Advanced Calibration Topics - I

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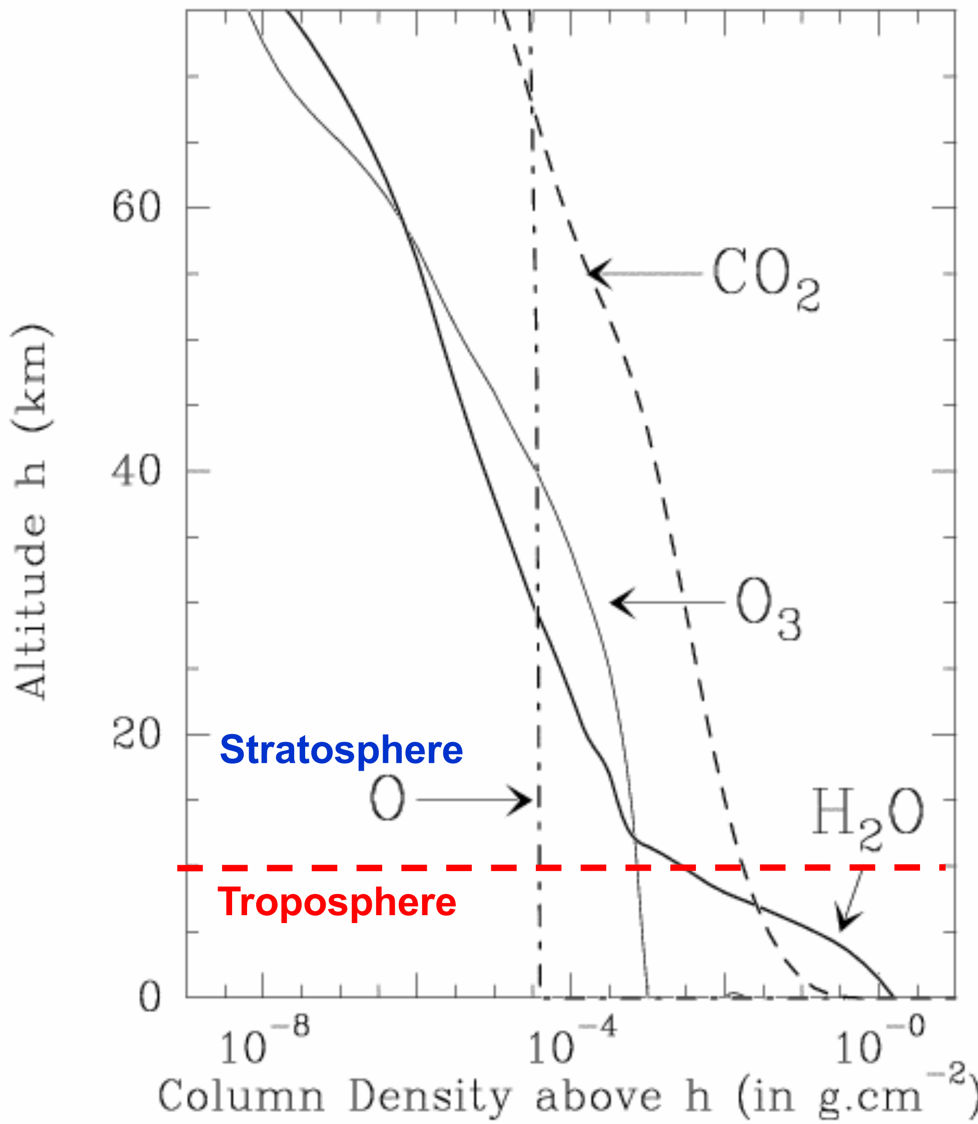
Atmospheric Opacity and Correction Techniques

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

Column Density as a Function of Altitude



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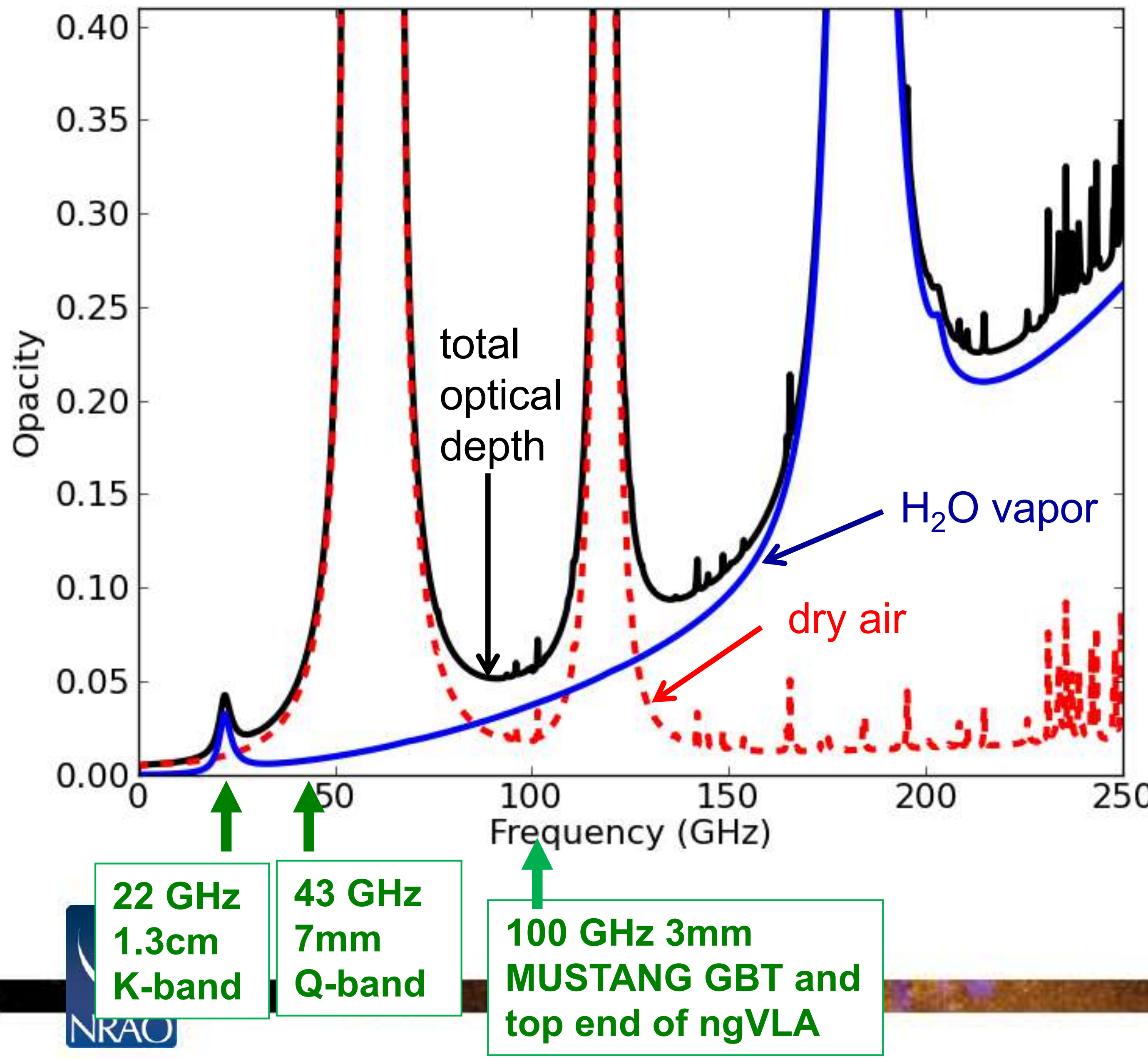
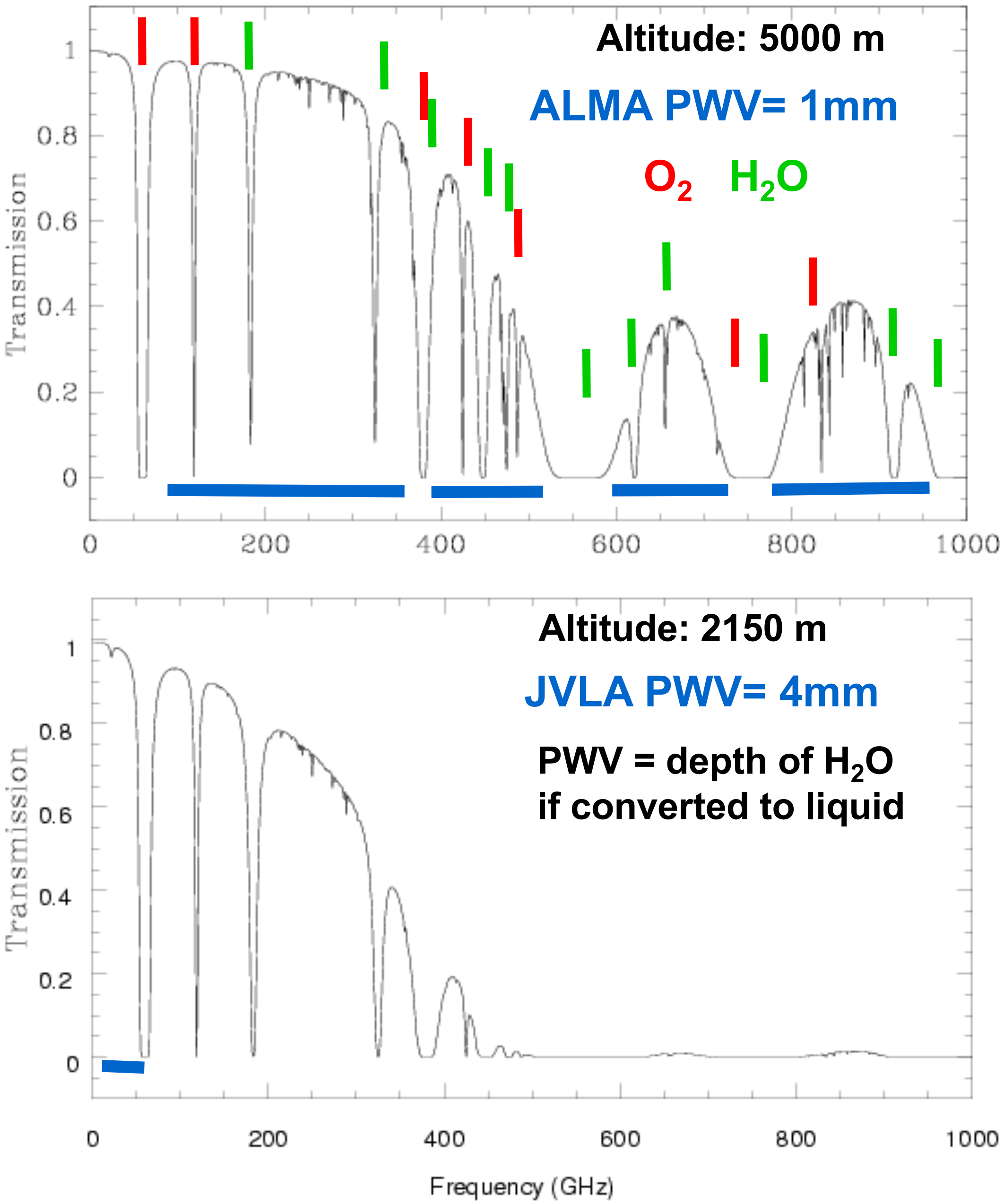
Optical Depth as a Function of Frequency

VLA with 4mm PWV



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

Tropospheric Opacity Depends on Altitude:



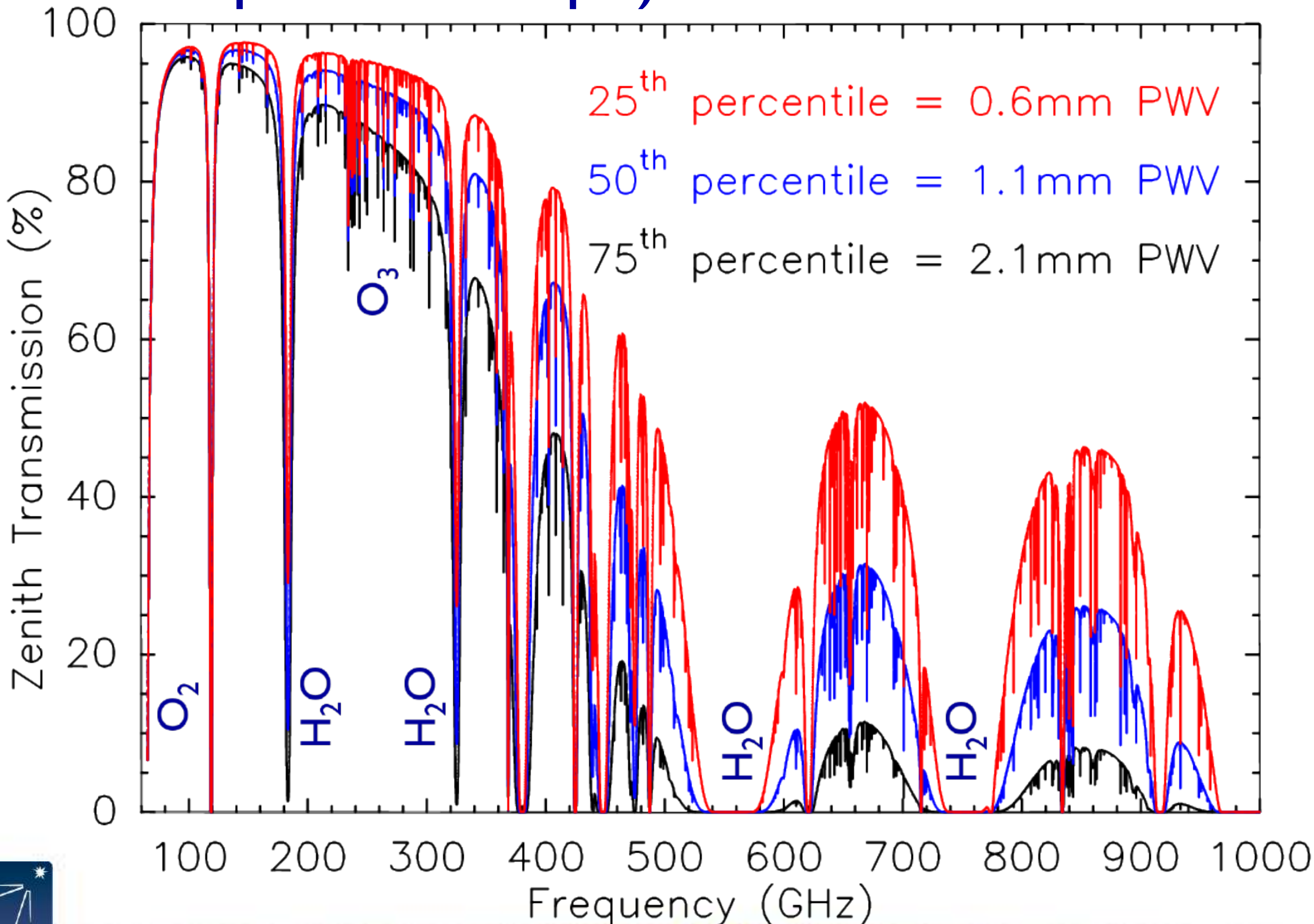
Models of atmospheric transmission from 0 to 1000 GHz for the ALMA site in Chile, and for the VLA site in New Mexico

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

$\Rightarrow$ Atmospheric transmission not a problem for λ > cm (most VLA bands)

Atmospheric Opacity at ALMA

(PWV = Precipitable Water Vapor)



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

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

T_{atm} = temperature of the atmosphere $\approx$ 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

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

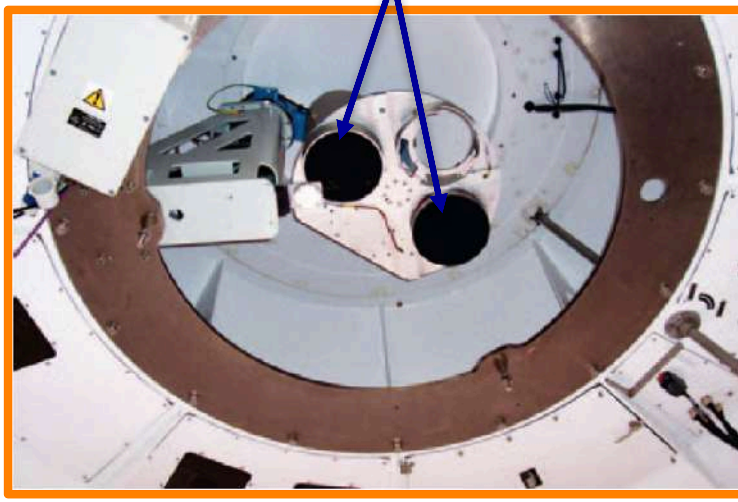
assume $T_{atm} \approx T_{load}$

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

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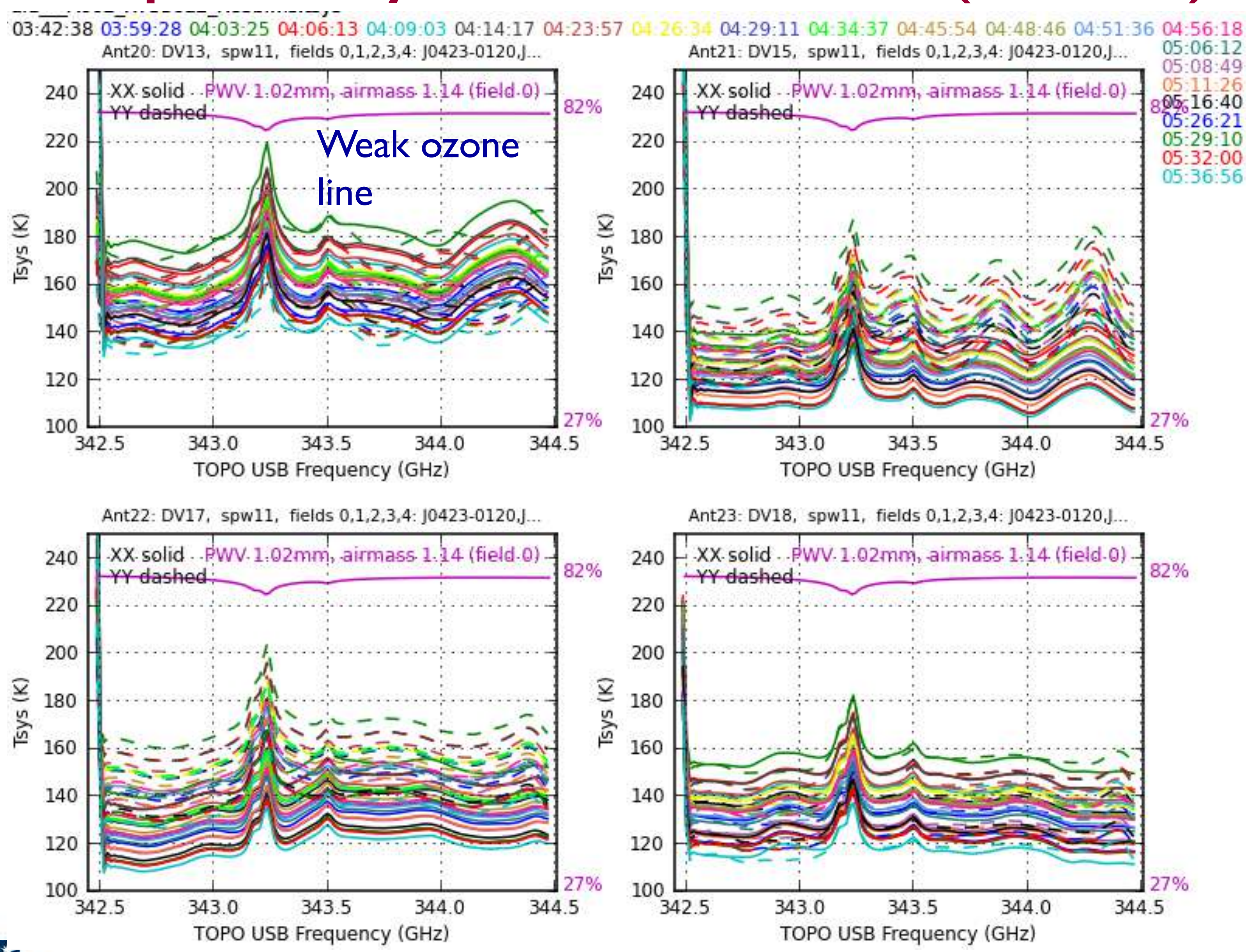
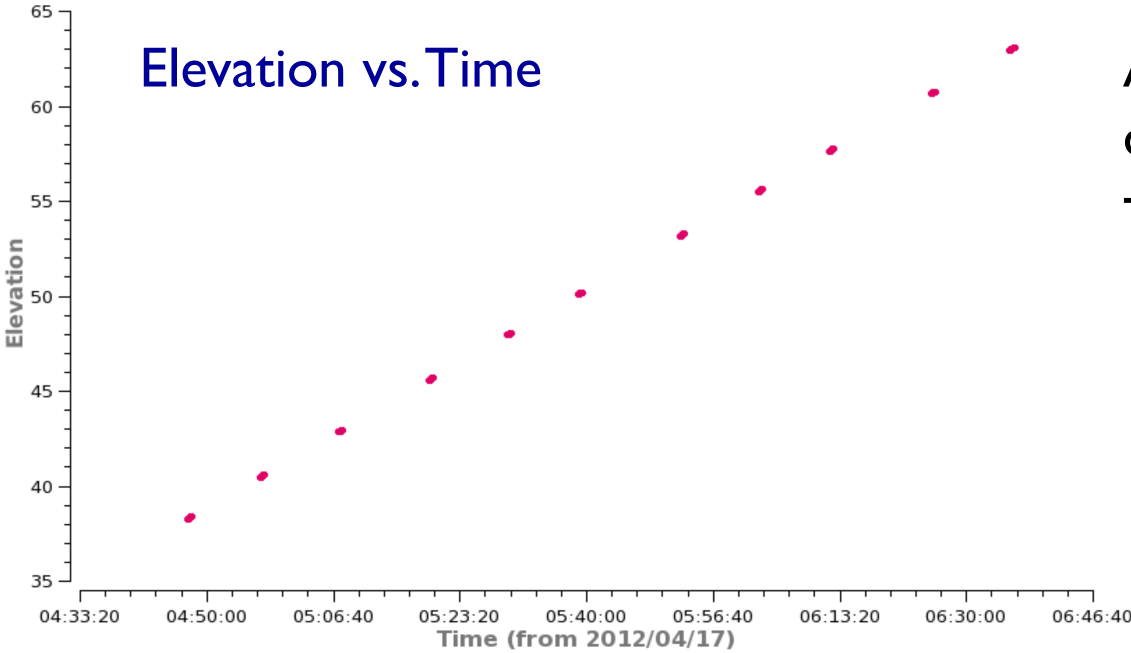
ALMA Spectral Tsys: 4 Antennas Band 6 (230 GHz)



Colors show changes with time (and sometimes source)

ALMA System Temperature: Example-1

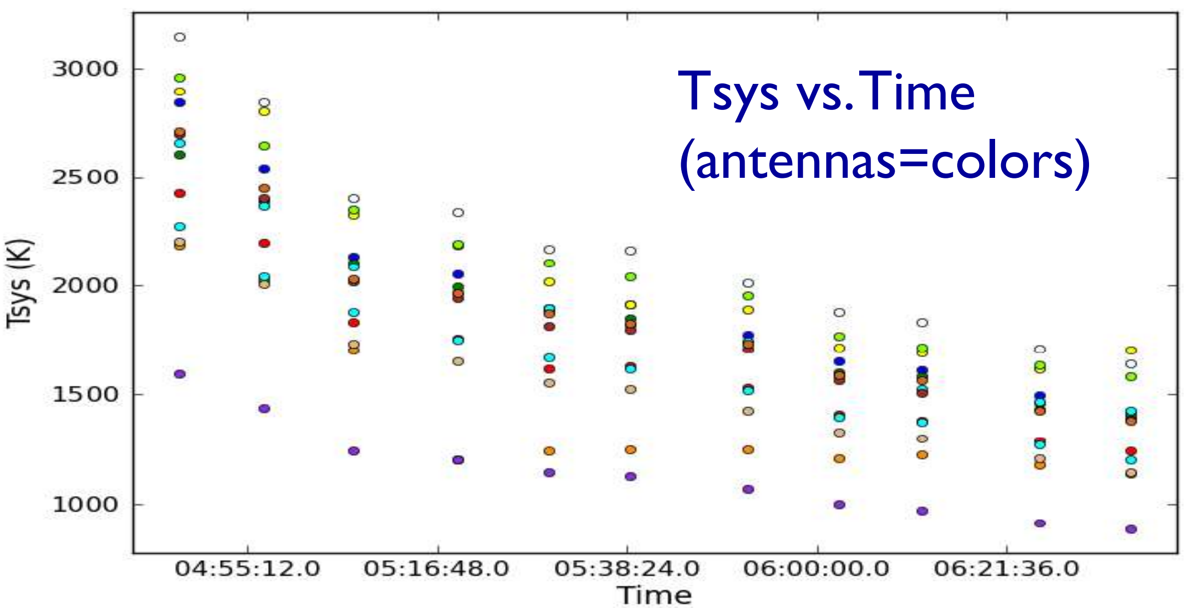


ALMA Band 9 Test Data on the quasar NRAO530

Tsys measured every ~16 min

Notice:

- Inverse relationship between elevation and Tsys

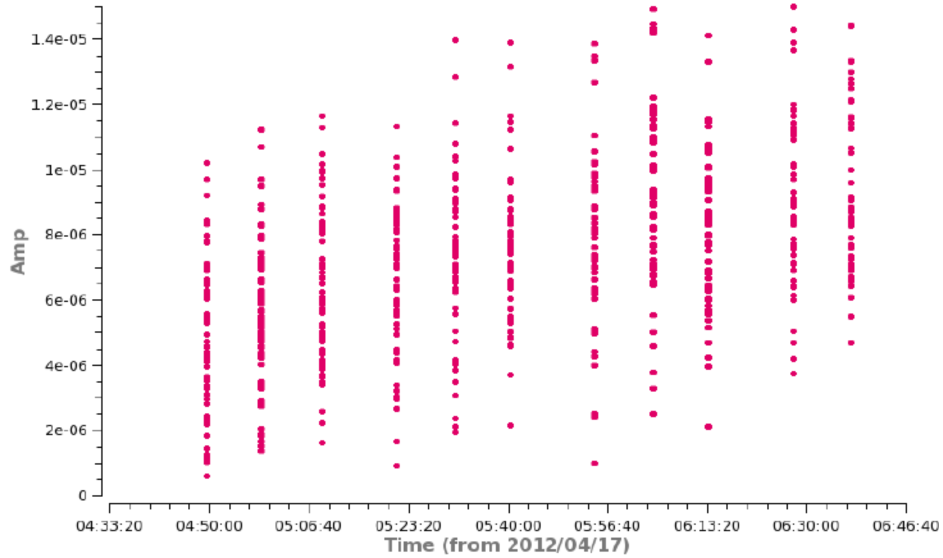


- Large variation of Tsys among the antennas

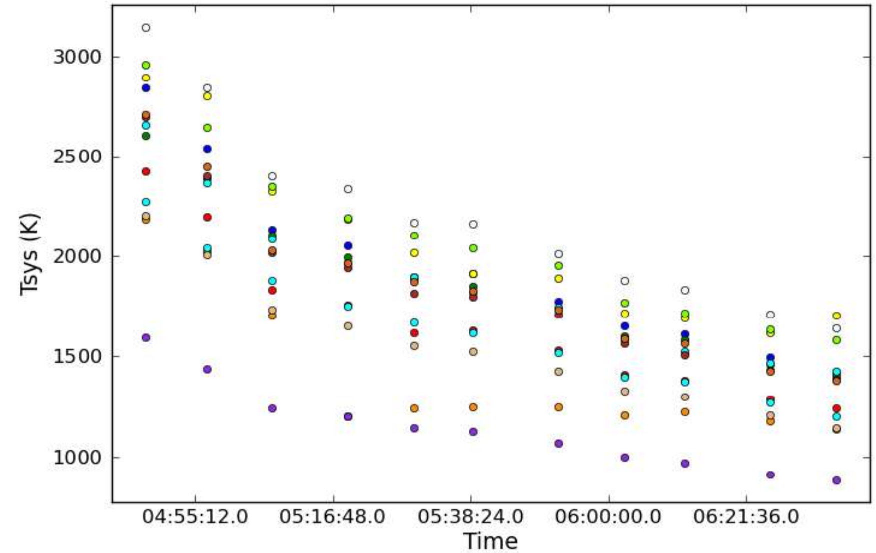
$$VisibilityWeight \propto \frac{1}{T_{sys}(i)T_{sys}(j)}$$

ALMA System Temperature: Example-2

Raw Amplitude vs. Time

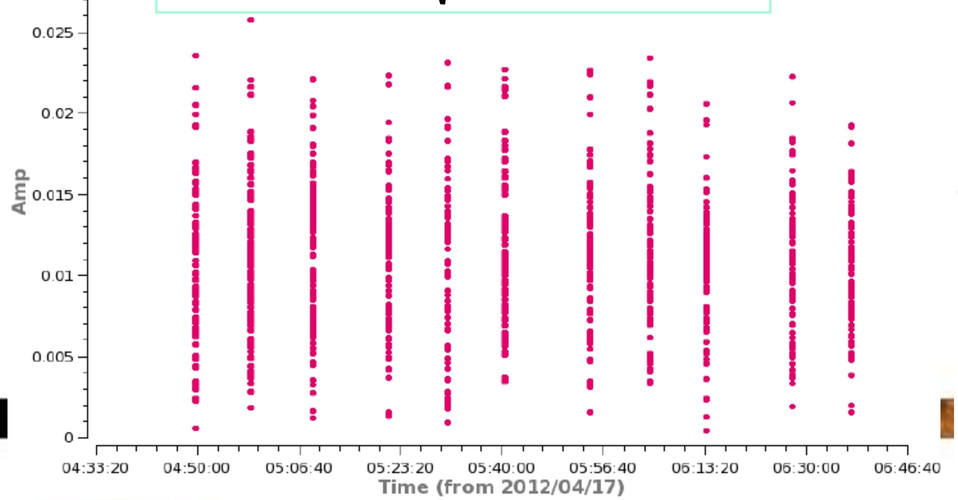


Tsys vs. Time (all antennas)



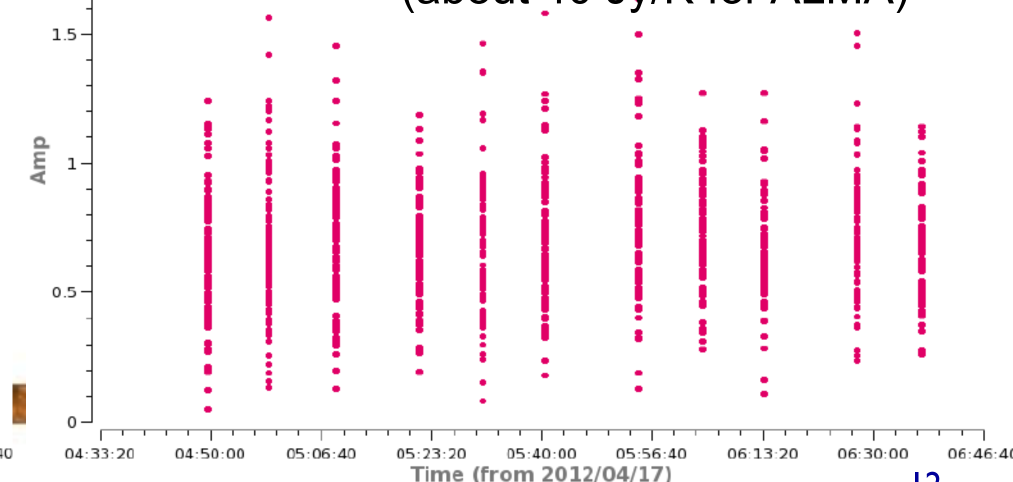
Amplitude Corrected for Tsys

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



Fully Calibrated using flux reference

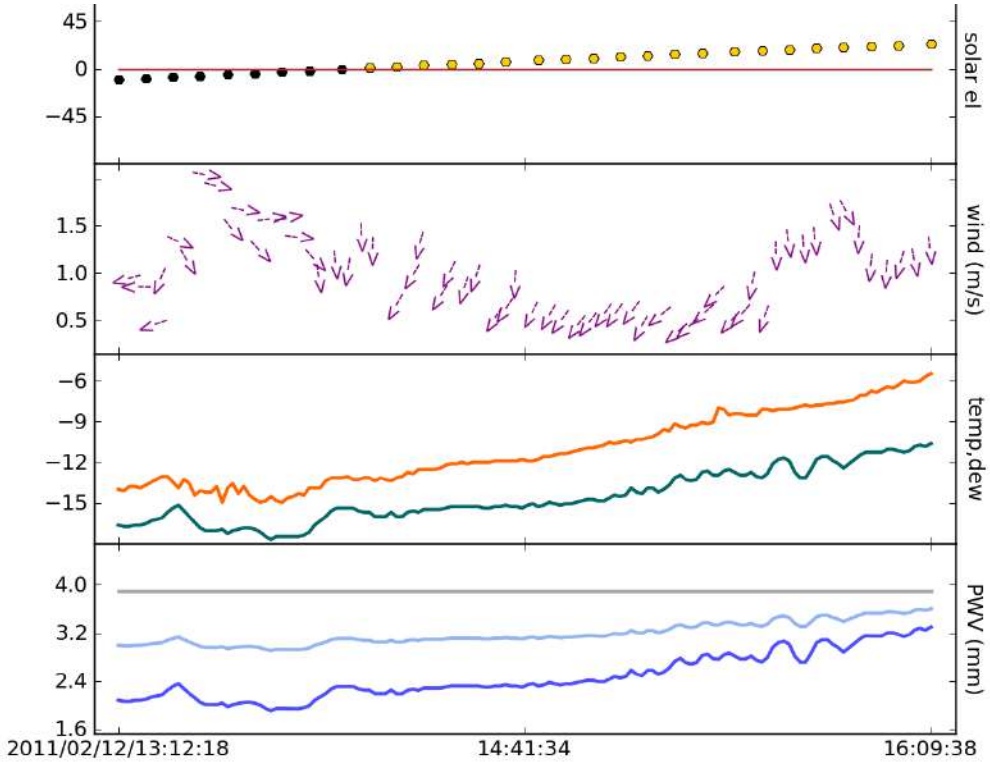
S_{final} ~ S_{Tsys} * Antenna Efficiency Factor (about 40 Jy/K for ALMA)

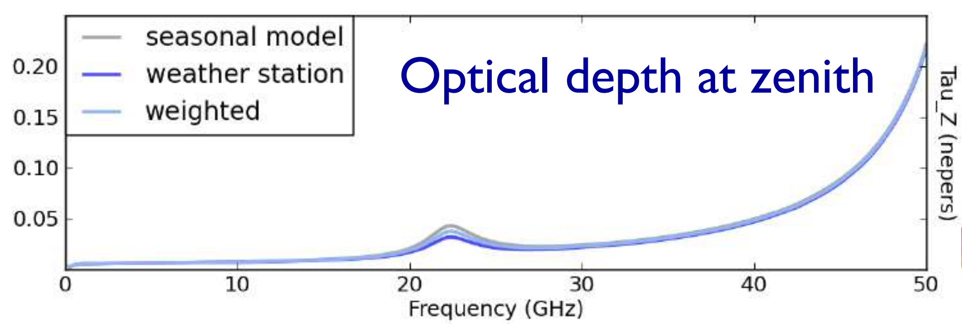


JVLA Atmospheric Correction

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

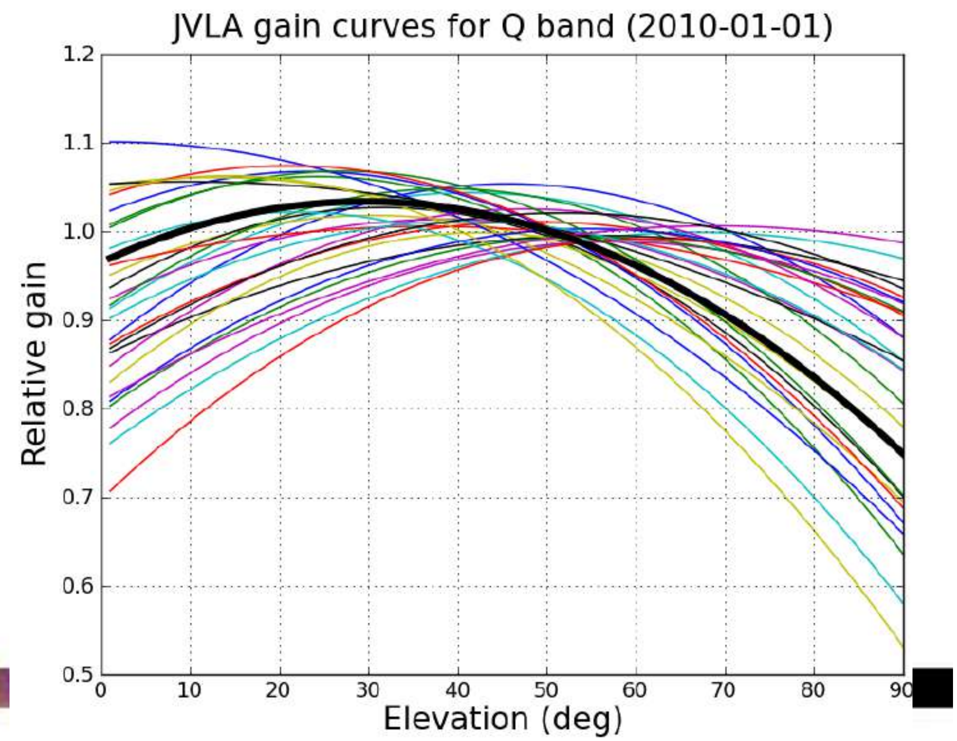
plotweather task available in CASA





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

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
- Svnchronous 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

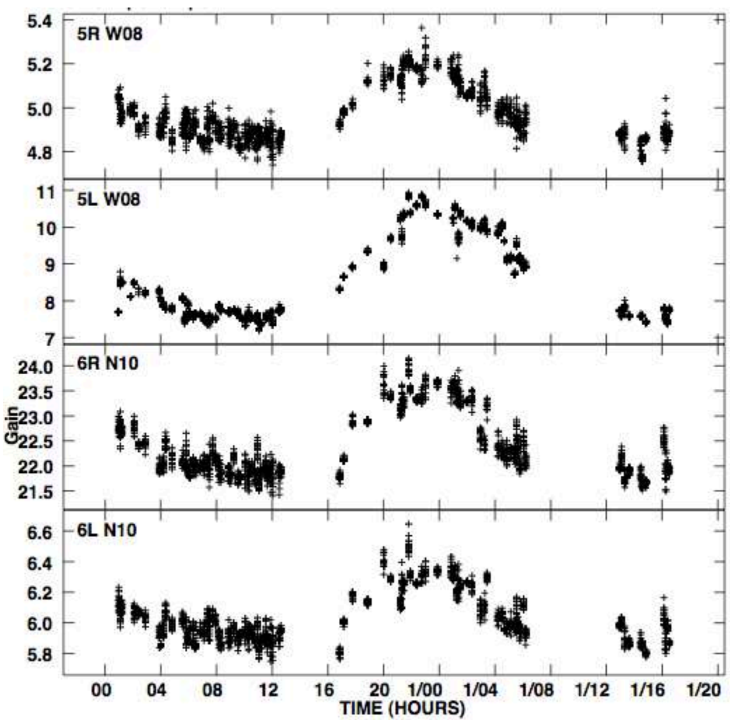
- Removes gain variations due to electronics between the diode and correlator on 1 second timescales
- Puts data on absolute temperature scale

Caveats:

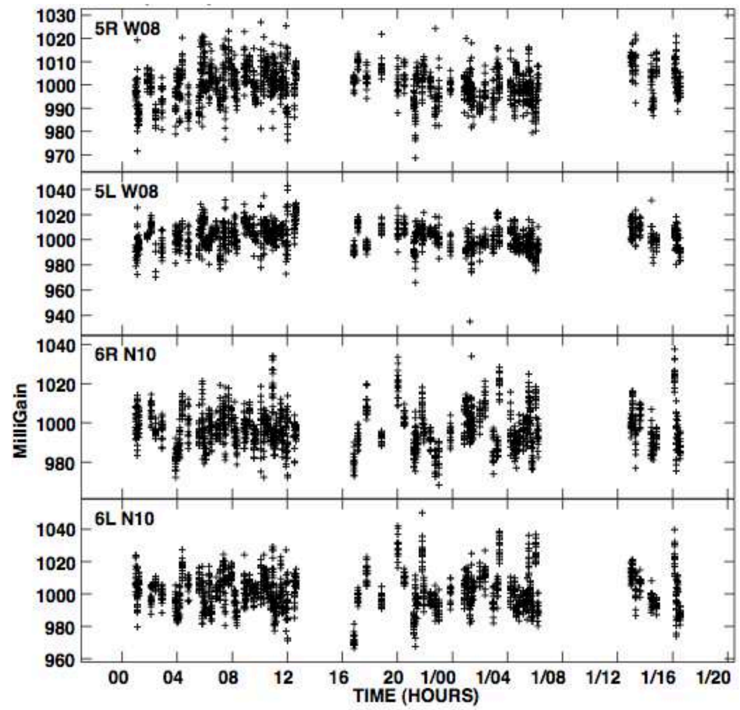
- Does not account for opacity effects
- Does not account for antenna gain curve

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.

Absolute Flux Calibration

Absolute Flux Calibration

Goal:

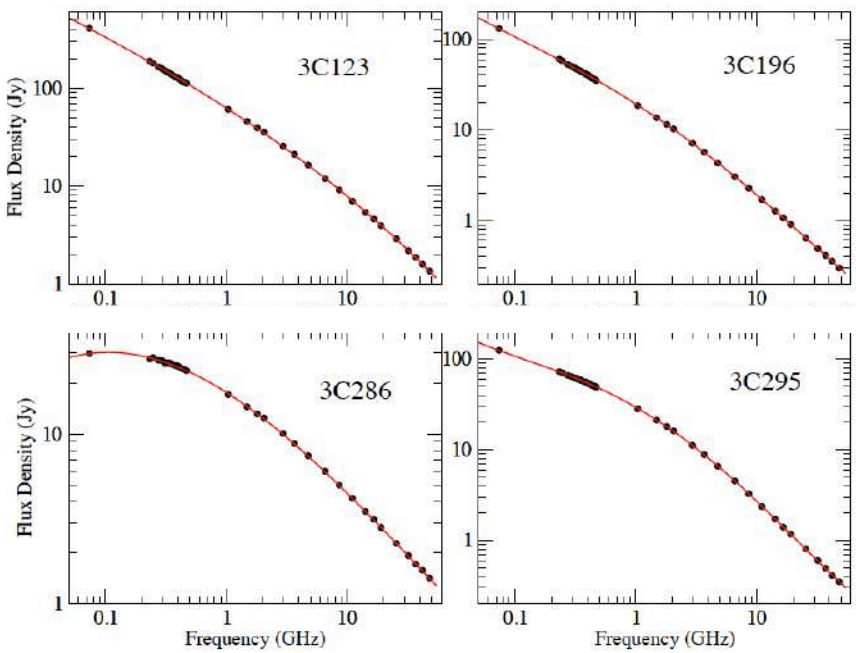
- Observe a source of known flux density and spectral index, that is a point source on all observed scales (and thus constant phase and amplitude) and has no spectral line emission in the observing band
- Measure ratio of known flux density to observed mean amplitude (corrected for Tsys, phase, and amplitude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

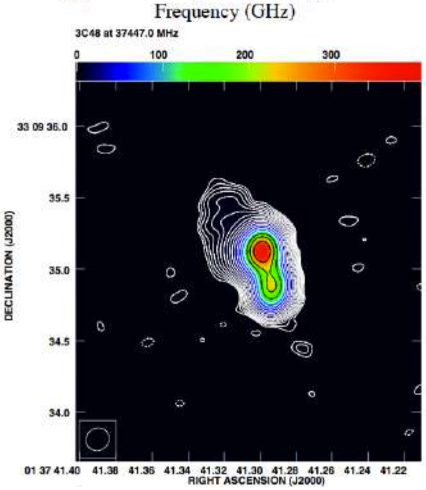
Reality -- there are no perfect absolute flux calibrators

- 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 JVLA frequency range





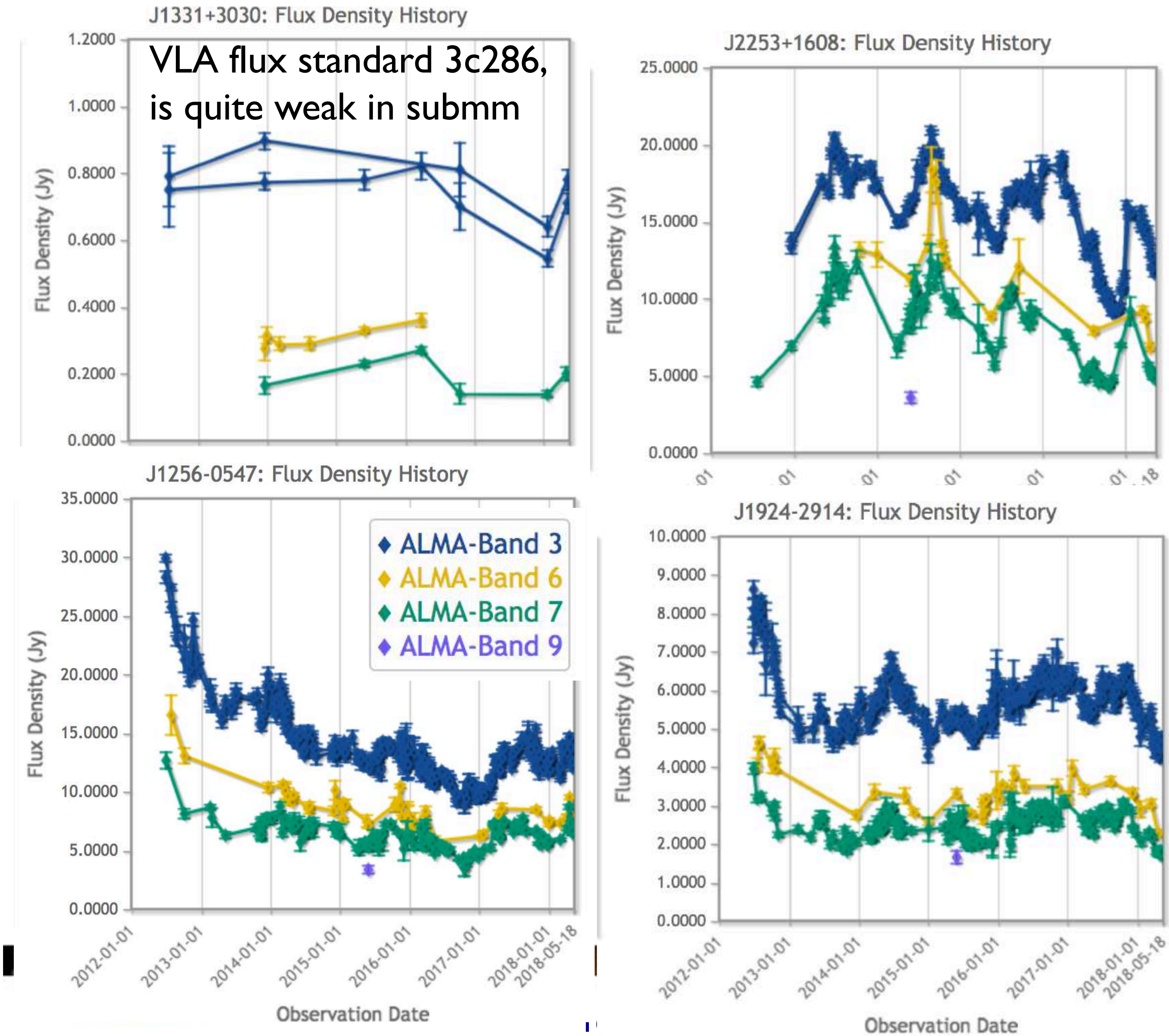
Name	Alternate Names	4	P	L	S	C	X	Ku	K	Ka	Q	LAS[a] (arcsec)
J0133−3629			•	•								900
J0137+3309	3C48	•	•	•	•	•	•	•	•	•	•	1.2
J0322−3712	Fornax A		•	•								3000
J0437+2940	3C123	•	•	•	•	•	•	•	•	•	•	43
J0444−2809			•	•								120
J0519−4546	Pictor A		•	•	•							480
J0521+1638	3C138		•	•	•	•	•	•	•	•	•	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/



- Strong quasars in the submm tend to be highly time-variable

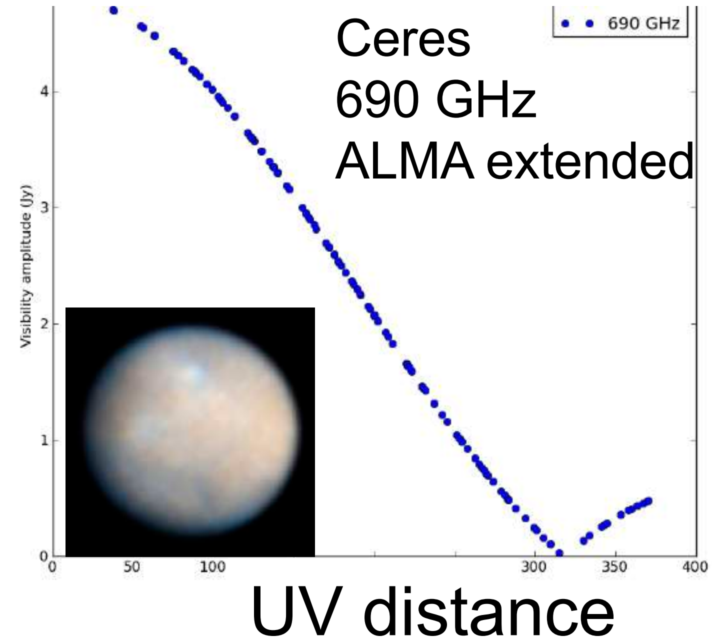
Flux calibrators – ALMA

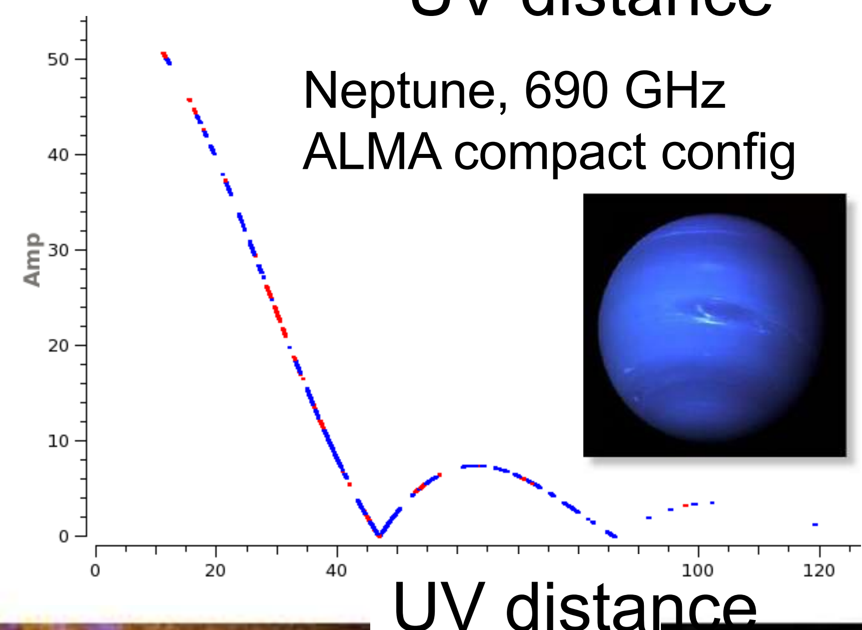
- Solar system bodies are used as primary flux calibrators (Neptune, Jovian moons, Titan, Ceres) but with many challenges:
  - All are resolved on long ALMA baselines
  - Brightness varies with distance from Sun and Earth
  - Line emission (Neptune, Titan)

- 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?





"SEFD" (System Equivalent Flux Density) Method

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

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

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)
- A_{eff}: antenna effective area = $\eta_a\,\pi r^2$ where η_a is the aperture efficiency which depends on the antenna surface accuracy (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

Summary

- Altitude and PWV have a very large impact on tropospheric opacity
- Atmospheric emission dominates the system temperature at higher frequencies
  - Calibration through T_{sys} or opacity/gain curves is essential
- Absolute flux calibration is difficult
  - At cm, there are few stable quasars but they have structure on small and large scales that require accurate models
  - At submm it is difficult due to options being either weak, over-resolved, or highly time variable

Next phase - model spectral lines
Example: CO in Titan