The Effects of the Atmosphere and Weather on Radio Astronomy Observations

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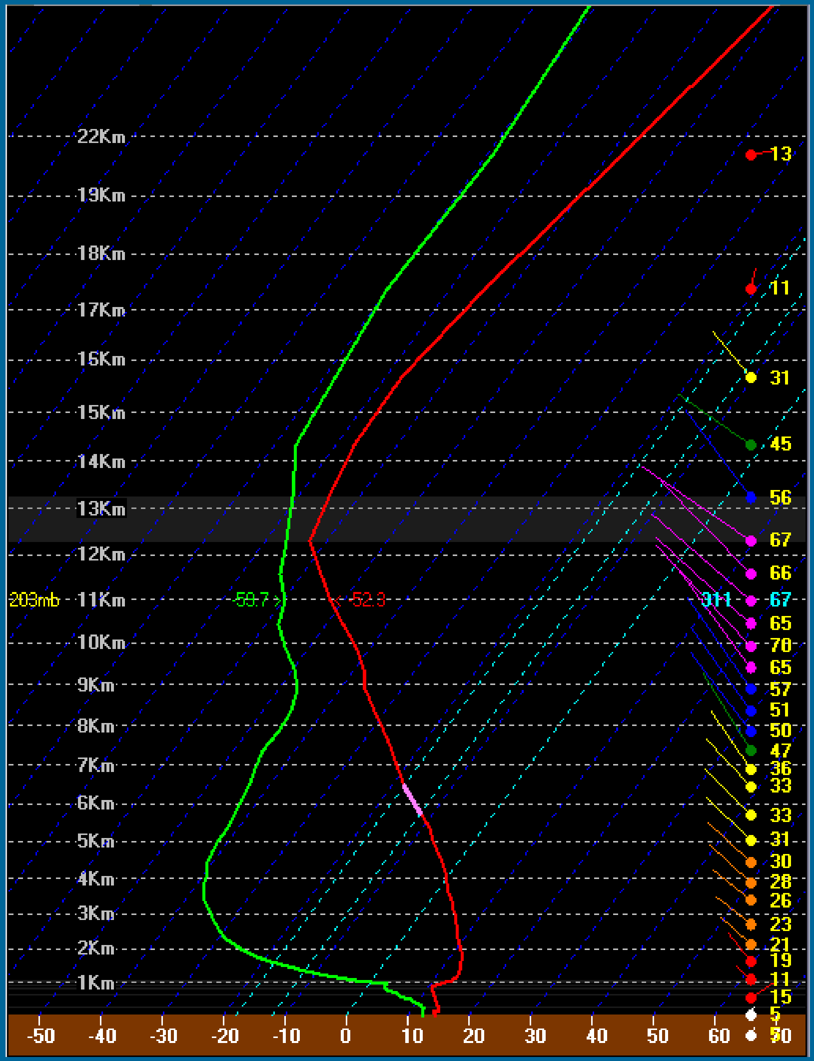
July 2011

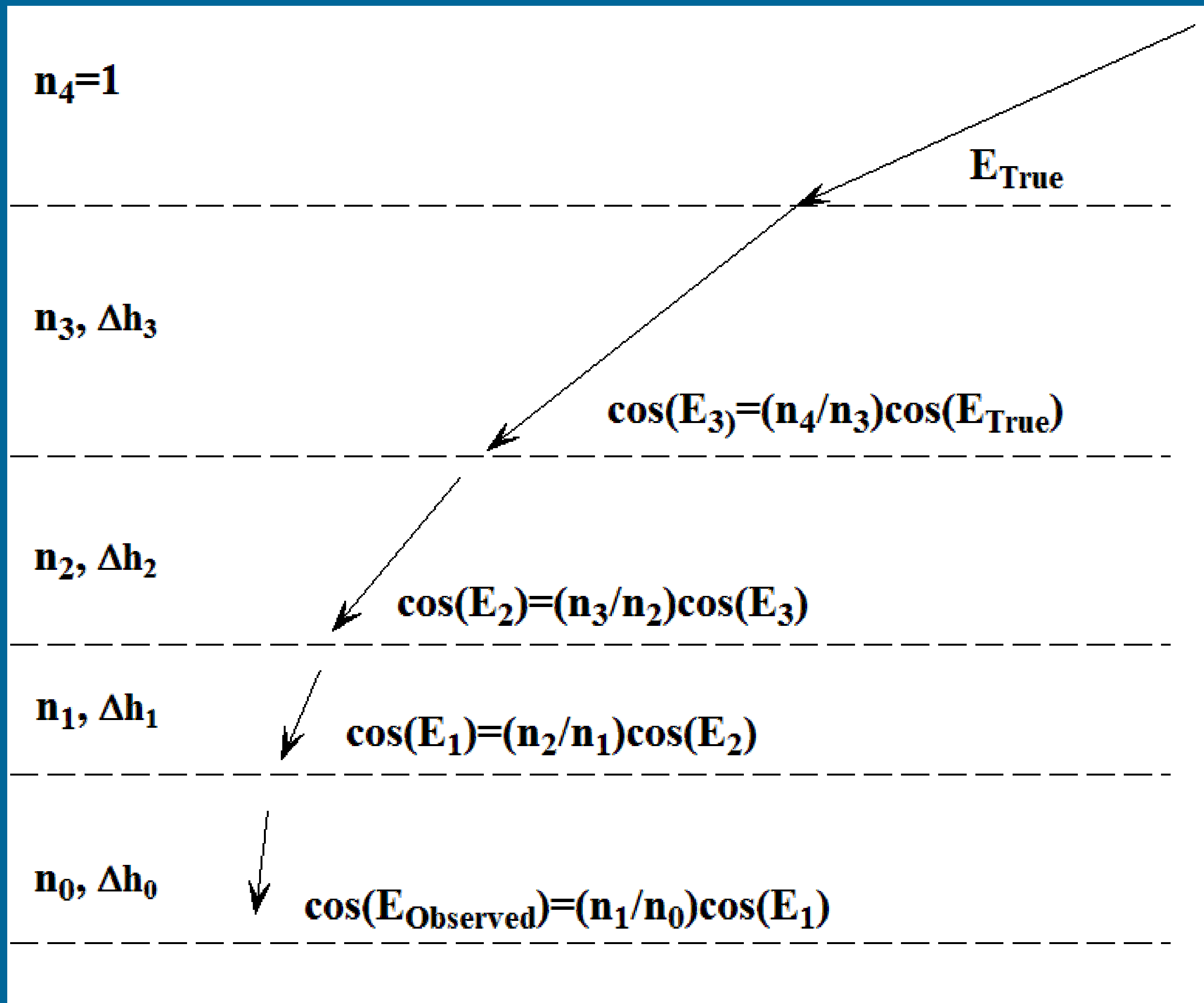
The Influence of the Atmosphere and Weather at cm- and mm-wavelengths

- Opacity
  - Calibration
  - System performance – Tsys
  - Observing techniques
  - Hardware design
- Refraction
  - Pointing
  - Air Mass
    - Calibration
    - Interferometer & VLB phase errors
  - Aperture phase errors
- Cloud Cover
  - Continuum performance
  - Calibration
- Winds
  - Pointing
  - Safety
- Telescope Scheduling
  - Proportion of proposals that should be accepted
  - Telescope productivity

Structure of the Lower Atmosphere



Refraction



Grossly exaggerated and assuming plane parallel approximation

Refraction

- Index of Refraction is weather dependent:

$$(n_0 - 1) \cdot 10^6 \approx \frac{77.6 \cdot P_{Total}(mBar)}{T(C) + 273.15} + \frac{3.73 \times 10^5 \cdot P_{H_2O}(mBar)}{\left(T(C) + 273.15\right)^2} + \ldots$$

$$P_{H_2O}(mBar) \approx 6.112 \cdot e^a$$

$$\text{where } a \approx \frac{7.62 \cdot T_{DewPt}(C)}{243.12 + T_{DewPt}(C)}$$

Froome & Essen, 1969
http://cires.colorado.edu/~voemel/vp.html
Guide to Meteorological Instruments and Methods of Observation (CIMO Guide) ***(WMO, 2008)***

Refraction

- For plane-parallel approximation:
  - $n0 \cdot \mathrm{Cos}(Elev_{Obs}) = \mathrm{Cos}(Elev_{True})$
  - $R = Elev_{Obs} - Elev_{True} = (n_0 - 1) \cdot \mathrm{Cot}(Elev_{Obs})$
  - Good to above 30° only
- For spherical Earth:

$$Elev_{Obs} - Elev_{True} = a \cdot n_0 \cdot \cos(Elev_{Obs}) \cdot \int_1^{n_0} \frac{dn(h)}{n(h) \cdot \sqrt{(a+h)^2 \cdot n(h)^2 - a^2 \cdot n_0^2 \cdot \cos^2(Elev_{Obs})}}$$

a = Earth radius; h = distance above sea level of atmospheric layer, n(h) = index of refraction at height h; n_0 = ground-level index of refraction

See, for example, Smart, "Spherical Astronomy"

Refraction

- Important for good pointing when combining:
  - large aperture telescopes
  - at high frequencies
  - at low elevations
  - (i.e., the GBT)
- Every observatory handles refraction differently.
- Offset pointing helps eliminates refraction errors
- Since n(h) isn't usually known, most (all?) observatories use some simplifying model. Example:

$$Elev_{Obs} - Elev_{True} = (n_0 - 1) \cdot Cot\left(Elev_{Obs} + \frac{4.70}{2.24 + Elev_{Obs}} \right)$$

Updated from: Maddalena, GBT memo 112, 1994.

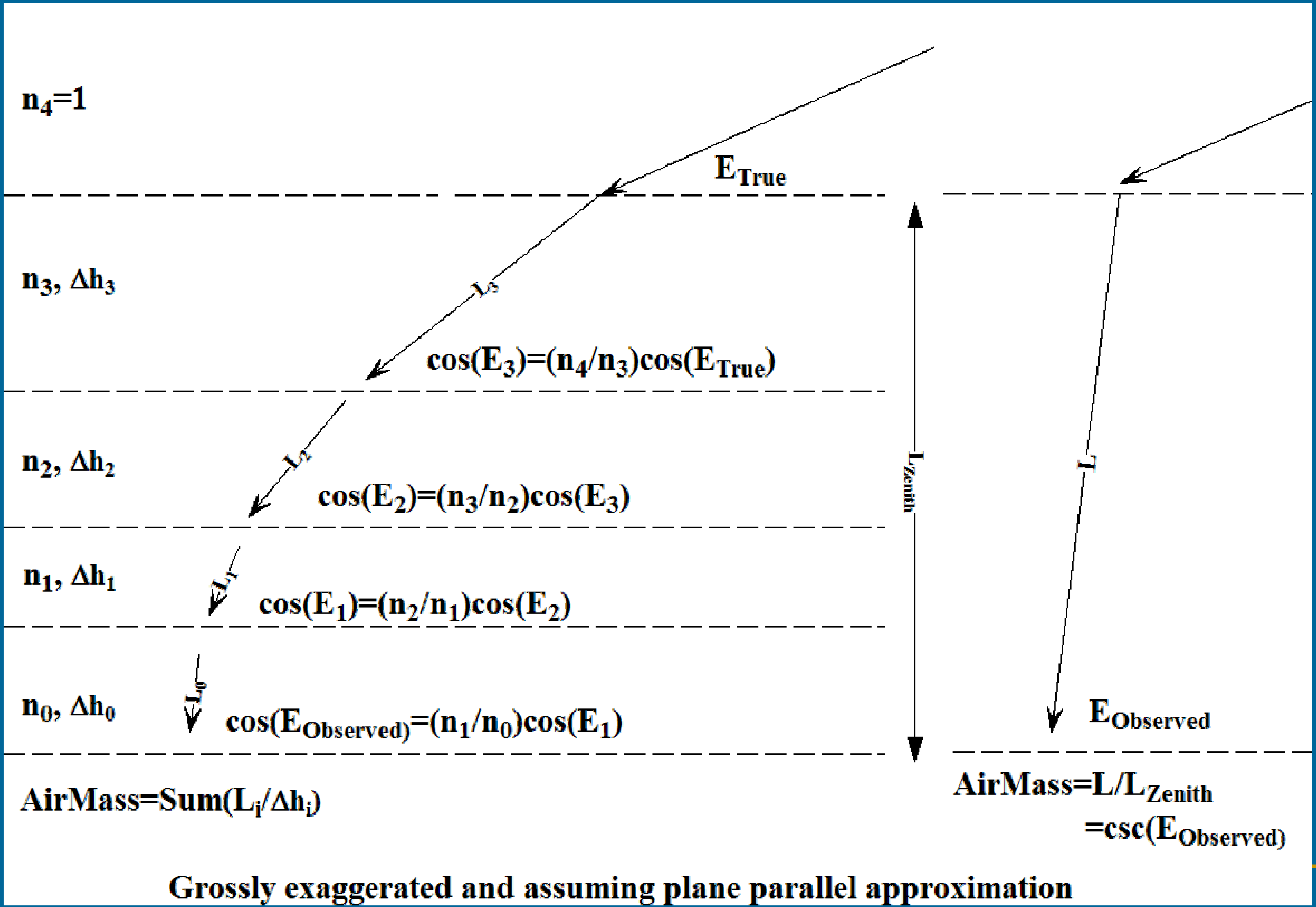
Relative Air Mass

- Ratio of column density along line of sight to column density toward zenith

$$AirMass(Elev_{Obs}) = \frac{1}{\int_0^{\infty} \rho(h) \cdot dh} \cdot \int_0^{\infty} \frac{\rho(h) \cdot dh}{\sqrt{1 - \left(\frac{a}{a+h} \frac{n_0}{n(h)} \right)^2 \cos^2(Elev_{Obs})}}$$

Rohlfs & Wilson, "Tools of Radio Astronomy"

Relative Air Mass



Exercise 1: Air Mass and Refraction for Elev=6°

H (km)	ΔH (km)	n	$Elev_{Obs}$	L_{los} (km)	AirMass
Above Atmosphere		0	6	0	0
34.8	12.00	1.0000019			
17.3	17.55	1.0000341			
11.7	5.557	1.0000764			
8.5	3.260	1.0001105			
6.0	2.465	1.0001442			
4.2	1.778	1.0001745			
2.9	1.308	1.0002056			
2.0	0.956	1.0002374			
1.4	0.565	1.0002771			
1.1	0.315	1.0002872			
0.8	0.251	1.0003108			

Formulae:

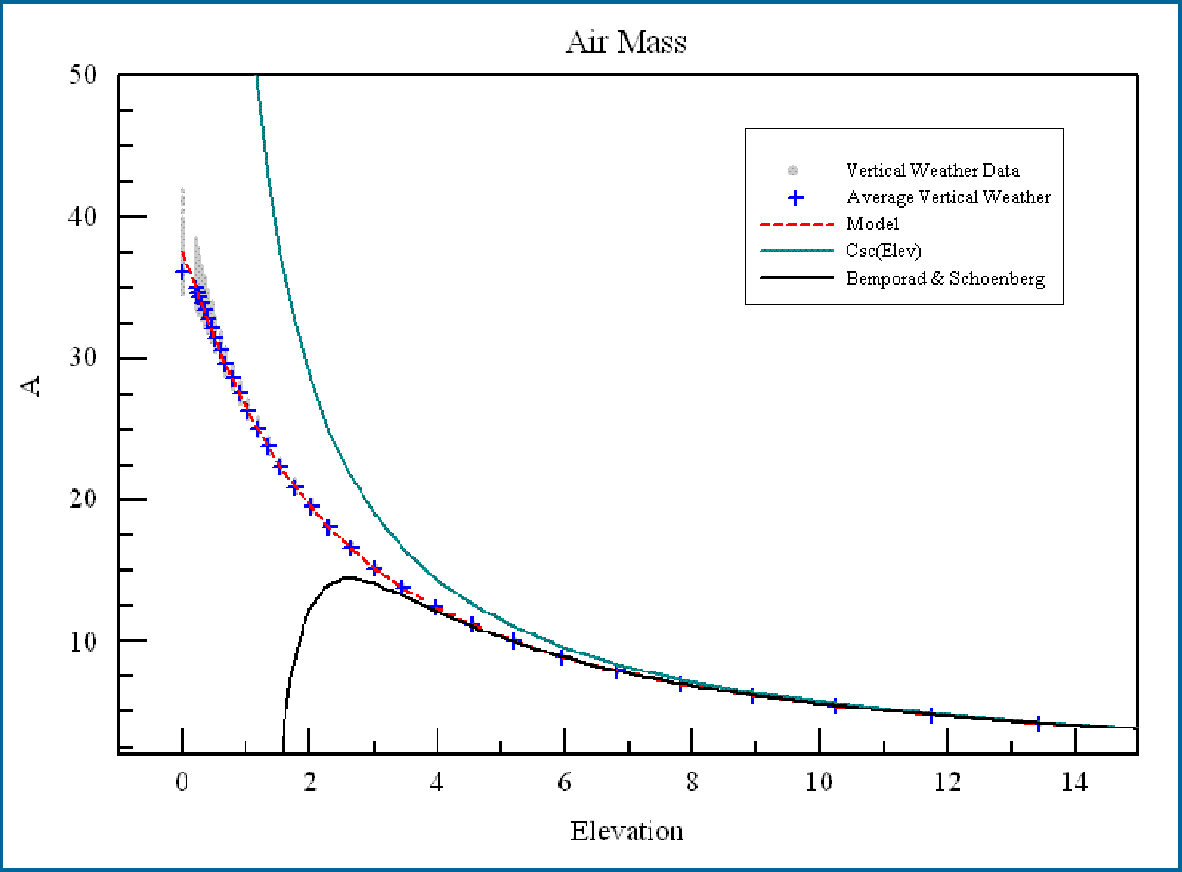
$$Elev_{Obs} = \text{ArcCos}[\, \text{Cos}(Elev_{Obs}^{Previous}) \cdot n / n^{previous} \,]$$

$$L_{los} = \Delta H / \sin(Elev_{Obs})$$

$$AirMass = AirMass^{Previous} + L_{los} / \Delta H$$

Relative Air Mass

- Not significantly weather dependent
- $\csc(Elev_{Obs})$ breaks down when Elev < 15°



- Use instead:

$$AirMass = -0.02344 + \frac{1.0140}{\sin\left(Elev_{Obs} + \frac{5.18}{Elev_{Obs} + 3.35}\right)} \text{ for Elev}_{\text{Obs}} \le 32$$

$$= \csc(Elev_{Obs}) \quad \text{for Elev}_{\text{Obs}} > 32$$

Maddalena & Johnson, 2006

Atmospheric Opacity (τ)

- Hits observations twice:
  - Attenuates the source
  - Adds to received power (T_{sys})

$$T_A = T_R^* \cdot e^{-\tau \cdot AirMass}$$

$$T_{sys} = T_{Rcvr} + f_{Spillover} T_{Ground} + \left(1 - f_{Spillover}\right) \cdot \left[T_{CMB} e^{-\tau \cdot AirMass} + T_R^* \cdot e^{-\tau \cdot AirMass} + T_{Atm} \cdot \left(1 - e^{-\tau \cdot AirMass}\right)\right]$$

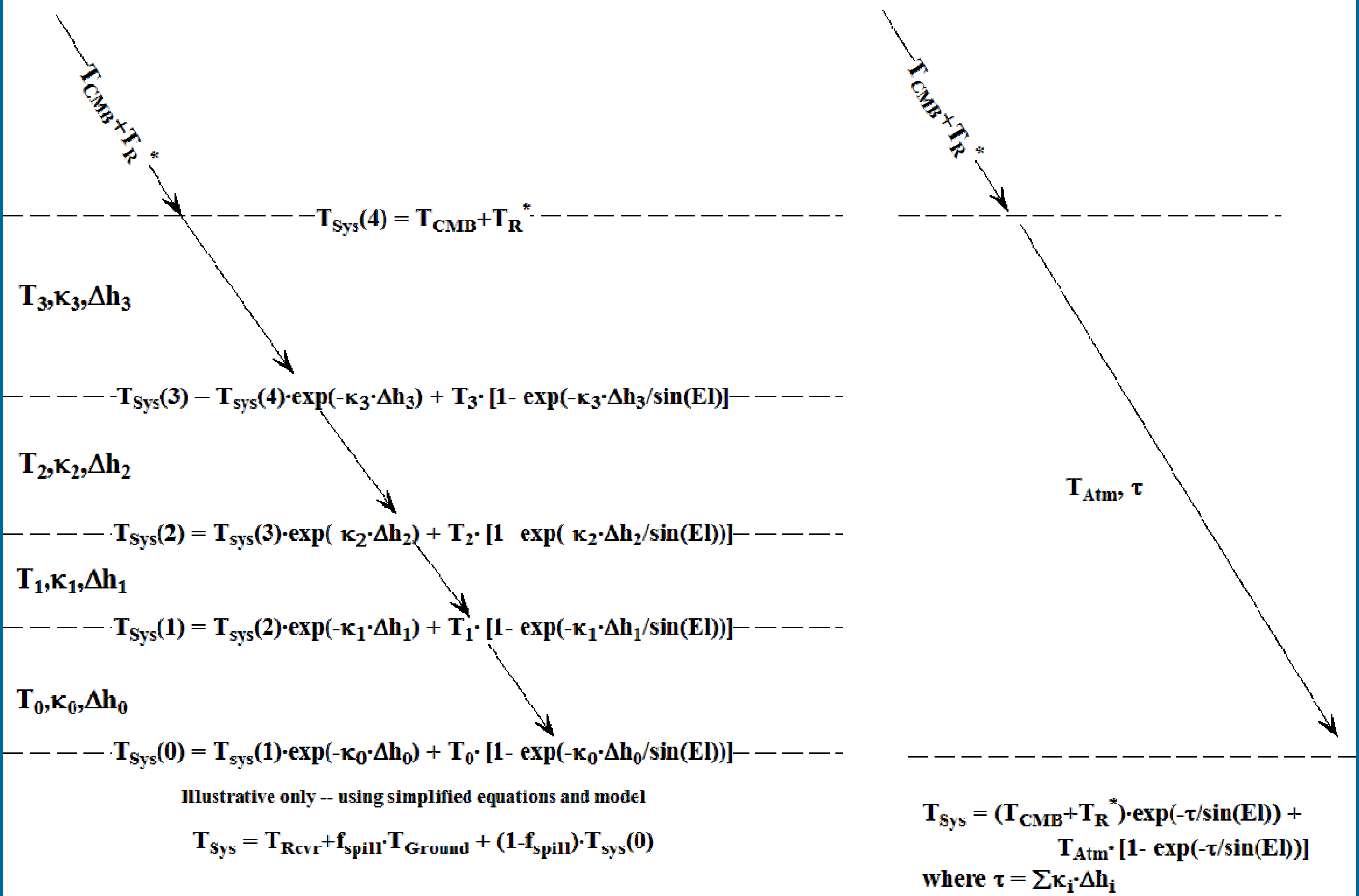
- Signal-to-noise $\propto T_A/T_{sys}$
- Important for calibration:

$$\frac{\Delta T_R^*}{T_R^*} = \Delta\tau \cdot AirMass + \Delta AirMass \cdot \tau$$

- Some simplifications:
  - Optically Thick ($\tau >> 1$): Last term in T_{sys} becomes T_{Atm}
  - Optically Thin ($\tau << 1$): Last term becomes $T_{Atm} \cdot \tau \cdot AirMass$
- Sometimes written as:

$$T_{sys} \approx T_{Rcvr} + T_{CMB} e^{-\tau \cdot AirMass} + T_{Atm} \cdot \left(1 - e^{-\tau \cdot AirMass}\right) \approx T_{Rcvr} + T_{CMB} + T_{Atm} \cdot \tau \cdot AirMass$$

Radiative Transfer Through any Atmosphere



Exercise 2: τ, T_{sys} , T_{Atm} and Attenuation for Observation at the Zenith with No Spillover for a 10K Source

H(km)	ΔH (km)	κ(Nepers/km)	T_{Layer}(K)	τ	$\sum\tau$	Attenuation	T_A (K)	T_{sys} (K)
Above Atmosphere		0		0	0	1.0	10	12.7
34.8	12.00	1.0189e-07	222.34					
17.3	17.55	1.6119e-05	203.99					
11.7	5.557	1.0405e-04	225.49					
8.5	3.260	4.0313e-04	250.79					
6.0	2.465	5.4708e-04	265.69					
4.2	1.778	8.9588e-04	275.99					
2.9	1.308	1.8908e-03	282.59					
2.0	0.956	4.0906e-03	287.89					
1.4	0.565	8.2437e-03	287.79					
1.1	0.315	0.0121247	288.69					
0.8	0.251	0.0169950	288.59					

$T_{Atm} = (T_{sys} - T_A - T_{CMB} \cdot \exp(-\sum\tau)) / (1 - \exp(-\sum\tau))$ = ______________

Total $T_{sys} = T_{sys} + T_{rcvr}$ = ______________

Formulae:

$\tau = \kappa \cdot \Delta H$

Attenuation = $\exp(-\tau)$

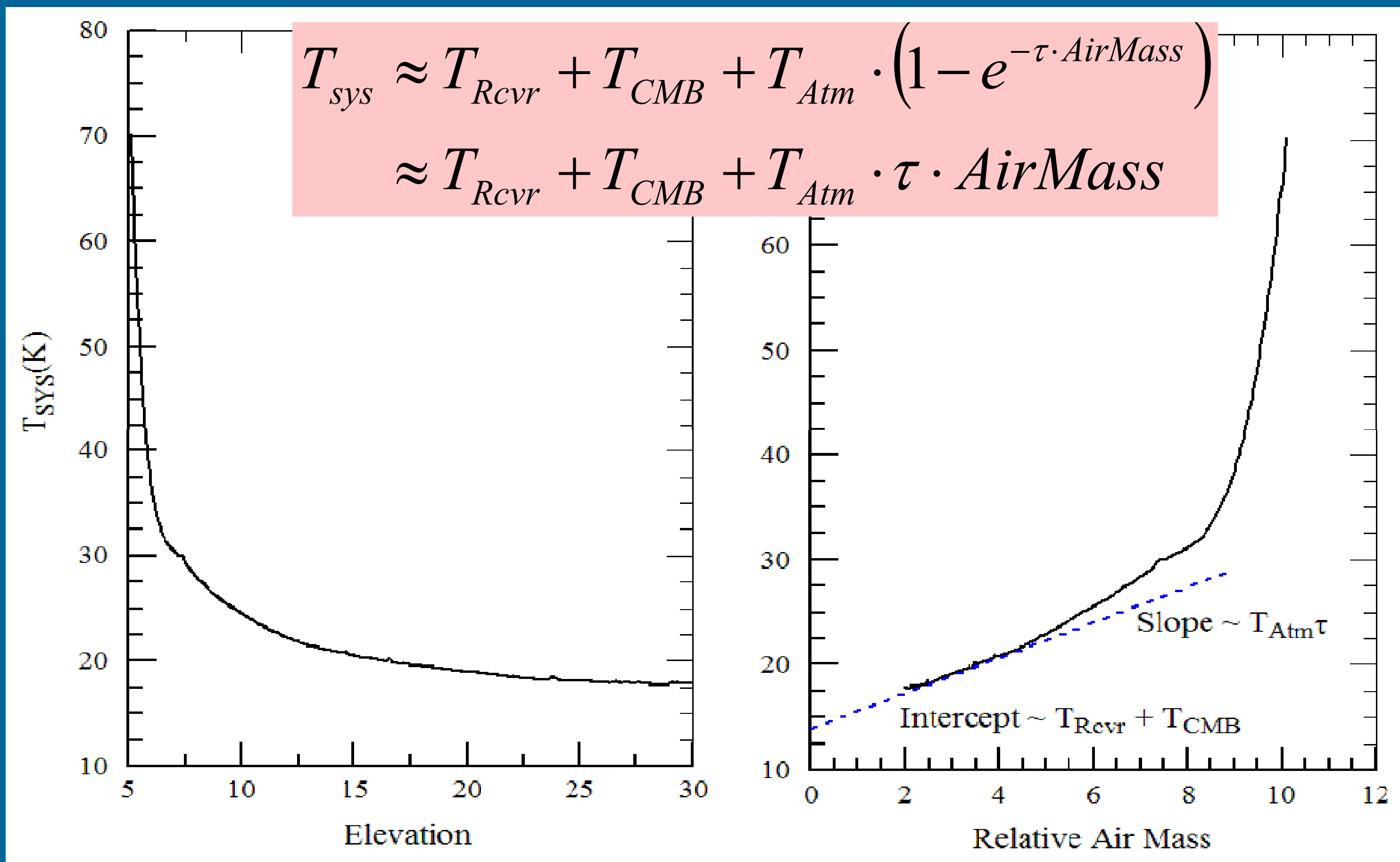
$T_A = T_A^{Previous} \cdot$ Attenuation

$T_{sys} = Tsys^{Previous} \cdot$ Attenuation + $T_{Layer} \cdot$ (1 - Attenuation)

Use: T_{rcvr} = 15 K, T_{CMB} = 2.7 K

Tippings to Determine τ

$$T_{sys} \approx T_{Rcvr} + T_{CMB} + T_{Atm} \cdot \left(1 - e^{-\tau \cdot AirMass}\right)$$
$$\approx T_{Rcvr} + T_{CMB} + T_{Atm} \cdot \tau \cdot AirMass$$



- Requires knowing T_{Atm} and $f_{Spillover}$ and good calibration
  - $\Delta T_{cal}/T_{cal} = \Delta T_{Sysl}/T_{Sys} = \Delta\, \tau/\tau$

Definition of T_{Atm}

$$T_{Atm} \approx \frac{\int \kappa(h)\cdot T(h)\cdot dh}{\int \kappa(h)\cdot dh} = \frac{\int \kappa(h)\cdot T(h)\cdot dh}{\tau}$$

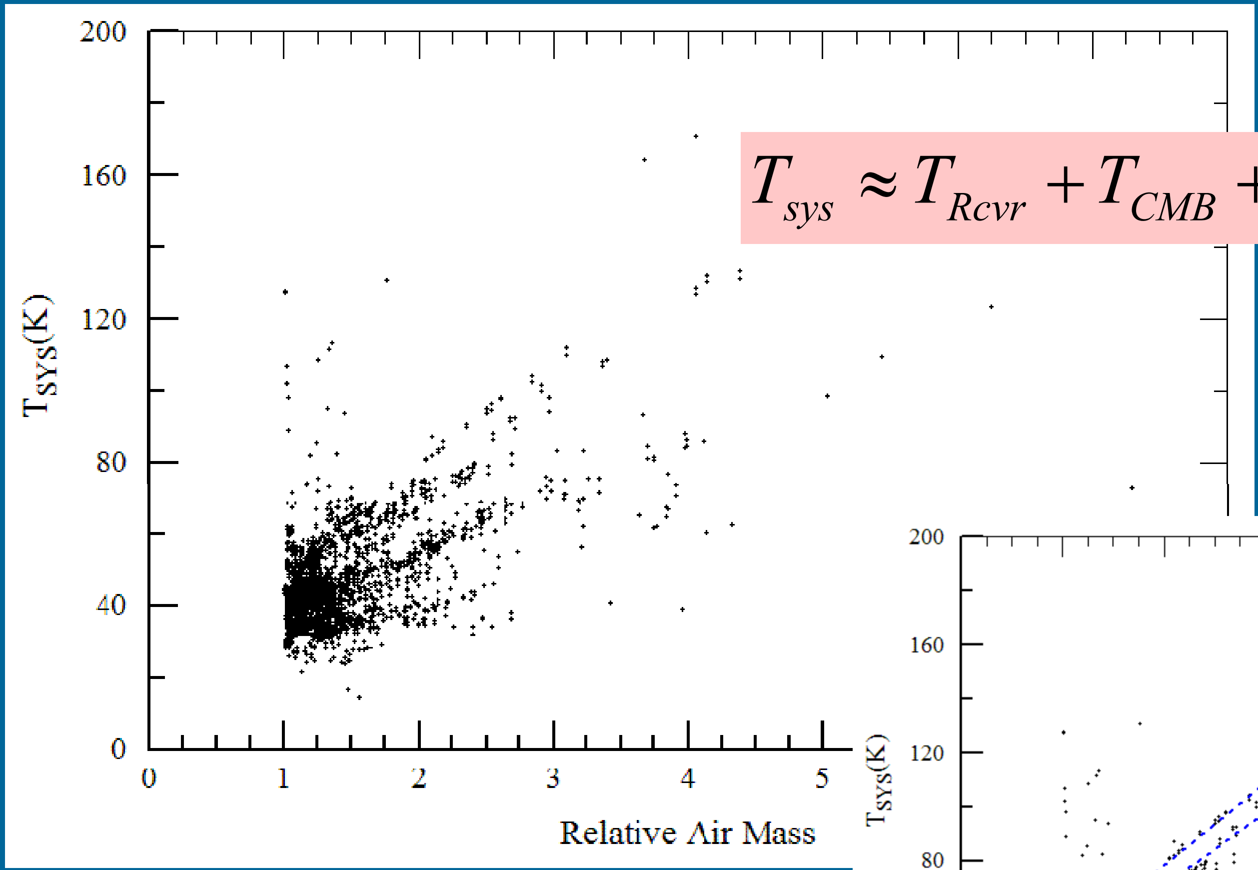
$$\text{Thus, the slope in Tipping Curve} \approx T_{Atm}\tau \approx \int \kappa(h)\cdot T(h)\cdot dh$$

The slope in a tipping curve really isn't related to the opacity!!

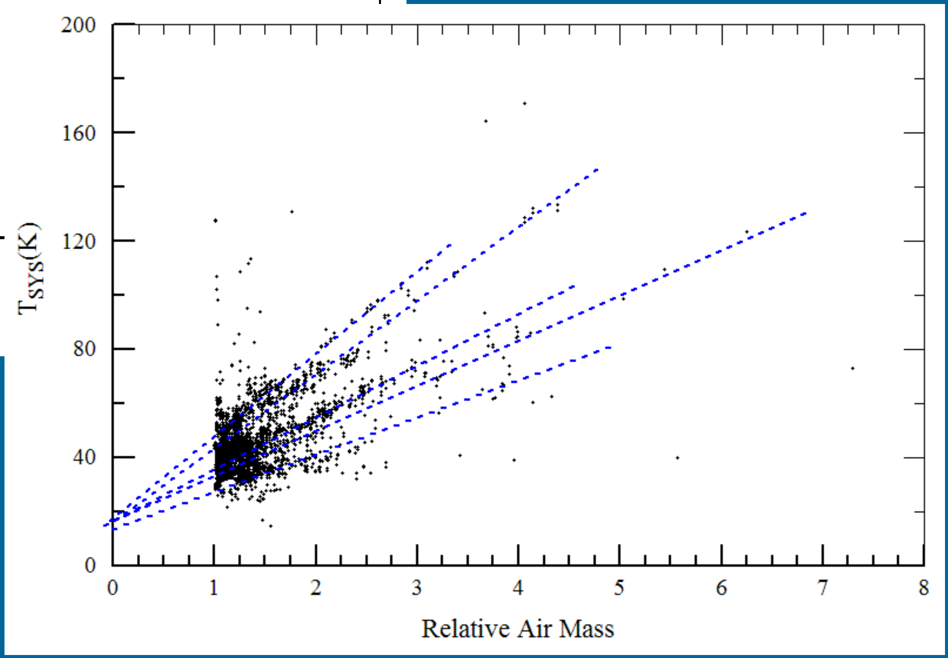
Try instead:

```
; Calculates an estimate to Tatm from ground air temperature and frequencies.
; Only appropriate for freqs < 50 GHz. The rms uncertainty in my model is 3.5 K
; Maddalena & Johnson (2005, BAAS, Vol. 37, p.1438).
;
; freqs : list of frequencies in MHz
; TempK :  ground temperature in K
;
function quickTatm, freqs, TempK
   f = freqs/1000.
   A = 259.691860 - 1.66599001*f + 0.226962192*f^2 - 0.0100909636*f^3 + 0.00018402955*f^4 - 0.00000119516*f^5
   B = 0.42557717 + 0.03393248*f + 0.000257983*f^2 - 0.0000653903*f^3 + 0.00000157104*f^4 - 0.00000001182*f^5
   return, A + B*(TempK-273.15)
end
```

Quick, Simple, and Accurate τ



$$T_{sys} \approx T_{Rcvr} + T_{CMB} + T_{Atm} \cdot \tau \cdot AirMass$$



Quick, Simple, and Accurate τ

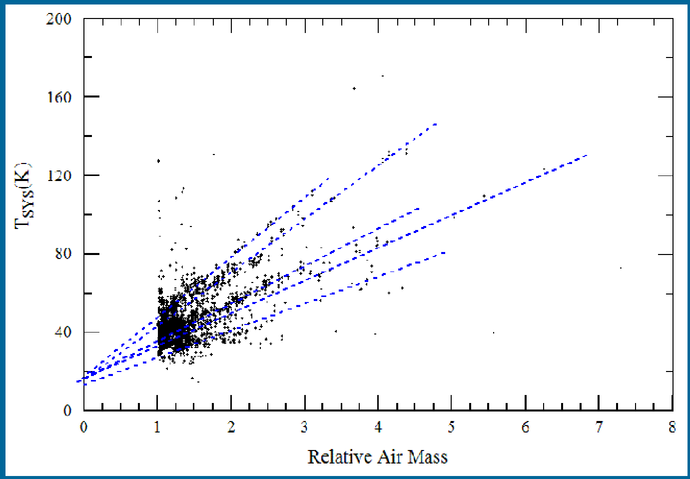
- Invert T_{sys} equation to solve for attenuation

$$e^{-\tau \cdot AirMass} = \frac{\left(1-f_{Spillover}\right)\cdot T_{Atm} - T_{sys} + T_{Rcvr} + f_{Spillover}T_{Ground}}{\left(1-f_{Spillover}\right)\cdot\left(T_{Atm} - T_{CMB} - T_R^*\right)}$$

$$\approx \frac{T_{Atm} - T_{sys} + T_{Rcvr}}{T_{Atm} - T_{CMB}}$$

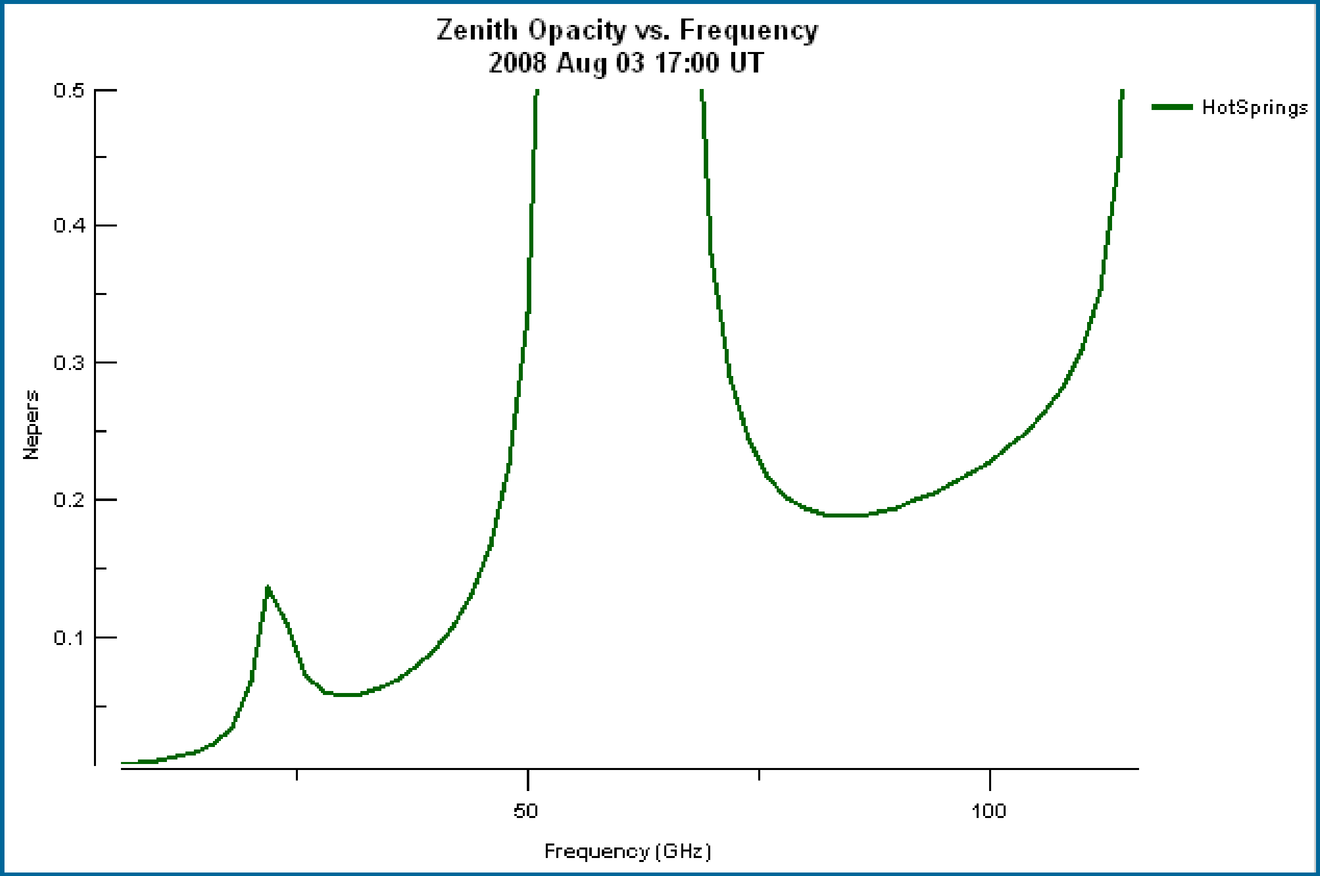
- At low frequencies and low Air Mass:

$$\tau \approx \frac{T_{sys} - T_{Rcvr} - T_{CMB}}{T_{Atm}\, AirMass}$$



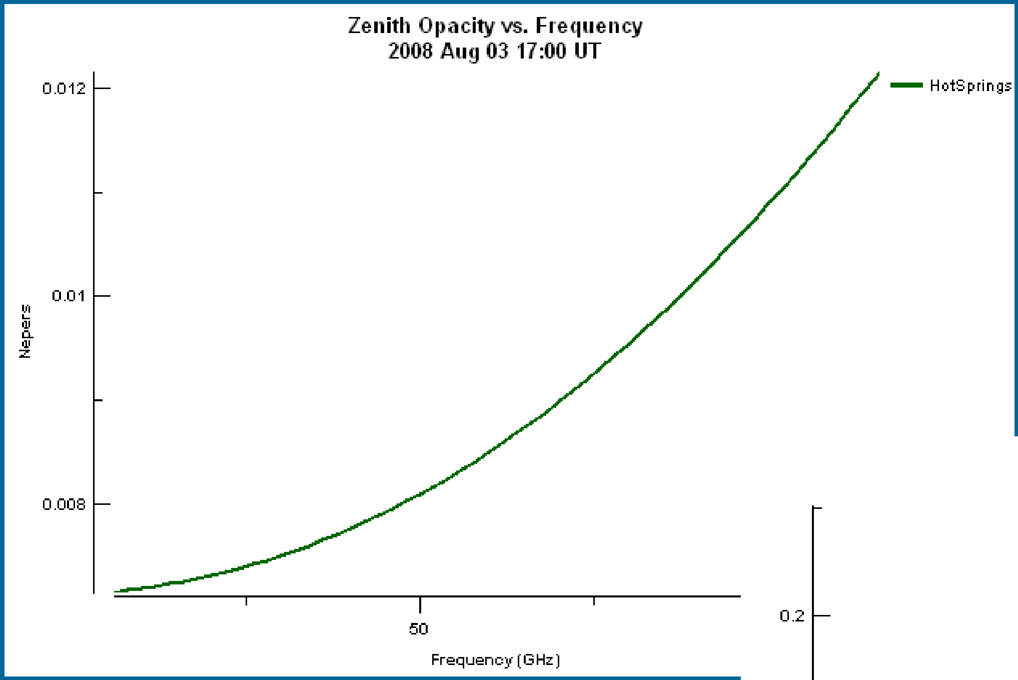
- Every single observation tells you its opacity !!
- Just need to use your ensemble of observations to determine T_{Rcvr}

Opacity vs Frequency



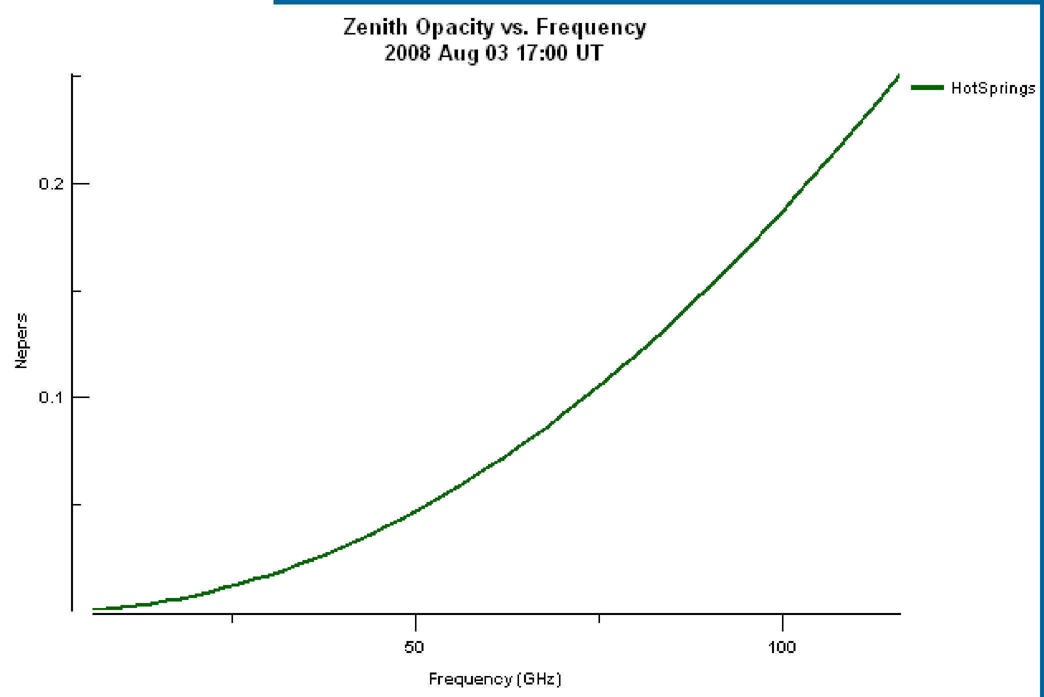
Total Opacity

Opacities from Various Atmosphere Components

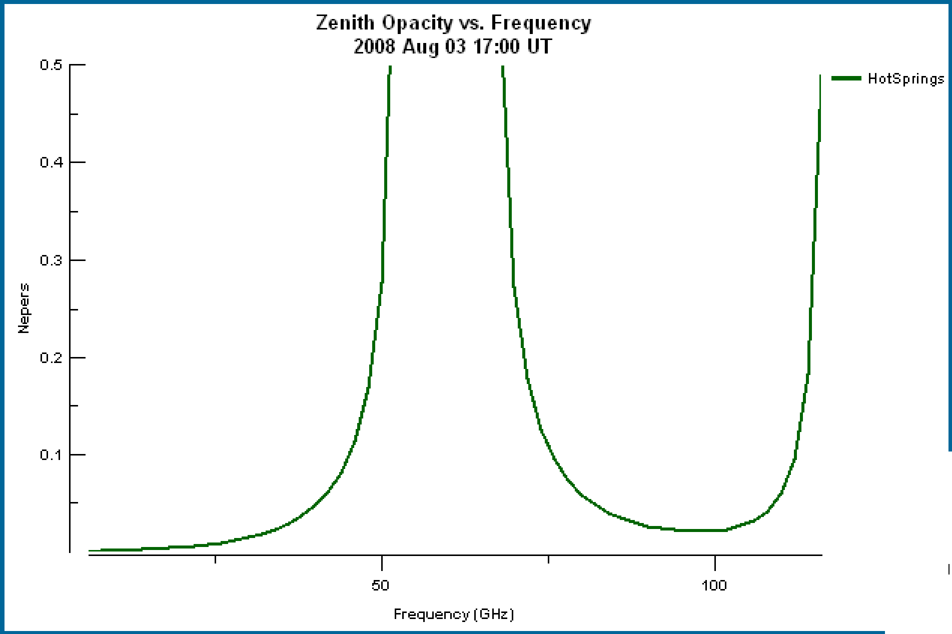


Dry Air Continuum

Water Continuum

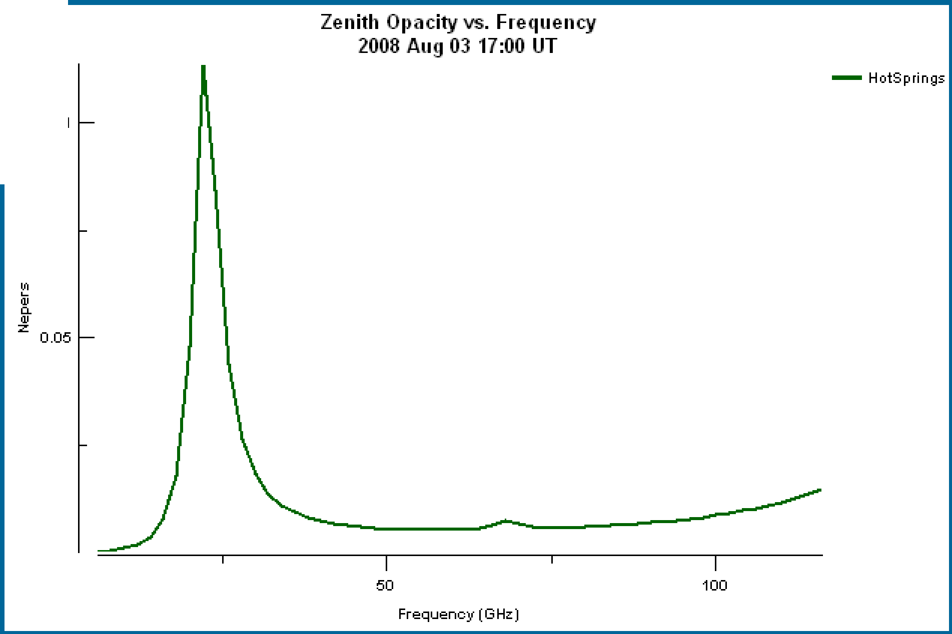


Opacities from Various Atmosphere Components

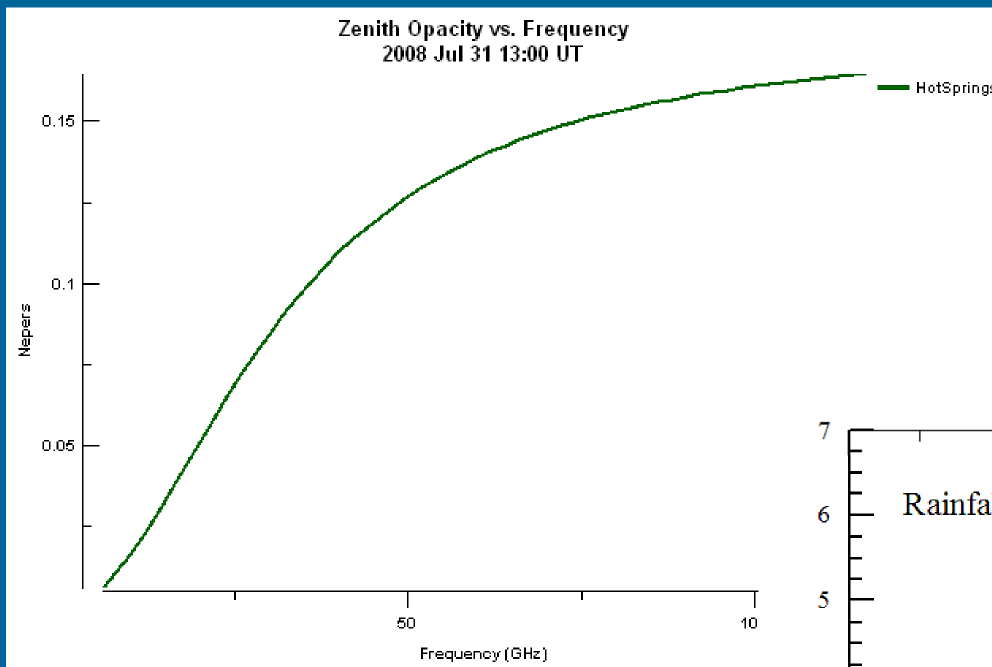


Oxygen Line

Water Line

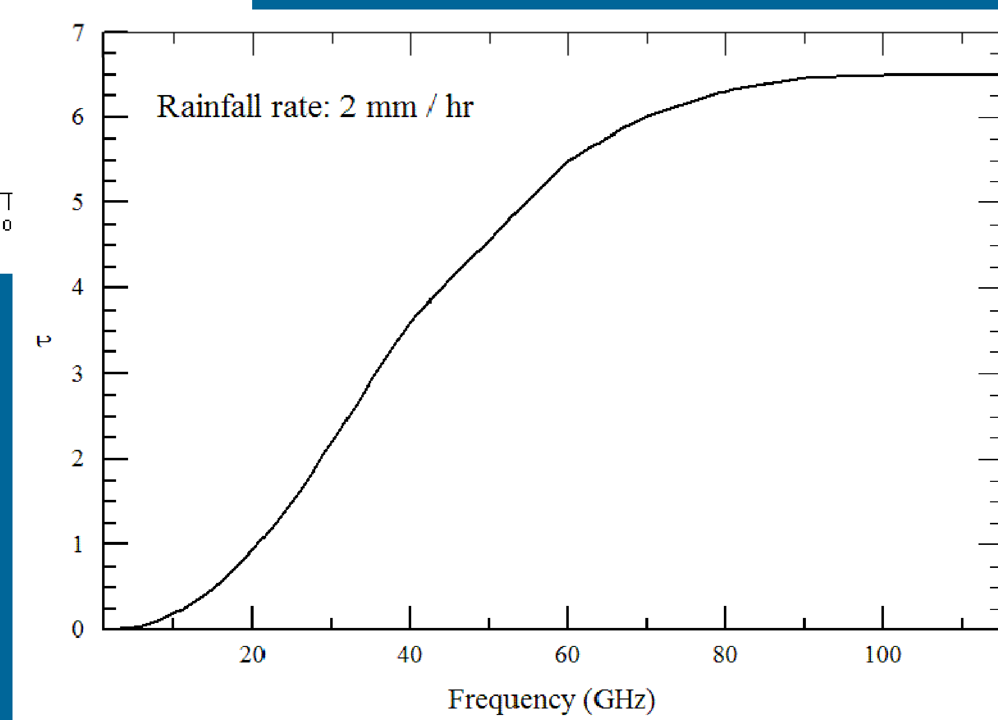


Opacities from Various Atmosphere Components

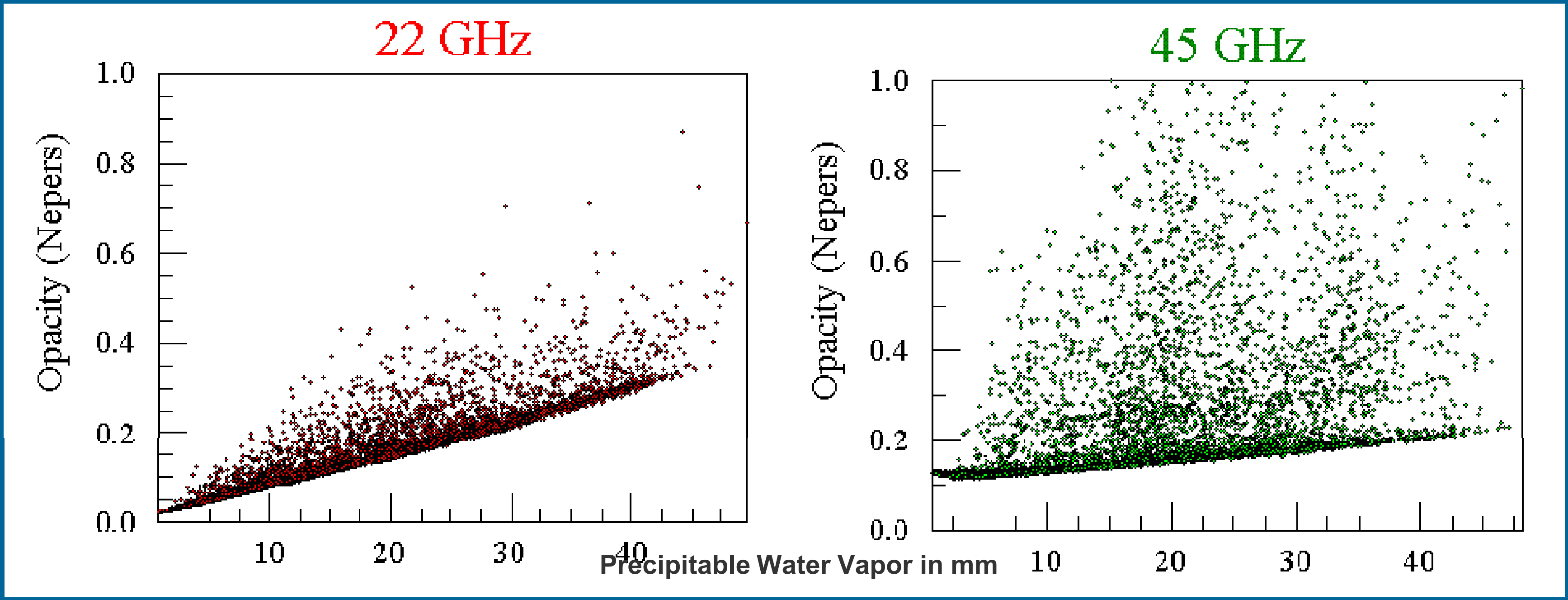


Hydrosols

Rain



Precipitable Water Vapor (PWV) vs Opacity



Graphs suggest that

$$\tau \sim A + B \cdot PWV(mm)$$

Where A and B are frequency dependent.

See Marvil (2010) EVLA Memo 143 for values of A and B for 1-50 GHz

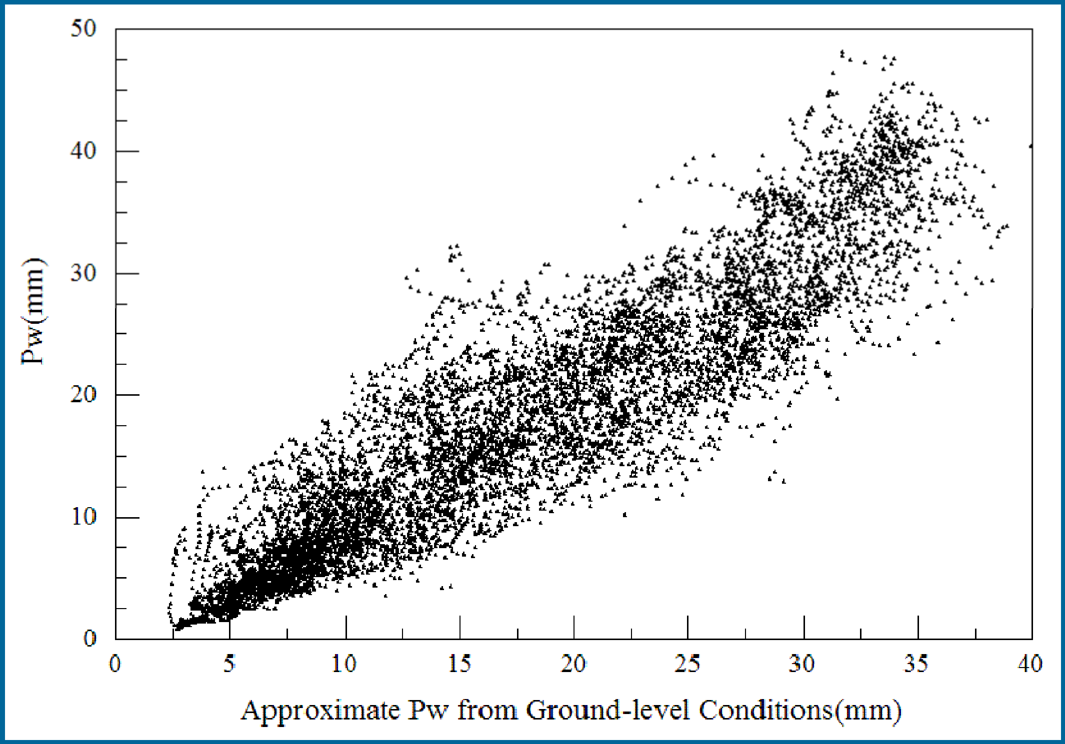
But, estimates can be in error if there are hydrosols or rain present.

Precipitable Water Vapor from Ground-Level Conditions

PWV_{H2O} (mm) ~ Scale Height (km) • 216.7(mBar) • P_{H20} / T_{Ground} (K)

Where Scale Height ~ 2.2 km

Butler (1998), "MMA Memo 237"



But, it's a very rough value only and more useful for site statistics and not really suitable for calibration

Affects of Winds

- Force = Air Density • Wind Speed^2
- Hooke's Law: Force ∝ Displacement ∝ Δθ
- Telescope Beams are Gaussian

$$\frac{G}{G_0} = e^{-a\cdot\Delta\theta^2\cdot Frequency^2} = e^{-b\cdot Velocity^4\cdot Frequency^2}$$

$$\frac{t_{Best}}{t_{Needed}} = \eta_{Tracking} = \left(\frac{G}{G_0}\right)^2 = e^{-2b\cdot Velocity^4\cdot Frequency^2}$$

For small $\Delta\theta$:

$$\eta_{Tracking} = \left(1 - b\cdot Velocity^4\cdot Frequency^2\right)^2$$

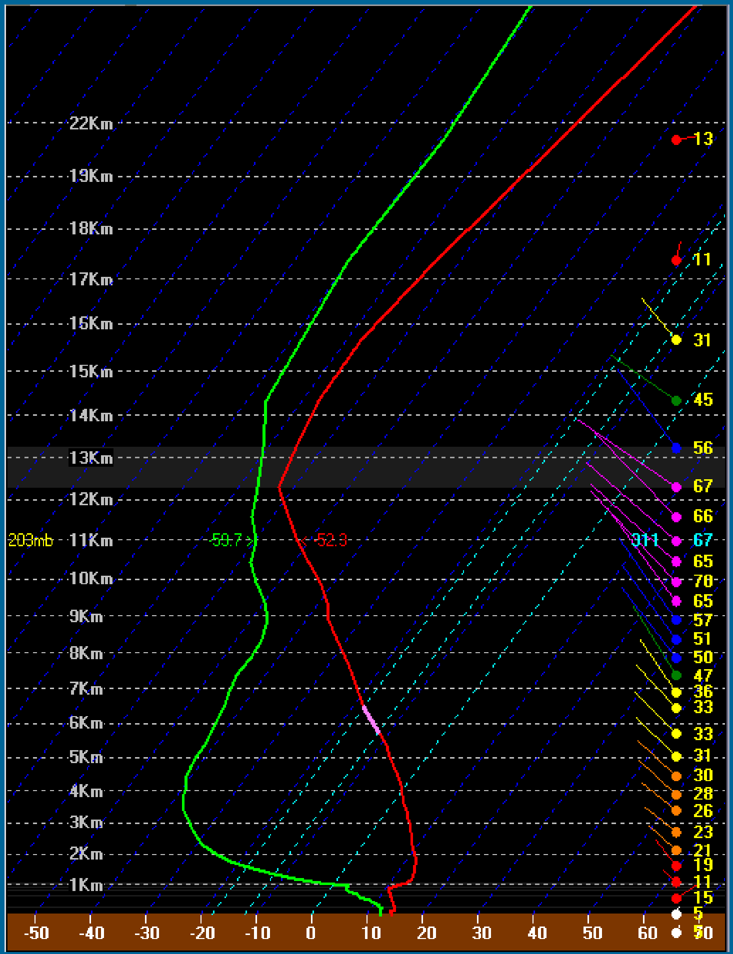
Condon & Balser (2011), DSS memo 5

Weather Forecasting for Radio Astronomy

- The standard products of the National Weather Service (other than winds, cloud cover, precipitation, and somewhat PWV) do not serve radio astronomy directly.
- But, the NWS products be reprocessed to generate forecast values that are more useful for radio astronomy.

Vertical profiles

- Atmospheric pressure, temperature, and humidity as a function of height above a site (and much more).
- Derived from *Geostationary Operational Environmental Satellite* (GOES) soundings and, now less often, balloon soundings
- Generated by the *National Weather Service*, an agency of the *NOAA*.



Bufkit, a great vertical profile viewer
http://www.wbuf.noaa.gov/bufkit/bufkit.html

Vertical Profiles

- 65 layers from ground level to 30 km
  - Stratospheric (Tropapause ~10 km)
- Layers finely spaced (~40 m) at the lower heights, wider spacing in the stratosphere
- Available for major towns (Elkins, Hot Springs, Lewisburg)
- Three flavors of forecasts:
  - 1 hr and 12 km resolution, 12 hr range, 1 hr updates
  - 1 hr and 12 km resolution, 84 hr range, 6 hr updates
  - 3 hr and 35 km resolution, 120 hr range, 12 hr updates

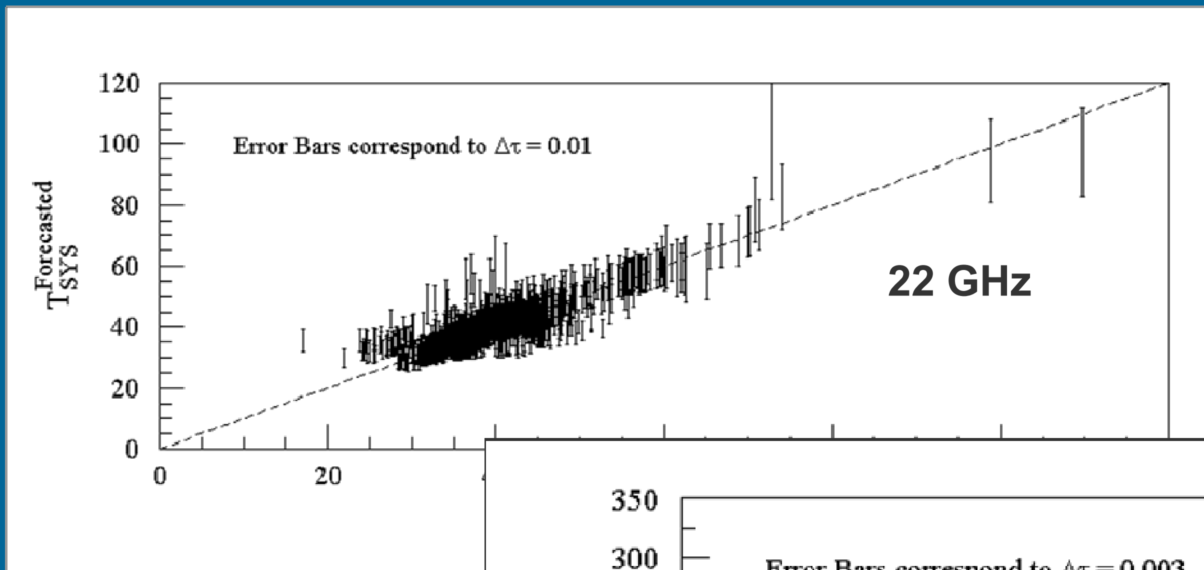
Bufkit files available for “Standard Stations”

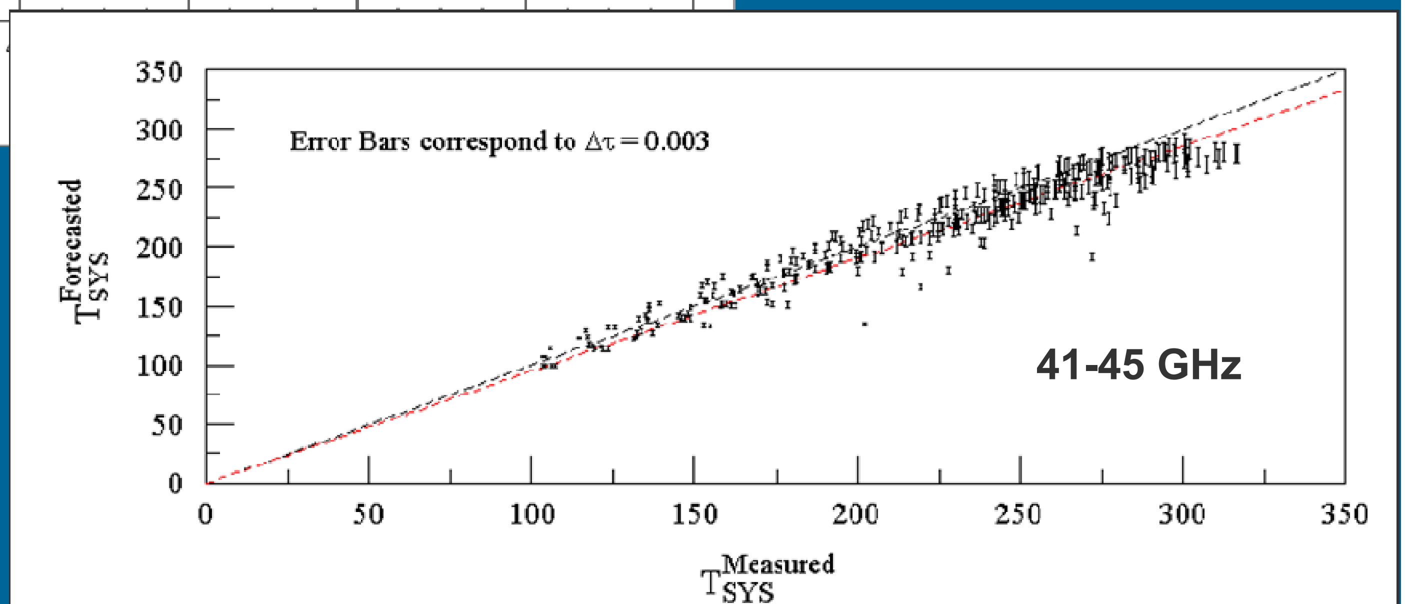
Basics of Atmospheric Modeling

- Liebe, 1985, “Radio Science”, Vol 20, p. 1069.
- Maddalena (http://www.gb.nrao.edu/~rmaddale/Weather)

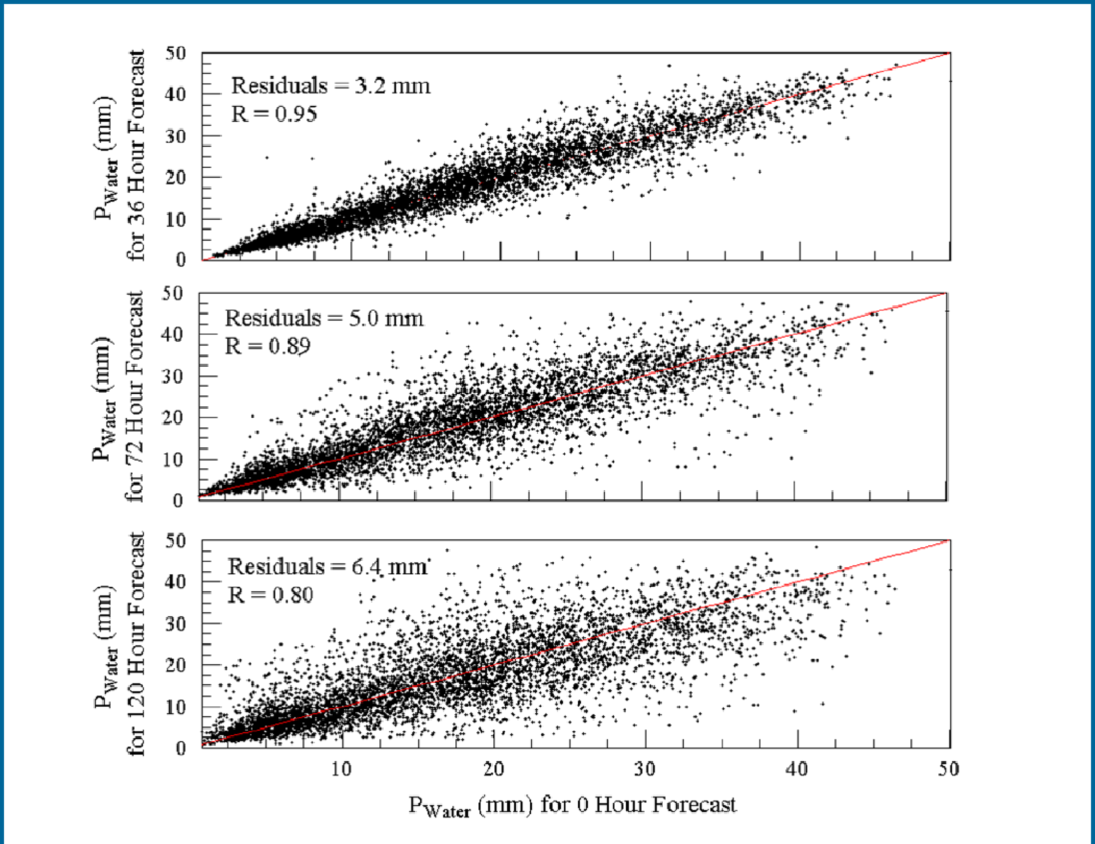
h	T	P	DP	CFRL	Δh	ρ_{Water}	ρ_{Dry}	n	$\Delta Elev$	κ_{Dry}	κ_{H2O} Cont	κ_{H2O} Line	κ_{O2}	$\kappa_{Hydrosols}$	κ_{Total}	ΔT_{Sys}
30 km																
…																
920 m																
880 m																
									R						τ T_{Atm}	T_{Sys}

The Accuracy of Radio-Astronomy Forecasts is High





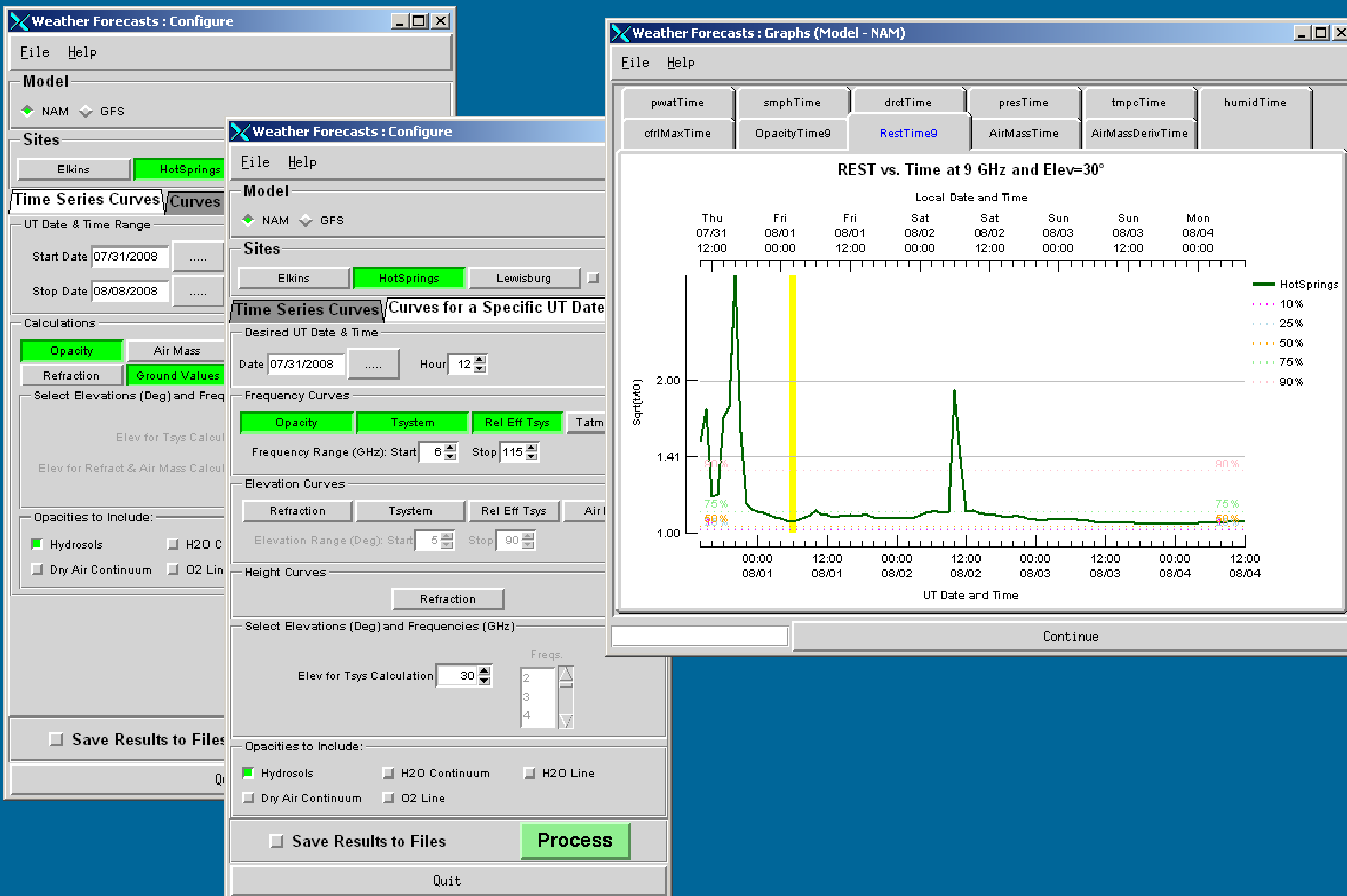
The Reliability of Radio-Astronomy Forecasts is High



Correlation Between Forecasts

Hr	R	rms (mm)
6	0.985	1.76
12	0.978	2.11
18	0.972	2.41
24	0.968	2.58
30	0.960	2.91
36	0.952	3.15
42	0.942	3.46
48	0.932	3.73
54	0.922	4.03
60	0.910	4.35
66	0.898	4.64
72	0.885	4.95
78	0.875	5.19

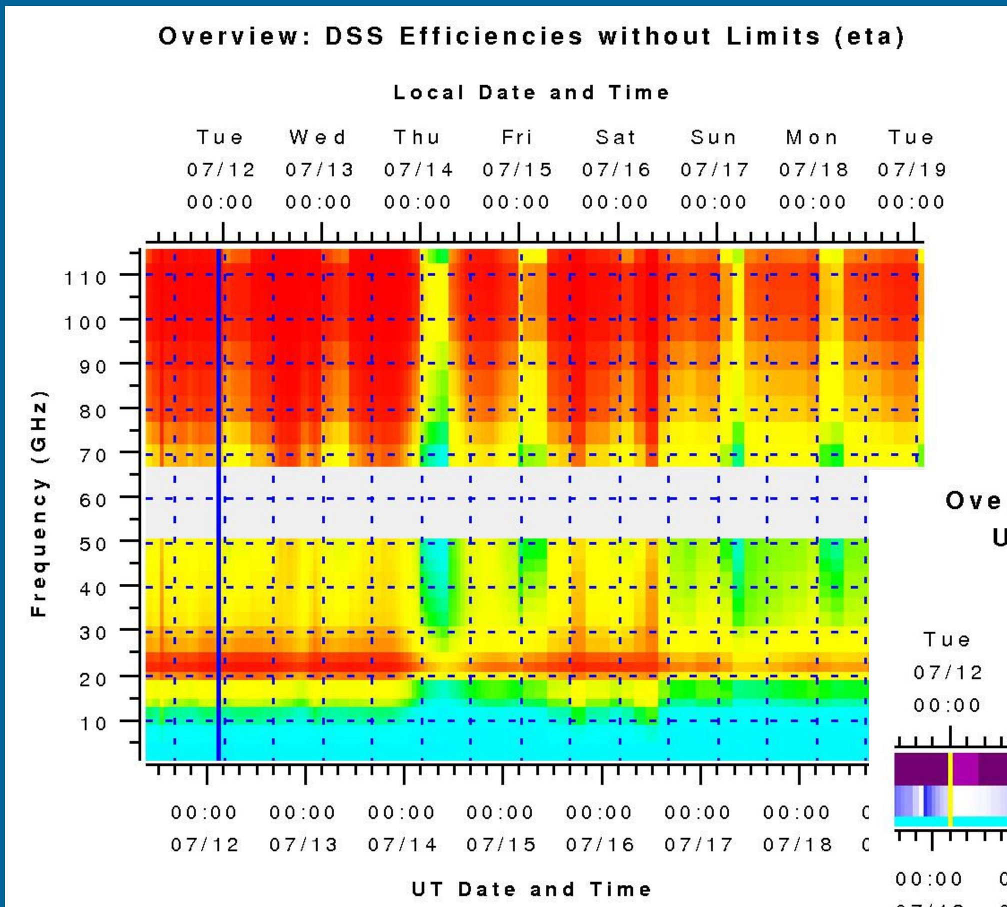
User Software: cleo forecasts

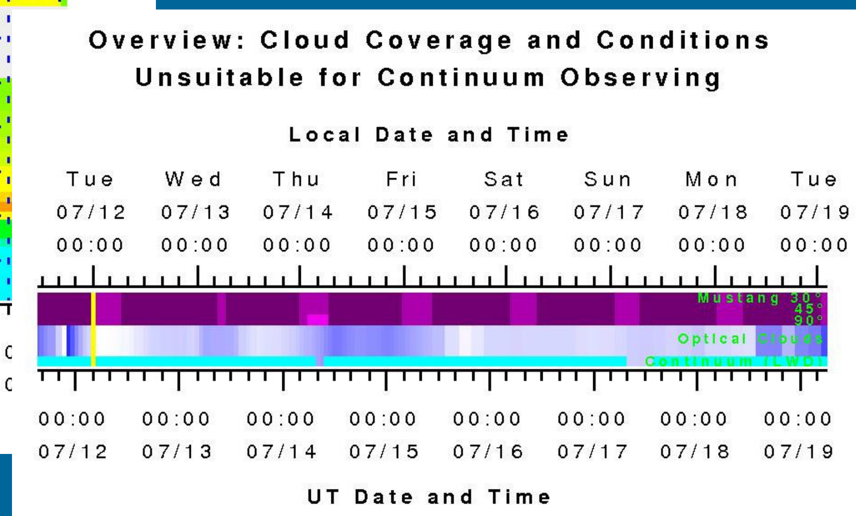


Web Page Summaries

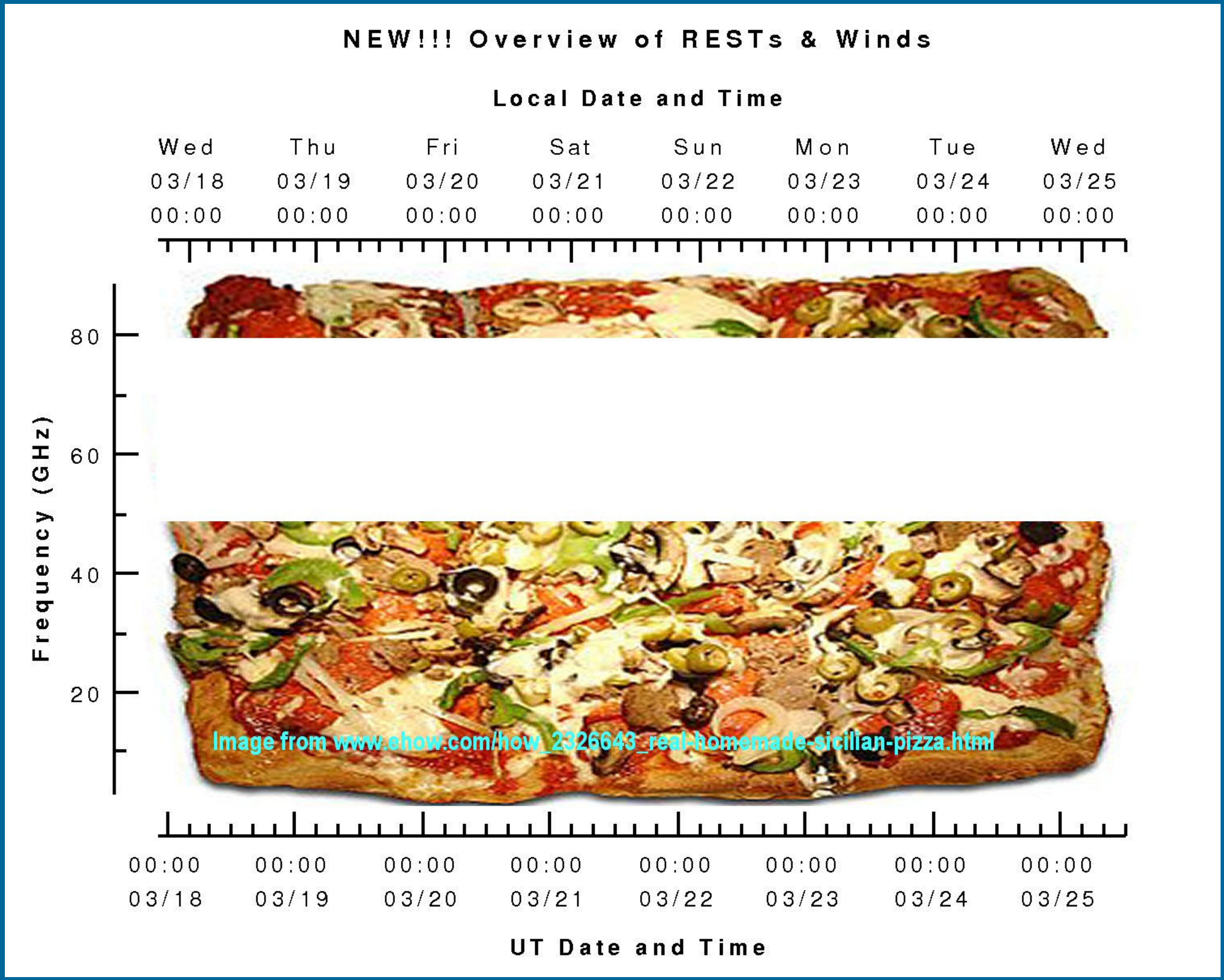
- http://www.gb.nrao.edu/~rmaddale/Weather
- 3.5 and 7 day forecasts.
- Provides:
  - Ground weather conditions
  - Opacity and T_{Atm} as a function of time and frequency
  - T_{sys} and RESTs as functions of time, frequency, and elevation
  - Refraction, differential refraction, comparison to other refraction models
- Weather.com forecasts
- NWS alerts
- Short summary of the modeling and list of references
- Overview (Pizza) Plots

Overview (Pizza) Plots and GBT Scheduling





Pizza Plots and GBT Scheduling



GBT Dynamic Scheduling

- Uses cm- and mm-wave weather forecasts to determine the optimum way to schedule projects for the next 2 days
- Additional factors:
  - Project ranking
  - Availability of hardware
  - Observer blackouts dates/times
    - Allows for multiple observers on a project
  - Proposal pressure vs frequency and LST range
- Observers are provided with emails when they are scheduled.
- If remotely observing, observers use VNC to conduct their experiment.
- Before one can remotely observe, one must first observe locally so that we can ensure remote observing will be fruitful.
- For more details, see:
  - http://science.nrao.edu/gbt/scheduling/dynamic.shtml
  - Condon & Balser (2011), DSS memo 4
  - Condon & Balser (2011), DSS memo 5

DSS Project Weather 'Scoring'

- Product of three measures of observing efficiency:

$$\eta_{Atmosphere} = \left(\frac{T_{SYS}^{Best} \cdot e^{\tau^{Best} \cdot AirMass}}{T_{SYS}^{Forecasted} \cdot e^{\tau^{Forecasted} \cdot AirMass}} \right)^2 \propto \frac{t^{Best}}{t^{Needed}} \leq 1$$

- $\eta_{Surface}$: Loss in observing efficiency due to degradation of surface (<1 during the 'day', =1 at night)
- $\eta_{Tracking}$: Loss in observing efficiency due to winds (outlined above) plus servo system errors.

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