Weather Forecasting for Radio Astronomy

Lecture for the 2009 REU Summer Students

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July, 2009

The influence of the weather at cm- and mm-wavelengths

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

Broad-brush goals of this research

Improve our estimations of:

- Current conditions
  - Calibration, pointing, safety, telescope productivity
- Near-future conditions
  - Safety, telescope productivity
- Past conditions
  - Calibration
  - Weather statistics
    - Telescope productivity, hardware decisions, observing techniques, proposal acceptance

Project inspiration

- 5-years of observing at 115 GHz at sea level.
- Harry Lehto’s thesis (1989)
- Research requiring high accuracy calibration
- Ardis Maciolek’s RET project (2001)
- Too many rained-out observations

Project inspiration

- Lehto : Measured vertical weather profiles are an excellent way of determining past observing conditions
  - No practical way to obtain vertical profiles and use Harry’s technique until…
- Maciolek : Vertical profiles are now easily available on the WWW for the current time and are forecasted!!

Project aspirations

- Leverage Lehto's ideas to use Maciolek' profiles
  - Current and near-future weather conditions
- Automate the archiving of Maciolek' profiles
  - Weather conditions for past observations
  - Makes possible the generation of detailed weather statistics
    - Archive integrity supersedes all else – Don't embed the physics into the archive
- Produce the tools to mine the archive, display and summarize past, current and future conditions
- After two years labor on the mechanics and physics, alpha system launched in May, 2004, full release in June 2005, with on-going, sometimes extensive modifications and refactoring.

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*.

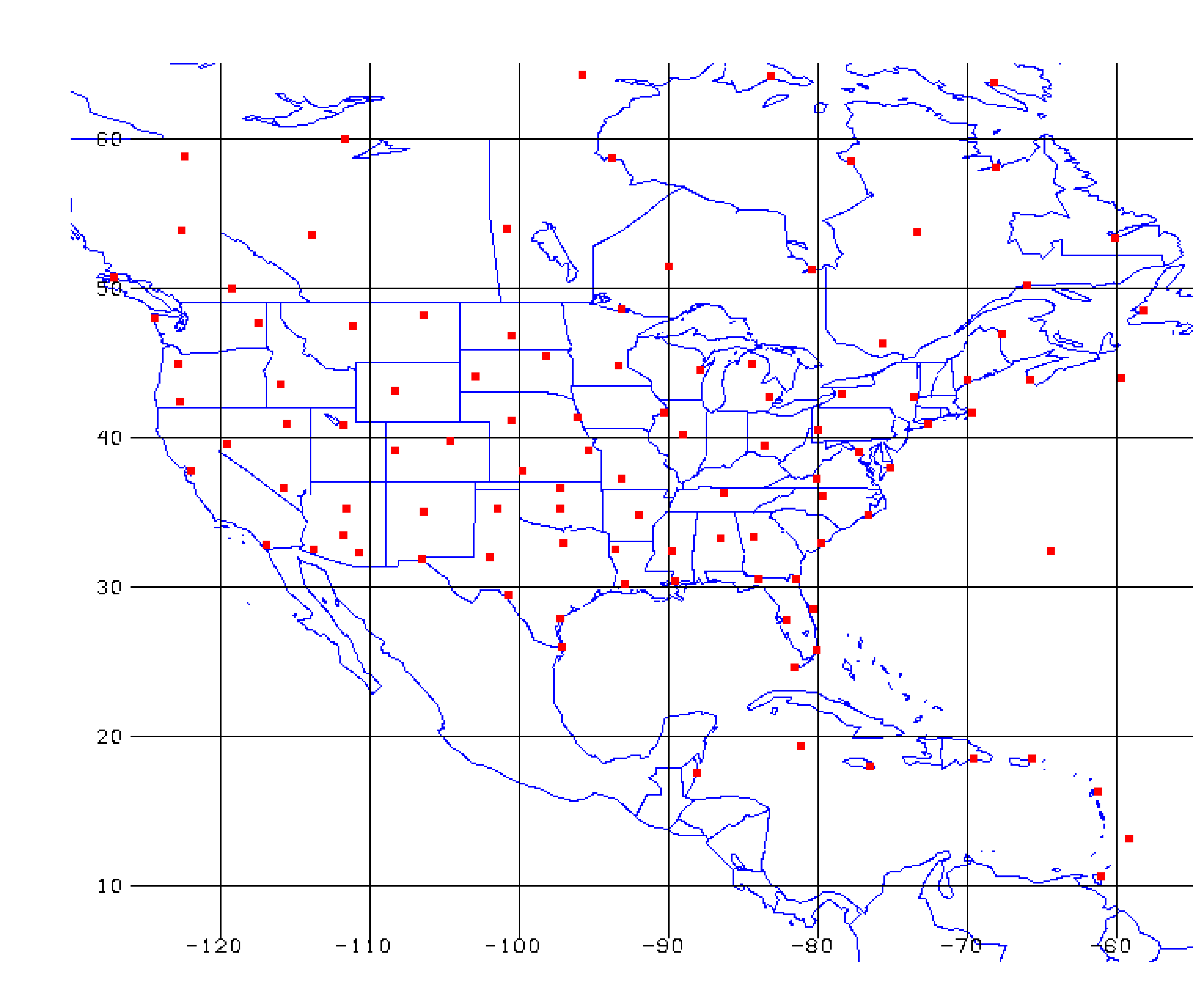
Bufkit, a great vertical profile viewer

http://www.wbuf.noaa.gov/bufkit/bufkit.html

Bufkit and Bufkit files

- 65 layers from ground level to 30 km
  - Stratospheric (Tropopause ~10 km)
- Layers finely spaced (~40 m) at the lower heights, wider spaced in the stratosphere
- Available for Elkins, Hot Springs, Lewisburg

Bufkit files available for “Standard Stations”



Balloon Soundings

Bufkit and Bufkit files

- North American Mesoscale (NAM)
  - The 3.5 day (84 hours) forecasts
  - Updated 4-times a day
  - 12 km horizontal resolution
  - 1 hour temporal resolution
  - Finer detail than other operational forecast models
  - 1350 stations, all North America

Bufkit and Bufkit files

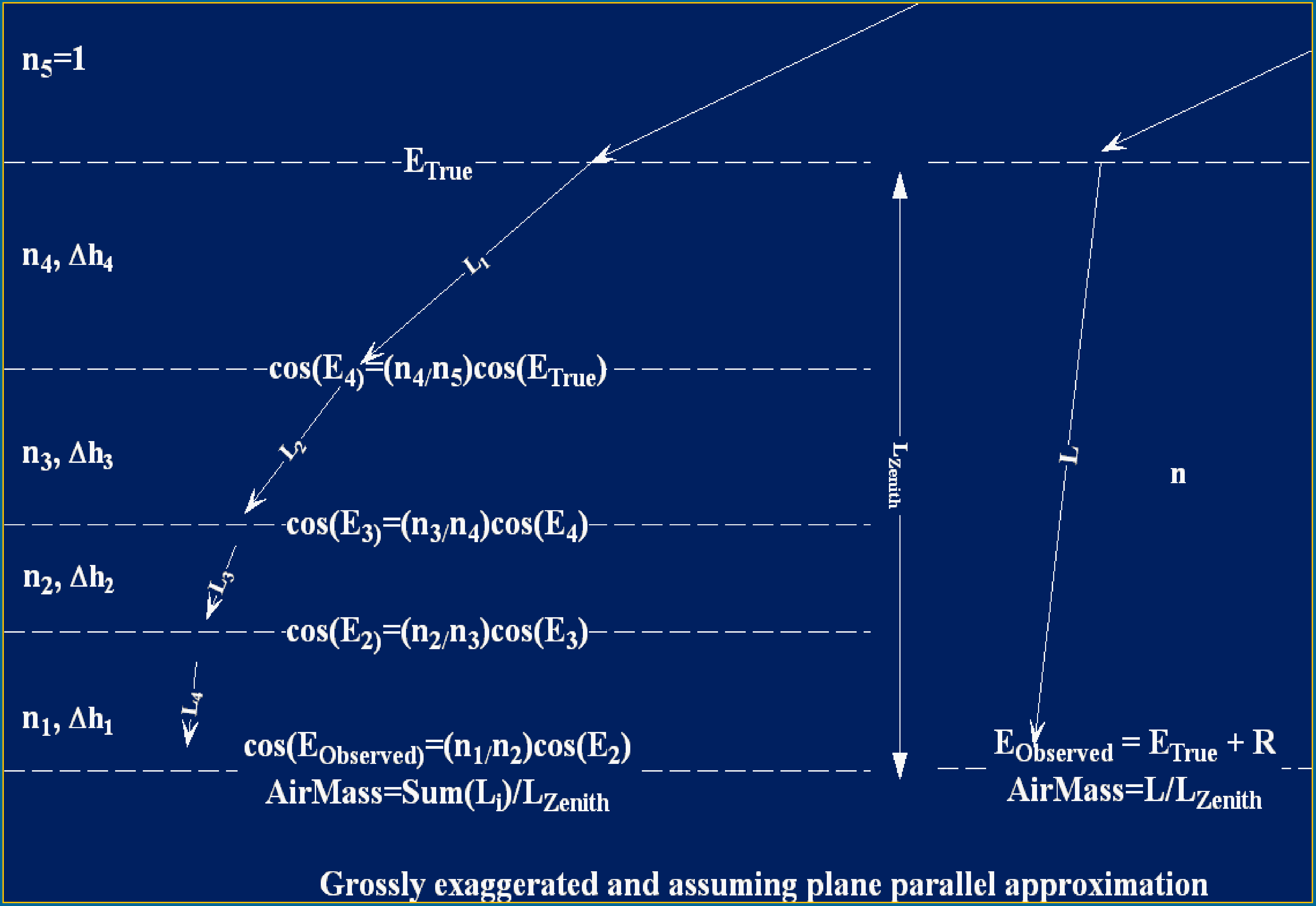
- Global Forecast System (GFS)
  - 7.5-day (180 hrs) forecasts
  - Based on the first half of the 16-day GFS models
  - 35 km horizontal resolution
  - 3 hour temporal resolution
  - Updated twice a day
  - Do not include percentage cloud cover
  - 1450 stations, some overseas

Basics of atmospheric modeling

- "Macroscopic measure of interactions between radiation and absorbers expressed as complex refractivity…" (Liebe, 1985)

- For each layer of the atmosphere, calculate:
  - Density of water vapor and dry air

- For each layer of the atmosphere, for five different components of the atmosphere, for any desired frequency calculate :
  - Real part of refractivity
    - Ray-trace at desired observing elevation through the atmosphere to determine total refraction and air mass
  - Imaginary part of refractivity
    - Determines absorption and emissivity as a function of height
    - Use radiative transfer to determine:
      - Total opacity at desired observing elevation
      - Contribution of the atmosphere to system temperature at desired observing elevation



n5=1
ETrue
n4, Δh4
L1
cos(E4)=(n4/n5)cos(ETrue)
n3, Δh3
L2
cos(E3)=(n3/n4)cos(E4)
n2, Δh2
L3
cos(E2)=(n2/n3)cos(E3)
n1, Δh1
L4
cos(EObserved)=(n1/n2)cos(E2)
AirMass=Sum(Li)/LZenith
LZenith
L
n
EObserved = ETrue + R
AirMass=L/LZenith
Grossly exaggerated and assuming plane parallel approximation

Basics of refraction and relative air mass

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

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

a = Earth radius

n(h) = index of refraction at height h

n_0 = index of refraction at surface

ρ(h) = air density

$Elev_{Obs}$, $Elev_{True}$ = refracted and airless elevations

T_{BG}

$$T_{Sys\_Atm}(5) = T_{BG}$$

$T_4, \kappa_4, \Delta h_4$

$$T_{Sys\_Atm}(4) = T_{BG} \cdot \exp(-\kappa_4 \cdot \Delta h_4) + T_4 \cdot [1 - \exp(-\kappa_4 \cdot \Delta h_4)]$$

$T_3, \kappa_3, \Delta h_3$

$$T_{Sys\_Atm}(3) = T_{sys}(4) \cdot \exp(-\kappa_3 \cdot \Delta h_3) + T_3 \cdot [1 - \exp(-\kappa_3 \cdot \Delta h_3)]$$

$T_2, \kappa_2, \Delta h_2$

$$T_{Sys\_Atm}(2) = T_{sys}(3) \cdot \exp(-\kappa_2 \cdot \Delta h_2) + T_2 \cdot [1 - \exp(-\kappa_2 \cdot \Delta h_2)]$$

$T_1, \kappa_1, \Delta h_1$

$$T_{Sys\_Atm}(1) = T_{sys}(2) \cdot \exp(-\kappa_1 \cdot \Delta h_1) + T_2 \cdot [1 - \exp(-\kappa_1 \cdot \Delta h_1)]$$

T_{BG}

T_{Atm}, τ

$$T_{BG} \cdot \exp(-\tau) + T_{Atm} \cdot [1 - \exp(-\tau)]$$

Basics of radiative transfer

$$\kappa_{Total}(h,\nu) = \sum \kappa_i(h,\nu)$$

$$\tau(\nu) = \int_0^H \kappa_{Total}(h,\nu) \cdot dh$$

$$T_{Sys}^{Atm}(h,\nu) = T_{Sys}^{Atm}(h+dh) \cdot e^{-\kappa_{Total}(h,\nu) \cdot dh} + T(h) \cdot (1 - e^{-\kappa_{Total}(h,\nu) \cdot dh})$$

$$T_{Sys}^{Atm}(0,\nu) = T_{Atm} \cdot (1 - e^{\tau(\nu) \cdot AirMass})$$

$$T_{Atm} = \frac{\int_0^H \kappa_{Total}(h,\nu) \cdot T(h) \cdot dh}{\int_0^H \kappa_{Total}(h,\nu) \cdot dh}$$

Refractivity at different heights

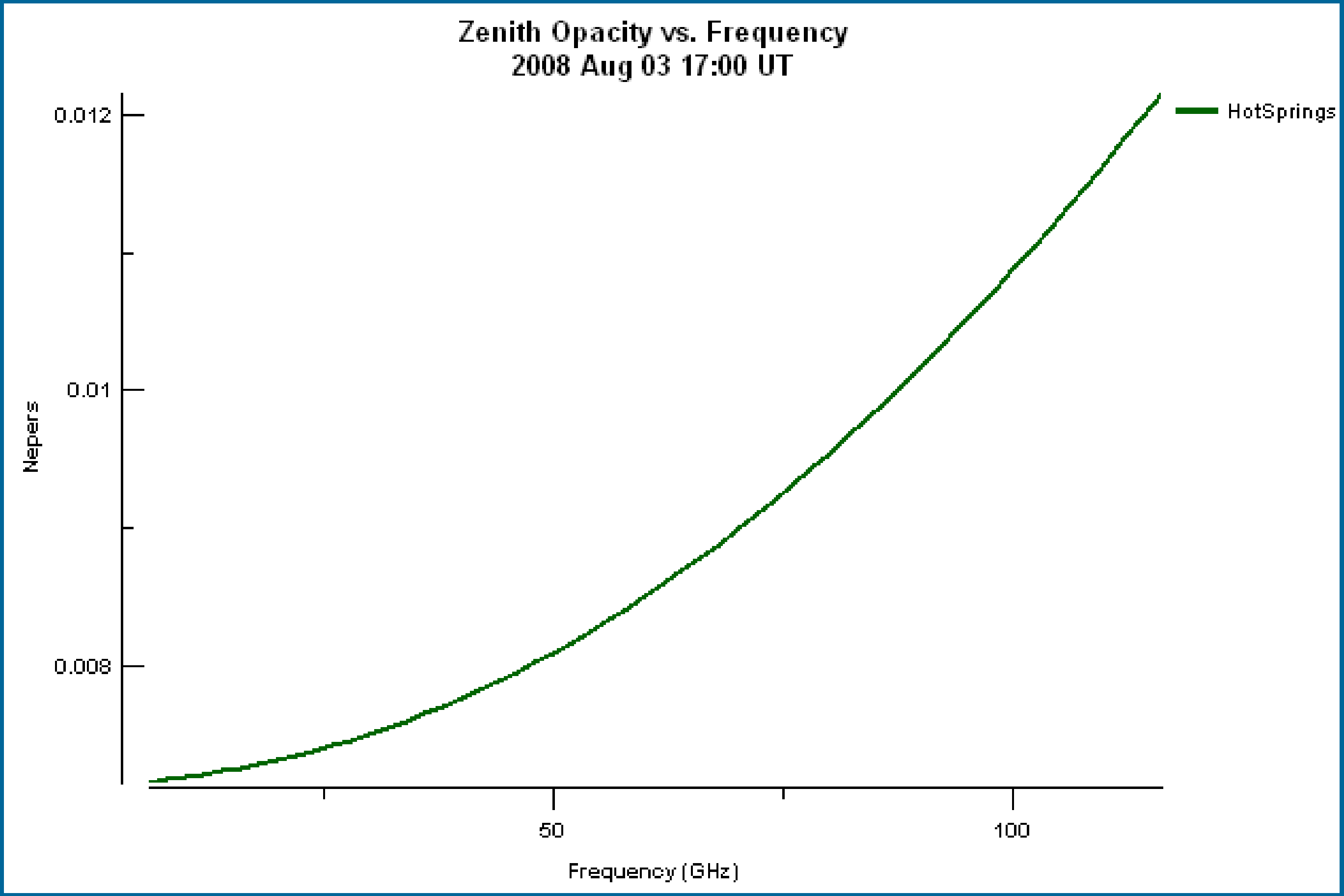
- Modeled as arising from five components of the atmosphere
  - Dry air continuum
    - Non-resonant Debye spectrum of O_2 below 100 GHz, pressure-induced N_2 attenuation > 100 GHz
  - Water vapor rotational lines:
    - 22.2, 67.8 & 120.0, 183.3 GHz, and higher
  - Water vapor continuum from an unknown cause
    - “Excess Water Vapor Absorption” problem
  - Oxygen spin rotation resonance line
    - Band of lines 51.5 – 67.9 GHz, single line at 118.8 GHz, and higher
    - Modeled using Rosenkranz’s (1975) impact theory of overlapping lines
  - Hydrosols
    - Mie approximation of Rayleigh scattering from suspended water droplets with size < 50 μm

How it works….

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

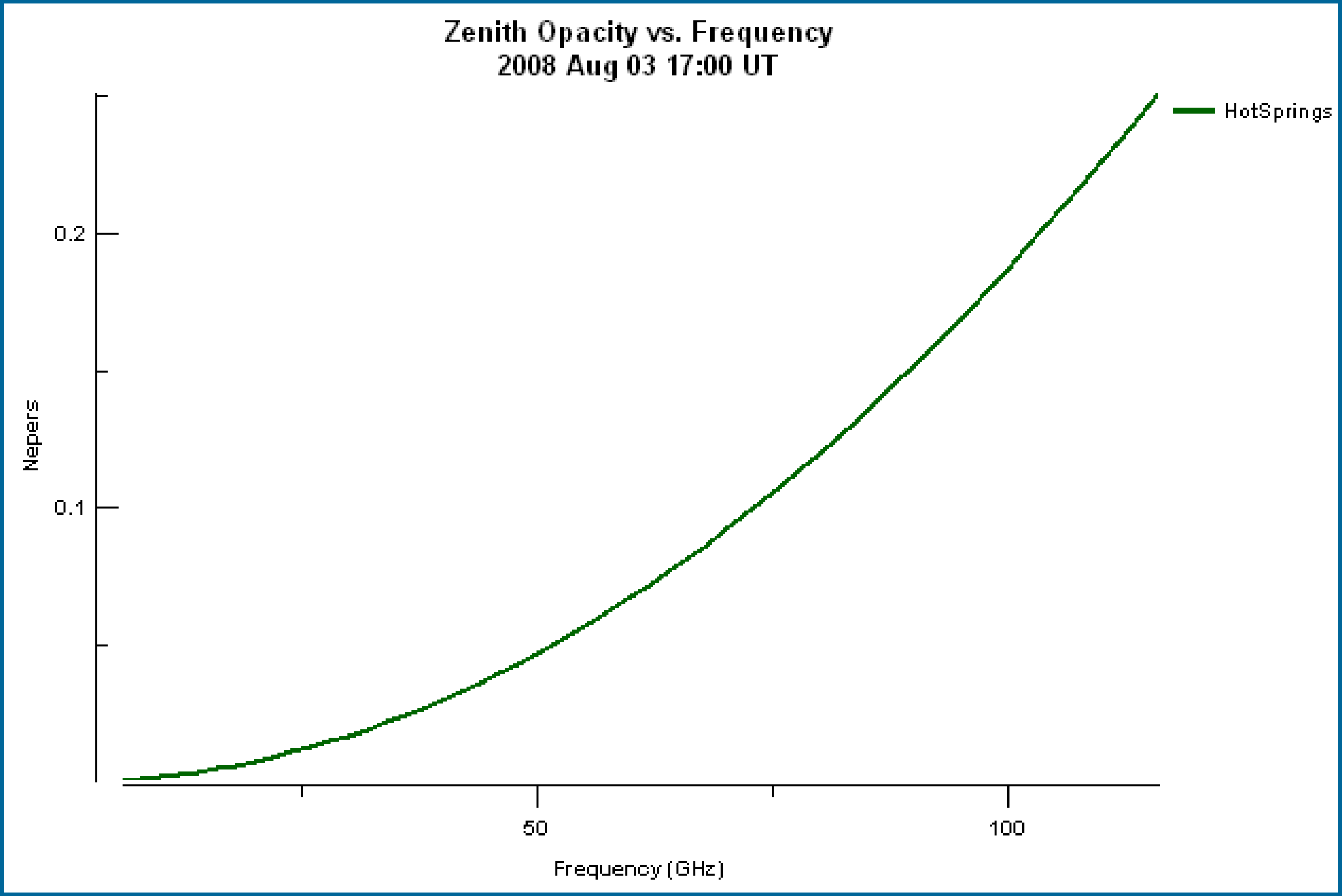
Generate a table for every desired frequency, site, time

Opacities from the various components



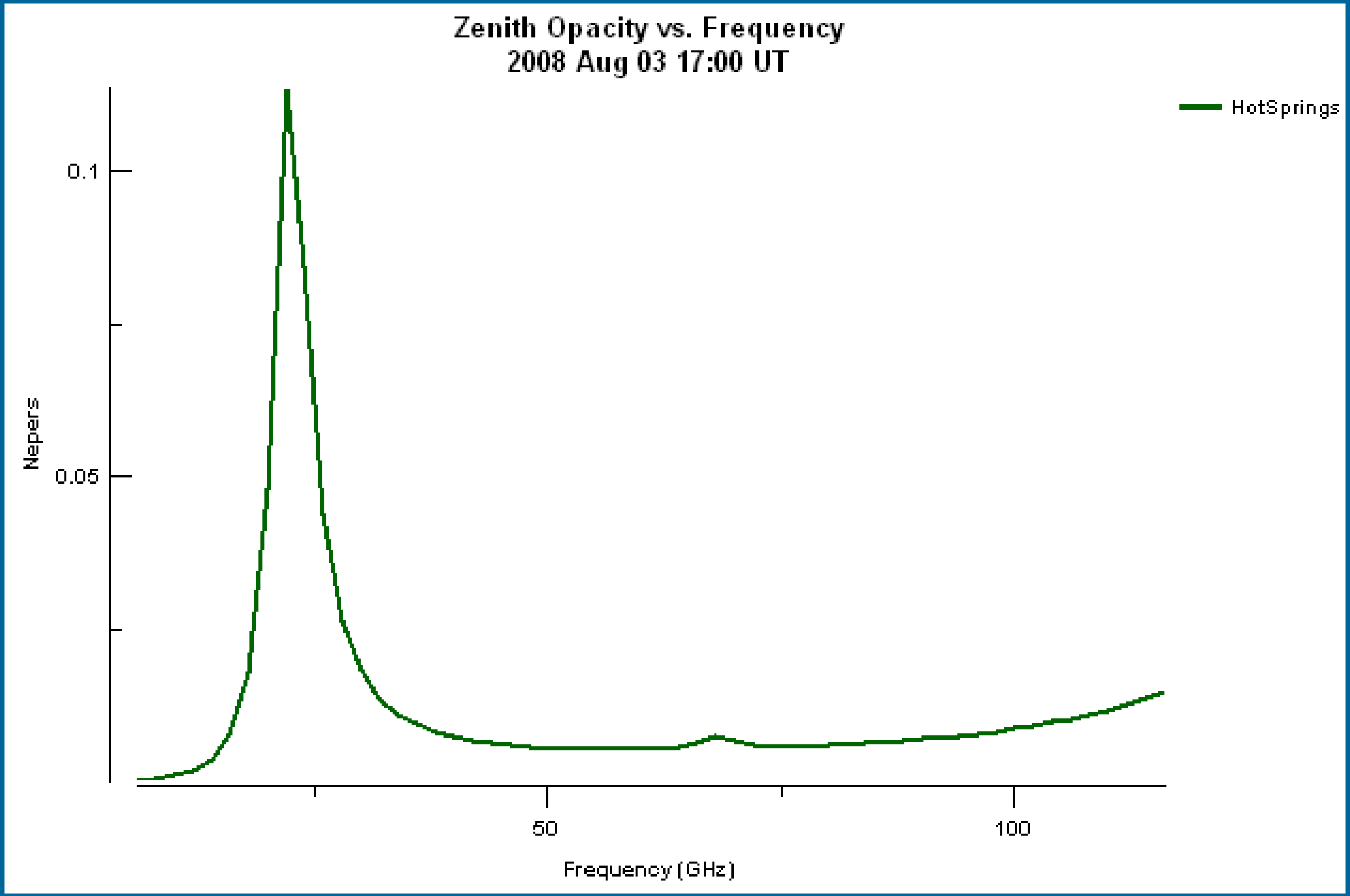
Dry Air Continuum

Opacities from the various components



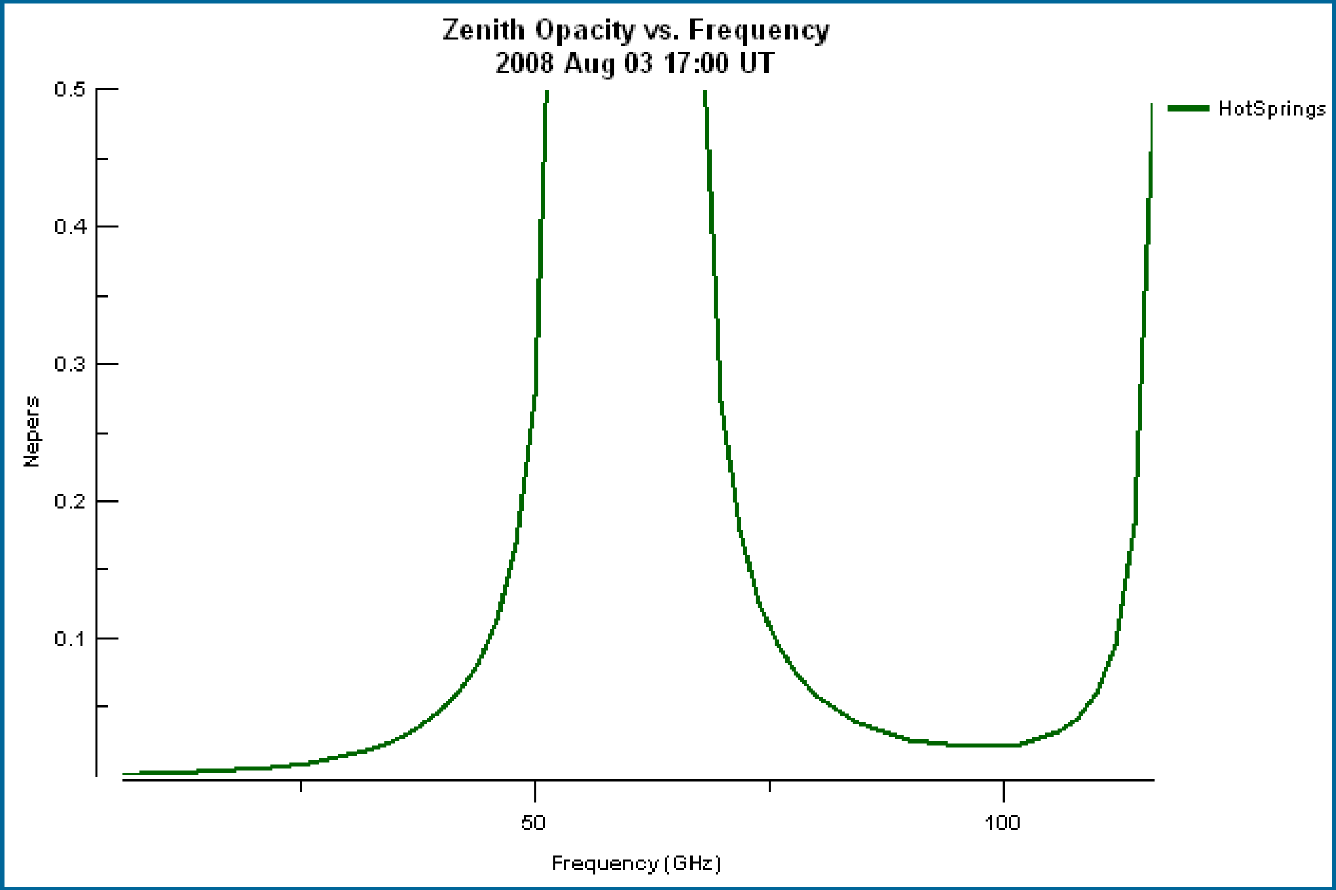
Water Continuum

Opacities from the various components



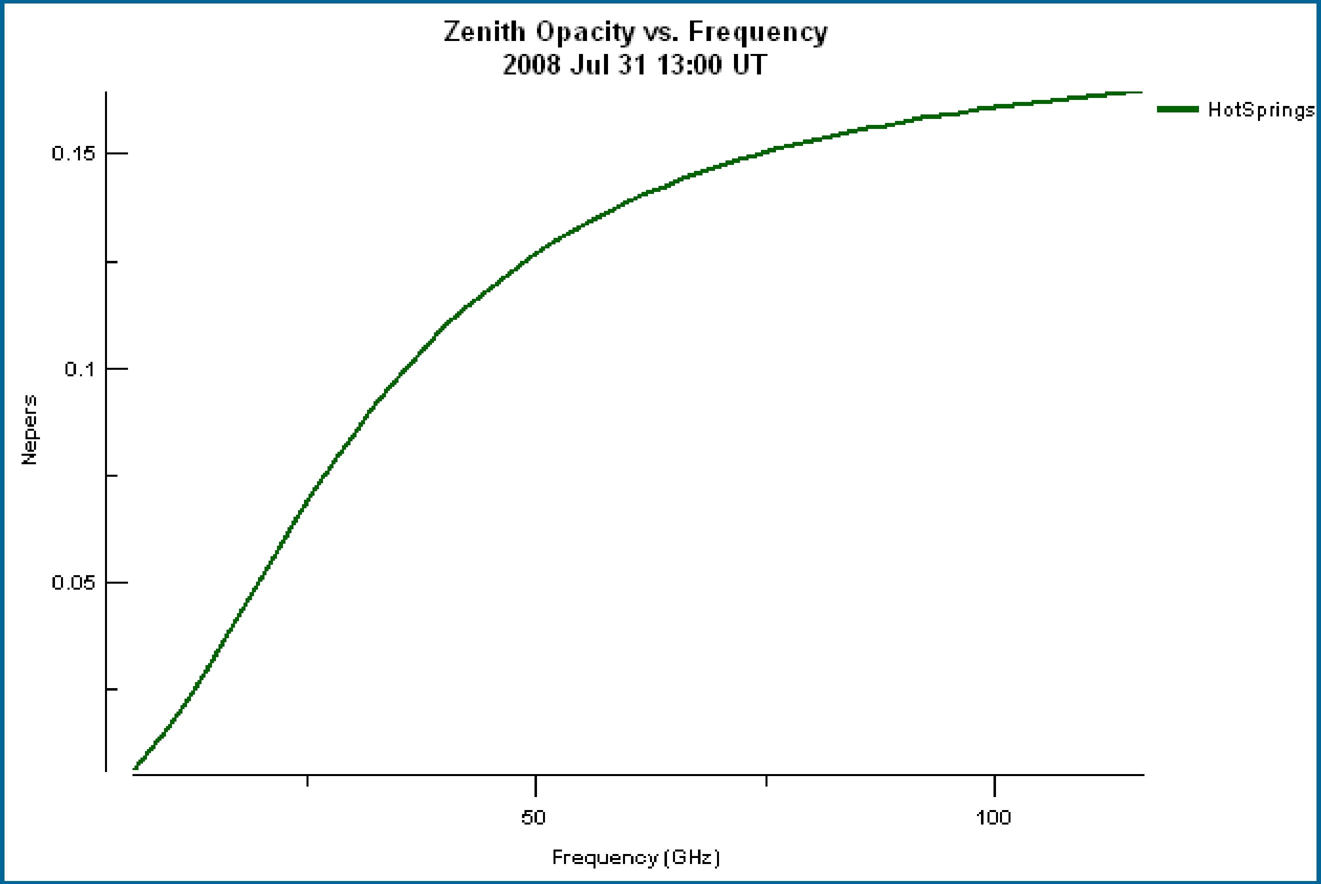
Water Line

Opacities from the various components



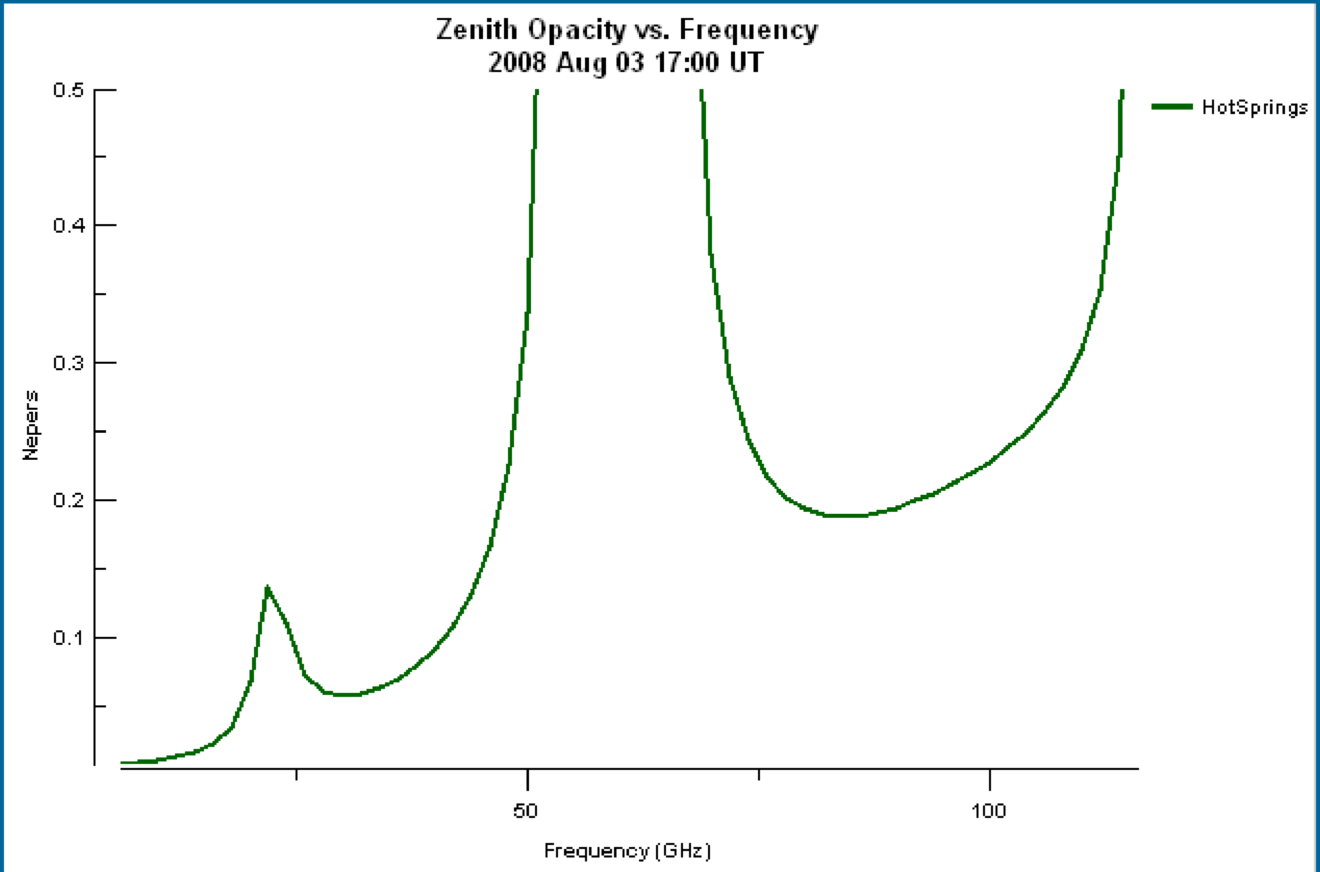
Oxygen Line

Opacities from the various components



Hydrosols

Opacities from the various components



Total Opacity

Hydrosols – the big unknown

- Require water droplet density
- Not well forecasted
- Using the Schwab, Hogg, Owen (1989) model of hydrosols
  - Compromise technique
  - Assumes a cloud is present in any layer of the atmosphere where the humidity is 95% or greater.
  - The thickness of the cloud layer determines the density
    - 0.2 g/m^3 for clouds thinner than 120 m
    - 0.4 g/m^3 for clouds thicker than 500 m,
    - linearly-interpolated densities for clouds of intermediate thickness
- And forget about it when it rains! No longer droplets!!

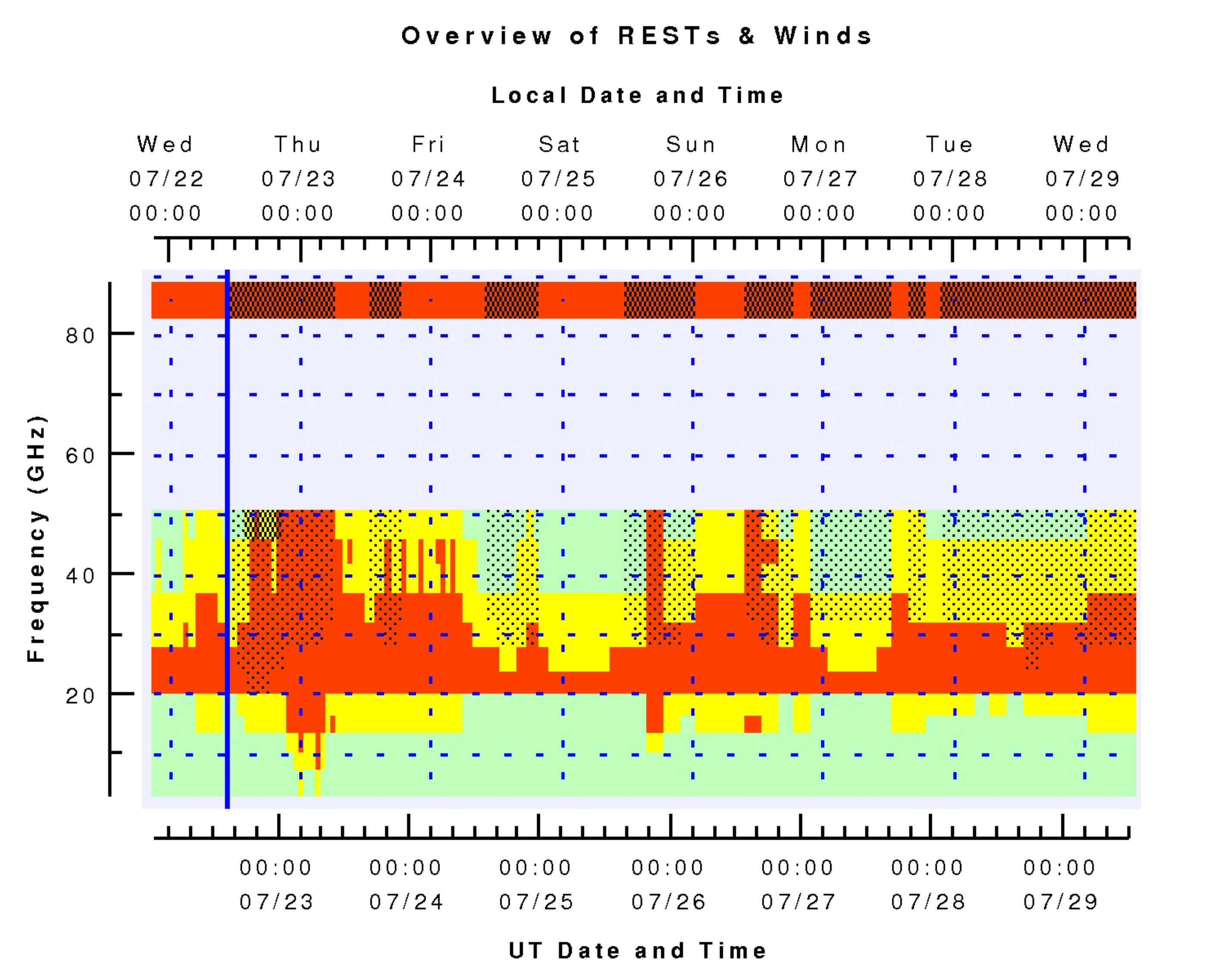
How to access archive and forecasts

- http://www.gb.nrao.edu/~rmaddale/Weather/
- Linux:
  - cleo forecasts –help
  - ~rmaddale/bin/forecastCmdLine -help
  - ~rmaddale/bin/getForecastValues -help

Web Page Summaries

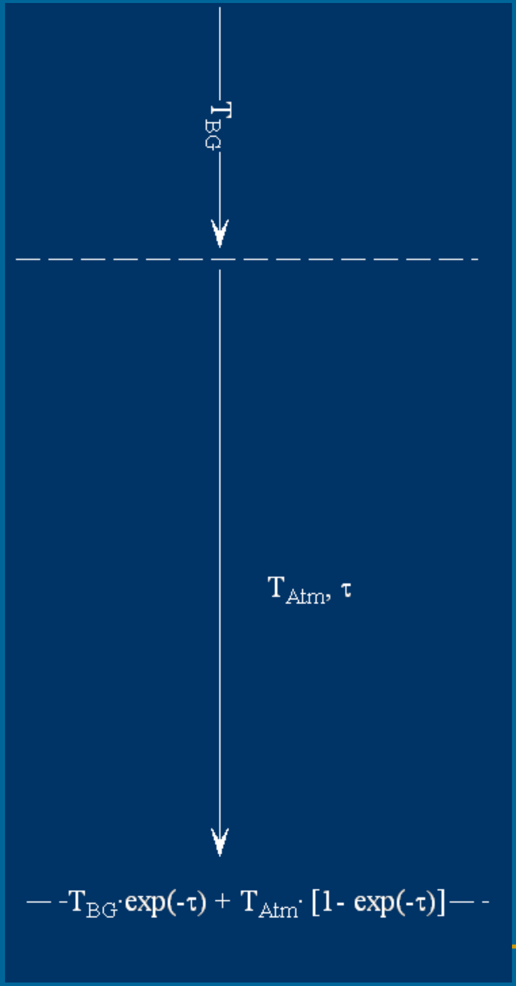
- http://www.gb.nrao.edu/~rmaddale/Weather/
- The PIZZA plot
- 3.5 and 7 day NAM and GFS forecasts. For each, provides::
  - Ground weather conditions
  - Opacity and T_{Atm} as a function of time and frequency
  - T_{sys} and RESTs as functions of time, frequency, and elevation
  - Refraction, differential refraction, comparison to other refraction models
- Weather.com forecasts
- NWS alerts
- Short summary of the modeling
- List of references

The Pizza Plot



Relative Effective System Temperatures:

A way to judge what frequencies are most productive under various weather and observing conditions



Atmosphere hurts you twice

- Absorbs so your signal is weaker: $T_{BG}\exp(-\tau)$
- Emits so your Tsys and noise go up:

  $T_{sys} = T_{Rcvr} + T_{Spill} + T_{CMB}\exp(-\tau)] + T_{Atm}[1 - \exp(-\tau)]$
- Signal-to-noise goes as:
  - $T_{BG}\exp(-\tau)/T_{sys}$
- Define Effective System Temperature (EST) as:

$$\frac{T_{Rcvr} + T_{Spill} + T_{CMB}\, e^{-\tau} + T_{Atm}[1 - e^{-\tau}]}{e^{-\tau}} = \frac{T_{Sys}}{e^{-\tau}}$$

- Proportional to the square root of the integration time needed to achieve a desired signal to noise

Relative Effective System Temperatures:

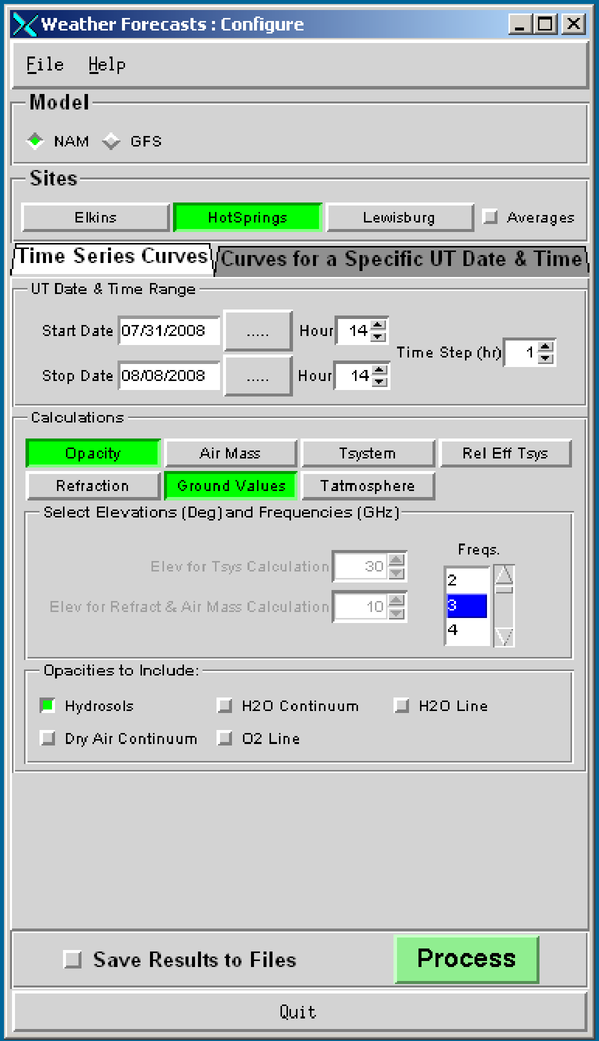
A way to judge what frequencies are most productive under various weather and observing conditions

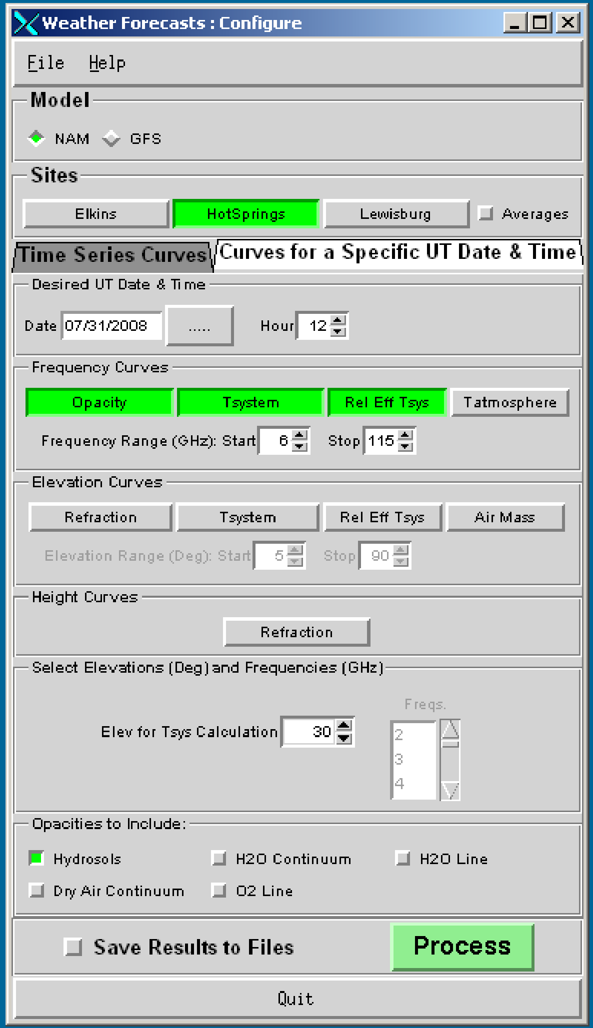
- RESTs = EST / The best possible EST
  - RESTs proportional to Sqrt(t / t_{Best})
    - t_{Best} = integration time needed to achieve your signal to noise on the best weather days
    - t = integration time needed under current weather conditions
  - RESTs > 1.41 require twice as much telescope time and are likely to be unproductive use of the telescope.
- Requires a good weather archive to determine “the best possible EST:

Also provide

- Ground level values for
  - Precipitable Water $\propto \sum \rho_{Water}(h)$ – good summary statistic
  - Temperature and wind speeds (safety limits)
  - Pressure, humidity, wind direction
  - Fractional cloud cover = max[CFRL(h)] – for continuum observers
- Comparison of various refraction models
  - Differential refraction and air mass
  - Surface actuator displacement to take out atmospheric-induced, weather-dependent astigmatism
- Summary forecasts from weather.com
  - Also archived
- NWS weather alerts.

User Software: cleo forecasts





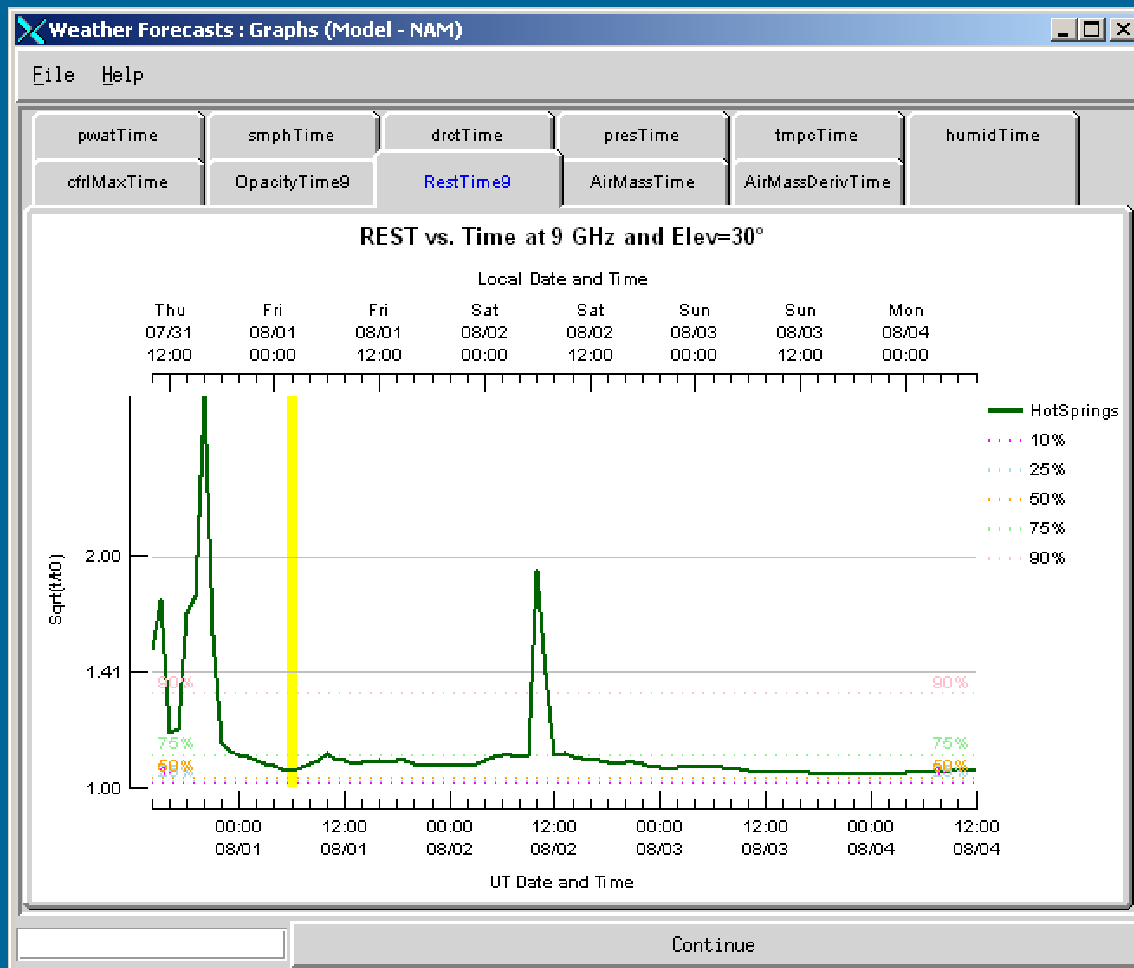
Type:

cleo forecasts

Or

cleo forecasts -help

User Software: cleo forecasts



User Software : forecastsCmdLine

- To run, type:
  ~rmaddale/bin/forecastsCmdLine -help
- *cleo forecasts* is a user-friendly GUI front end to *forecastsCmdLine*
- Much more powerful and flexible than what the GUI allows
- Generates text files only, no graphs
  - *cleo forecasts* can graph files generated by a previous run of *forecastsCmdLine*

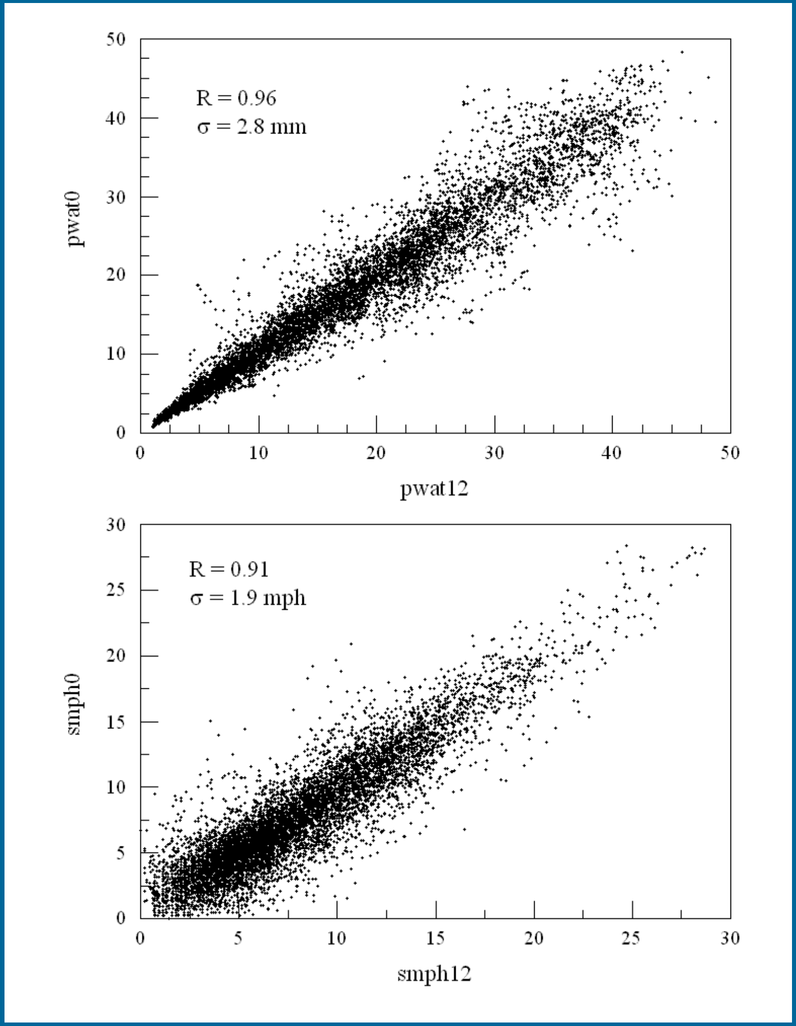
User Software : getForecastValues

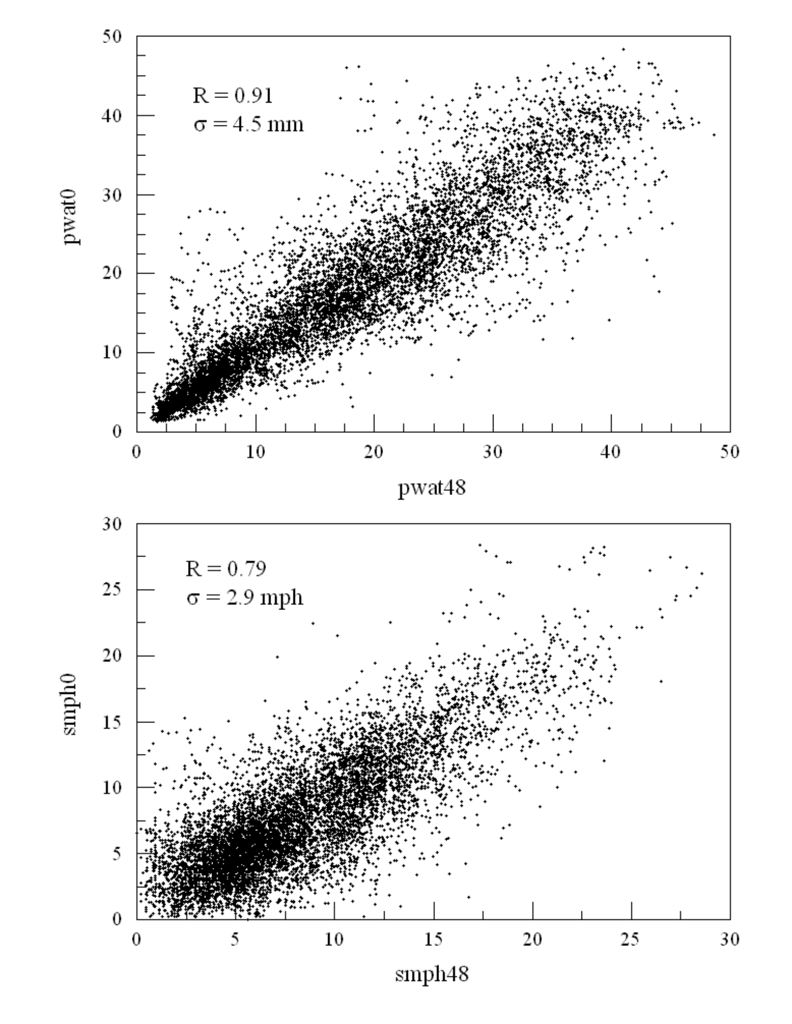
- To run, type:
  *~rmaddale/bin/*getForecastValues *–help*
- Fast way to retrieve opacities, T_{Sys}, RESTs, and T_{Atm} for any frequency and any time after April 1, 2008
- Returns results to standard output
- Uses a polynomial fit of these quantities
  - Automatically produced and archived by the system that generates the web pages

Current modeling and limitations

- Uses Liebe's *Microwave Propagation Model*, with Danese & Partridge's (1989) modifications plus some practical simplifications
  - Although accurate up to 1000 MHz, current implementation < 230 GHz to save processing time
  - Uses the Froome & Essen frequency-independent approximation of refraction (to save processing time)
  - Opacities < 5 GHz are too high for an unknown reason
  - Cloud predictions (presence, thickness) are not very accurate
  - Model for determining opacities from clouds (hydrosols) may not match observations
    - Schwab, Hogg, Owen model for water drop density and size may not be accurate enough

How accurate are the forecasts?





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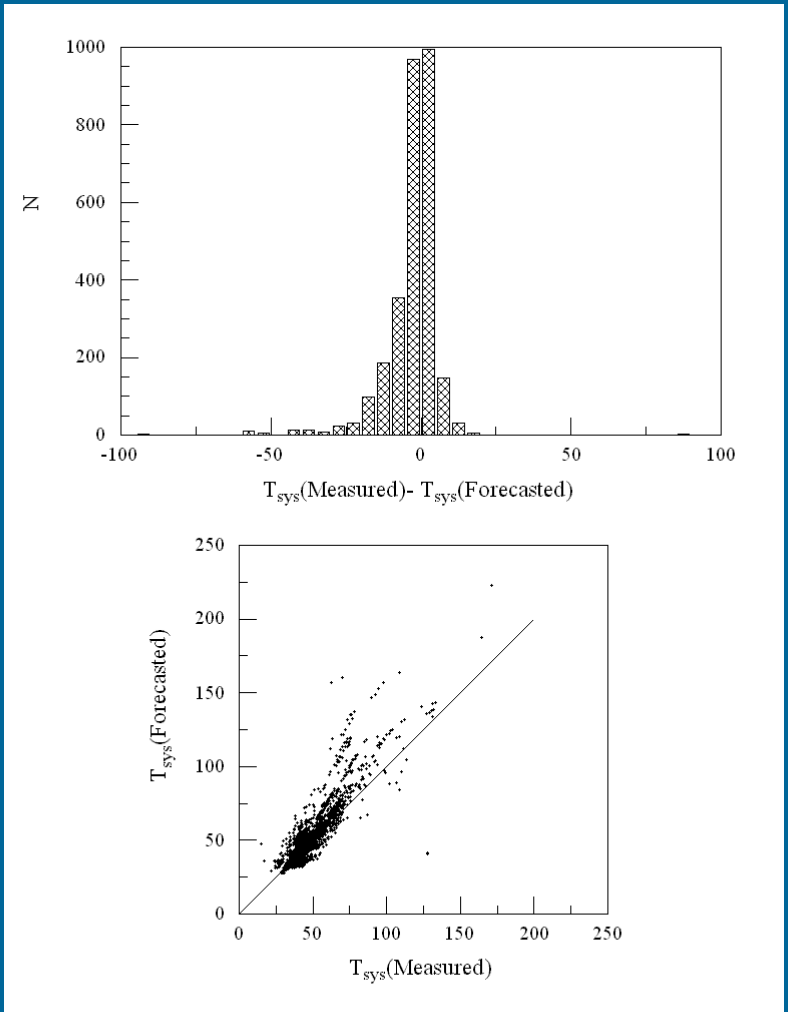
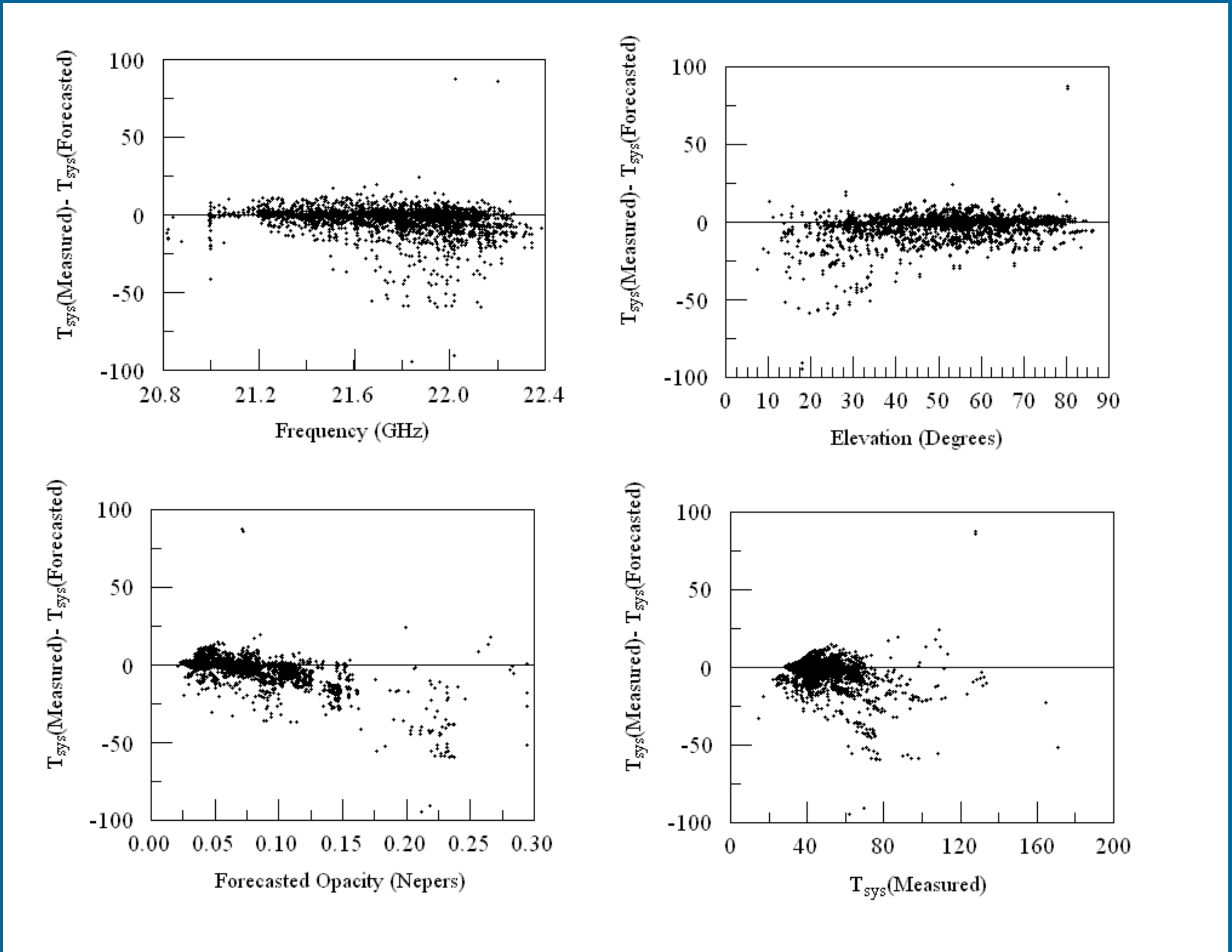
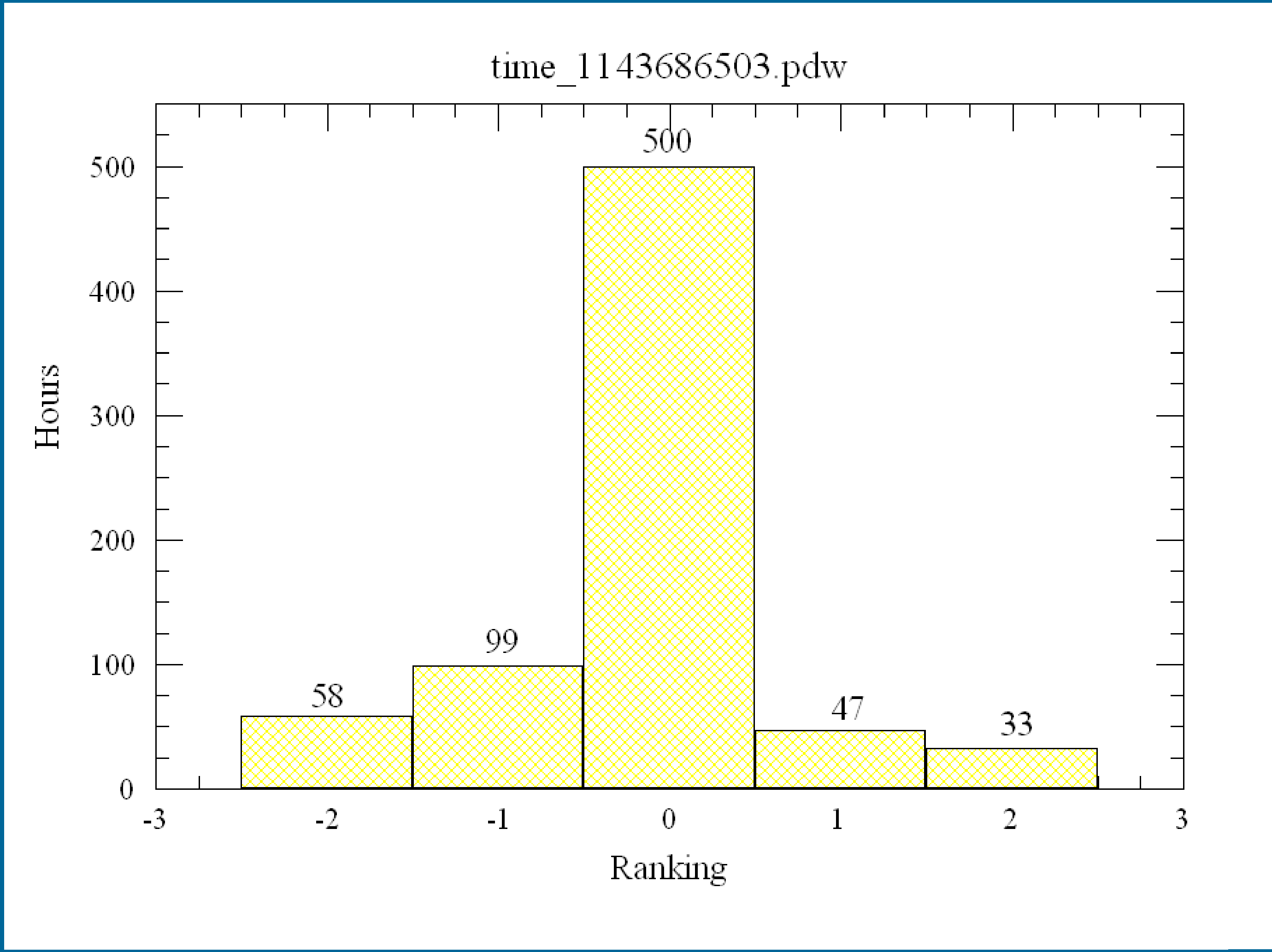


How accurate are the forecasts?



How was our old DSS working?



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