Weather Forecasting for Radio Astronomy

Part I: The Mechanics and Physics

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August 1, 2008

Outline

- Part I
  - Background -- research inspirations and aspirations
  - Vertical weather profiles
    - Description
    - Bufkit files
    - Atmospheric physics used in cm- and mm-wave forecasting
  - Details on software: downloading, processing, archiving, archive retrieval, web site generation, watch dogs, ….
- Part II
  - Results on refraction & air mass (with Jeff Paradis)
- Part III
  - Results on opacity, weather statistics, observing techniques and strategies.

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

Improved 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

- Unfortunately, the standard products of the weather services (other than winds, cloud cover, precipitation, and PW somewhat) do not serve radio astronomy directly.
- But, can their product be used for radio astronomy?

Project inspiration

- 5-years of observing at 115 GHz at sea level.
- Harry Lehto’s thesis (1989)
- 140-ft/GBT pointing - refraction correction
- 12-GHz phase interferometer & 86 GHz tipper
- 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 for radio astronomy

Vertical profiles are:

Atmospheric pressure, temperature, and humidity as a function of height above the telescope (and much, much more).

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

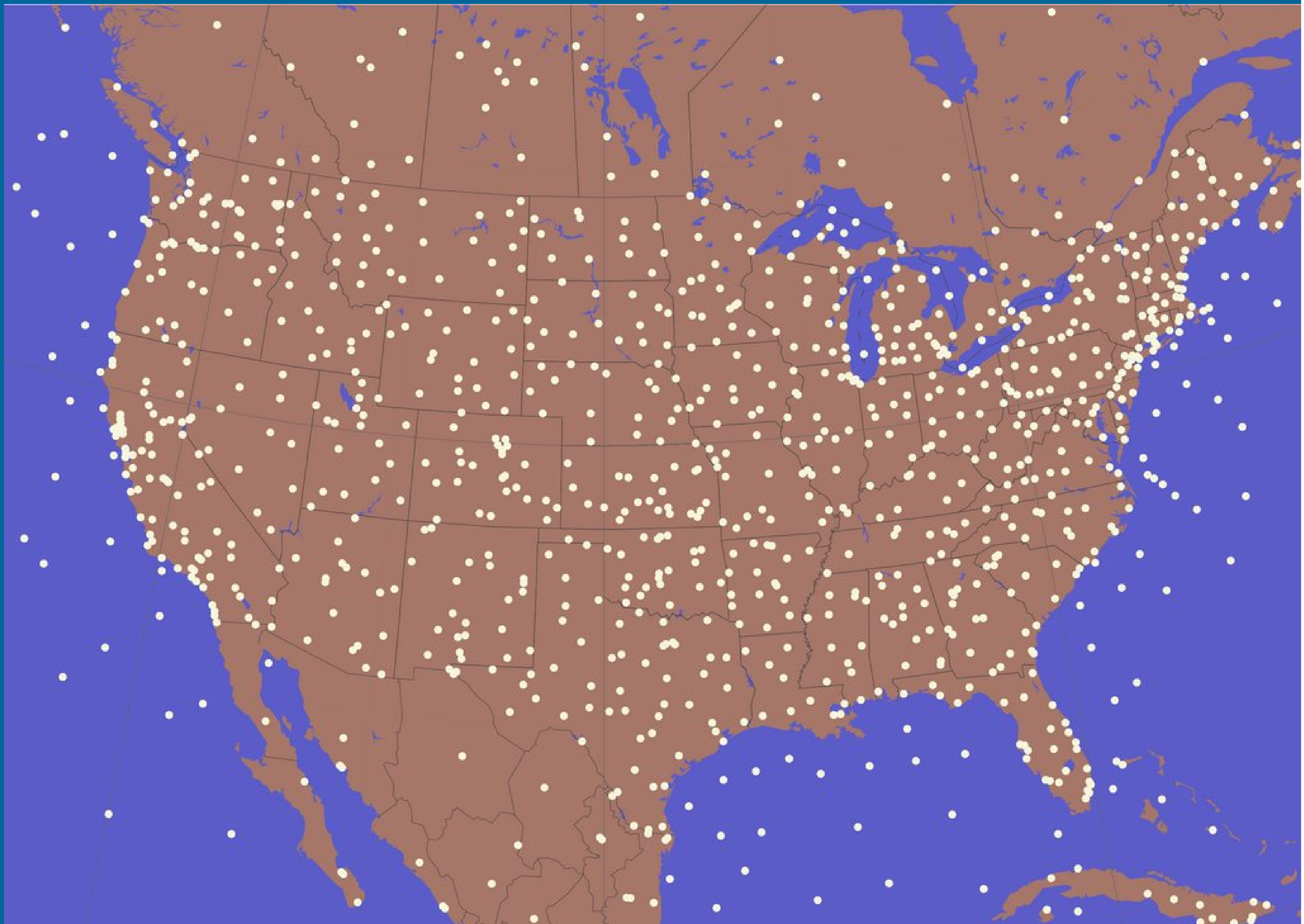
- Atmospheric pressure, temperature, and humidity as a function of height above a site (and much more).
- Derived from *Geostationary Operational Environmental Satellite* **(**GOES) soundings and, now less often, balloon soundings
- Generated by the *National Weather Service***,** an agency of the *NOAA***.**

Bufkit, a great vertical profile viewer

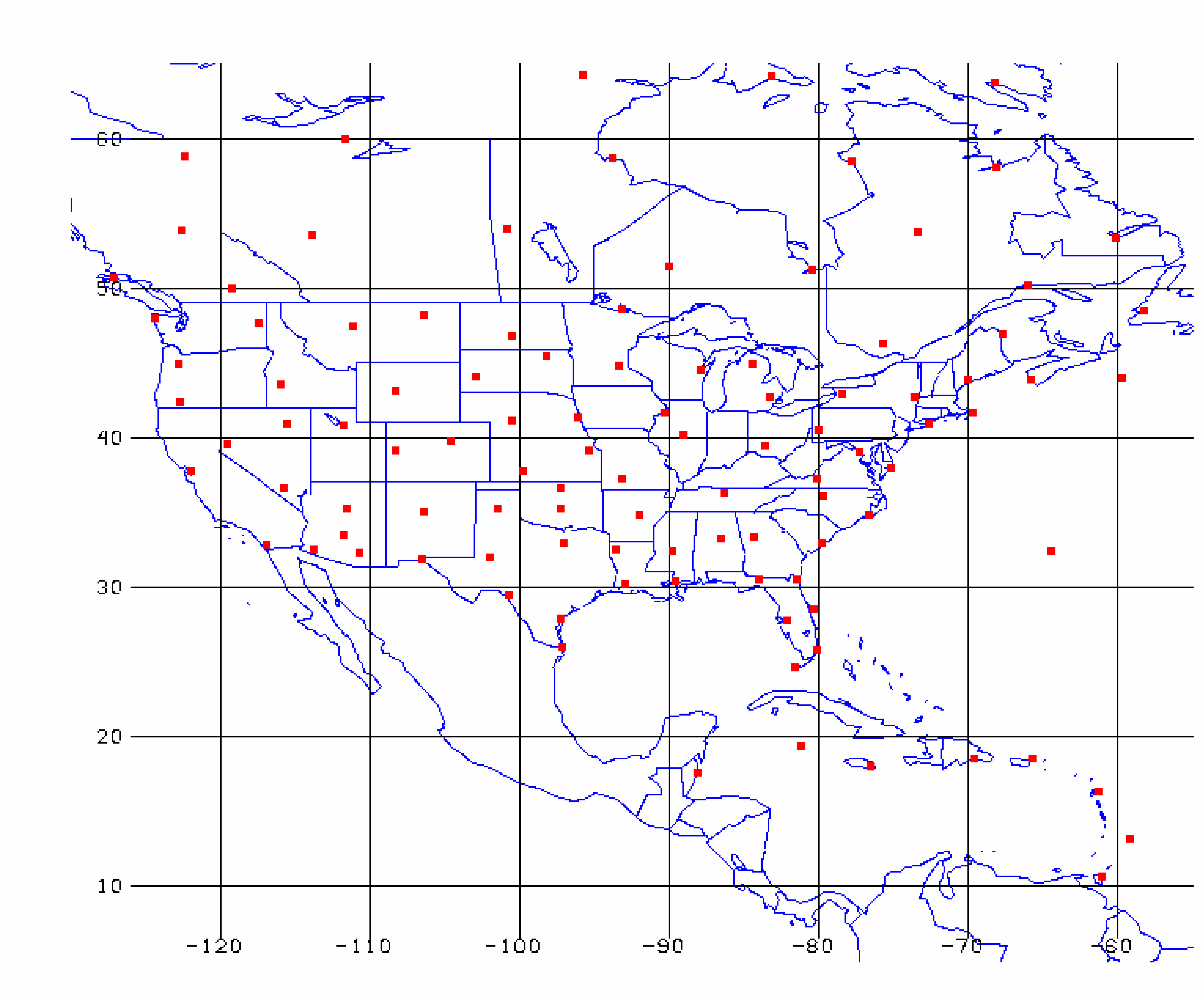
http://www.wbuf.noaa.gov/bufkit/bufkit.html

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 from Penn State University (and only PSU!)



Bufkit files available for “Standard Stations”



Balloon Soundings

Bufkit and Bufkit files

- Three flavors of Bufkit forecast files available, all in the same format
- 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

Bufkit and Bufkit files

- Rapid Update Cycle
  - Accurate short range 0-12 hrs only
  - Updated hourly with an hour delay in distribution (processing time)
  - 12 km horizontal resolution
  - 1 hour temporal resolution
  - Not used or archived

Bufkit & Bufkit files

- Raw numbers include:
  - Wind speeds and directions, temperatures, dew point, pressure, cloud cover, … vs. height vs. time vs. site.
  - Summary indices: K-index, precipitable water (PW), rain/snowfall, etc. vs. time vs. site
- Derived numbers:
  - Inversion layers, likelihood of fog, snow growth, storm type, …

Issues with Bufkit files

- PSU -- a one-point failure but with a solution
  - PSU derives Bufkit files from BUFR sounding files (the meteorologist's equivalent of FITS files).
  - Half a dozen FTP sites provide BUFR files
  - MODSND utility converts BUFR files to Bufkit (and other) formats.
- BUFR/Bufkit files contain errors that readers must circumvent
  - 5 yrs of experience.
- Other than winds, clouds, precipitation, and PW, Bufkit doesn't display anything else significant for radio astronomy.
  - This is where cm- and mm-wave atmospheric physics comes in.

References

- **G. Brussaard and P.A. Watson, "Atmospheric Modelling and Millimetre Wave Propagation,", 1995, (New York: Chapman & Hall)**
- B. Butler, "Precipitable Water Vapor at the VLA -- 1990 - 1998", 1998, *NRAO MMA Memo* #237 (and references therein).
- L. Danese and R.B. Partridge, "Atmospheric Emission Models: Confrontation between Observational Data and Predictions in the 2.5-300 GHz Frequency Range", 1989, *AP.J.* 342, 604.
- K.D. Froome and L. Essen, *"The Velocity of Light and Radio Waves"*, 1969, (New York: Academic Press).
- W.S. Smart, *"Textbook on Spherical Astronomy"*, 1977, (New York: Cambridge Univ. Press).
- H.J. Lehto, "High Sensitivity Searches for Short Time Scale Variability in Extragalactic Objects", 1989, Ph.D. Thesis, University of Virginia, Department of Astronomy, pp. 145-177.
- **H.J. Liebe, "An Updated model for millimeter wave propagation in moist air", 1985, *Radio Science*, 20, 1069**
- R.J. Maddalena "Refraction, Weather Station Components, and Other Details for Pointing the GBT", 1994, *NRAO GBT Memo 112* (and references therein).
- J. Meeus, *"Astronomical Algorithms*", 1990 (Richmond: Willman-Bell).
- K. Rohlfs and T.L. Wilson, *"Tools of Radio Astronomy, 2nd edition"*, 1996, pp. 165-168.
- P.W. Rosenkranz, 1975, IEEE Trans, AP-23, 498.
- J.M. Rueger, *"Electronic Distance Measurements"*, 1990 (New York: Springer Verlag).
- **F.R. Schwab, D.E Hogg, and F.N. Owen, "Analysis of Radiosonde Data for the MMA Site Survey and Comparison with Tipping Radiometer Data" (1989), from the IAU Symposium on "Radio Astronomical Seeing", pp 116-121.**

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

Basics of atmospheric modeling

- So far, this is not new stuff. Has been done many times before with balloon data or using a ‘model’ atmosphere. What is new?
  - Uses recently-available forecasted weather data
  - Updates automatically twelve times a day for every desired frequency, elevation, time, site, and model (GFS, NAM, …).
  - Automatically summarizes the results on the WWW in a useful way for predicting conditions for radio astronomy
  - Automates the generation of an archive
  - Provides tools that anyone can use to mine the current and archived forecasts in ways the WWW summaries do not.
  - Applied to a sea-level, mid-Atlantic, 100-m telescope that can observe up to 115 GHz and down to an elevation of 5º.

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	ρ_{Water}	ρ_{Dry}	n	κ_{Dry}	κ_{H2O_Cont}	$\kappa_{H2O\ Line}$	κ_{O2}	$\kappa_{Hydrosols}$	κ_{Total}
880 m													
920 m													
…													
30 km													

Generate a table for every desired frequency, site, time

Basics of radiative transfer

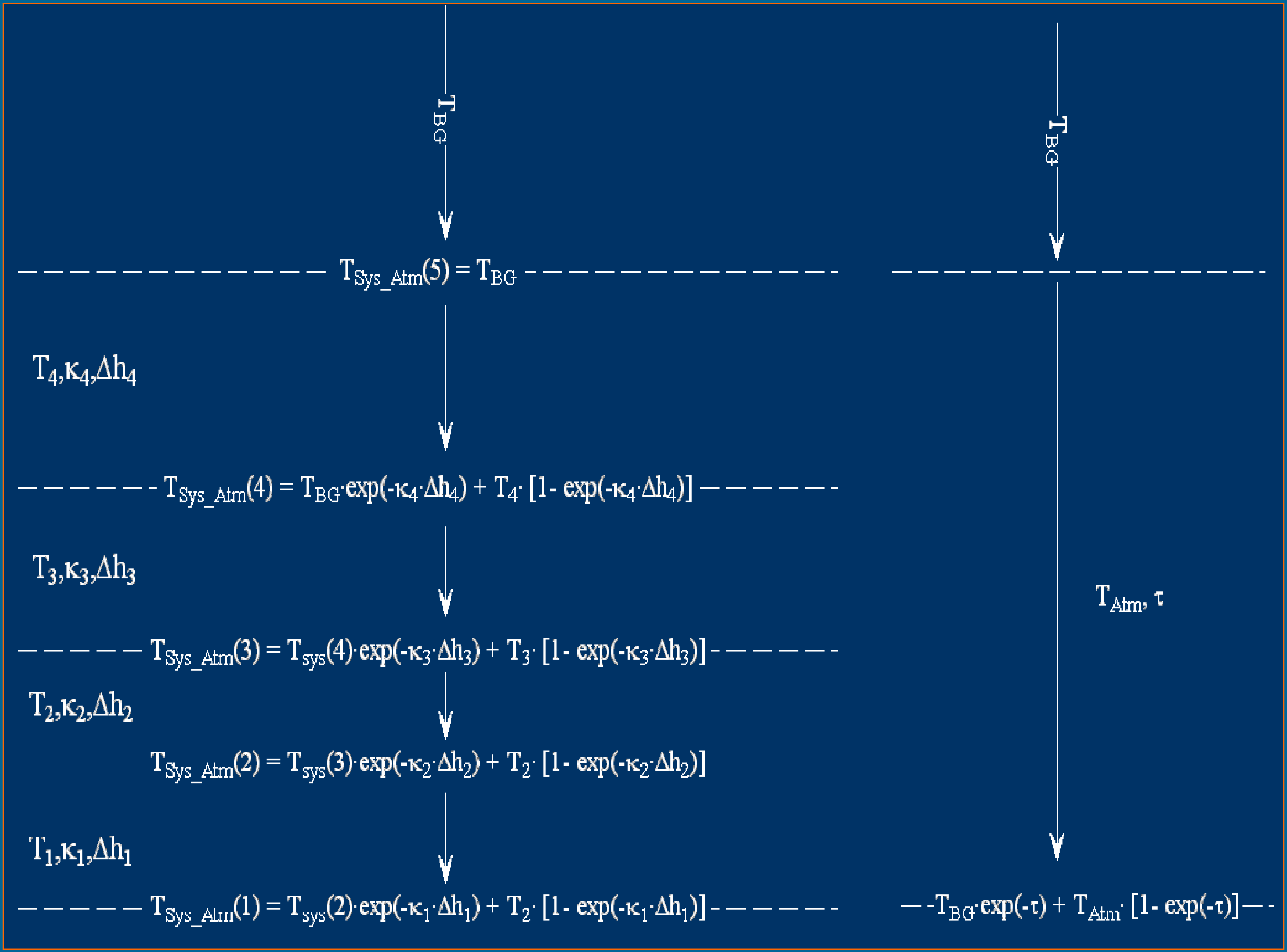
$$\kappa_{Total}(h,\nu) = \sum \kappa_i(h,\nu)$$

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

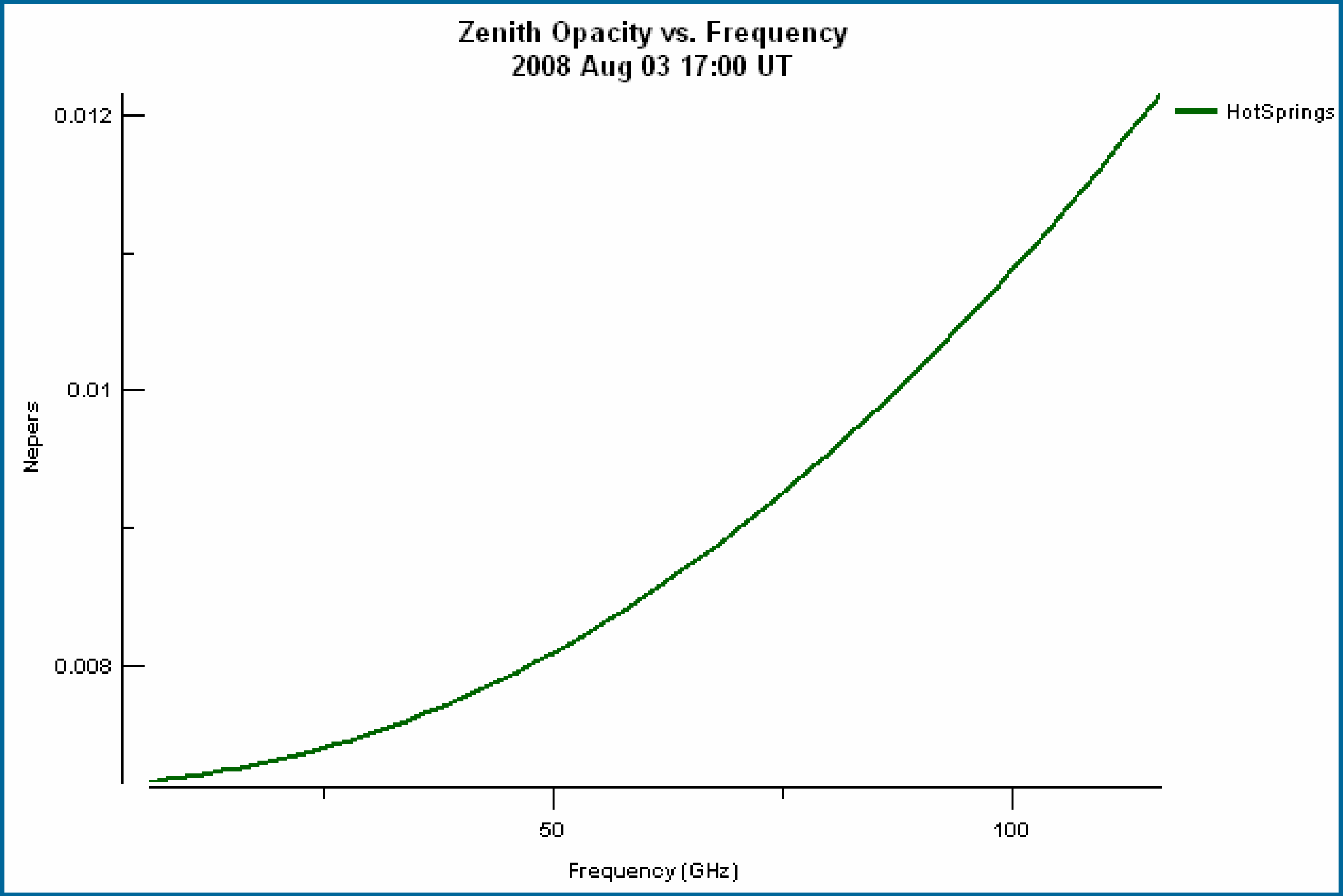
$$T_{Sys}^{Atm}(h,\nu) = T_{Sys}^{Atm}(h+dh) \cdot e^{-\kappa_{Total}(h,\nu) \cdot dh} + T(h) \cdot (1 - e^{-\kappa_{Total}(h,\nu) \cdot dh})$$

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

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

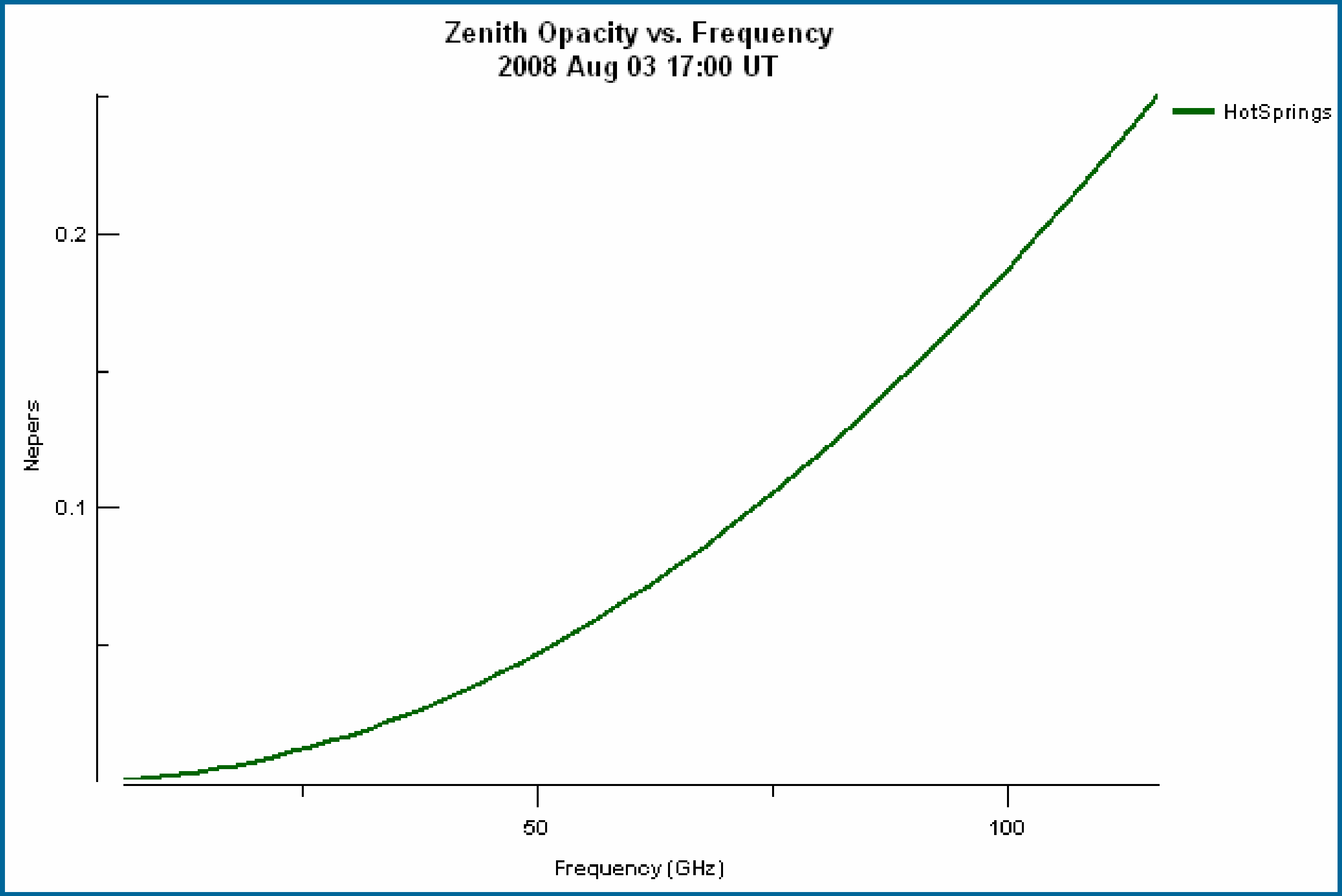

T_{BG}
T_{BG}
$T_{Sys\_Atm}(5) = T_{BG}$
$T_4, \kappa_4, \Delta h_4$
$T_{Sys\_Atm}(4) = T_{BG} \cdot exp(-\kappa_4 \cdot \Delta h_4) + T_4 \cdot [1 - exp(-\kappa_4 \cdot \Delta h_4)]$
$T_3, \kappa_3, \Delta h_3$
T_{Atm}, τ
$T_{Sys\_Atm}(3) = T_{sys}(4) \cdot exp(-\kappa_3 \cdot \Delta h_3) + T_3 \cdot [1 - exp(-\kappa_3 \cdot \Delta h_3)]$
$T_2, \kappa_2, \Delta h_2$
$T_{Sys\_Atm}(2) = T_{sys}(3) \cdot exp(-\kappa_2 \cdot \Delta h_2) + T_2 \cdot [1 - exp(-\kappa_2 \cdot \Delta h_2)]$
$T_1, \kappa_1, \Delta h_1$
$T_{Sys\_Atm}(1) = T_{sys}(2) \cdot exp(-\kappa_1 \cdot \Delta h_1) + T_2 \cdot [1 - exp(-\kappa_1 \cdot \Delta h_1)]$
$T_{BG} \cdot exp(-\tau) + T_{Atm} \cdot [1 - exp(-\tau)]$

Opacities from the various components



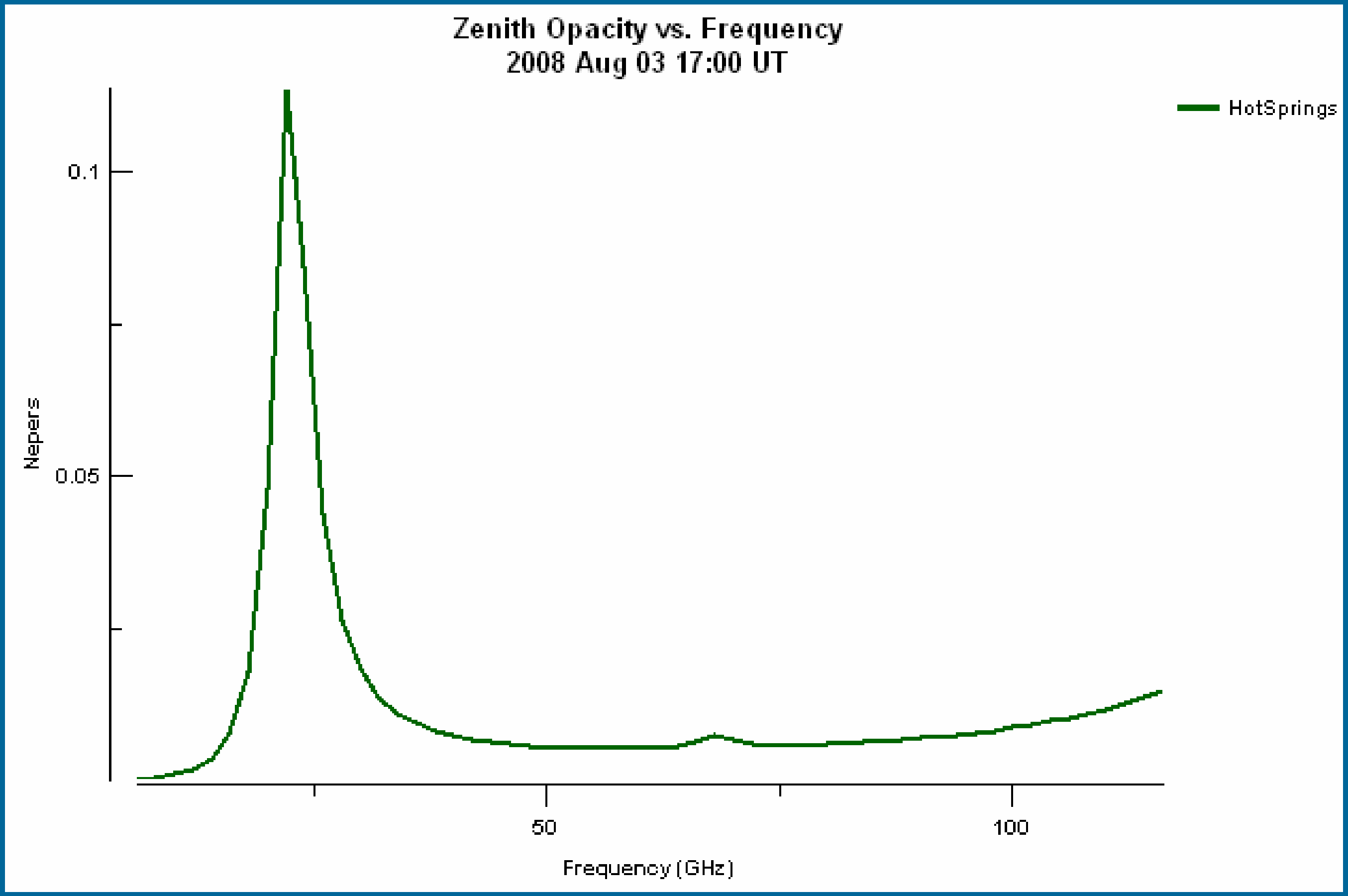
Dry Air Continuum

Opacities from the various components



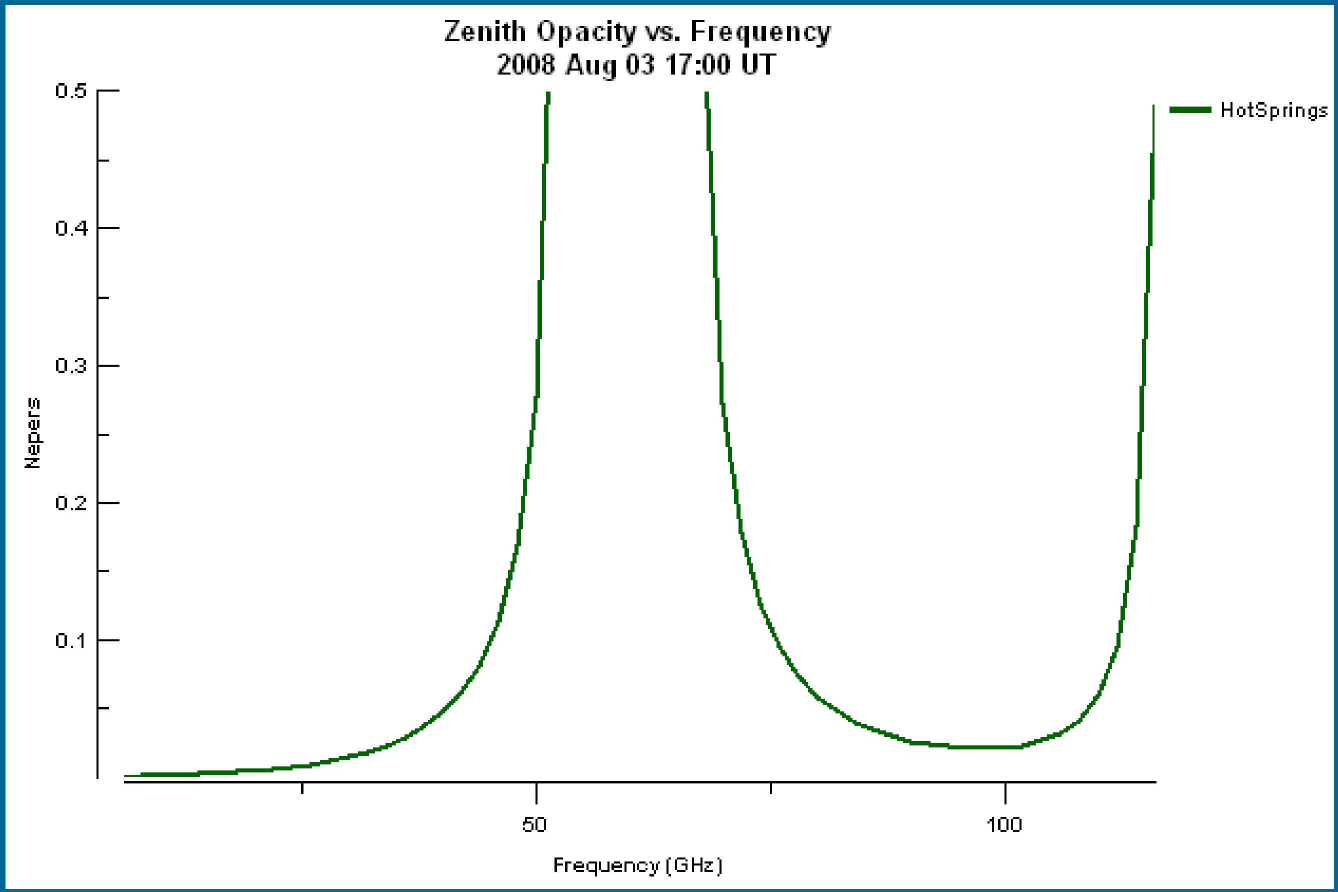
Water Continuum

Opacities from the various components



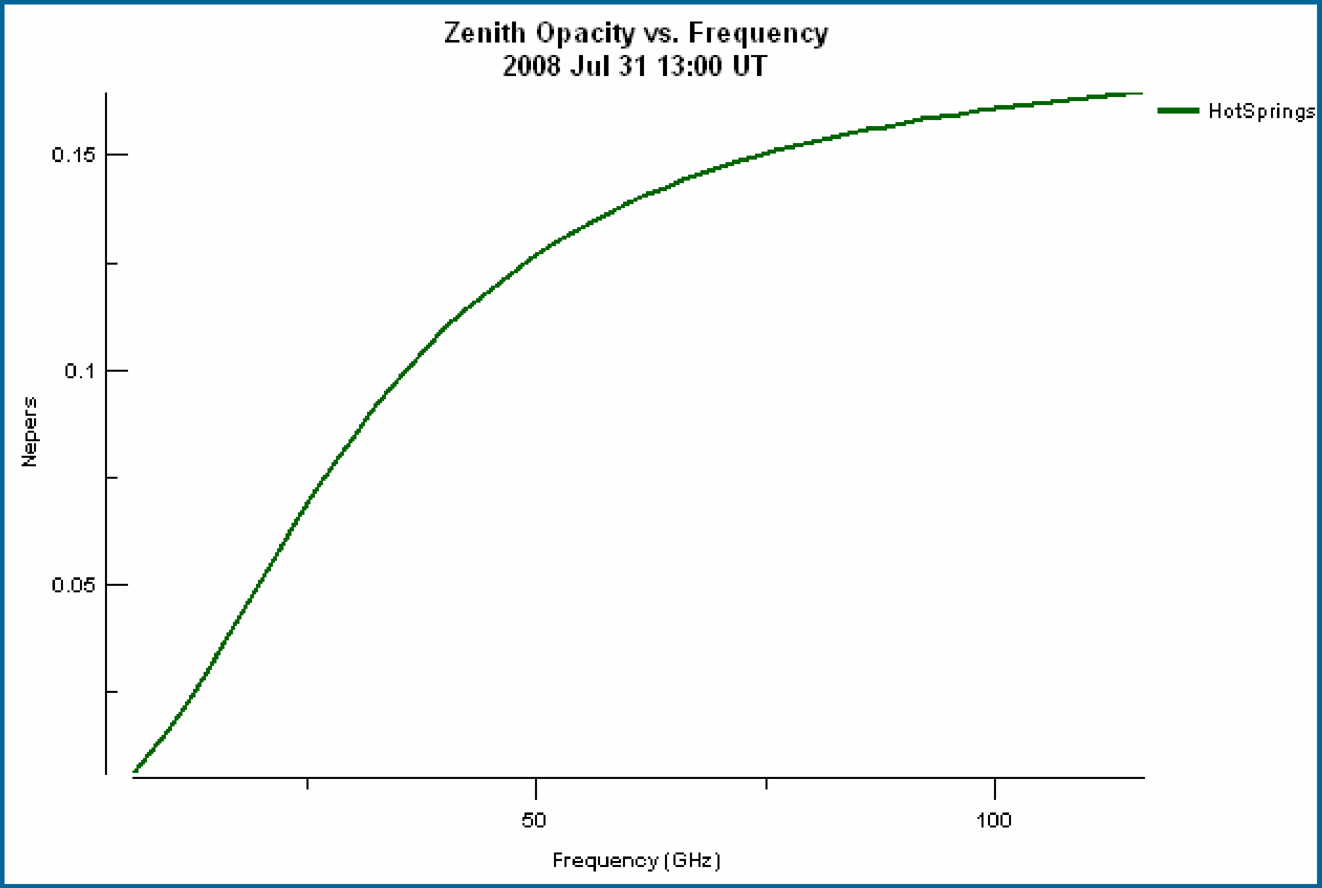
Water Line

Opacities from the various components



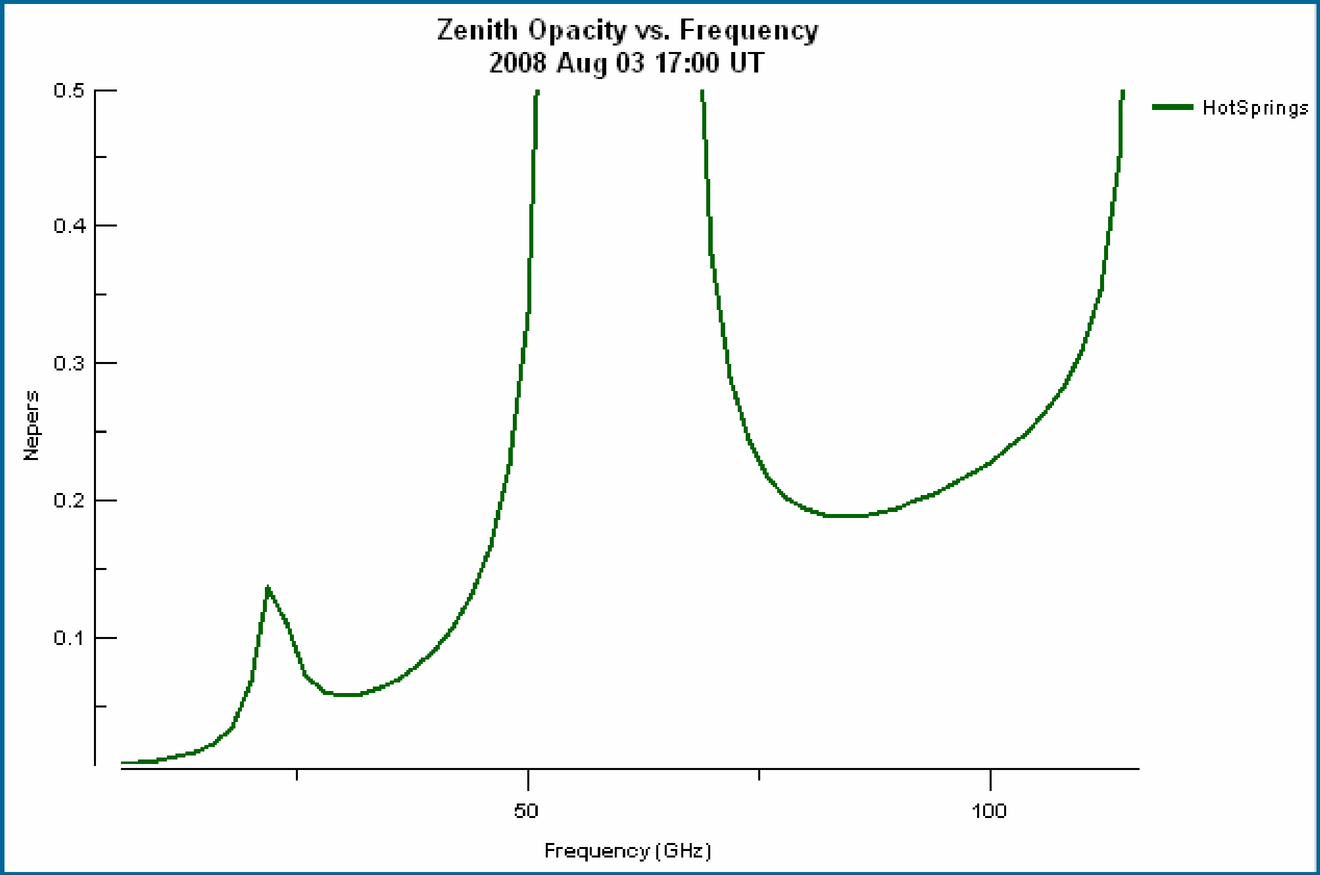
Oxygen Line

Opacities from the various components



Hydrosols

Opacities from the various components



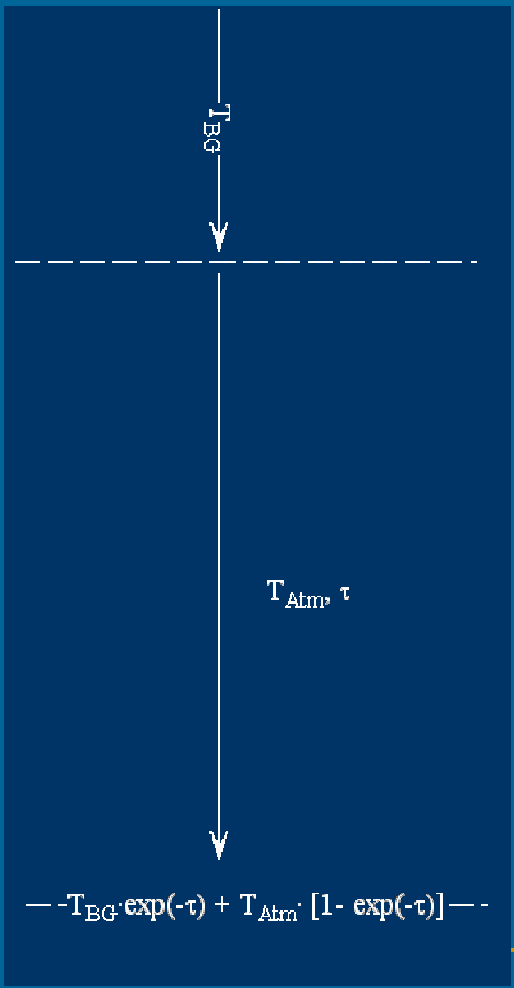
Total Opacity

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!!

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(-τ)
- 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:
- Uses:
  - The T_{Rcvr} measured by the engineers
  - An estimate of T_{Spill} ~ 3 K, T_{CMB} ~ 3 K
  - Forecasted T_{Sys_Atm}

Basics of refraction and relative air mass

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

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

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

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.

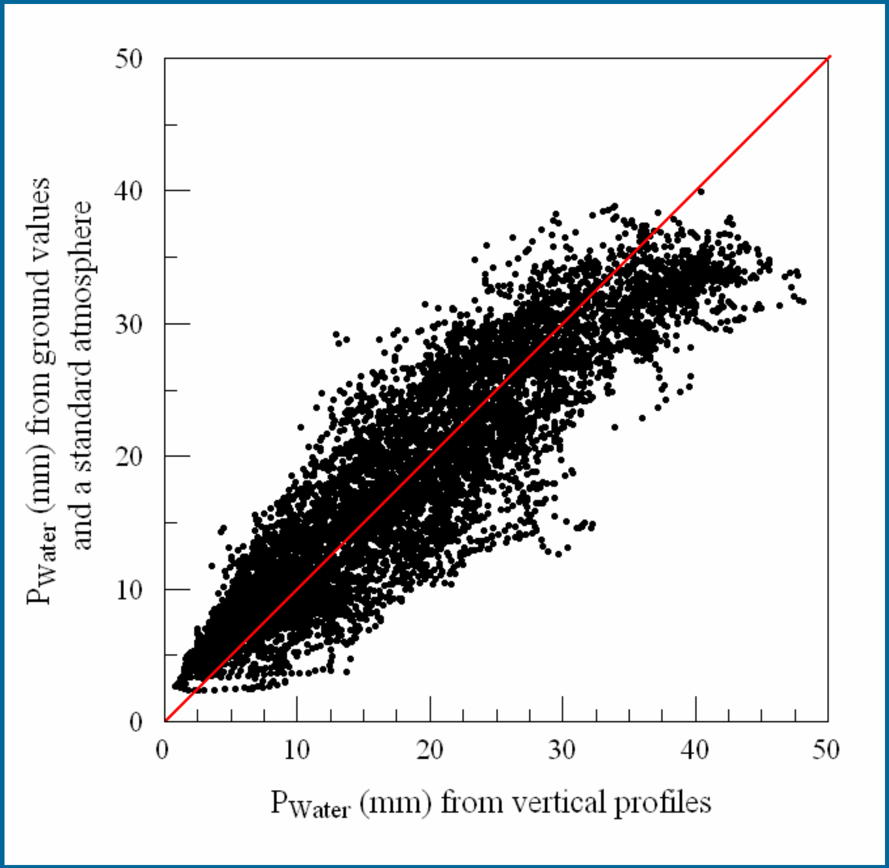
Current modeling and limitations

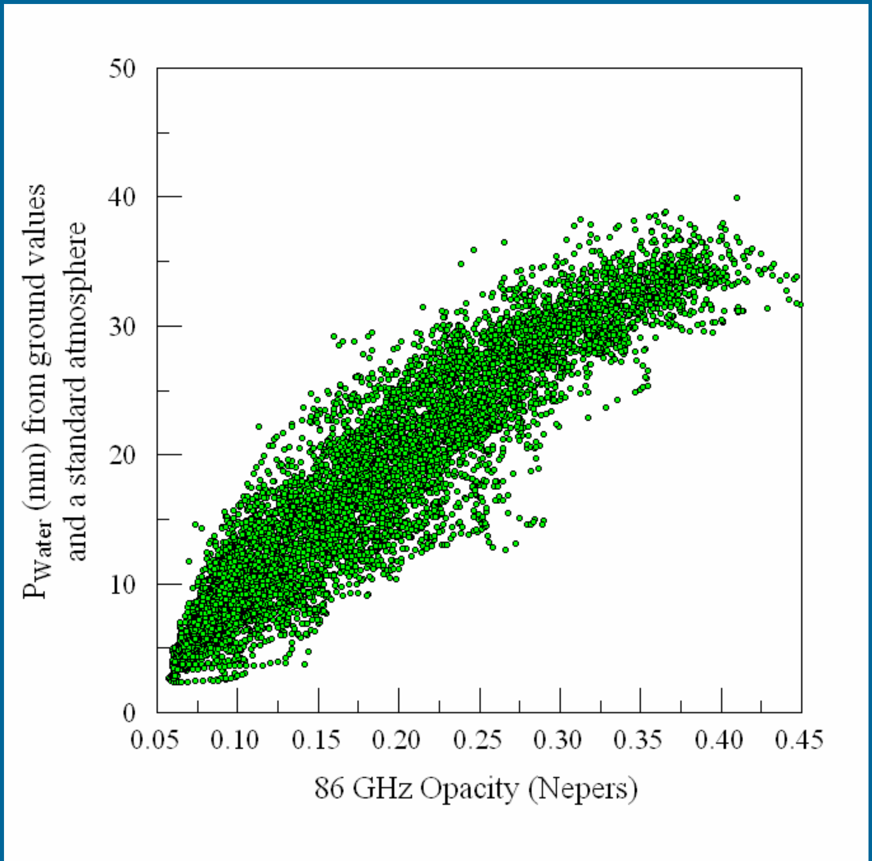
- Uses Liebe's *Microwave Propagation Model*, with Danese & Partridge's (1989) modifications plus some practical simplifications
  - Although accurate up to 1000 MHz, current implementation < 230 GHz to save processing time
  - Uses the Froome & Essen frequency-independent approximation of refraction (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) does not match observations
    - Schwab, Hogg, Owen model for water drop density and size may not be accurate enough

Current modeling and limitations

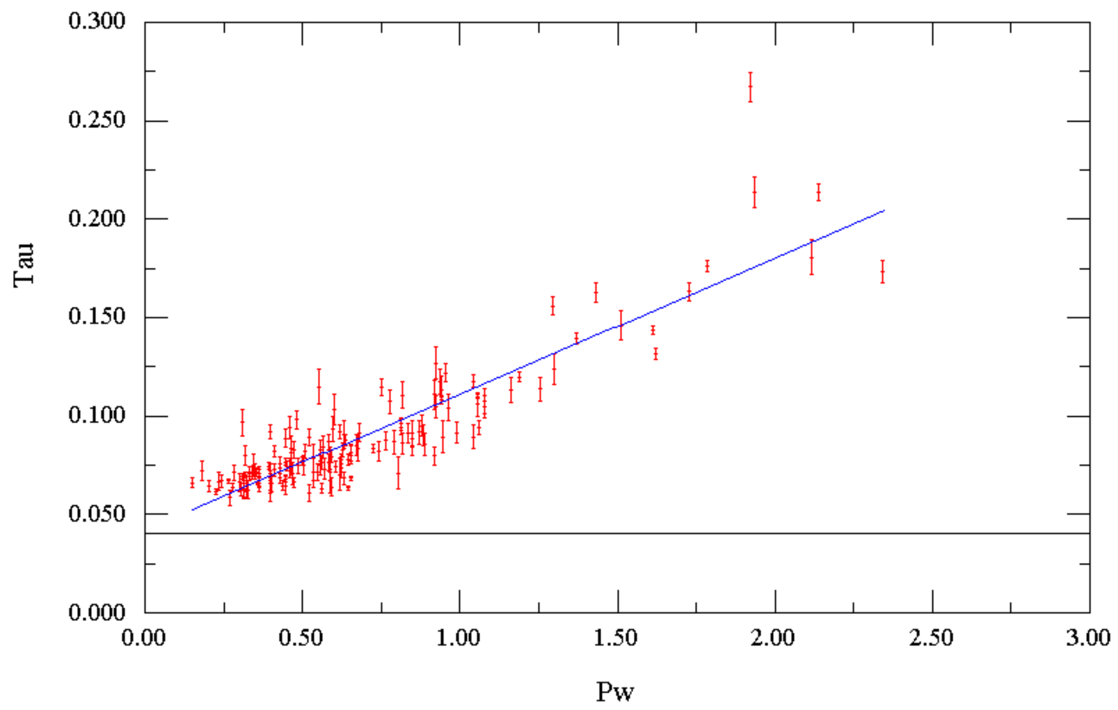
- Uses a ‘fuzzy’ cache of opacities to save processing at the expense of memory and accuracy
- Fractional cloud cover does not consider whether a cloud is cold or warm (i.e. its importantance).
- Must extrapolate real part of refractivity to 50 km (forecasts go to 30 km).
- Assumes all absorption is below 30 km
- Total opacity estimate uses 1/sin(elev) instead of ray-traced path
- T_{Rcvr} table, used for calculating RESTS, has a 1 or 2 GHZ resolution.

How accurate are ground-level values and a standard atmosphere?





How useful is the 86 GHz tipper?



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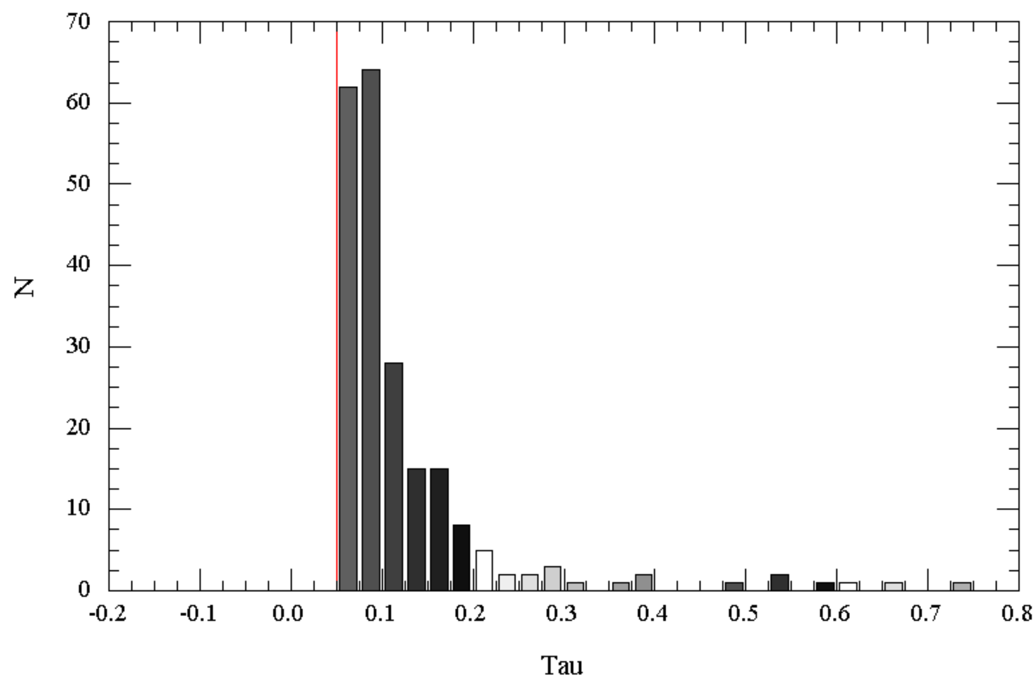

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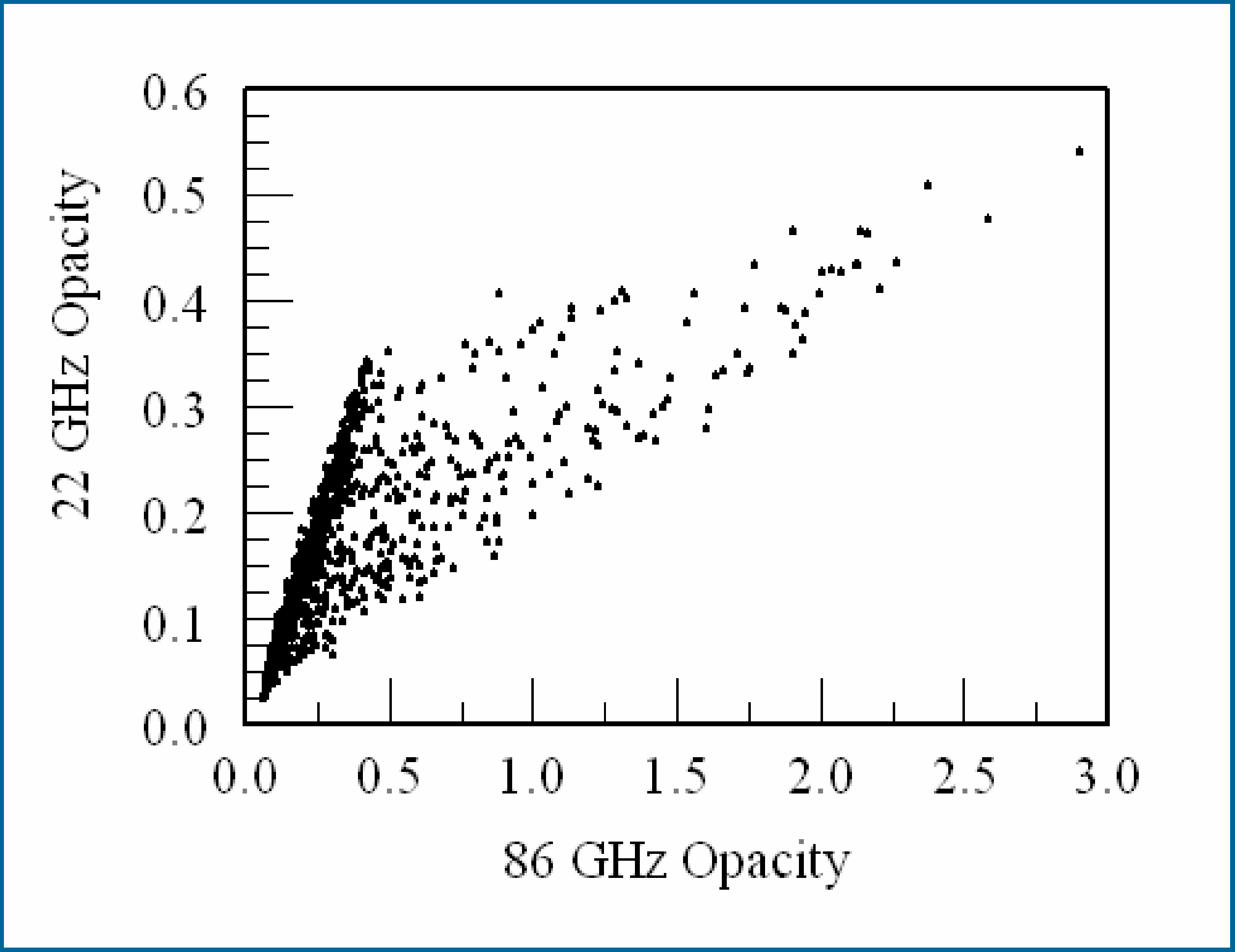
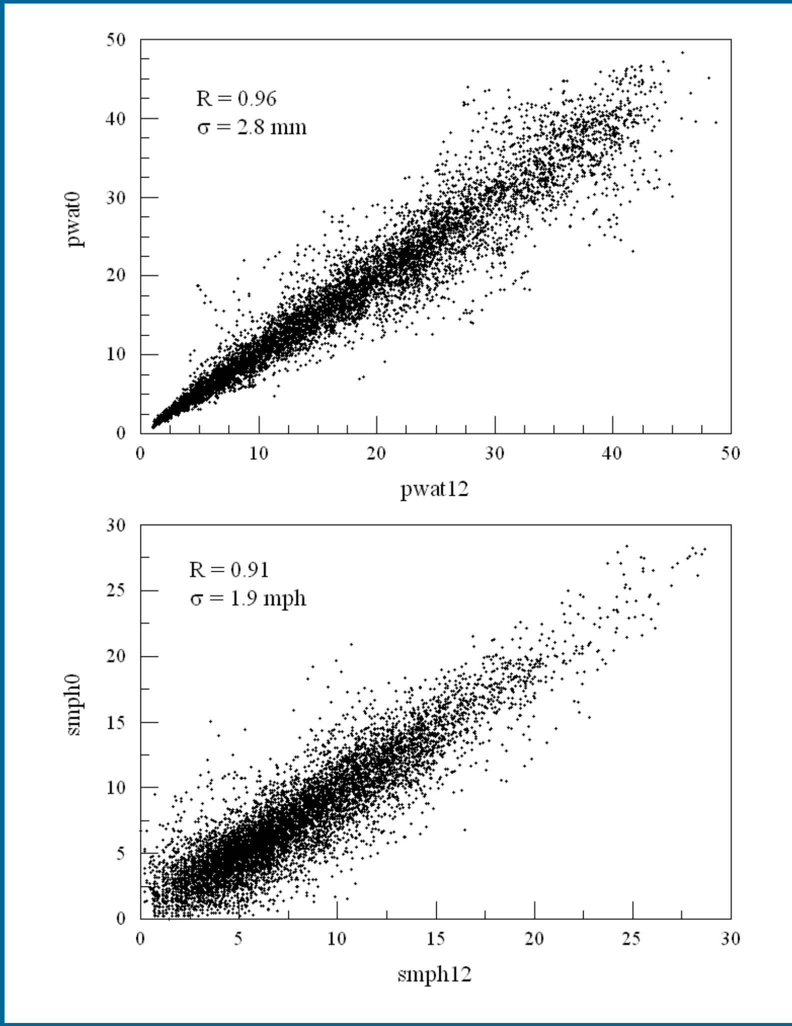
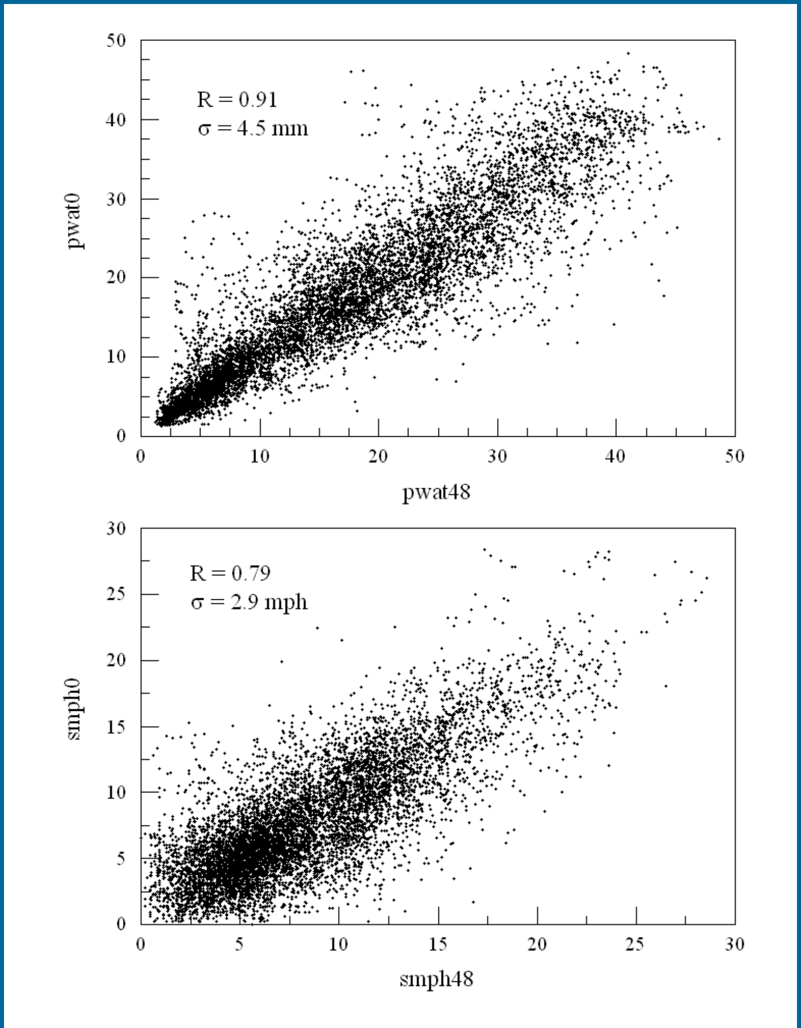


How accurate are the forecasts?





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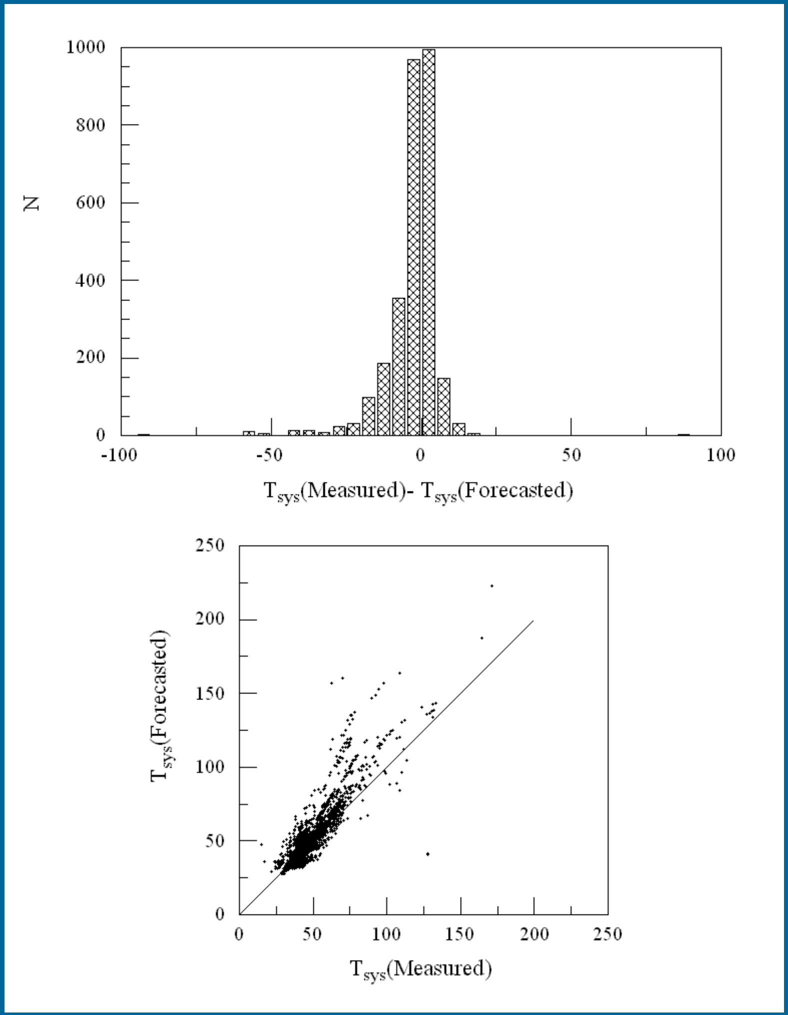

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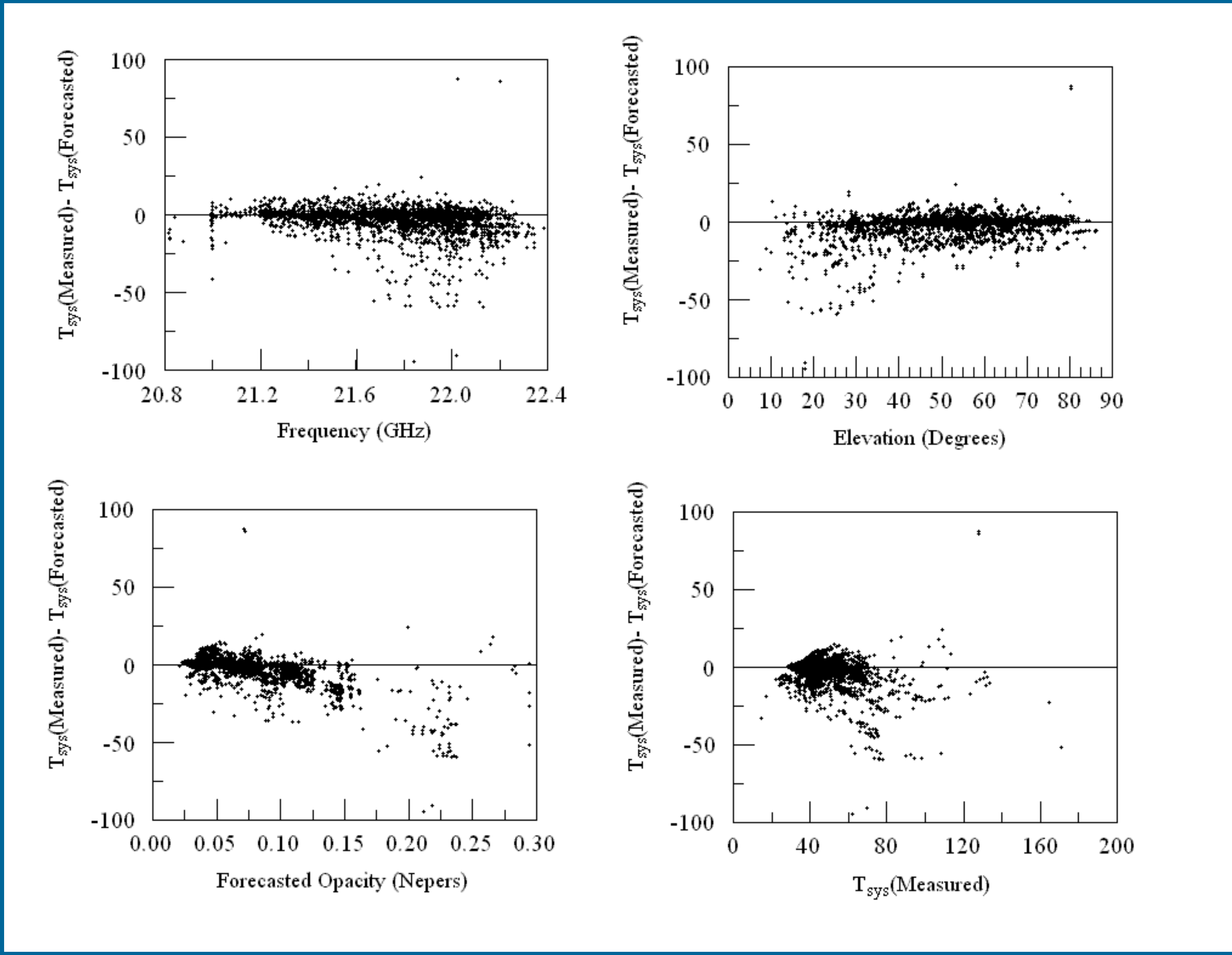
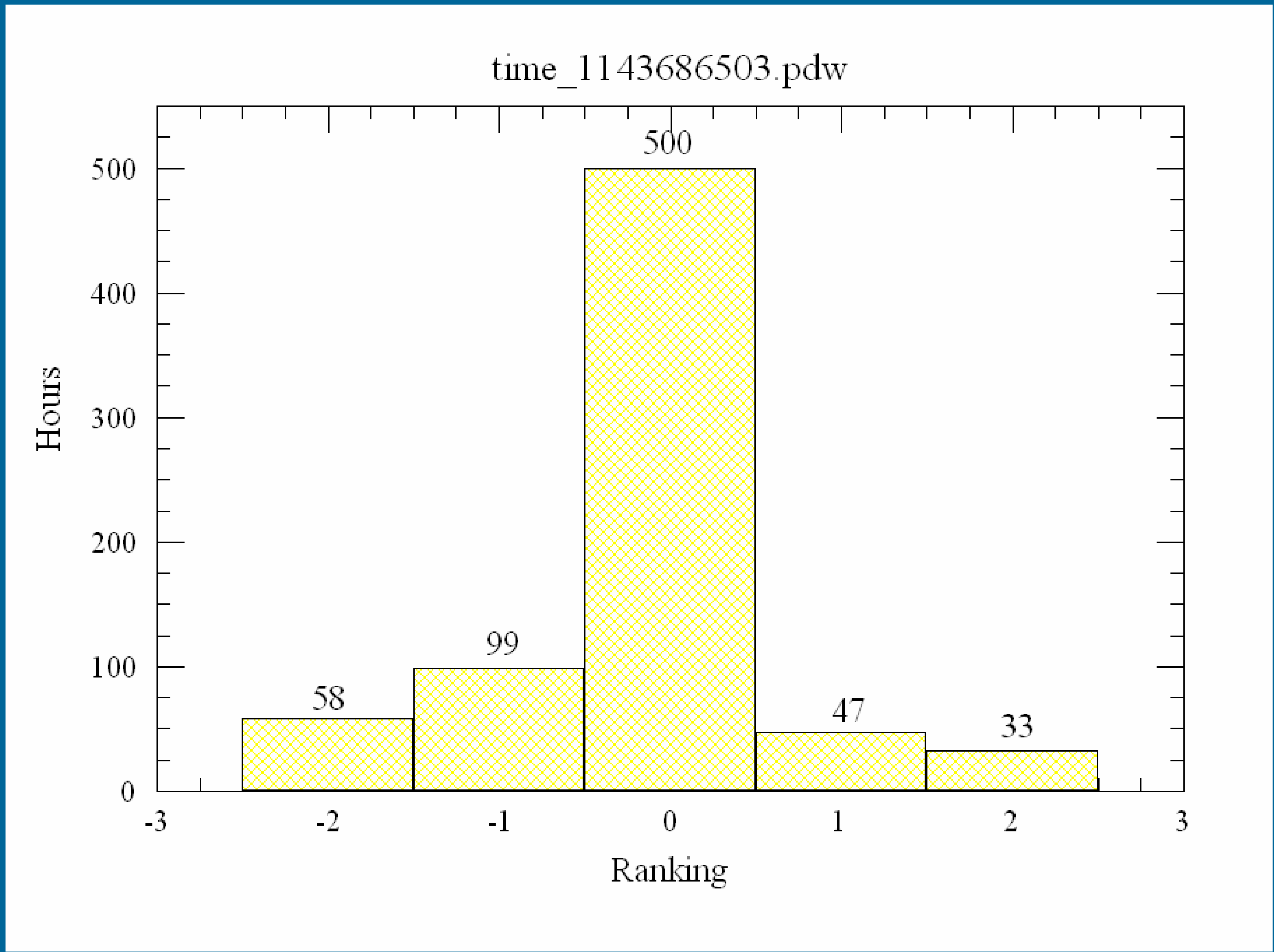


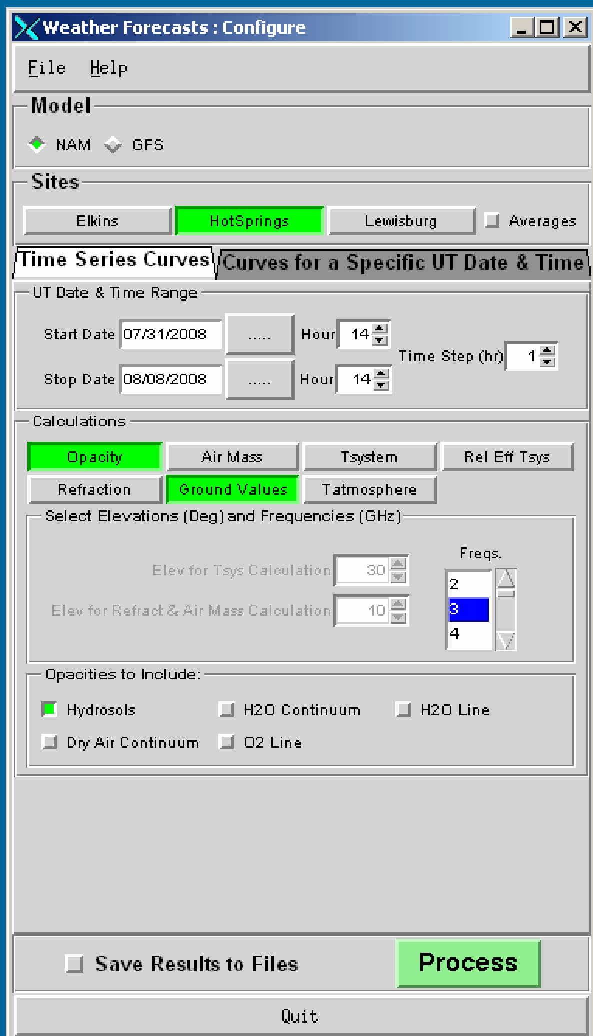
How was our old DSS working?

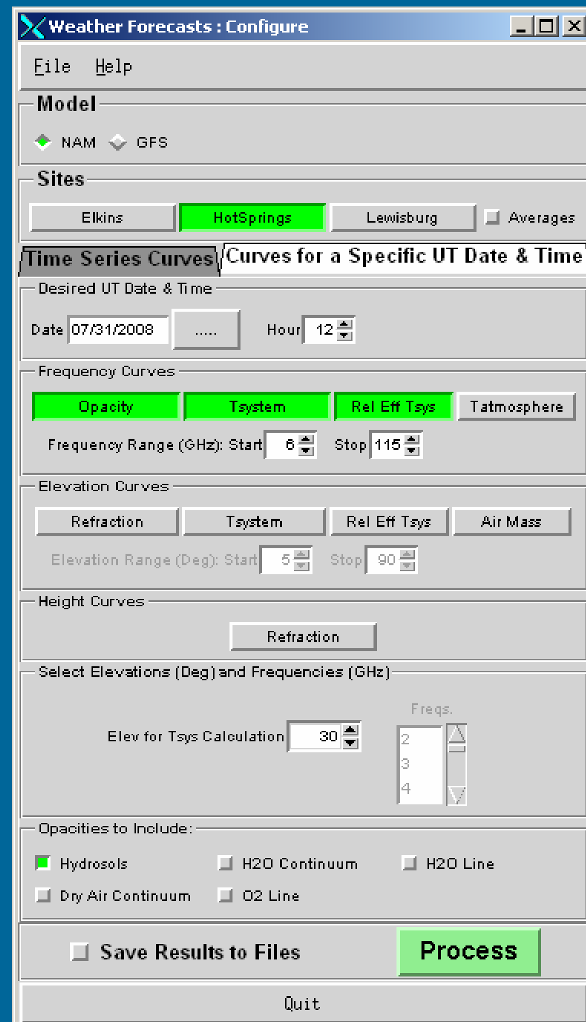


Web Page Summaries

- http://www.gb.nrao.edu/~rmaddale/Weather/index.html
- 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

User Software: cleo forecasts





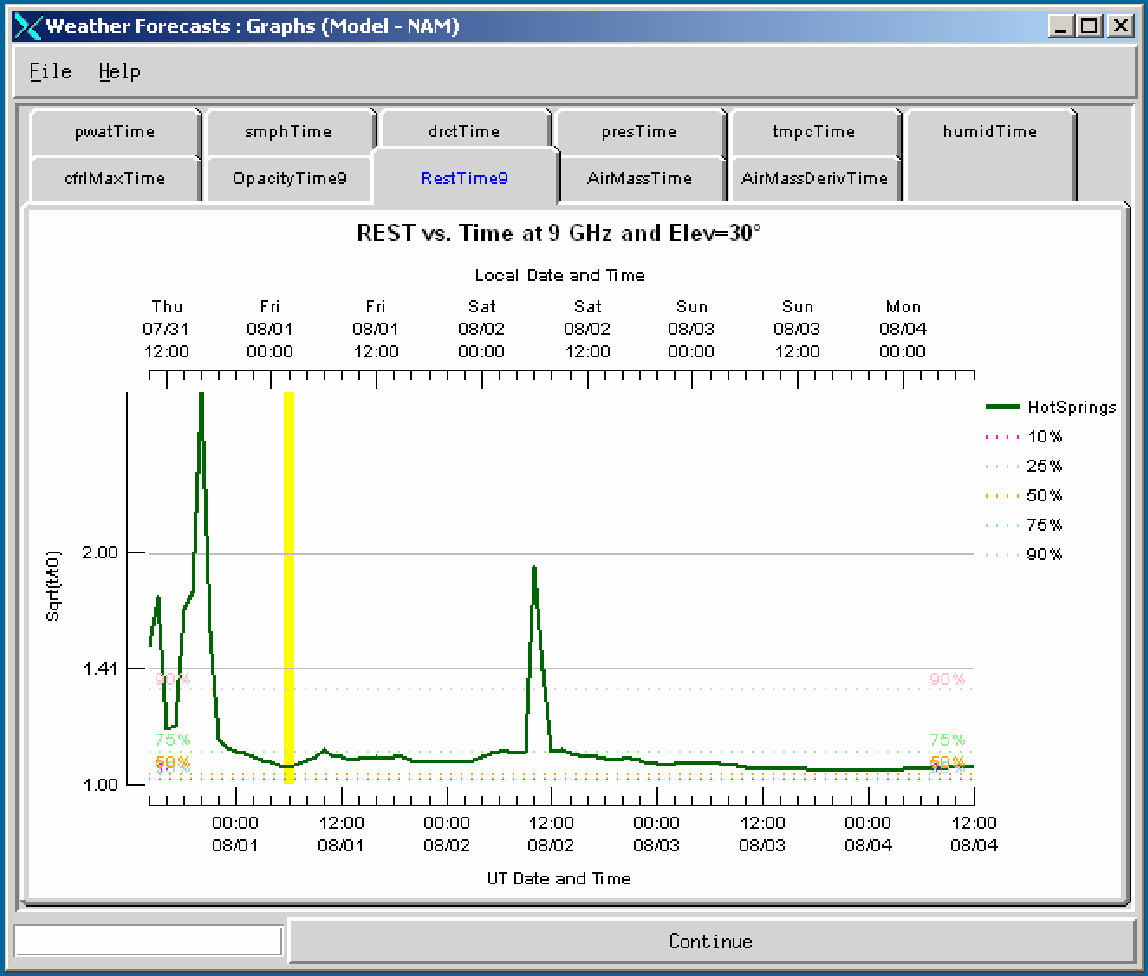
Type:

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 : forecastsCmdLine

- Fuzzy caching
- Reads Zipped archive files
- Writes processed data to time-tagged directories that contain a log of user inputs and self documented files
- Extrapolation for upper atmosphere refraction
- Interpolation of missing data
- Table of T_{Rcvr} with 1 GHz resolution
- Accurate algorithms and approximations for Air mass and T_{Atm}
- Lower accuracy but fast to calculate opacity estimates using the models of H. Lehto
- Default is to use the best data (last forecasted for any time slot) but there's a super-user mode of time-offsetting

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

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Part I: The Mechanics and Physics

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