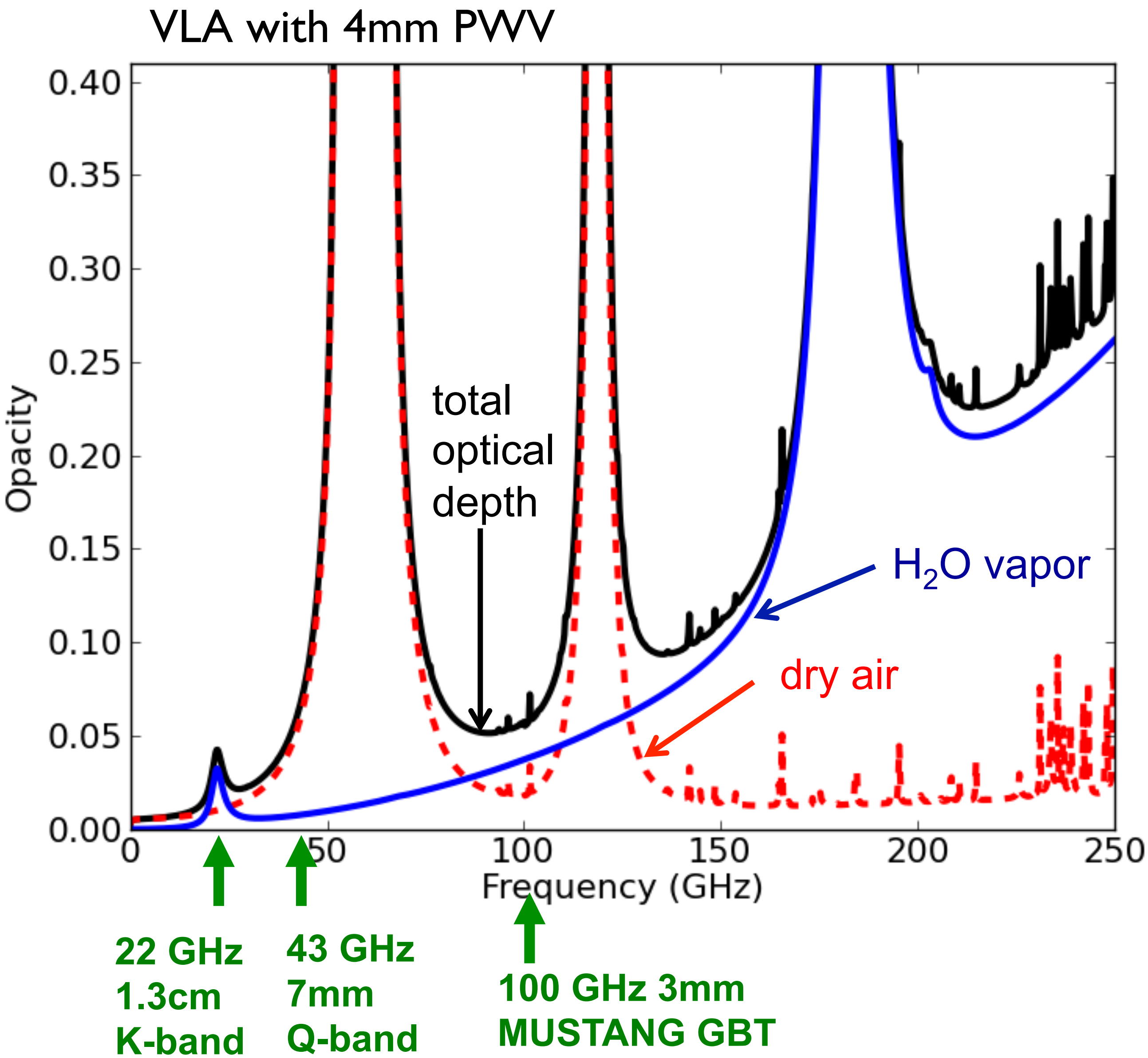
Constituents of Atmospheric Opacity

- Due to the troposphere (lowest layer of atmosphere): h < 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
- "Hydrosols" (water droplets in clouds and fog) also add a considerable contribution when present and not easily measured

Column Density as a Function of Altitude

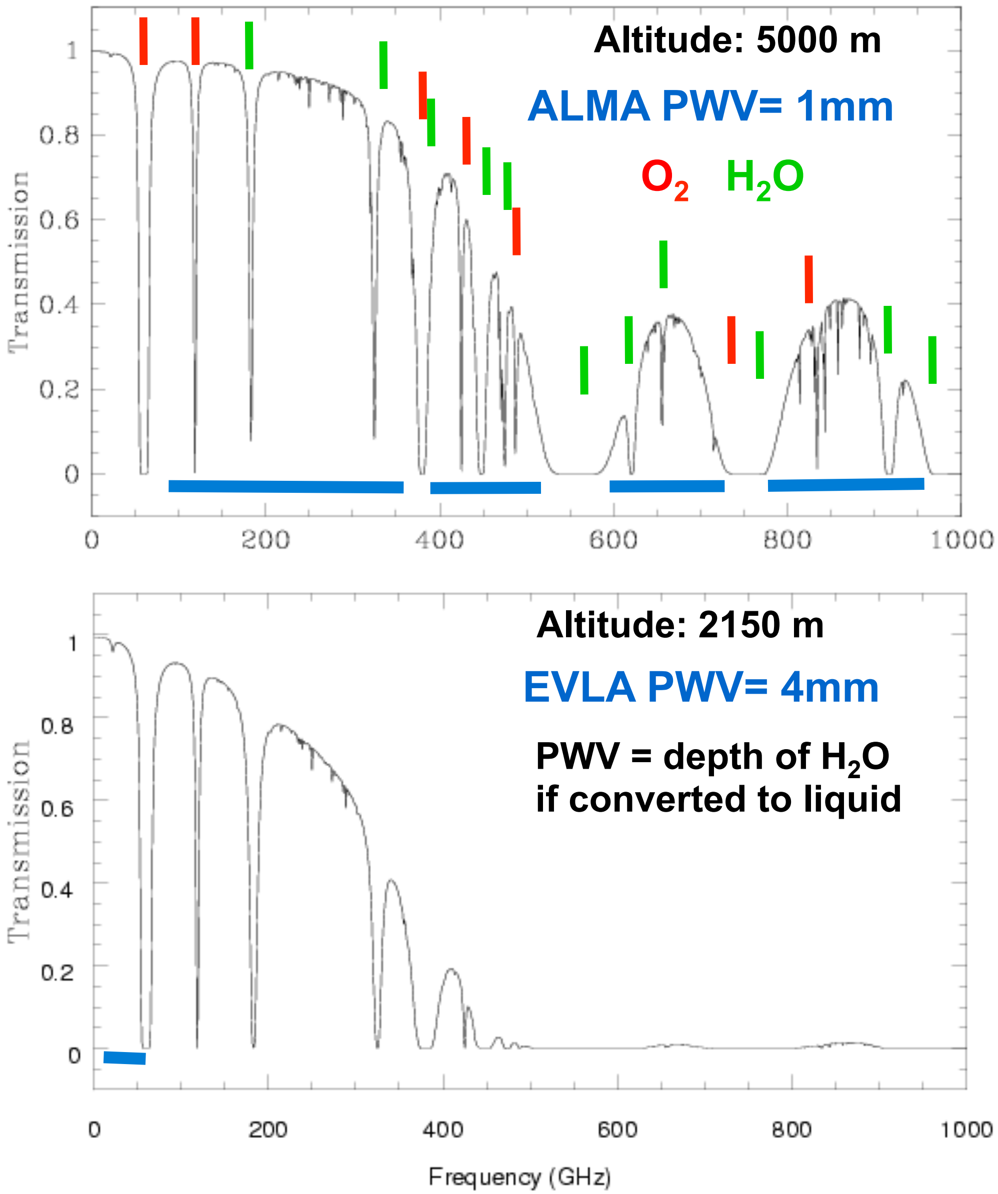


Optical Depth as a Function of Frequency



- At 1.3 cm 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 (not shown) can also add significantly to the opacity

Tropospheric Opacity Depends on Altitude:



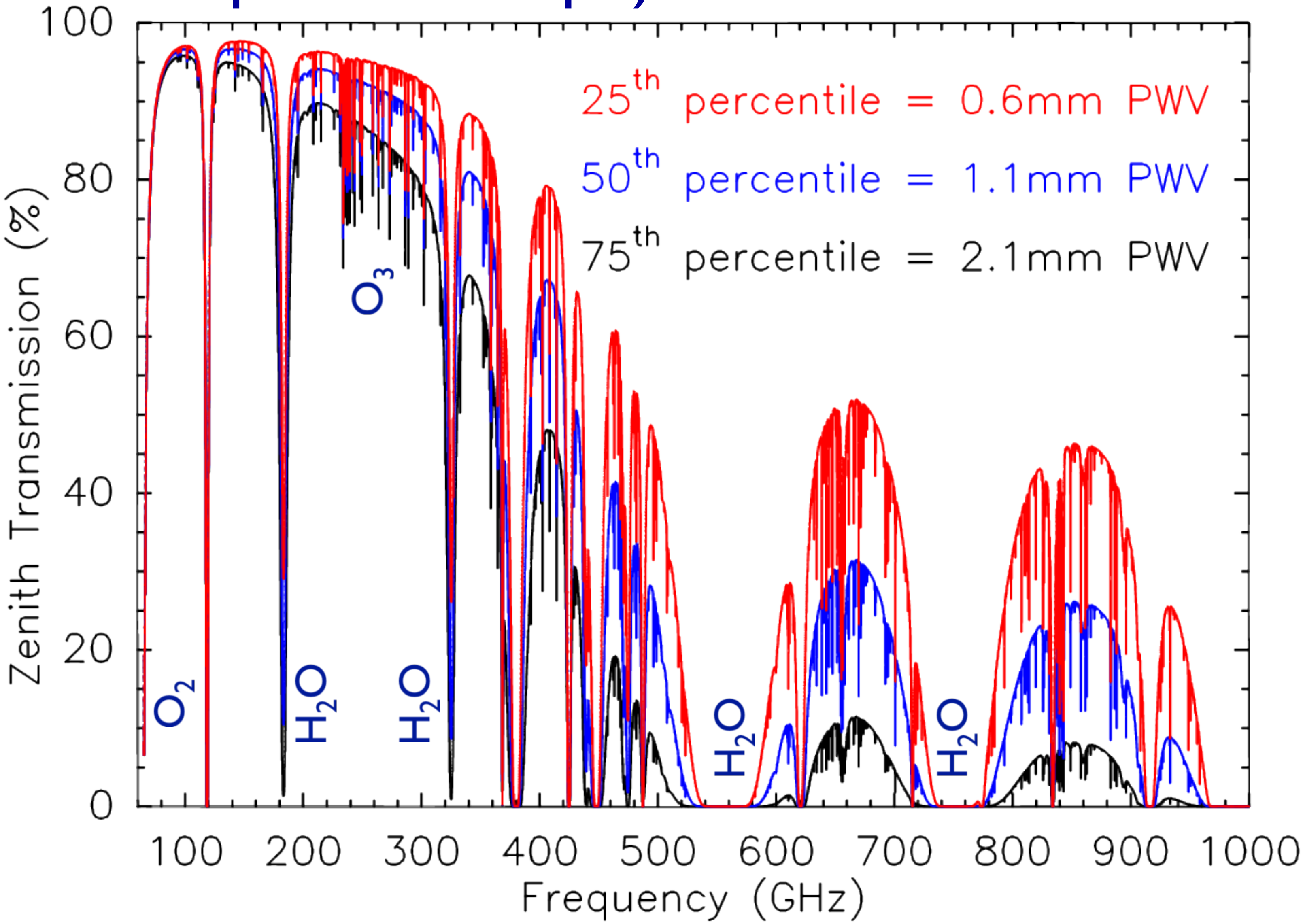
Models of atmospheric transmission from 0 to 1000 GHz for the ALMA site in Chile, and for the VLA site in New Mexico

The difference is due primarily to the scale height of water vapor, not the "dryness" of the site.

⇒ Atmospheric transmission not a problem for λ > cm (most VLA bands)

Atmospheric Opacity at ALMA

(PWV = Precipitable Water Vapor)



Mean Effect of Atmosphere on Phase

- Since the refractive index of the atmosphere ≠1, an electromagnetic wave propagating through it will experience 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

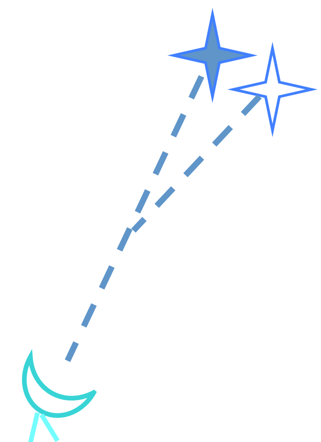
$$\phi_e = (2\pi/\lambda) \times n \times D$$

For water vapor $n \propto \frac{w}{D T_{atm}}$

w=precipitable water vapor (PWV) column

T_{atm} = Temperature of atmosphere

so $\boxed{\phi_e \approx \frac{12.6\pi \times w}{\lambda} \quad \text{for } T_{\mathbf{atm}} = 270\text{ K}}$



This refraction causes:

- Pointing off-sets, $\Delta\theta \approx 2.5 x 10^{-4}\ x\ tan(i)$ (radians)
  @ elevation 45^o typical offset~1'

- Delay (time of arrival) off-sets

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

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

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

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

$$\text{so } \underbrace{T_{noise} \approx T_{rx}}_{\text{Receiver temperature}} + \underbrace{T_{atm}(1-e^{-\tau})}_{\text{Emission from atmosphere}}$$

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:

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

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

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

Impact of Atmospheric Noise

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

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

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

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

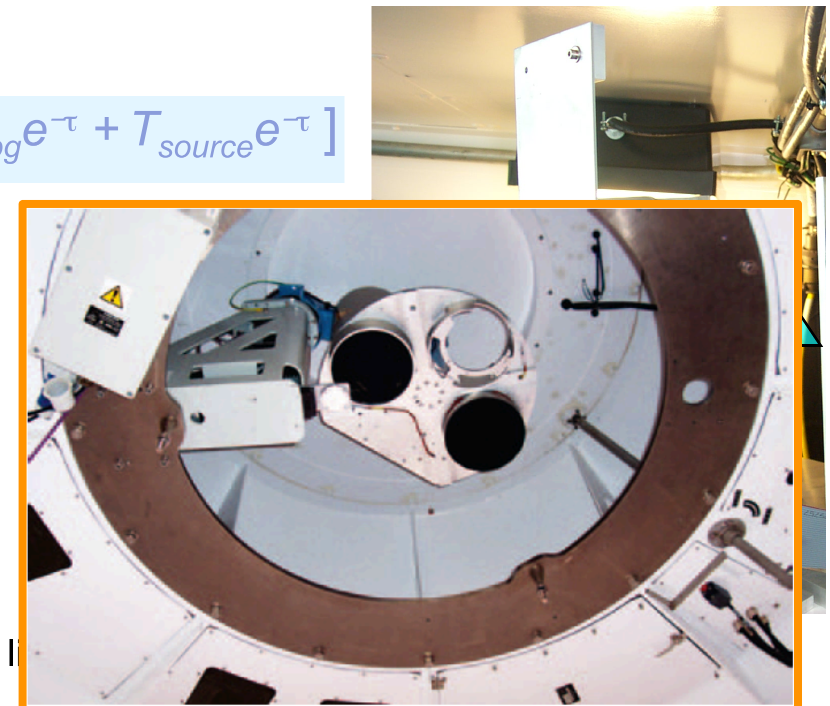
Load out $V_{out} = G\ T_{out} = G\ [T_{rx} + T_{atm}(1-e^{-\tau}) + T_{bg}e^{-\tau} + T_{source}e^{-\tau}\ ]$

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

Comparing in and out $\dfrac{V_{in} - V_{out}}{V_{out}} = \dfrac{T_{load}}{T_{sys}}$

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

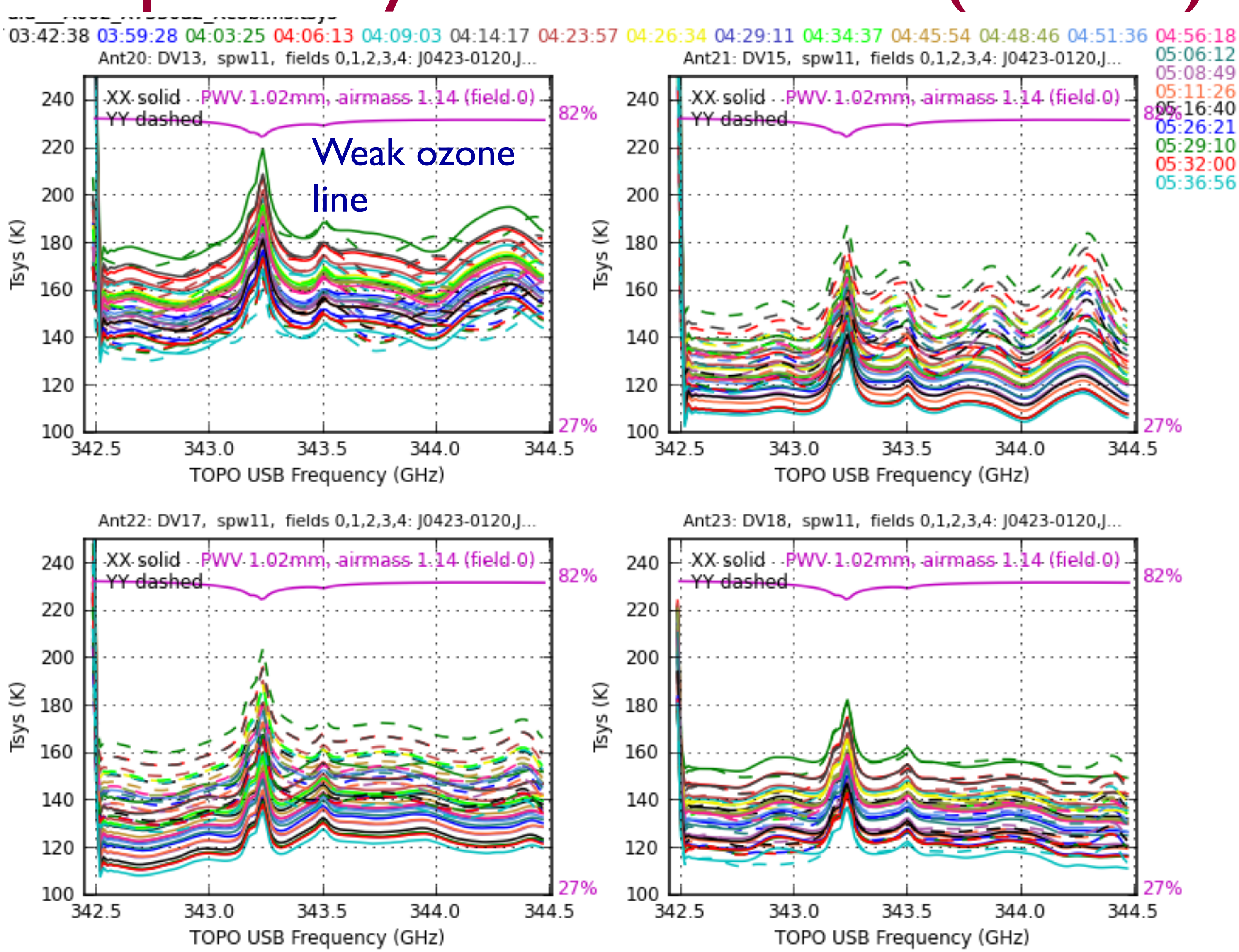
Power is really observed but is ∝ T in the R-J li



swings" in and out of beam

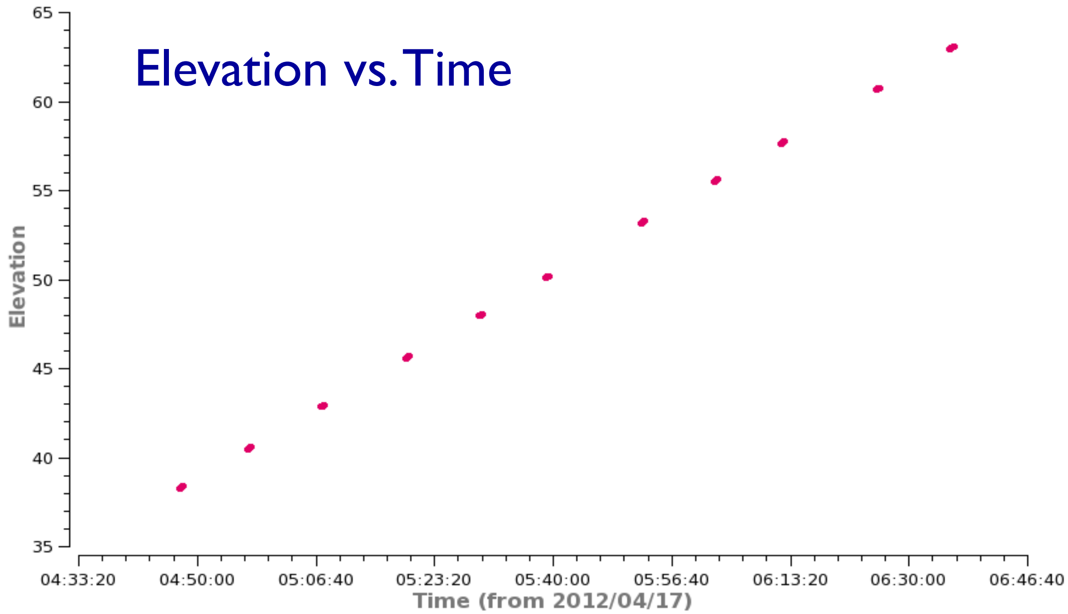
- IF $T_{atm} \approx T_{load}$, and T_{sys} is measured often, changes in mean atmospheric absorption are corrected. ALMA has a two temperature load system which allows independent measure of T_{rx}

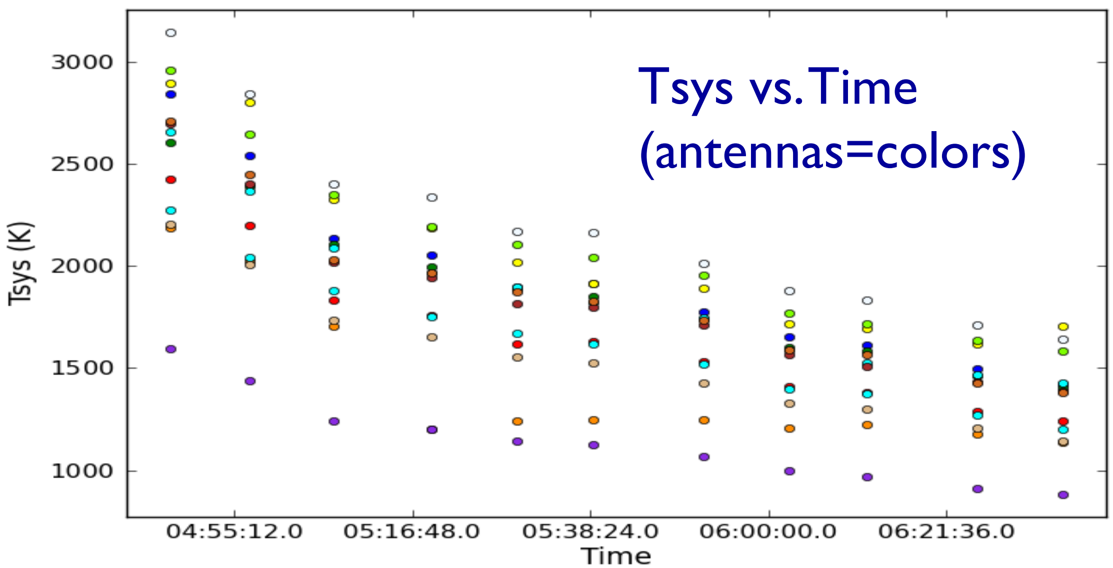
ALMA Spectral Tsys: 4 Antennas Band 6 (230 GHz)



Colors show changes with time (and sometimes source)

ALMA System Temperature: Example-1





ALMA Band 9 Test Data on the quasar NRAO530

Notice:

- Inverse relationship between elevation and Tsys

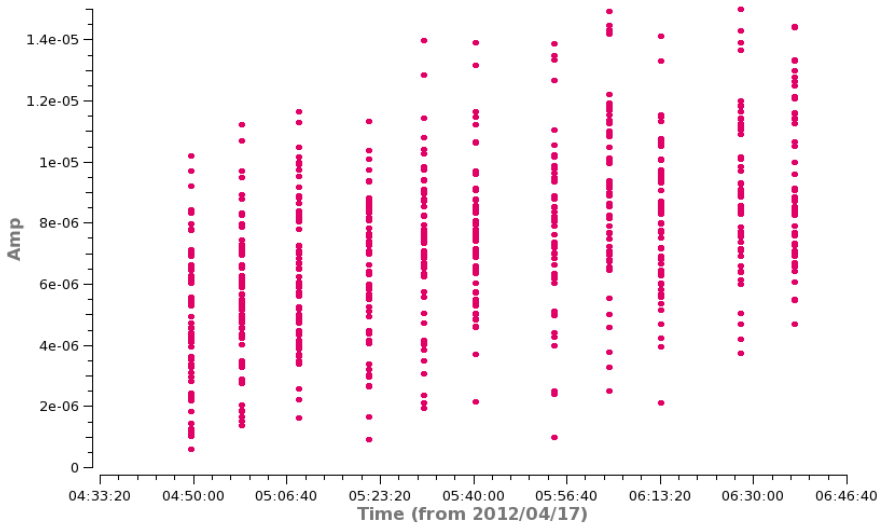
- Large variation of Tsys among the antennas

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

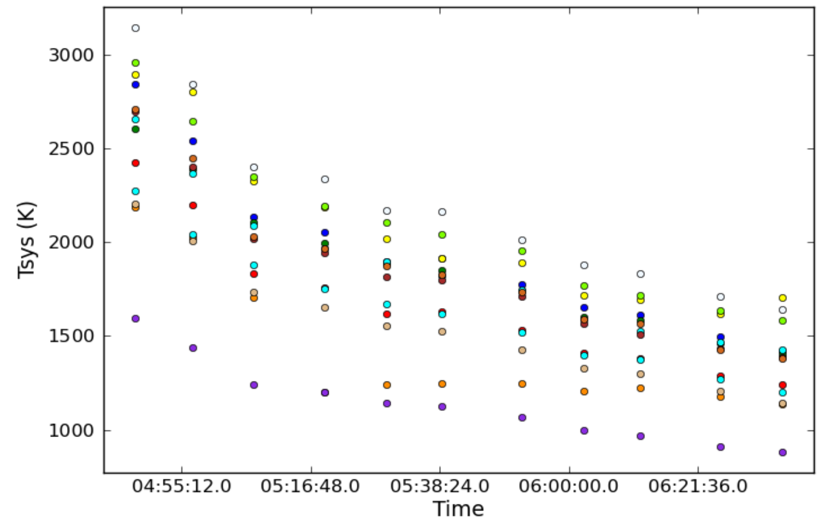
These weights are critical for good calibration and imaging

ALMA System Temperature: Example-2

Raw Amplitude vs. Time

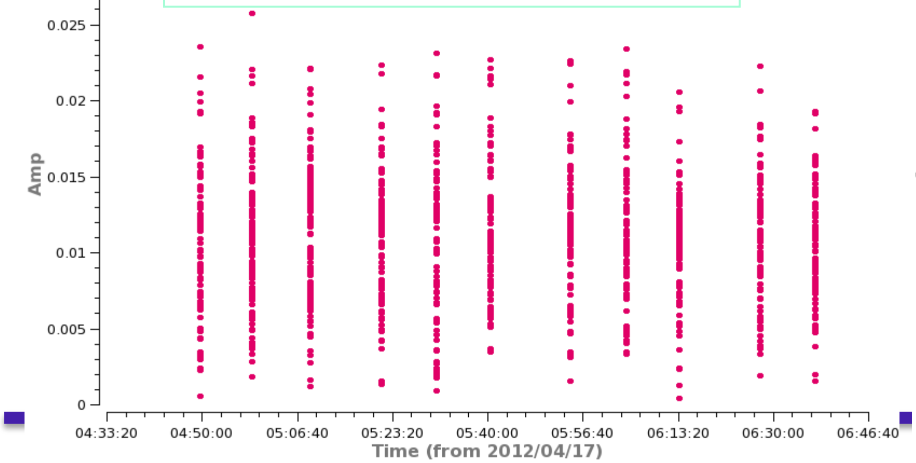


Tsys vs. Time (all antennas)



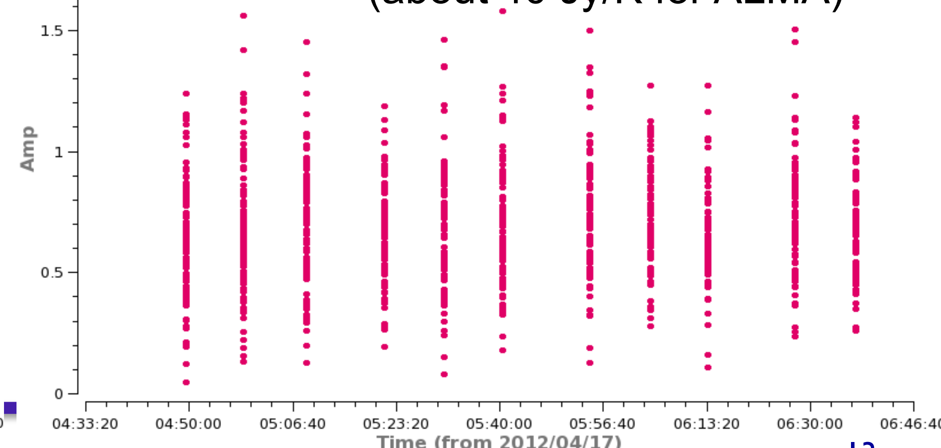
Amplitude Corrected for Tsys

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



Fully Calibrated using flux reference

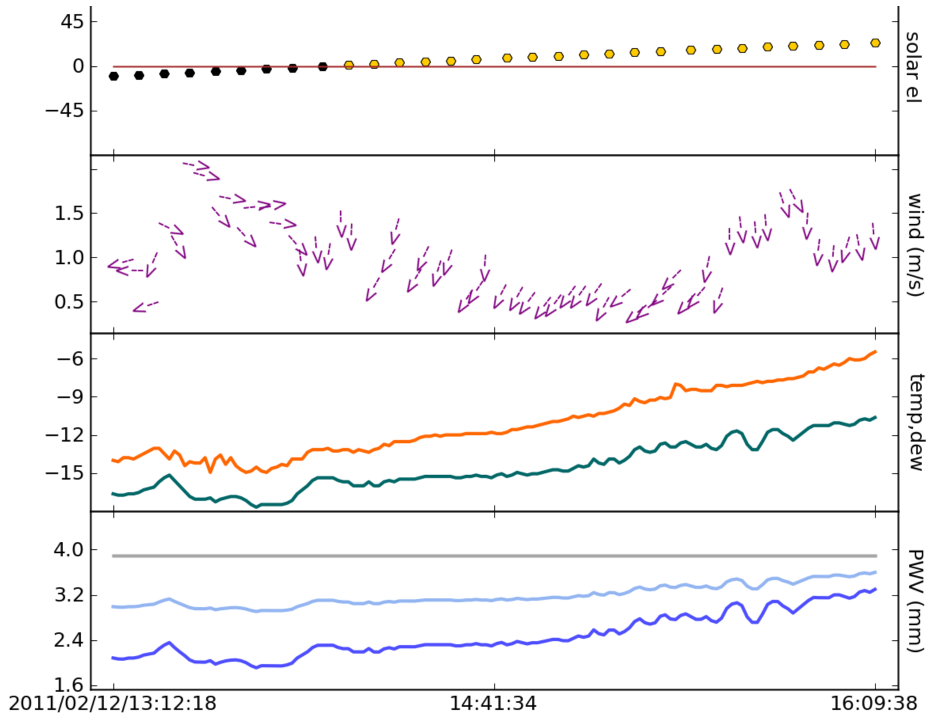
$S_{final} \sim S_{Tsys}$ * Antenna Efficiency Factor (about 40 Jy/K for ALMA)

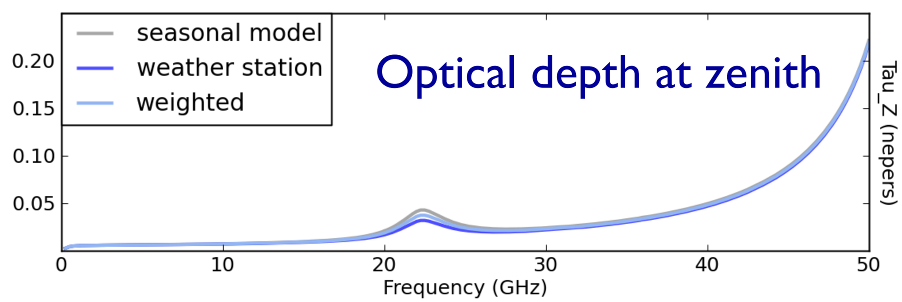


JVLA Atmospheric Correction

- At higher frequencies still need to account for atmospheric opacity and antenna gain variations with elevation (i.e. antenna gain curves)

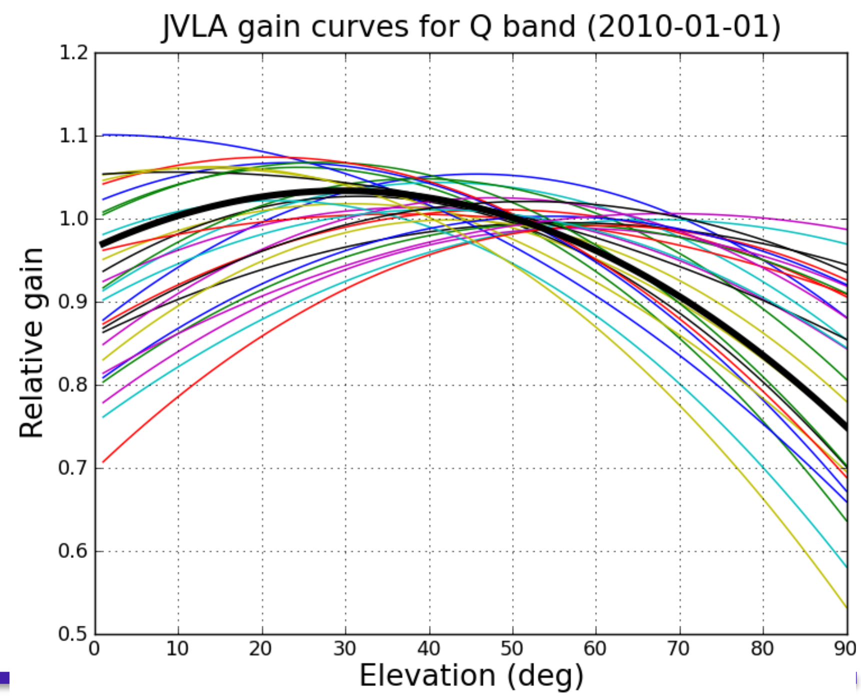
plotweather task available in CASA





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

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



JVLA 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 of gives sum & difference powers

3-bit or 8-bit signal → **Correlator**: Station Boards calculate **R** per second → Digitally Requantize to 4-bit → Correlation

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

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

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

Advantages

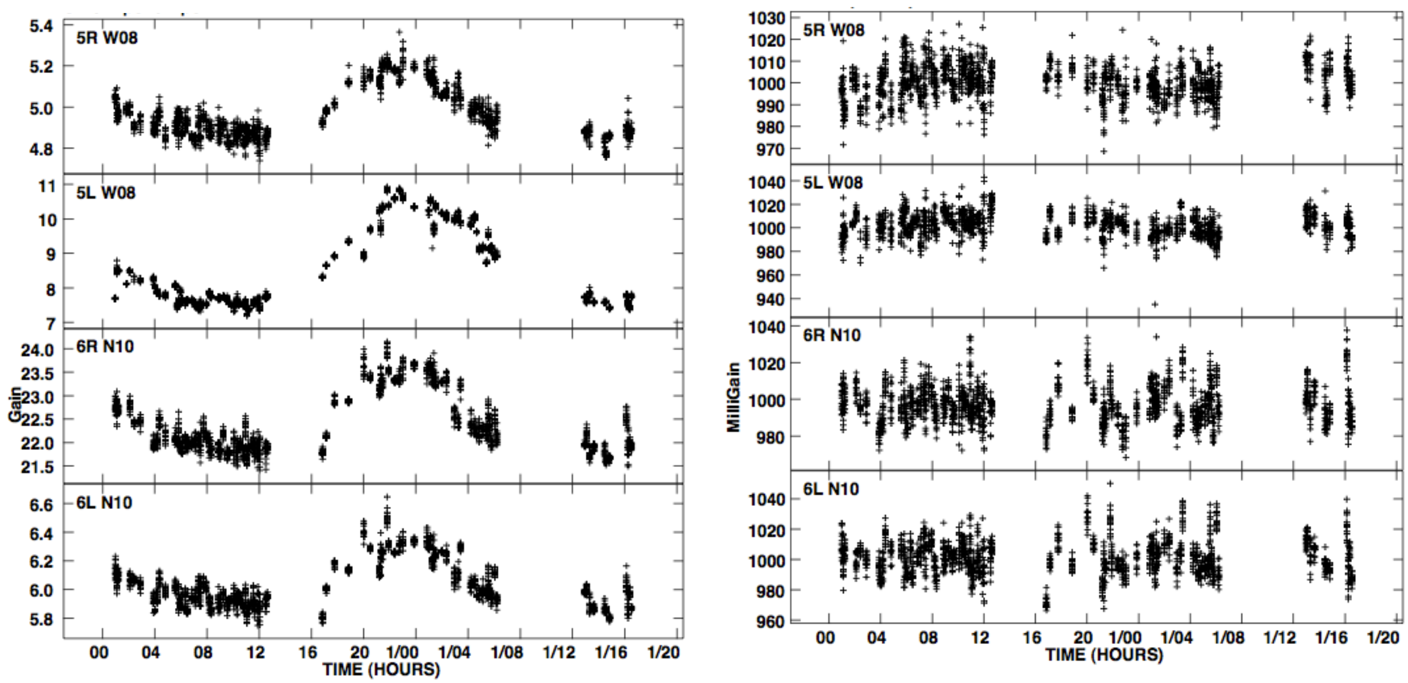
- Removes gain variations due to electronics between the diode and correlator on 1 second timescales
- Puts data on absolute temperature scale

Caveats:

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

JVLA 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

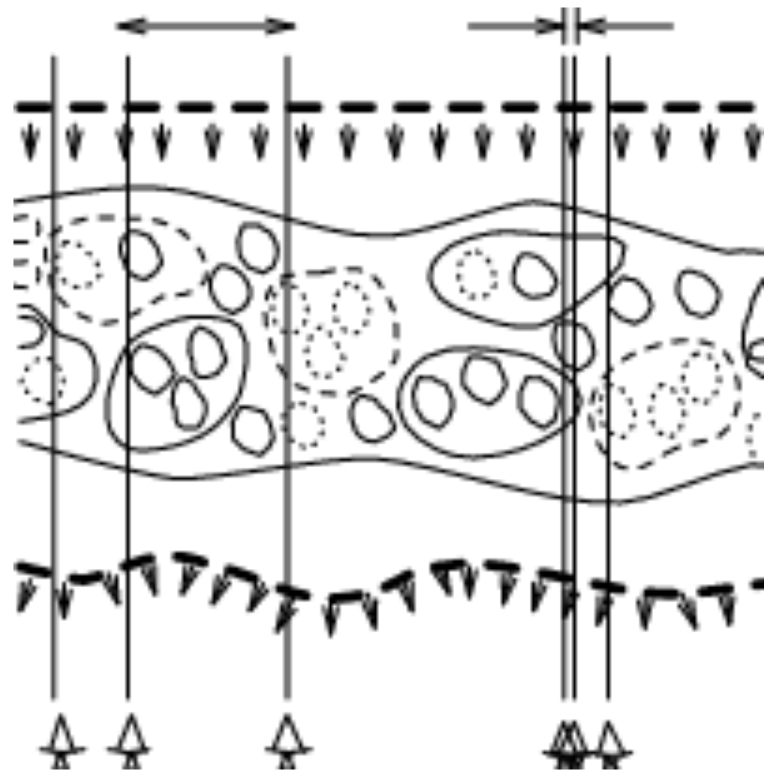
A science source will have similar gain variations with time, and only if you switch frequently to a strong calibrator for gain solutions can you TRY to take out these variations.

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

Atmospheric phase fluctuations

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

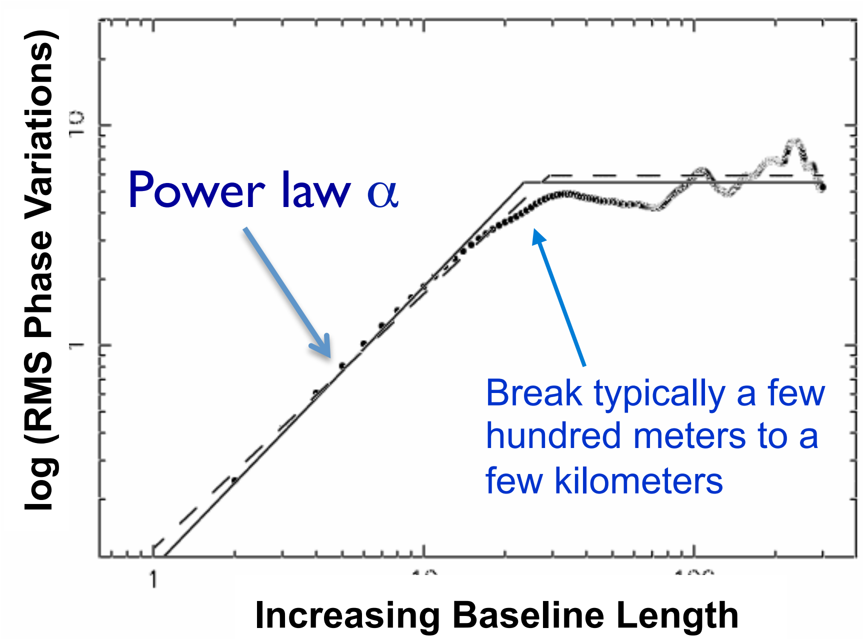
You can observe in apparently excellent submm weather (in terms of transparency, i.e. low PWV) and still have terrible "seeing" i.e. phase stability.



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

Atmospheric phase fluctuations, continued…

Phase noise as function of baseline length



- "Root phase structure function" (Butler & Desai 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 noise are weather and wavelength dependent

RMS phase of fluctuations given by Kolmogorov turbulence theory

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

b = baseline length (km)

α = 1/3 to 5/6 (thin atmosphere vs. thick atmosphere)

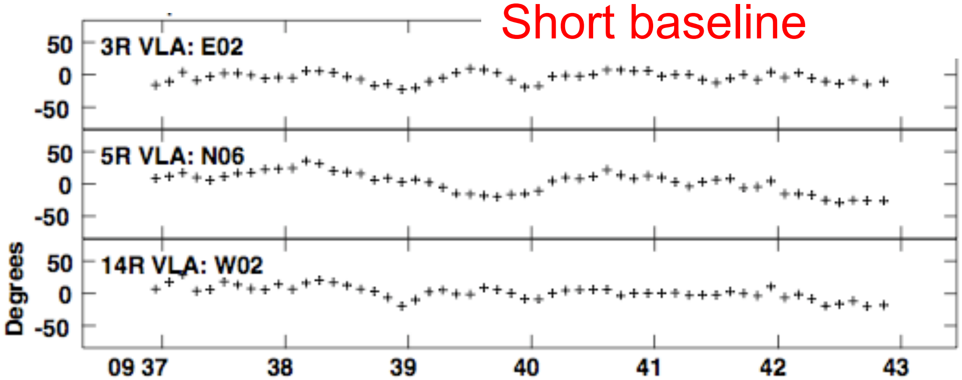
λ= wavelength (mm)

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

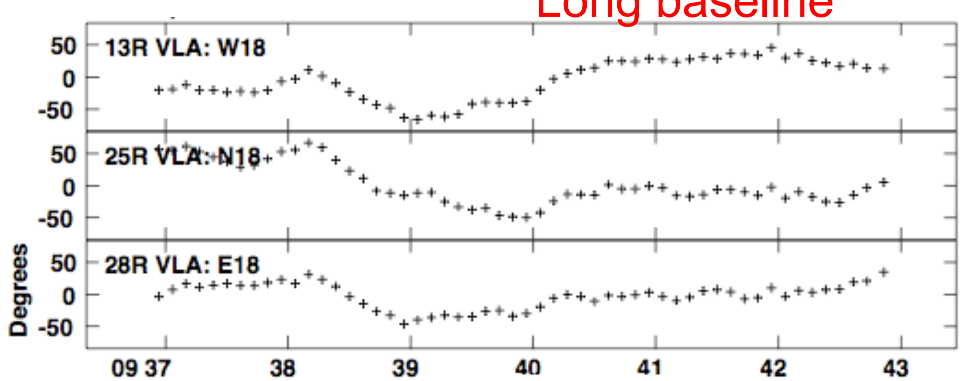
Residual Phase and Decorrelation

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, ϕ_{rms}, on the measured visibility amplitude :

$\langle V \rangle = V_0 \times \langle e^{i\phi} \rangle = V_0 \times e^{-\phi^2_{rms}/2}$
(Gaussian phase fluctuations)

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

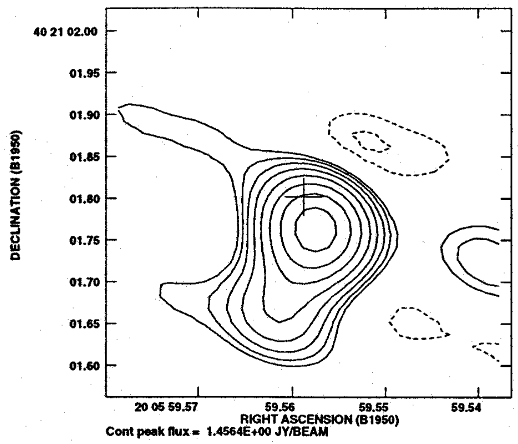
For these data, the residual rms phase (5-20 degrees) from applying an average phase solution produces a 7% error in the flux scale

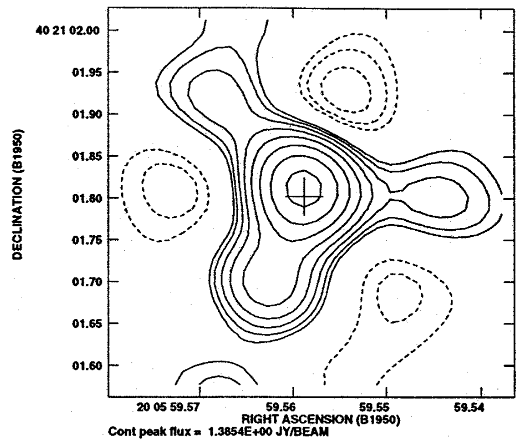
22 GHz VLA observations of the calibrator 2007+404

resolution of 0.1” (Max baseline 30 km)

one-minute snapshots at t = 0 and t = 59 minutes

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



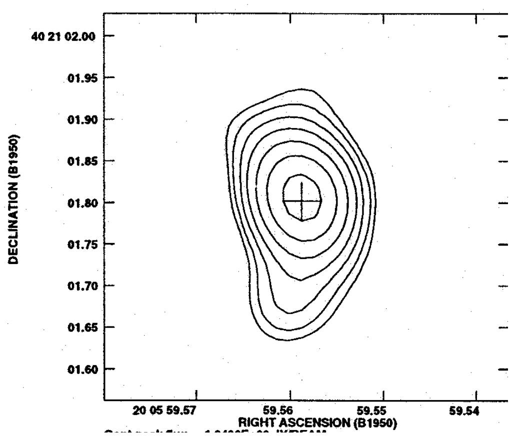


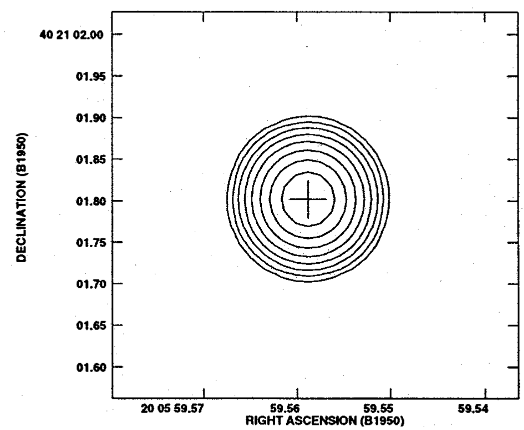
Sidelobe pattern shows signature of antenna based phase errors ⇨ small scale variations that are <u>uncorrelated</u>

Corrections 30min:

Corrections 30sec:

All data: Reduction in peak flux (decorrelation) and smearing due to phase fluctuations over 60 min





No sign of phase fluctuations with timescale ~ 30 s

- ⇨ Uncorrelated phase variations degrades and decorrelates image
- ⇨ Correlated phase offsets = position shift

Phase Correction Techniques

Phase fluctuation correction methods

- Fast switching: An Observing strategy - used at the EVLA for high frequencies and at ALMA for long baseline configs. Choose fast switching cycle time, t_{cyc}, short enough to reduce Φ_{rms} to an acceptable level. Calibrate in the normal way.
- Self-calibration: Good for bright sources that can be detected in a few seconds.
- Radiometer: Monitor phase (via path length) with special dedicated receivers
- Phase transfer: simultaneously observe low and high frequencies, and transfer scaled phase solutions from low to high frequency. Can be tricky, requires well characterized system due to differing electronics at the frequencies of interest.
- Paired array calibration: divide array into two separate arrays, one for observing the source, and another for observing a nearby calibrator.
  - Will not remove fluctuations caused by electronic phase noise
  - Can only work for arrays with large numbers of antennas (e.g., CARMA, JVLA, ALMA)

Fast Switching (an observing strategy)

Fast switching phase calibration will stop tropospheric phase fluctuations on baselines longer than an effective baseline length of:

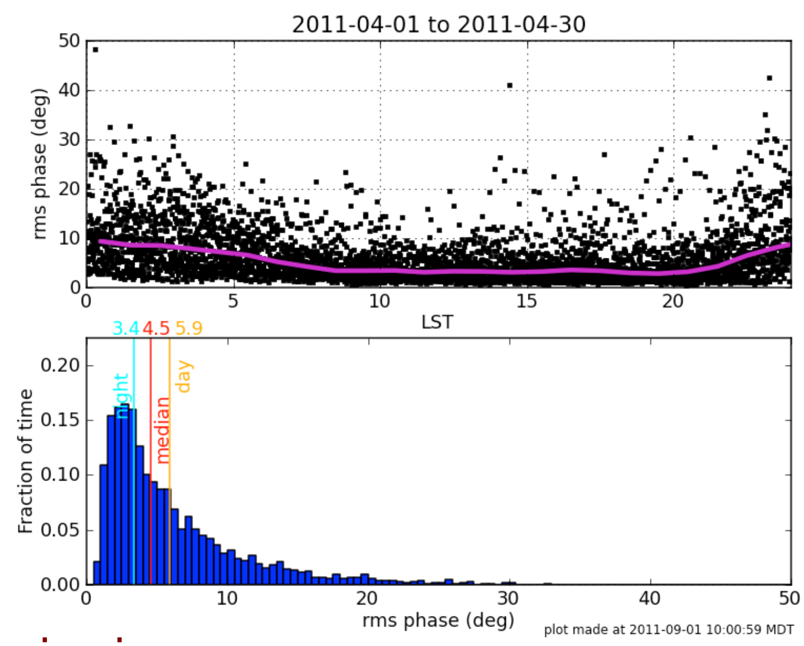
$$b_{eff} = \frac{V_a t_{cyc}}{2000}$$

b_{eff}: effective baseline length in km
V_a: velocity of the winds aloft in m/s (~10 m/s at JVLA)
t_{cyc}: cycle time in seconds (~120 sec)

Cycle times shorter than the baseline crossing time of the troposphere are needed. For example, substituting into the phase rms Eq on slide 17 with α = 0.7 and Va=10m/s (typical for JVLA site) yields:

$$t_{cyc}(s) = 200\left(\frac{\phi_{rms}(\mathrm{deg})\lambda(mm)}{K}\right)^{1.42}$$

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



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

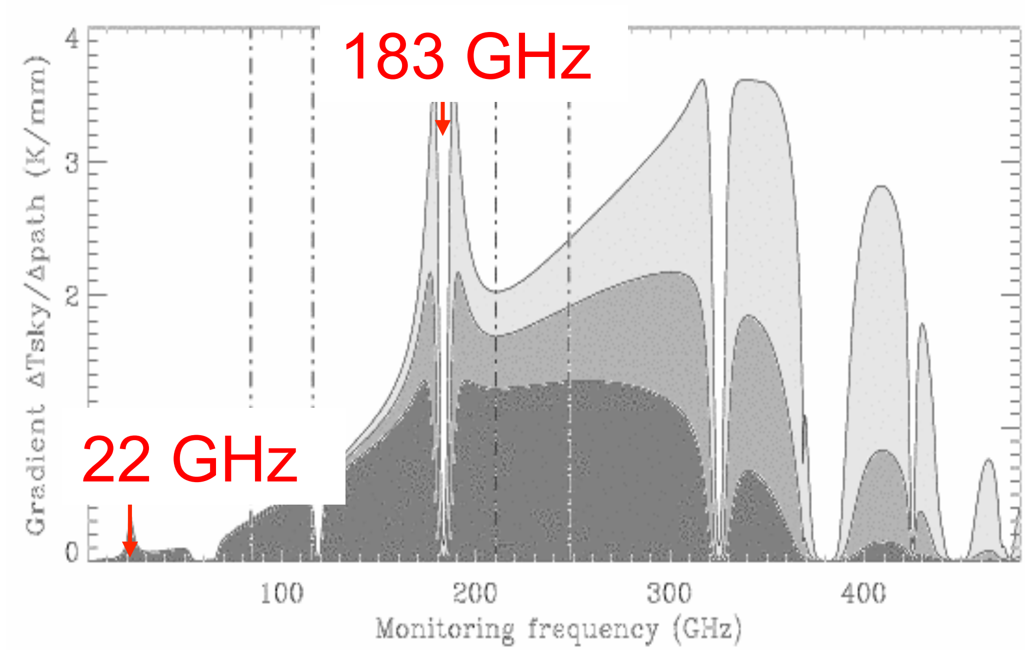
JVLA Phase monitor:
https://webtest.aoc.nrao.edu/cgi-bin/thunter/api.cgi

Radiometers (an observing strategy):

- Radiometry: measure fluctuations in T_B^{atm} with a radiometer, use these to derive changes in water vapor column (w) and convert this into a phase correction using

$$\phi_e \approx \frac{12.6\pi \times w}{\lambda}$$

w=precipitable water vapor (PWV) column

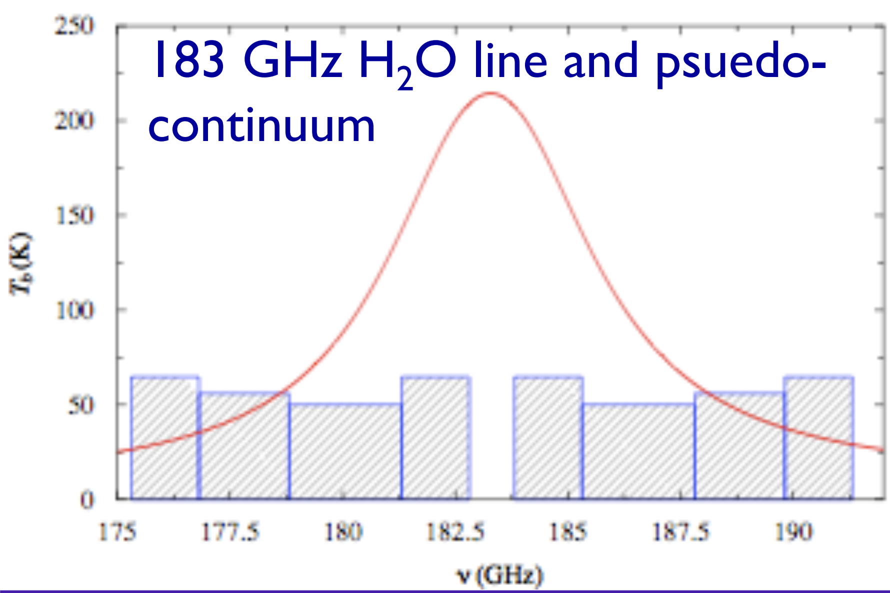


(Bremer et al. 1997)

Monitor: 22 GHz H_2O line (CARMA, VLA)
183 GHz H_2O line (CSO-JCMT, SMA, ALMA)
total power (IRAM)

ALMA's particular need for WVR correction:

- ALMA site testing suggests that the median path fluctuation due to the atmosphere is ~200 microns on 300 m baselines. The fluctuations increase with baseline length (up to several km) according to Kolmogorov with a power of about 0.6 for the ALMA site.
- Even on 300 m baselines, observations at 300 microns (Band 10) require a path error less than 25 microns for phases better than 30 degrees. ALMA maximum baseline is 15 km!
- Changes on timescales of Antenna diameter/wind speed are possible = 1 sec



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

Installed on all the 12m antennas

- Data taken every second
- Matching data from opposite sides are averaged
- The four channels allow flexibility for avoiding saturation

Modeling the Path Change

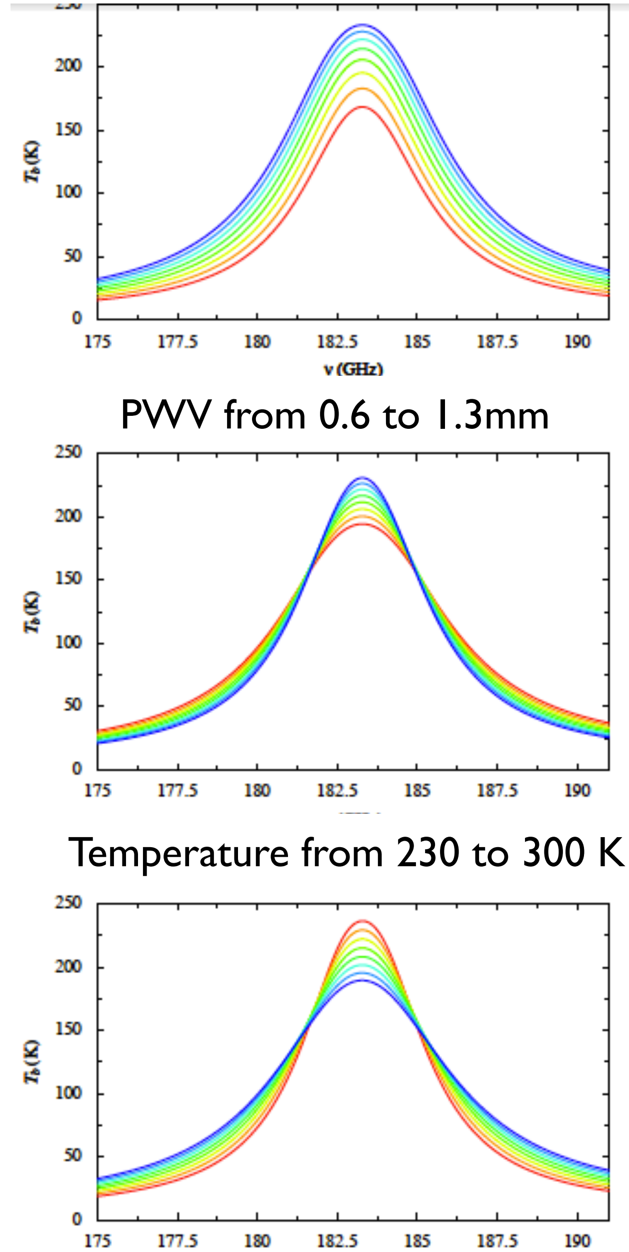
Challenge: Convert changes in 183 GHz brightness to changes in path length

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:

  Δ(path) = Δ(PWV) * 1741/T(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



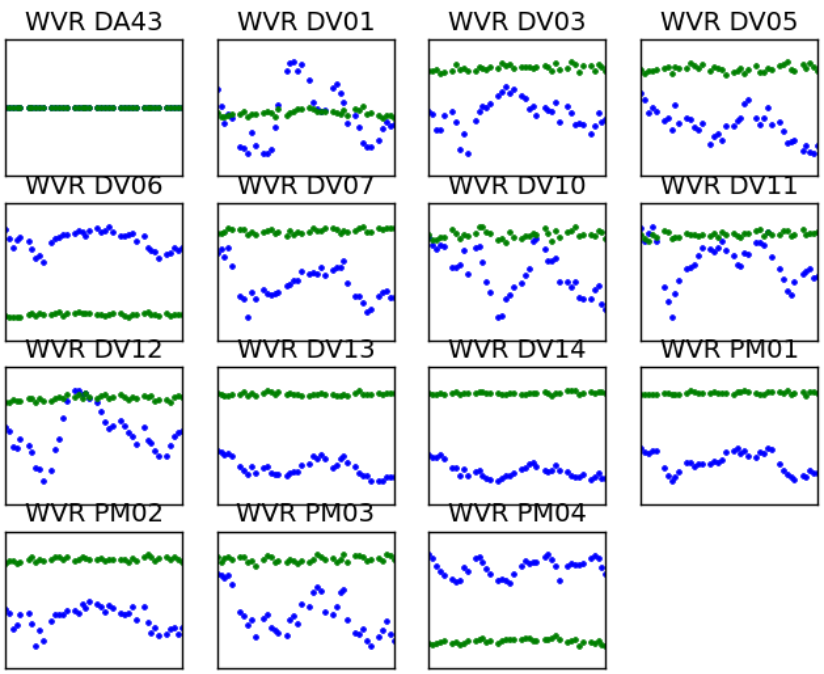
PWV from 0.6 to 1.3mm

Temperature from 230 to 300 K

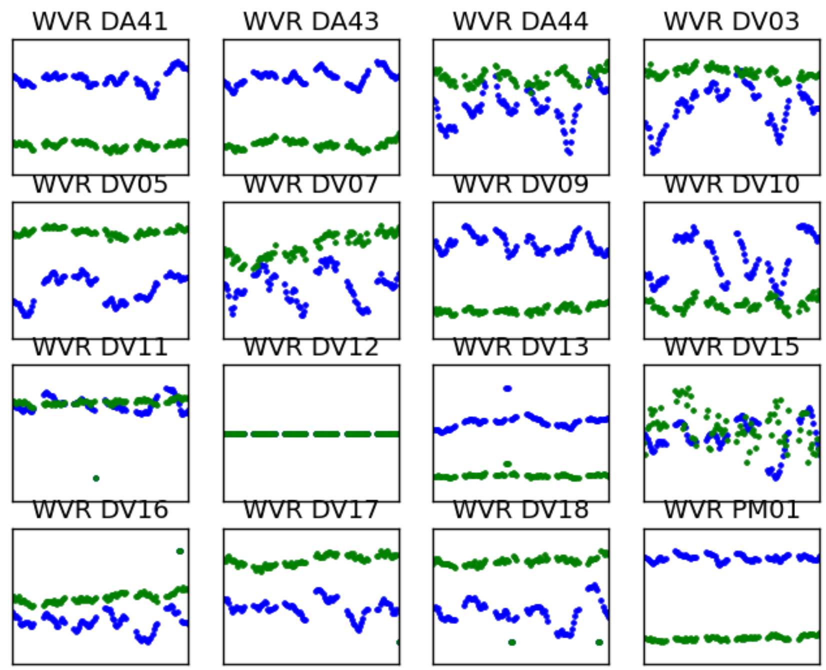
Pressure from 400 to 750 mBar

ALMA WVR Correction - Examples

Band 6 (230 GHz) Compact config



Band 7 (340 GHz) Extended config



Raw phase & WVR corrected phase

Self-Calibration: Motivation

JVLA 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 (when done correctly and conservatively). 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 temporal gain calibration which leads to a better source image.

Self-cal may not be included in the data pipelines. SO, YOU SHOULD LEARN HOW TO DO IT.

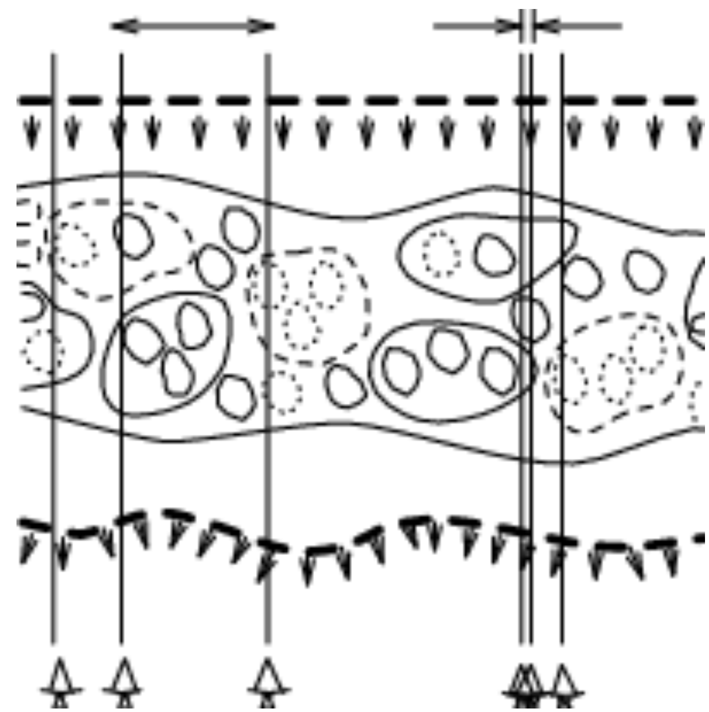
Data Corruption Types

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 hopefully small)

$V_{ij}(t)$ - True Visibility

$\varepsilon_{ij}(t) + \epsilon_{ij}(t)$ Additive offset (not antenna based and hopefully small) and thermal noise, respectively

  - Can typically 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 $M_{i,j}$ $(t_{k,}\, \nu)$
- Determine gain corrections, g_i, that minimizes S_k for each time stamp t_k where

$$S_k = \sum_k \sum_{i,j}^{i \neq j} \underbrace{w_{i,j}}_{\text{Data Weights}} \, |\underbrace{g_i(t_k) g_j^*(t_k)}_{\text{Complex Gains}} \underbrace{V_{i,j}^o(t_k)}_{\text{Complex Visibilities}} - \underbrace{M_{i,j}(t_k)}_{\text{Fourier transform of model image}}|^2$$

- The solution interval, **t_k**, is the data averaging time used to obtain the values of g_i, (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 science target image** for Self-calibration

Sensitivities for Self-Calibration-I

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

- Make an initial image, cleaning it conservatively
  - Measure rms in emission free region
  - rms_{Ant} = rms x sqrt(N-3) where N is # of antennas
  - rms_{self} = rms_{Ant} x sqrt(total time/solint)
  - Measure Peak flux density = Signal
  - If S/N_{self} = Peak/rms_{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 the image
  - If 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 > 10, in a solution time (solint) < 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, give 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
  - Caveat 1: Only if your source is unpolarized
- Combine = 'spw' to average spw's (assumes prior removal of spw to spw offsets)
  - Caveat 1: If source spectral index/morphology changes significantly across the band, do not combine spws, especially for amplitude self-cal
- Combine = 'fields' to average fields in a mosaic (use with caution, only fields with strong signal)

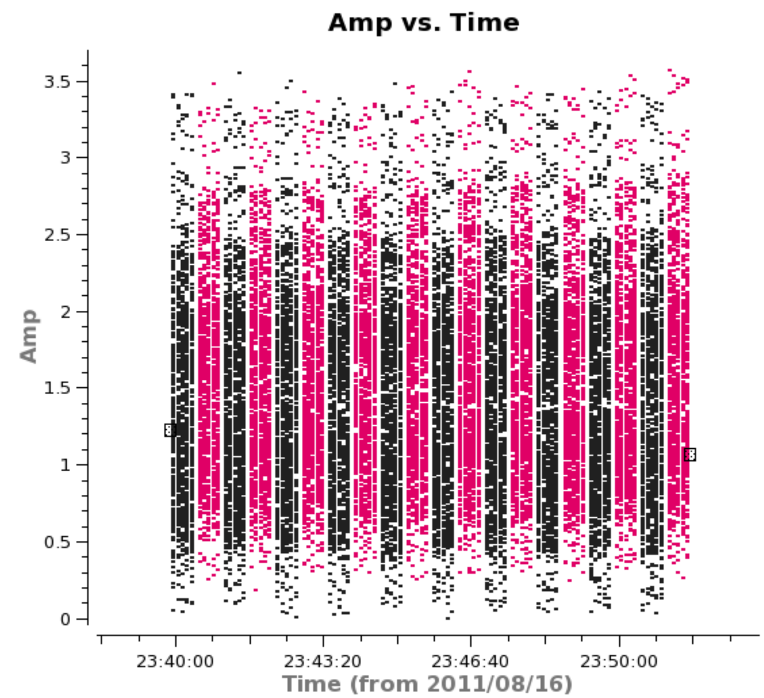
Self-calibration Example:
ALMA SV Data for IRAS16293 Band 6 (Ia)

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

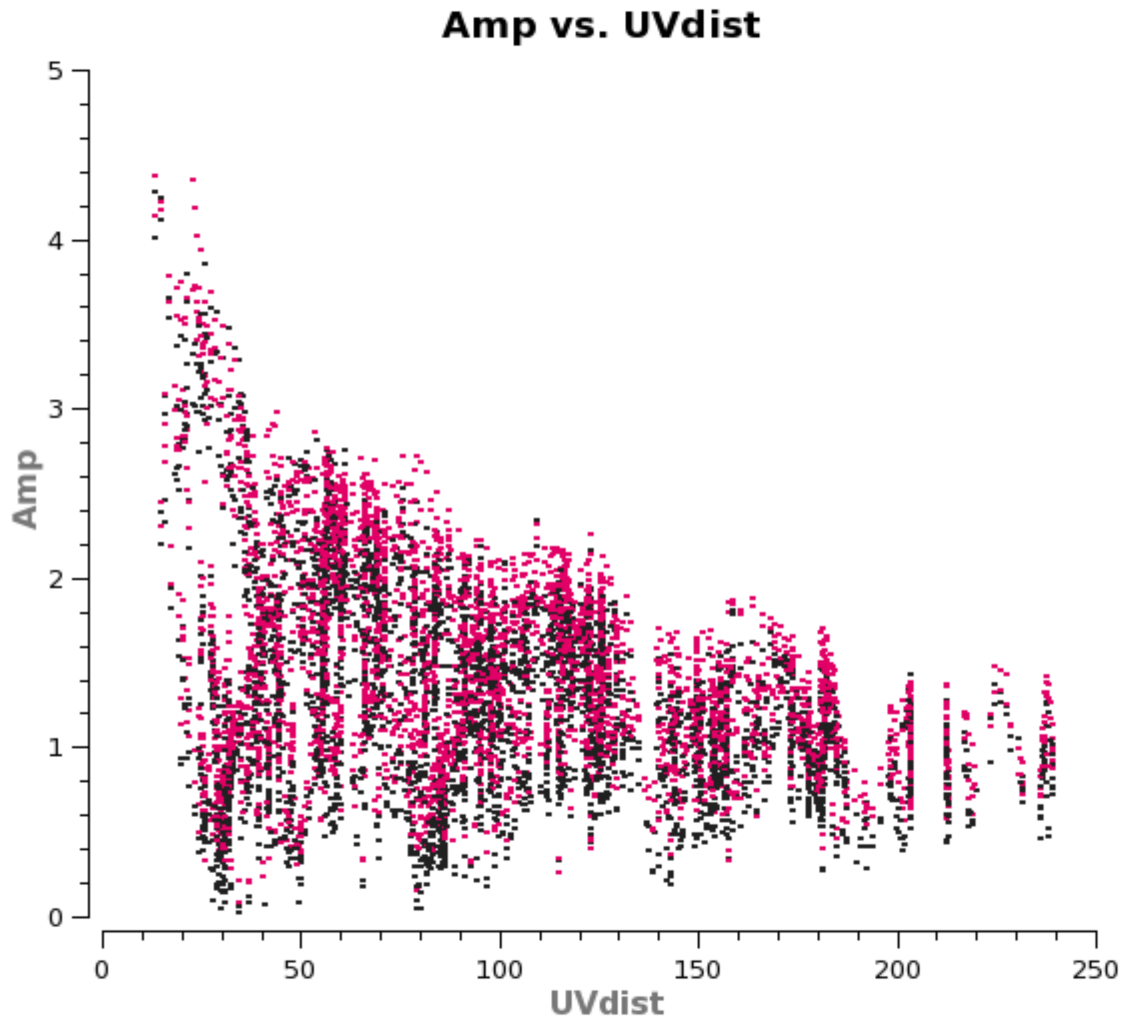


- ALMA mosaic: alternates fields in "subscan" this picture = 1 scan
- EVLA mosaic: alternates fields in scans
- Subscans are transparent to CASA (and AIPS)

Self-calibration Example:
ALMA SV Data for IRAS16293 Band 6 (1b)

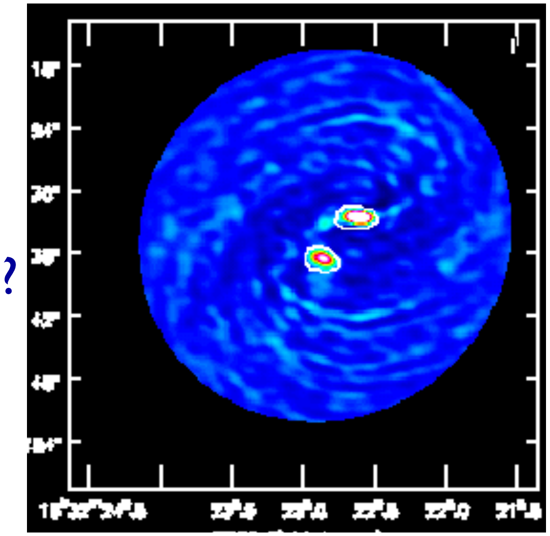
Step 3 – What does the amplitude vs uv-distance of your source look like?

- 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?



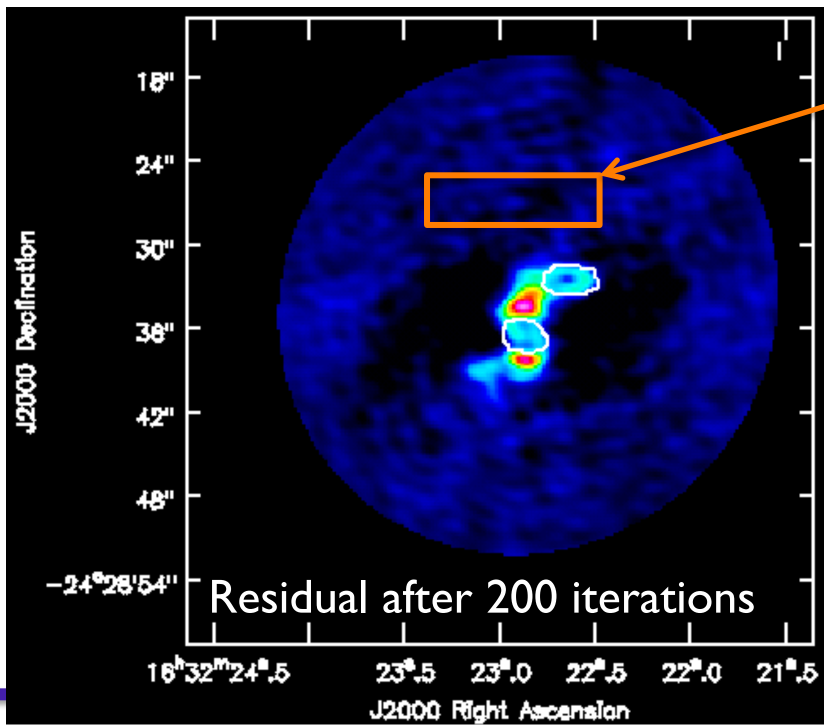
Self-calibration Example:

ALMA SV Data for IRAS16293 Band 6 (II)

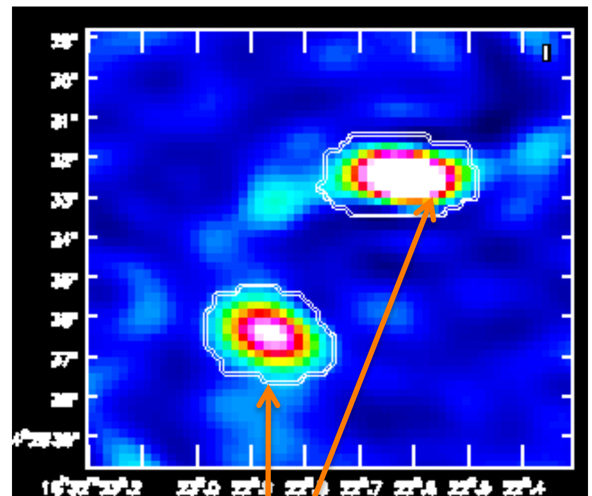


Step 4 – What is the S/N in a conservatively cleaned image?

- 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!



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

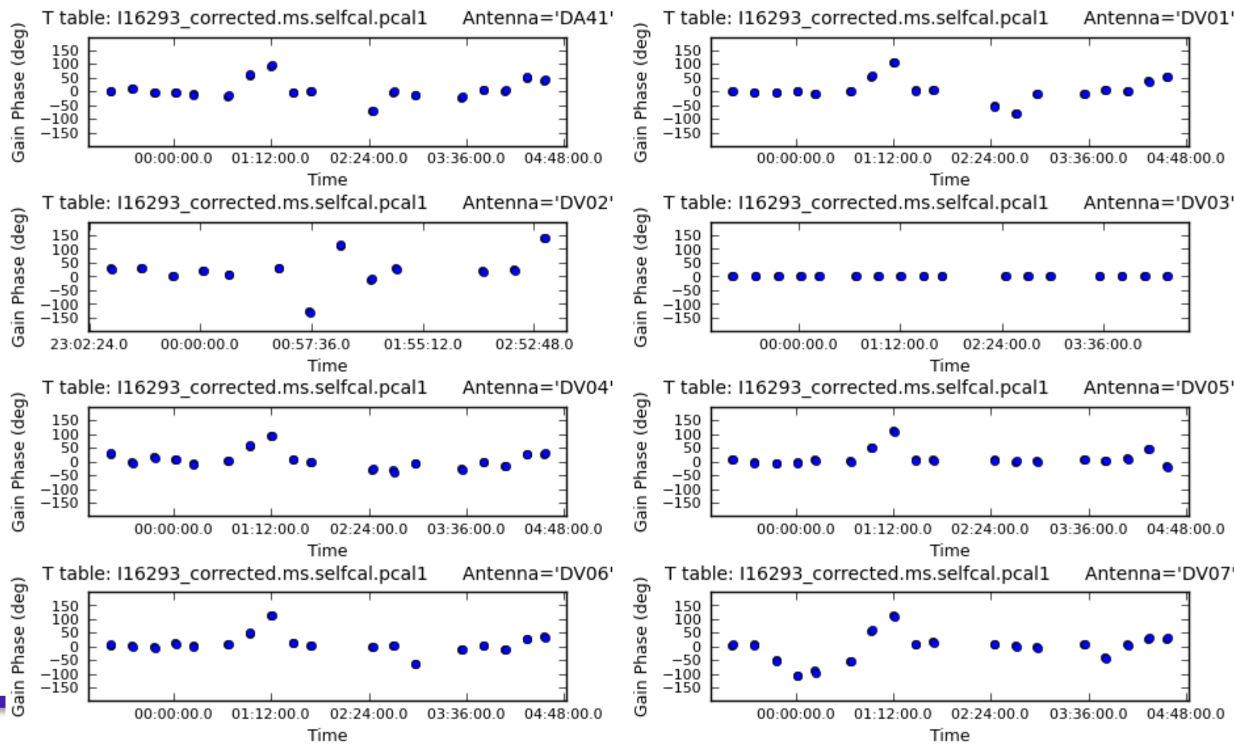


Clean boxes only around emission you are SURE are real at this stage

Self-calibration Example:
ALMA SV Data for IRAS16293 Band 6 (III)

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

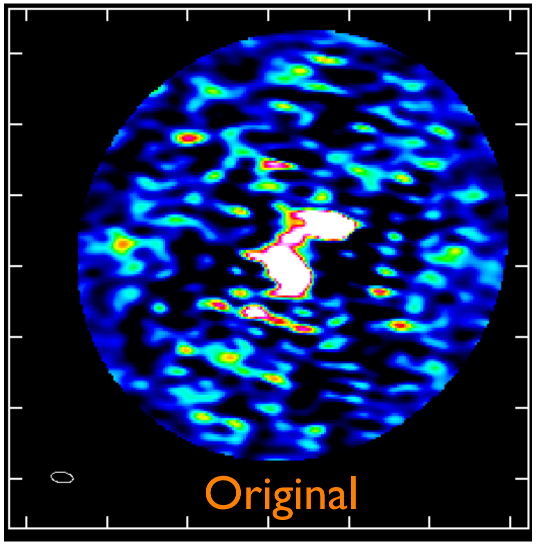
- A good choice is often the scan length (in this case about 5 minutes per field)
  - Exercise for reader: from page 31 show that $S/N_{self} \sim 5.4$
- In CASA you can just set solint='inf' (i.e. infinity) and as long as combine ≠ 'scan' AND ≠ 'field' you will get one solution per scan, per field.
- Use 'T' solution to combine polarizations



What to look for:

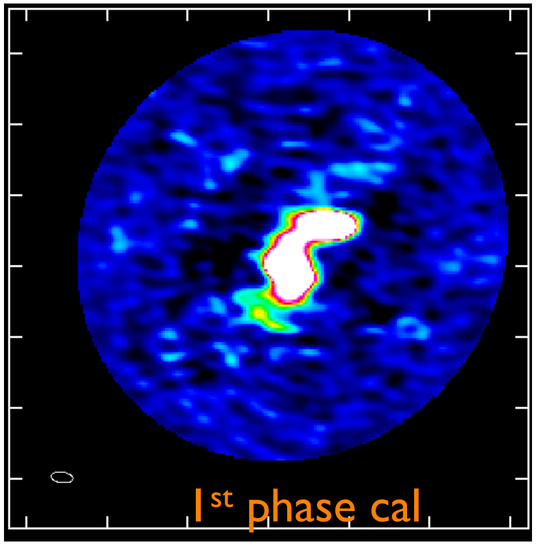
- Lot of failed solutions on most antennas? if so, go back and try to increase S/N of solution = more averaging of some kind
- Do the phases appear smoothly varying with time (as opposed to noise like)

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:

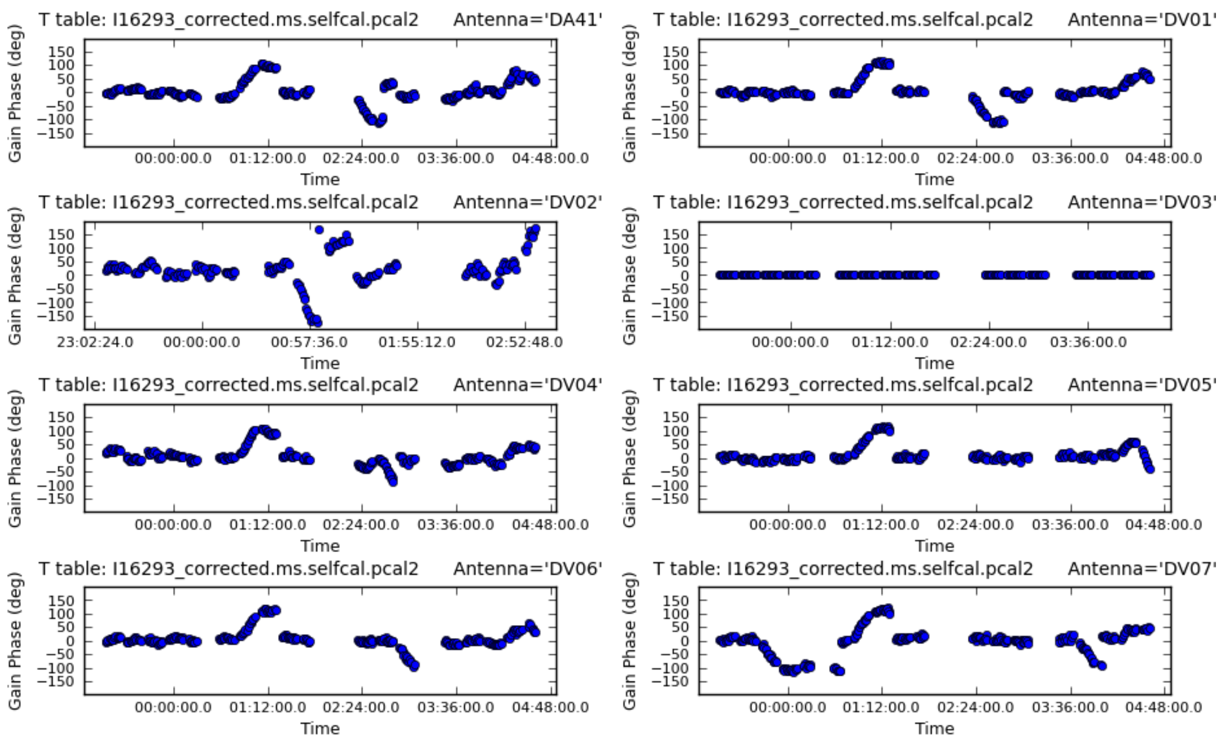
  Rms~ 15 mJy/beam; Peak ~ 1 Jy/beam ➔ S/N ~ 67
- 1st phase-only:

  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

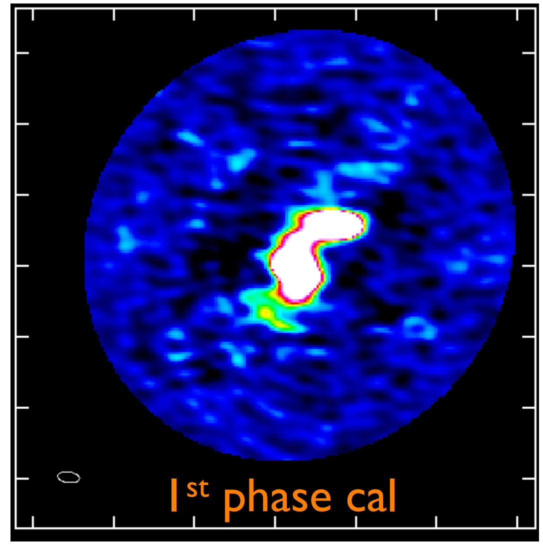
- In this case we'll try the subscan length of 30sec
- It is best NOT to apply the 1st self-cal while solving for the 2nd. i.e. incremental tables can be easier to interpret but you can also "build in" errors in first model by doing this



What to look for:

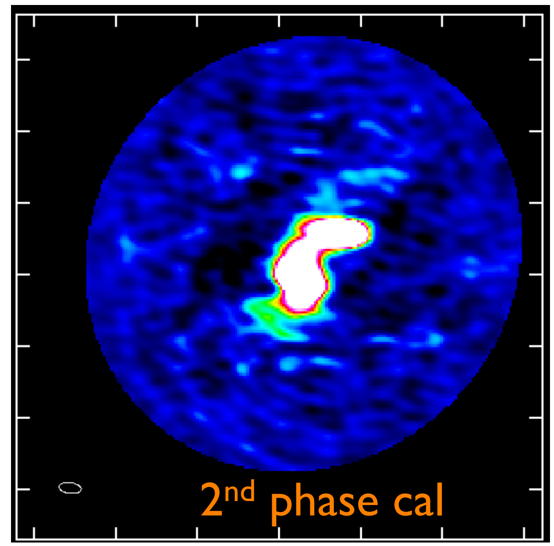
- Still smoothly varying?
- If this looks noisy, go back and stick with longer solint solution
- IF this improves things a lot, could try going to even shorter solint

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



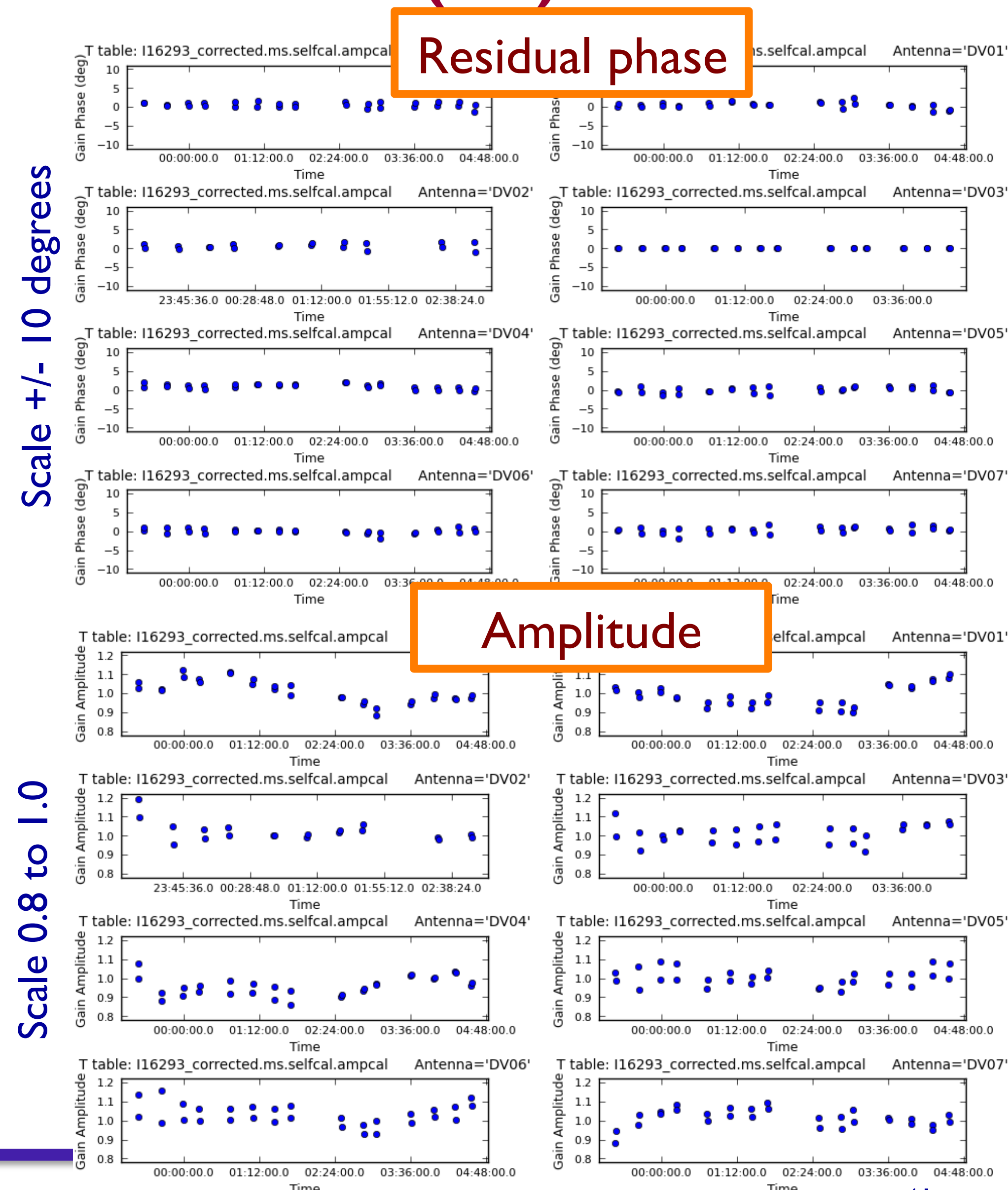
Step 10: Compare 1st and 2nd phase-only self-cal images

- 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 before 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.



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

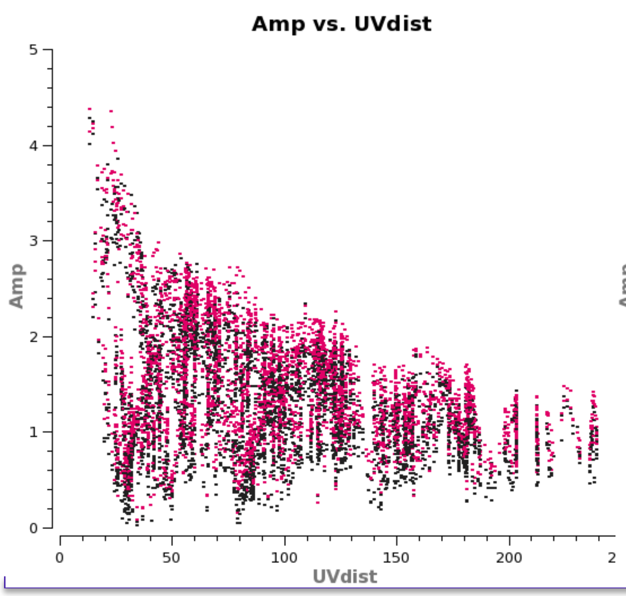
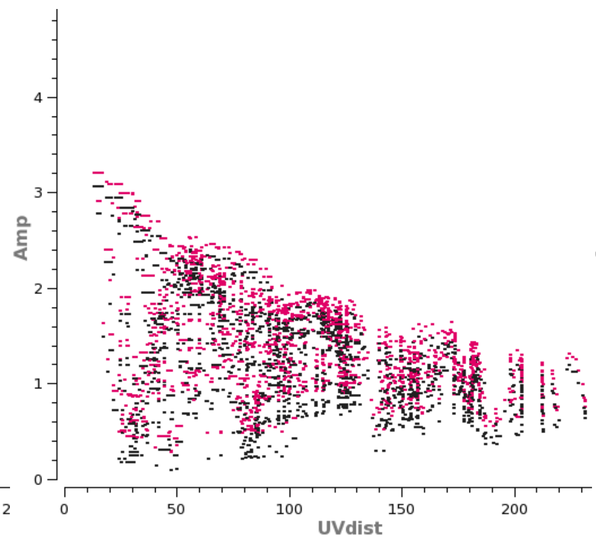
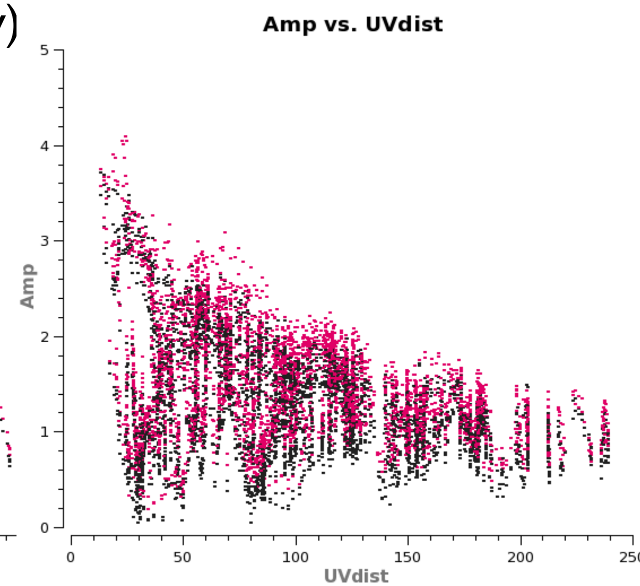


Image Model

(total cleaned flux = 3.4 Jy)



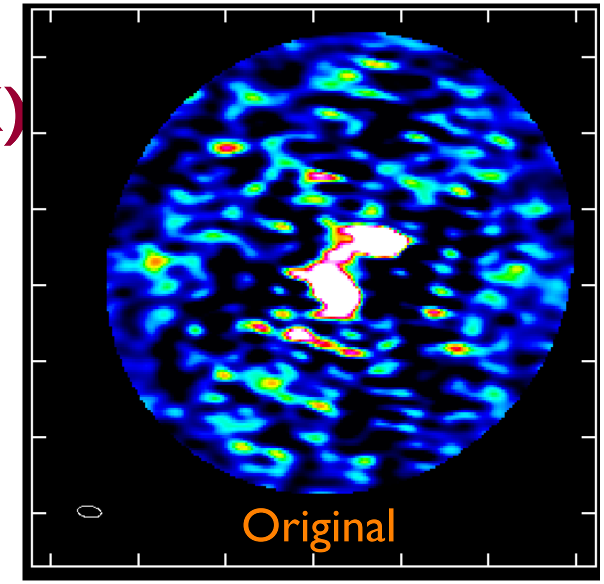
Amp & Phase applied



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

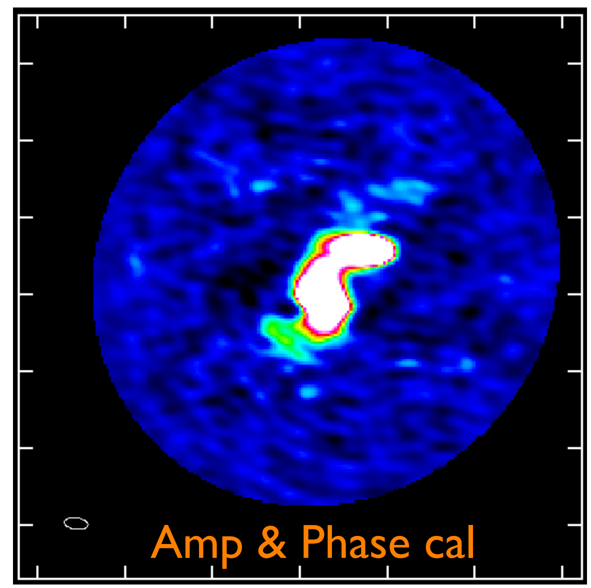


Step 14: Compare 2nd phase-only and amp+phase self-cal images

- 2nd phase-only:

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

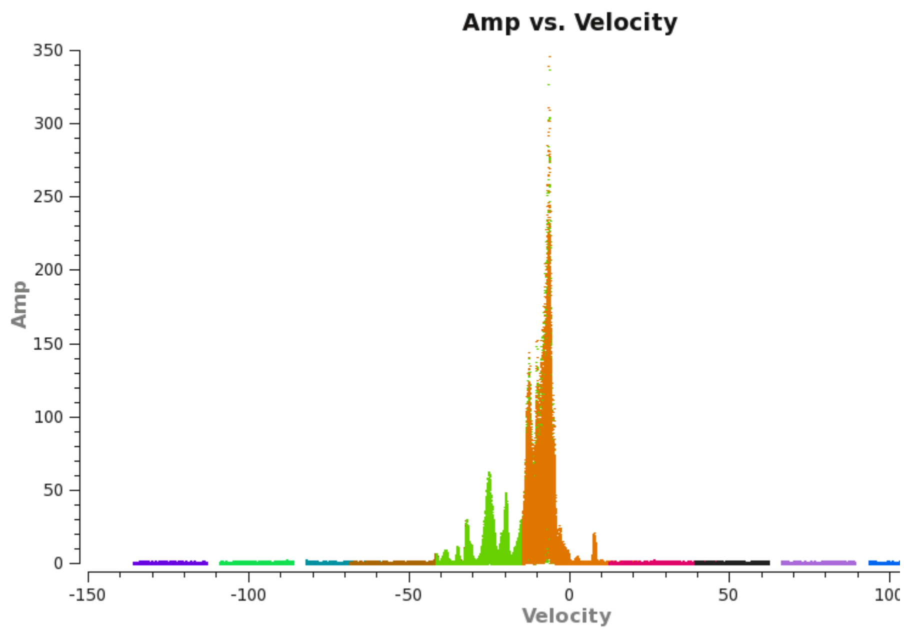
  Rms~4.6 mJy/beam; Peak~1.30 Jy/beam ➔ S/N ~283
- Did it improve? ➔ Done!



Final: S/N=67 vs 283!

But not as good as theoretical = dynamic range limit

Self-Calibration example 2: JVLA 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?

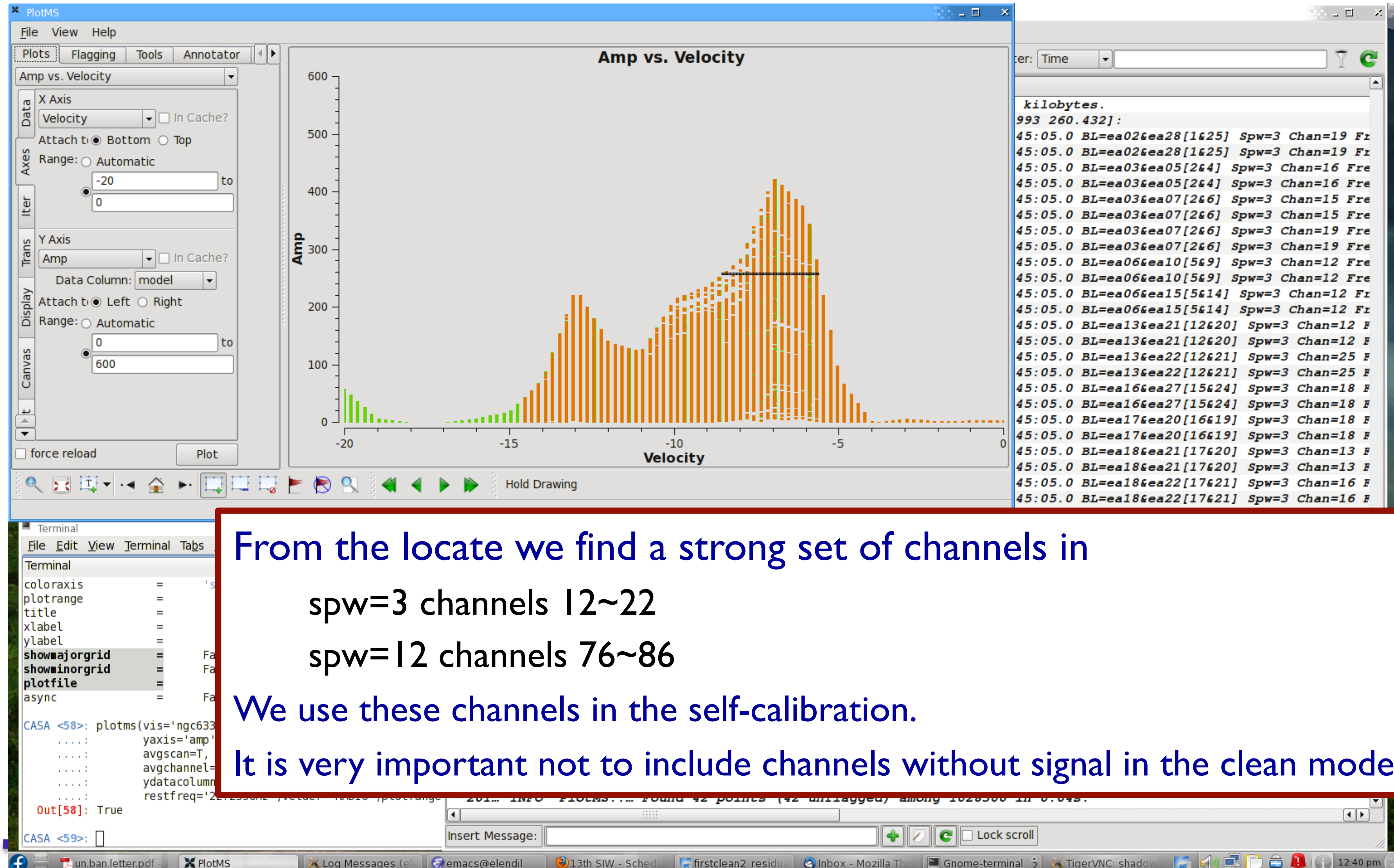
NOTE: In general unless you've already run CVEL, DATA CHANNEL NUMBER ≠ IMAGE CHANNEL NUMBER due to Doppler Shift

- Make an image and clean it conservatively (as described previously)
  - If you want to speed things up, limit the velocity to the region with strong emission in the uv-plot: -20 to 0 km/s in this case in the frame of your choice (LSRK here).
  - Then look at the model data column the same way with plotms

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

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

CASA's plotms of the MODEL with locate can help



From the locate we find a strong set of channels in

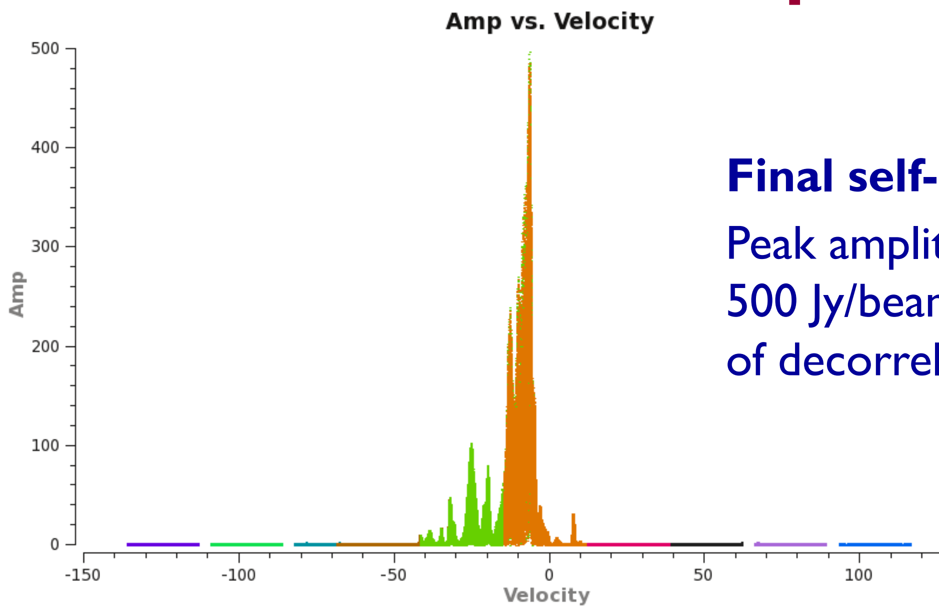
spw=3 channels 12~22

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: JVLA 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.

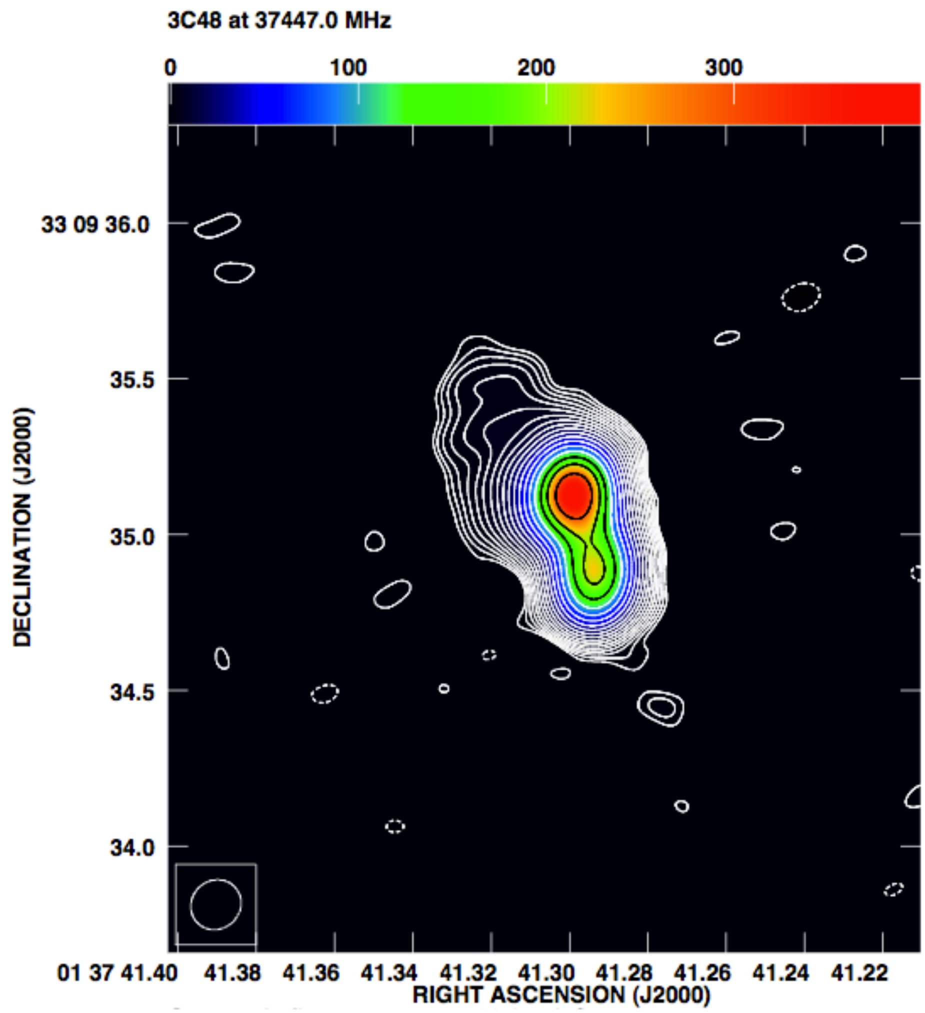
Absolute Flux Calibrators

Flux calibrators – JVLA

JVLA Flux Calibrators
3C 48 (0137+331)
3C286 (1331+305)
3C138 (0521+166)
3C147 (0542+498)

Stable brightness and morphology, but are resolved on long baselines
and high frequencies.

An image model must be used

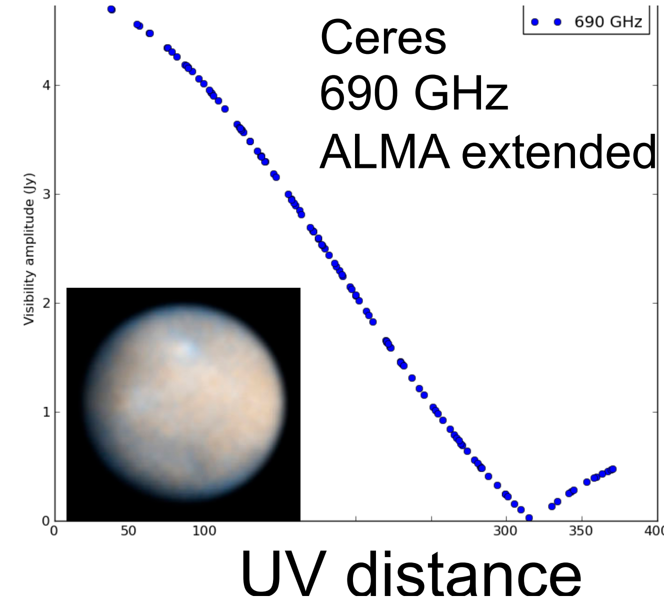


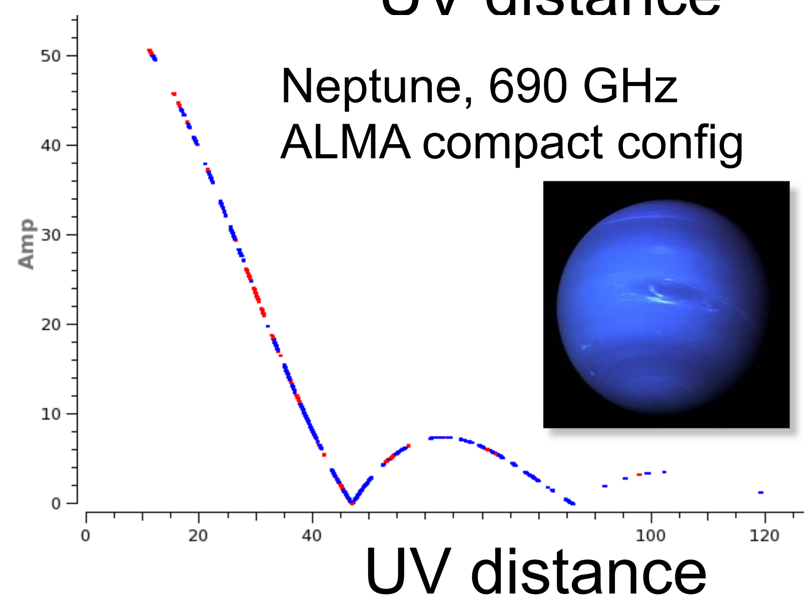
Flux calibrators – ALMA

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

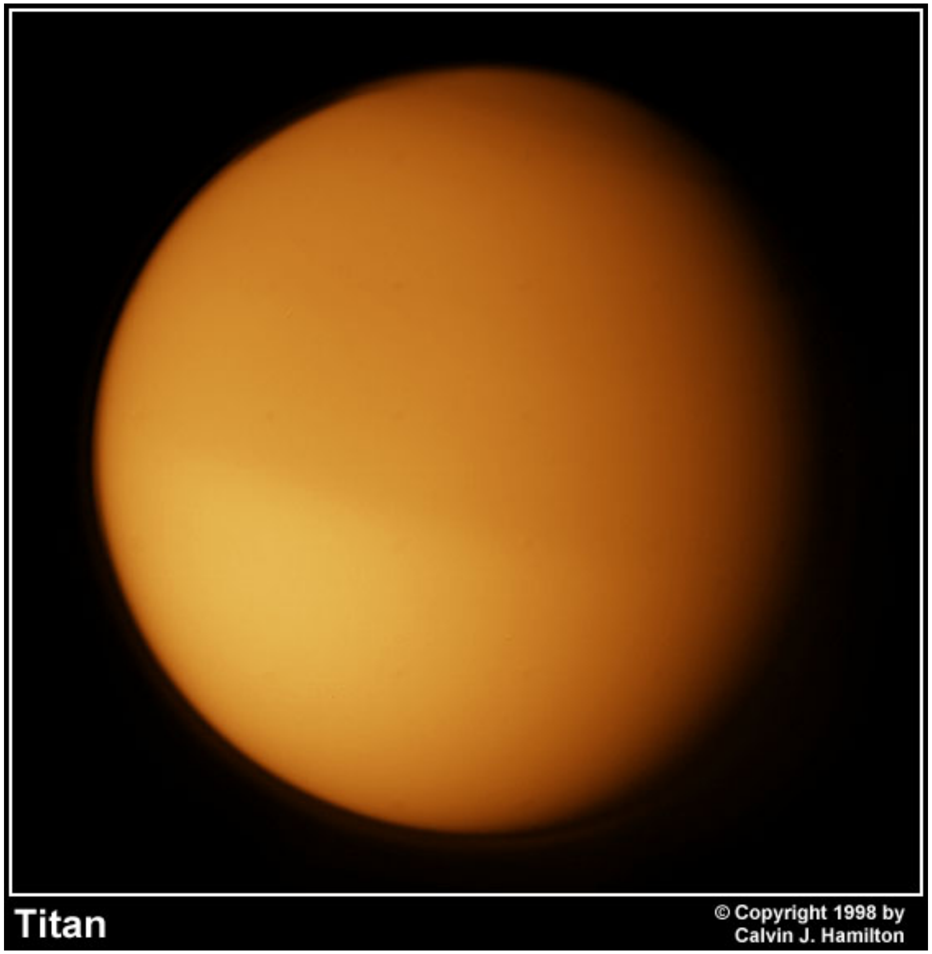
- Solar system bodies are used as primary flux calibrators (Neptune, Jovian moons, Titan, Ceres) but with many challenges:
  - All are resolved on long ALMA baselines
  - Brightness varies with distance from Sun and Earth
  - Line emission (Neptune, Titan)

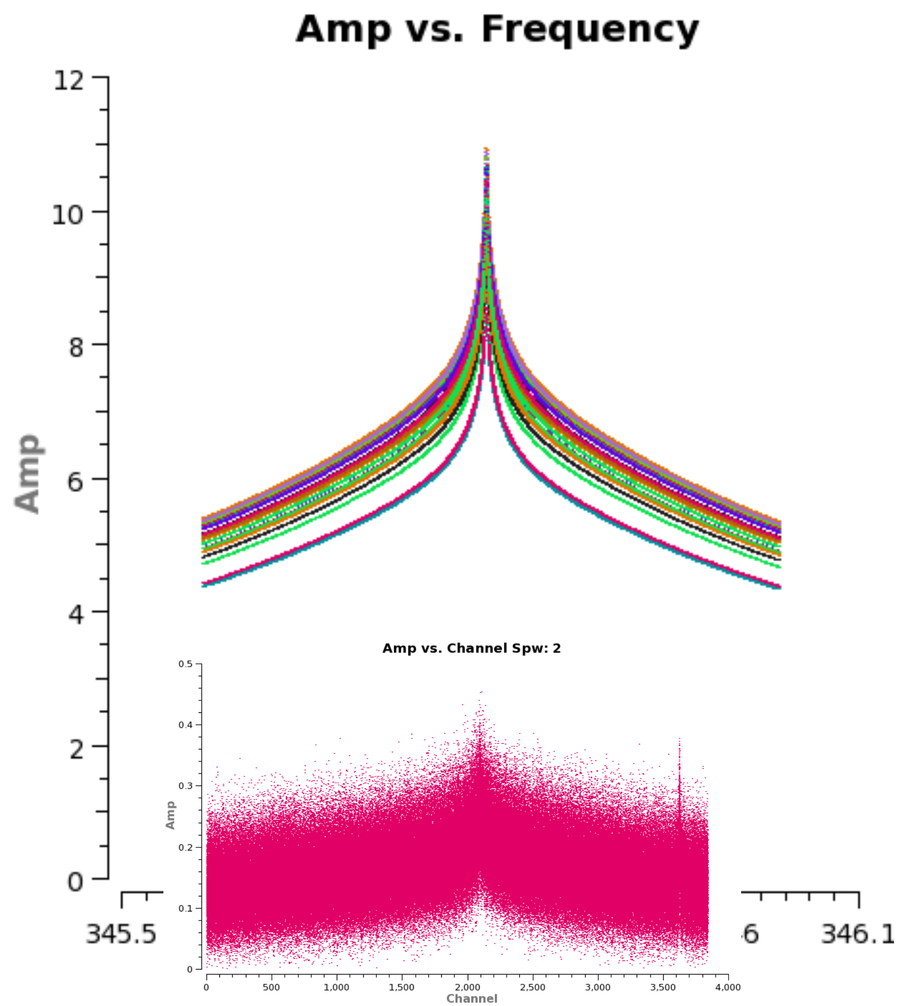
- More asteroids? modeling is needed because they are not round!
- Red giant stars may be better
- Regular monitoring of a small grid of point-like quasars as secondary flux calibrators.





Next phase - model spectral lines
Example: CO in Titan





Summary

- Atmospheric emission can dominate the system temperature
  - Calibration through T_{sys} or opacity/gain curves is essential
- Tropospheric water vapor causes significant phase fluctuations
  - Decorrelation can be severe
  - Phase correction techniques are essential: ALMA – WVRs
- 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!
- It is essential to use models for most currently available absolute flux density calibrators

Extra Slides

Calibration Sensitivities Effects (N=25)

S/N_{Ant}	Amp error	Phase error	S/N_{base}	S/N_{image}
0	100%	180 d	0	0
3	33%	15.0 d	0.6	11.0
5	20%	9.7 d	1.1	18.4
10	10%	5.7 d	2.1	36.9
25	4%	2.3 d	5.3	92.3
100	1%	0.6 d	21.3	370

d_{Ant} phase error must be smaller than expected instrumental and tropospheric phase error which is often 10-20 deg

d_{Ant} amp error must be smaller than expected instrumental and absorption amplitude errors, usually < 5%