Weather Forecasting for Radio Astronomy
Lecture for the 2009 REU Summer Students

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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.
- 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
\( n_5 = 1 \)

\[ \cos(E_4) = \left( \frac{n_4}{n_5} \right) \cos(E_{\text{True}}) \]

\( n_4, \Delta h_4 \)

\[ \cos(E_3) = \left( \frac{n_3}{n_4} \right) \cos(E_4) \]

\( n_3, \Delta h_3 \)

\[ \cos(E_2) = \left( \frac{n_2}{n_3} \right) \cos(E_3) \]

\( n_2, \Delta h_2 \)

\[ \cos(E_{\text{Observed}}) = \left( \frac{n_1}{n_2} \right) \cos(E_2) \]

\[ \text{AirMass} = \text{Sum}(L_i)/L_{\text{Zenith}} \]

\( n_1, \Delta h_1 \)

\[ E_{\text{Observed}} = E_{\text{True}} + R \]

\[ \text{AirMass} = \frac{L}{L_{\text{Zenith}}} \]

Grossly exaggerated and assuming plane parallel approximation
Basics of refraction and relative air mass

\[ \text{Elev}_{\text{Obs}} - \text{Elev}_{\text{True}} = a \ n_0 \ \cos(\text{Elev}_{\text{Obs}}) - \frac{dn(h)}{1 - \sqrt{(a-h)^2 n(h)^2 - a^2 n_0^2 \cos^2(\text{Elev}_{\text{Obs}})}} \]

\[ \text{AirMass} (\text{Elev}_{\text{Obs}}) = \frac{1}{\int_0^{\infty} \left( 1 - \frac{a}{a - h} \frac{n_0^2}{n(h)^2} \cos^2(\text{Elev}_{\text{Obs}}) \right) dh} \]

\( a = \) Earth radius

\( n(h) = \) index of refraction at height \( h \)

\( n_0 = \) index of refraction at surface

\( \rho(h) = \) air density

\( \text{Elev}_{\text{Obs}}, \text{Elev}_{\text{True}} = \) refracted and airless elevations
\[ T_{\text{Sys Atm}}(1) = T_{\text{Sys}}(2) \cdot \exp(-\kappa_1 \cdot \Delta h_1) - T_2 \cdot [1 - \exp(-\kappa_1 \cdot \Delta h_1)] \]

\[ T_{\text{Sys Atm}}(2) = T_{\text{Sys}}(3) \cdot \exp(-\kappa_2 \cdot \Delta h_2) - T_2 \cdot [1 - \exp(-\kappa_2 \cdot \Delta h_2)] \]

\[ T_{\text{Sys Atm}}(3) = T_{\text{Sys}}(4) \cdot \exp(-\kappa_3 \cdot \Delta h_3) - T_3 \cdot [1 - \exp(-\kappa_3 \cdot \Delta h_3)] \]

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

\[ T_{\text{Sys Atm}}(5) = T_{\text{BG}} \]
Basics of radiative transfer

\[ \kappa_{\text{Total}}(h, \nu) = \sum_{H} \kappa_i(h, \nu) \]

\[ \tau(\nu) = \int_{0}^{H} \kappa_{\text{Total}}(h, \nu) \cdot dh \]

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

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

\[ T_{\text{Atm}} = \frac{\int_{0}^{H} \kappa_{\text{Total}}(h, \nu) \cdot T(h) \cdot dh}{\int_{0}^{H} \kappa_{\text{Total}}(h, \nu) \cdot dh} \]
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….

<table>
<thead>
<tr>
<th>h</th>
<th>T</th>
<th>P</th>
<th>DP</th>
<th>CFR</th>
<th>L</th>
<th>Δh</th>
<th>ρ_{Water}</th>
<th>ρ_{Dry}</th>
<th>n</th>
<th>ΔElev</th>
<th>k_{Dry}</th>
<th>k_{H2O Cont}</th>
<th>k_{H2O Line}</th>
<th>k_{O2}</th>
<th>k_{Hydrosols}</th>
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<th>ΔT_{Sys}</th>
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</table>

Generate a table for every desired frequency, site, time
Opacities from the various components

![Graph showing Zenith Opacity vs. Frequency](image)

- **Zenith Opacity vs. Frequency**
  - 2008 Aug 03 17:00 UT
  - **Dry Air Continuum**

The graph illustrates the relationship between zenith opacity and frequency over a specific date and time. The data points suggest an increasing trend in opacity as frequency increases, with the label 'HotSprings' indicating a specific dataset or model.
Opacities from the various components

Water Continuum

Zenith Opacity vs. Frequency
2008 Aug 03 17:00 UT

Water Continuum
Opacities from the various components

Zenith Opacity vs. Frequency
2008 Aug 03 17:00 UT

Water Line
Opacities from the various components

Zenith Opacity vs. Frequency
2008 Aug 03 17:00 UT

Oxygen Line
Opacities from the various components

Zenith Opacity vs. Frequency
2008 Jul 31 13:00 UT

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/m³ for clouds thinner than 120 m
    - 0.4 g/m³ 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/](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/](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

Overview of RESTs & Winds

Local Date and Time

<table>
<thead>
<tr>
<th>Wed</th>
<th>Thu</th>
<th>Fri</th>
<th>Sat</th>
<th>Sun</th>
<th>Mon</th>
<th>Tue</th>
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Frequency (GHz)

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<thead>
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<th>40</th>
<th>60</th>
<th>80</th>
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UT Date and Time

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

$$ \frac{T_{Rcvr} + T_{Spill} + T_{CMB} e^{-\tau} + T_{Atm} \left[1 - e^{-\tau}\right]}{e^{-\tau}} = \frac{T_{sys}}{e^{-\tau}} $$
- 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 $\propto \sum \rho_{\text{Water}}(h)$ – good summary statistic
  - Temperature and wind speeds (safety limits)
  - Pressure, humidity, wind direction
  - Fractional cloud cover $= \max[\text{CFRL}(h)]$ – 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, $T_{\text{Sys}}$, RESTs, and $T_{\text{Atm}}$ 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?

- $R = 0.96$
- $\sigma = 2.8 \text{ mm}$

- $R = 0.91$
- $\sigma = 4.5 \text{ mm}$

- $R = 0.91$
- $\sigma = 1.9 \text{ mph}$

- $R = 0.79$
- $\sigma = 2.9 \text{ mph}$
How accurate are the forecasts?
How accurate are the forecasts?
How was our old DSS working?
References

- R.J. Maddalena "Refraction, Weather Station Components, and Other Details for Pointing the GBT", 1994, *NRAO GBT Memo 112* (and references therein).