Development and Demonstration of a New Global Climate Sensor: The Active Temperature Ozone and Moisture Microwave Spectrometer (ATOMMS)

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Rationale: Observational Needs for Climate

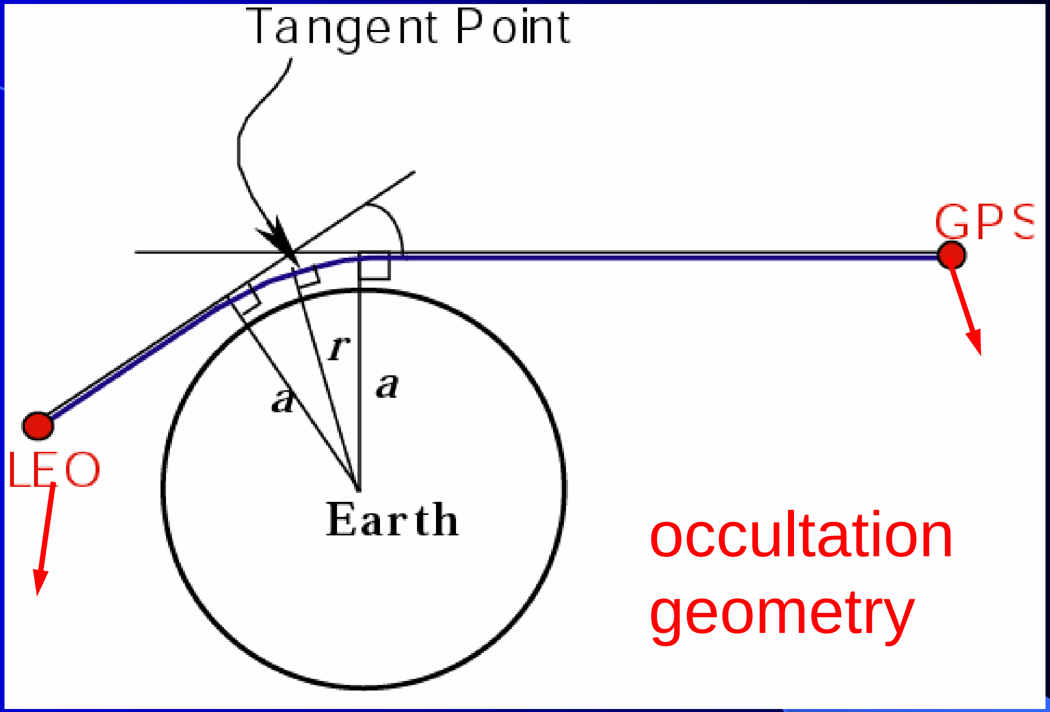
Climate models are wrong in ways that we don't yet know.

When you don't understand something, you measure it

Need observations as complete as possible and to **determine the atmospheric state** and what is actually happening, *independent of models*

Can we achieve this via satellite to satellite occultations?

Occultation Geometry



- An occultation occurs when the orbital motion of a GPS SV and a Low Earth Orbiter (LEO) causes the LEO 'sees' the GPS rise or set across the limb
- This causes the signal path between the GPS and the LEO to slice through the atmosphere
- Atmosphere acts as a lens bending the signal path and attenuating the signal strength
- From the bending and absorption profiles, we can profile the temperature, pressure and several constituents of the atmosphere

Why satellite to satellite occultations?

- Simple, direct technique: Used since 1965, GPSRO since 1995
- Global coverage from orbit
  - Full ***diurnal*** coverage via a constellation of $\geq$ 6 satellites (like COSMIC)
- Unique relation between bending angle and retrieved quantity, refractivity
  - Unlike radiance measurements for which the retrieval problem is ill-posed and requires additional information such as from a model
- Insensitive to surface emissivity: works over land and water
- Works in clear and cloudy conditions
  - Eliminates clear sky biases that limit visible & IR measurements
- High vertical resolution: GPS RO has demonstrated 200 m vertical resolution
- High precision
  - Example: Individual temperature profiles to 0.4K (close to climate quality)
  - Observe variability needed to reveal and understand processes
- High accuracy
  - Self-calibrating because signal source is observed immediately before or after each occultation

Limitations of GPS RO

- Can't separate effects of dry and wet contributions to refractivity from GPS RO measurements alone
  - Must rely on external information to separate these effects in the part of the troposphere (warmer than ~230K)
- Sensitive to ionosphere
  - Limits maximum altitude of GPS RO retrievals to 45 to 60 km depending on ionosphere activity
  - Subtle solar and diurnal cycle effects will leak into GPS RO temperature and pressure retrievals in middle atmosphere and upper troposphere
- Need additional information for upper boundary condition for both bending angle profile and hydrostatic pressure integral
  - Presently rely on climatological models and weather analyses
- Water Vapor vertical range
  - Limited to below the ~240 K level in troposphere (~9 km alt. in tropics, much lower in winter hemisphere)

What can we achieve if we design a RO system from scratch

- Select occultation frequencies to measure absorption of interesting constituents:
  - H_2O absorption to break wet-dry ambiguity of refractivity
  - other constituents like O_3, $H_2{}^{18}O$, HDO via absorption
- Extend profiles to much higher altitudes
  - reduce GPSRO sensitivity to ionosphere using much higher freq's
- No need for external hydrostatic boundary condition and use of middle atmosphere climatology/analyses:
  - measure high altitude temperature directly via Doppler broadening

Result is …

⇒ A cross between GPS RO & MLS

⇒ Standalone thermodynamic state estimator for climate and weather from near-surface to mesopause (& Mars)

Overdetermined vs. Underdetermined

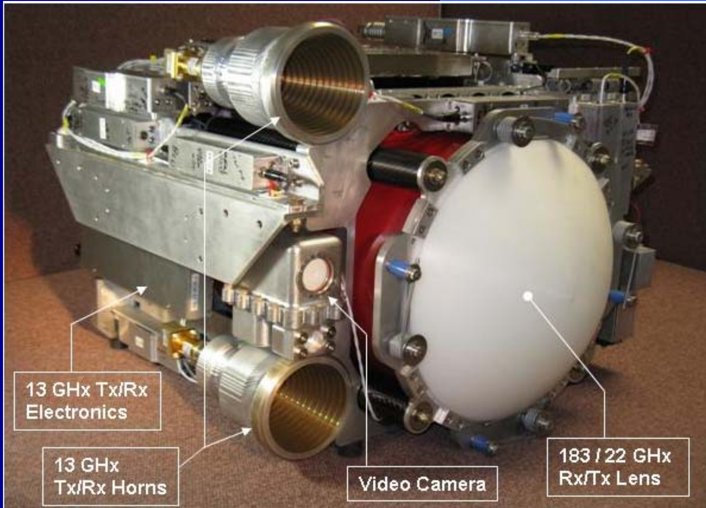
- Cost of ATOMMS will be high to implement as a constellation (perhaps not as much as decadal survey mission but $500M)
- It is critical to ATOMMS as a climate state measurement system that it provide a UNIQUE estimate of the state, independent of models.
- To do this requires at least 5 frequencies in the presence of liquid water
  - Common mode cancellation, water vapor, liquid water amount, liquid water temperature, spectroscopic refinement

Concept Evolution

- Theoretical development (1998 - present)
- Aircraft to aircraft demonstration (2011)
- Satellite to satellite demonstration
- Constellation of microsatellites for climate and NWP
  - Satisfy (NOAA) climate monitoring needs
  - Provided by NASA, NSF, ESA, eventually NOAA, …

ATOMMS Aircraft Occultation Instrument Overview

- 22 GHz water line
  - 8 tones space approximately 1 GHz apart between 18 and 26 GHz
  - Solve for water vapor mid-trop & below and liquid water content
- 183 GHz water and 195 GHz ozone lines
  - Presently 2 tones between 183 and 203 GHz
    - Add 2 more tones for turbulent variations in imaginary refractivity
  - Solve for water vapor in upper troposphere & above
  - Solve for ozone in upper troposphere and above
- 13 GHz phase tone(s)
  - Provide phase in lower troposphere where 183 GHz cannot penetrate to determine bending angle and real part of refractivity
- No cryogenics
- Build at UA
  - Presently testing instrument at UA



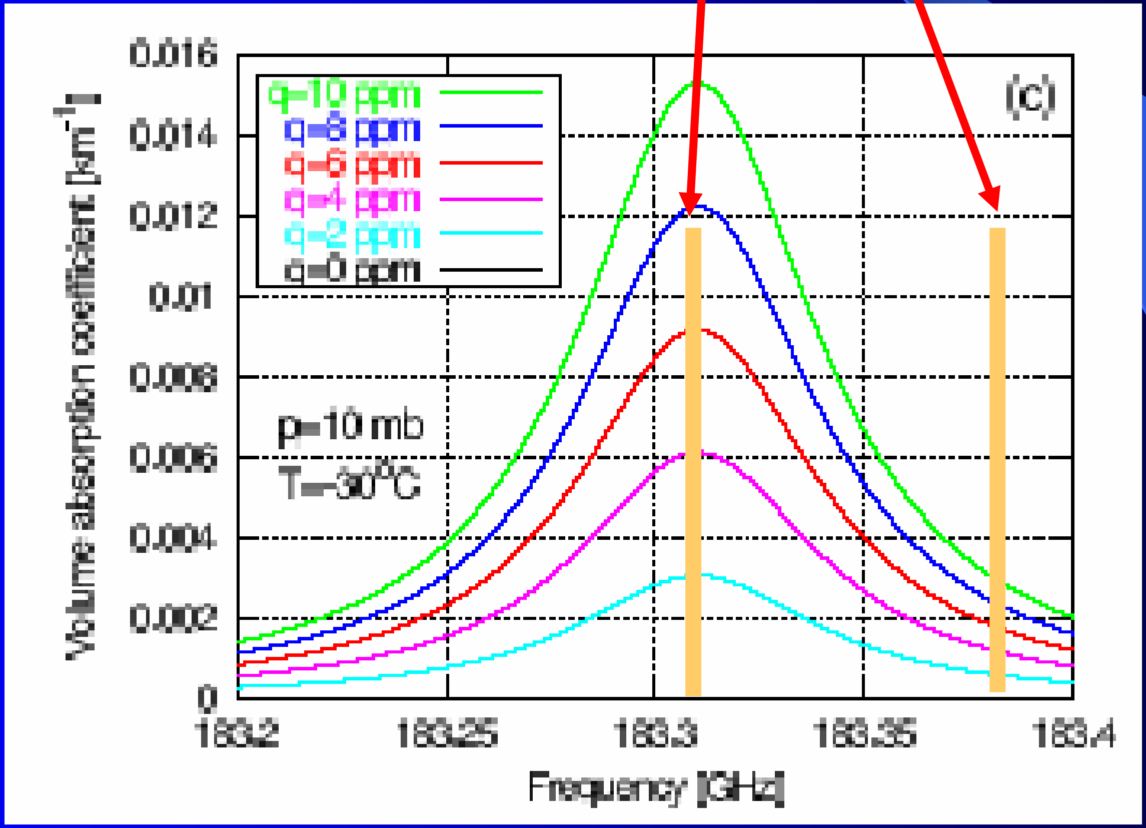
Challenges:

- Requires new transmitters in orbit
- Pointing
  - high SNR requires directional antennas
- High amplitude stability
- Sampling density vs. cost of additional transmitters & receivers
- Enhanced sensitivity to turbulence
- Separate water vapor from liquid water clouds

ATOMMS Measures Differential Absorption

Measure occultation signal amplitude simultaneously at 2 or more frequencies,

- One closer to line center to measure absorption
- Calibration tone farther from line center to ratio out unwanted effects



Retrieval Overview: Deriving Extinction Coefficient Profiles

Beer's law: At each wavelength, observed intensity, *I*, equals vacuum intensity (signal intensity with no atmosphere), I_0, times e^{-t} where *t* is the optical depth.

$$I = I_o \exp(-\tau) \quad or \quad \tau = \ln\left(\frac{I}{I_o}\right)$$

- Measured optical depth is along the signal path
  - What we want is a ***radial*** profile of the extinction coefficient, *k*.

=> Simplest solution is an abel integral transform pair for opacity and extinction coefficient: (**Note: *x = nr***)

absorption

$$\tau(a) = \int k\, dl = 2\int_{x=a}^{x=\infty} k \frac{x \, {dr}/{dx} \, dx}{\sqrt{x^2 - a^2}} \qquad k = -\frac{1}{\pi} \frac{da}{dr}\bigg|_{a=a_0} \int_{a=a_0}^{a=\infty} \frac{d\tau}{da} \frac{da}{\left(a^2 - a_0^2\right)^{1/2}}$$

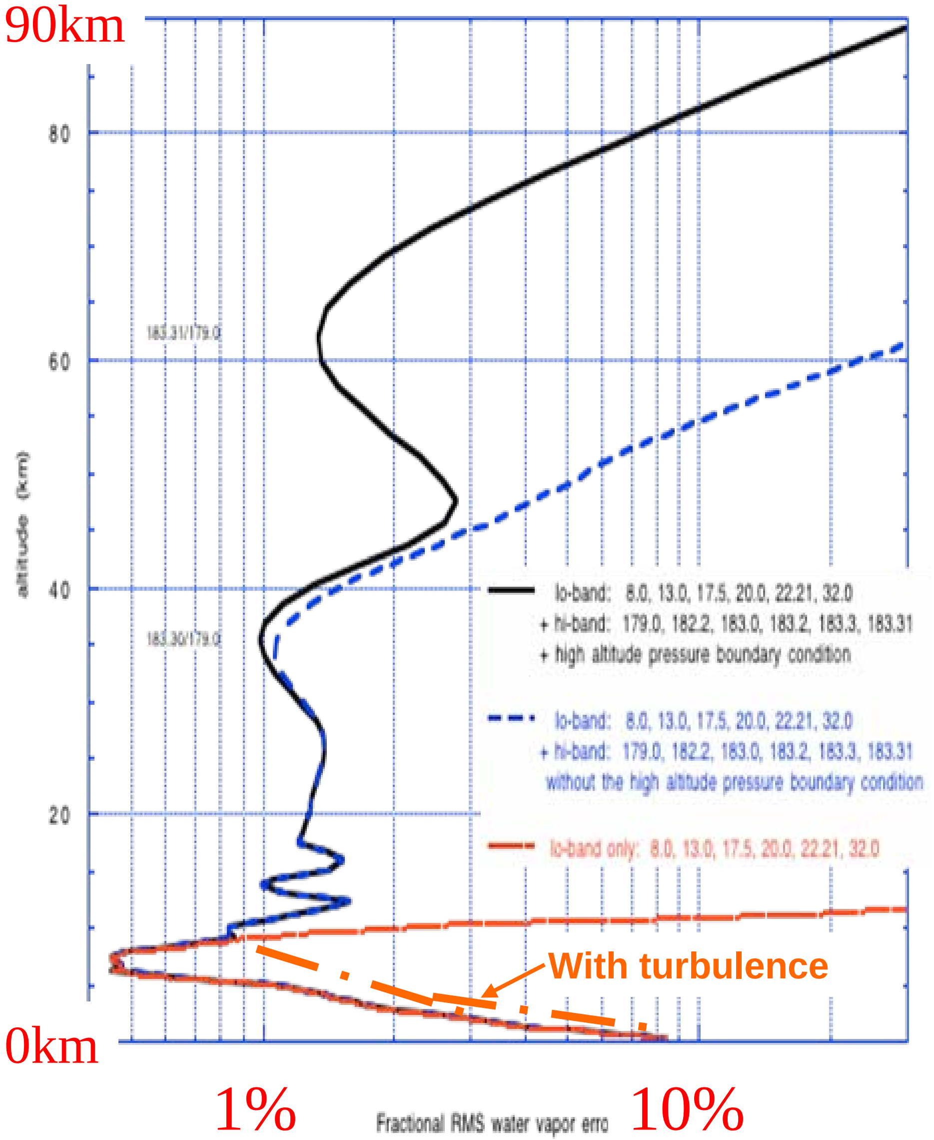
Forward relation — *Inverse relation*

bending

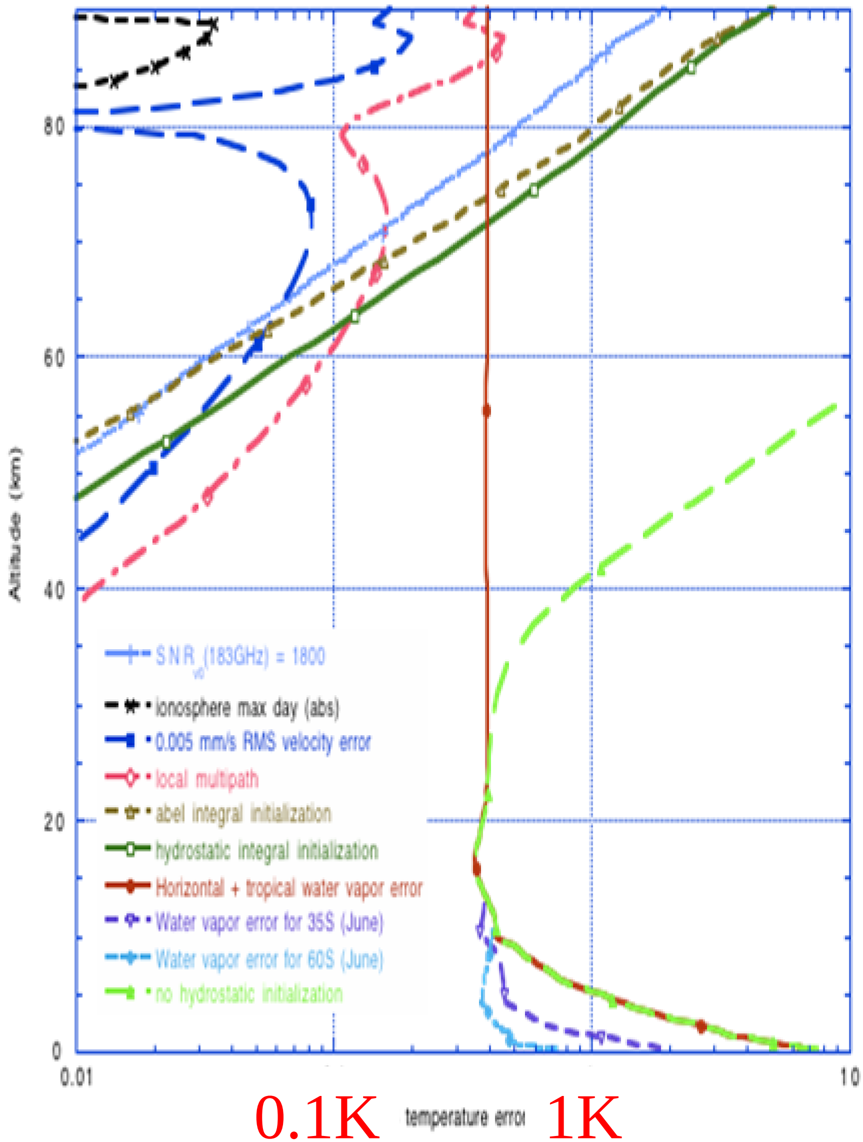
$$\alpha = \int d\alpha = 2a\int_{r_t}^{\infty} dr \frac{dn}{n\, dr} \frac{1}{\sqrt{n^2 r^2 - a^2}} \qquad n(r_{01}) = \exp\left[-\frac{1}{\pi}\int_{a_1}^{\infty} \frac{\alpha(a)\, da}{\sqrt{a^2 - a_1^2}}\right]$$

Precision of Individual ATOMMS Profiles

water vapor



temperature



ATOMMS Performance vs. Latitude

Precision of individual temperature and water vapor profiles

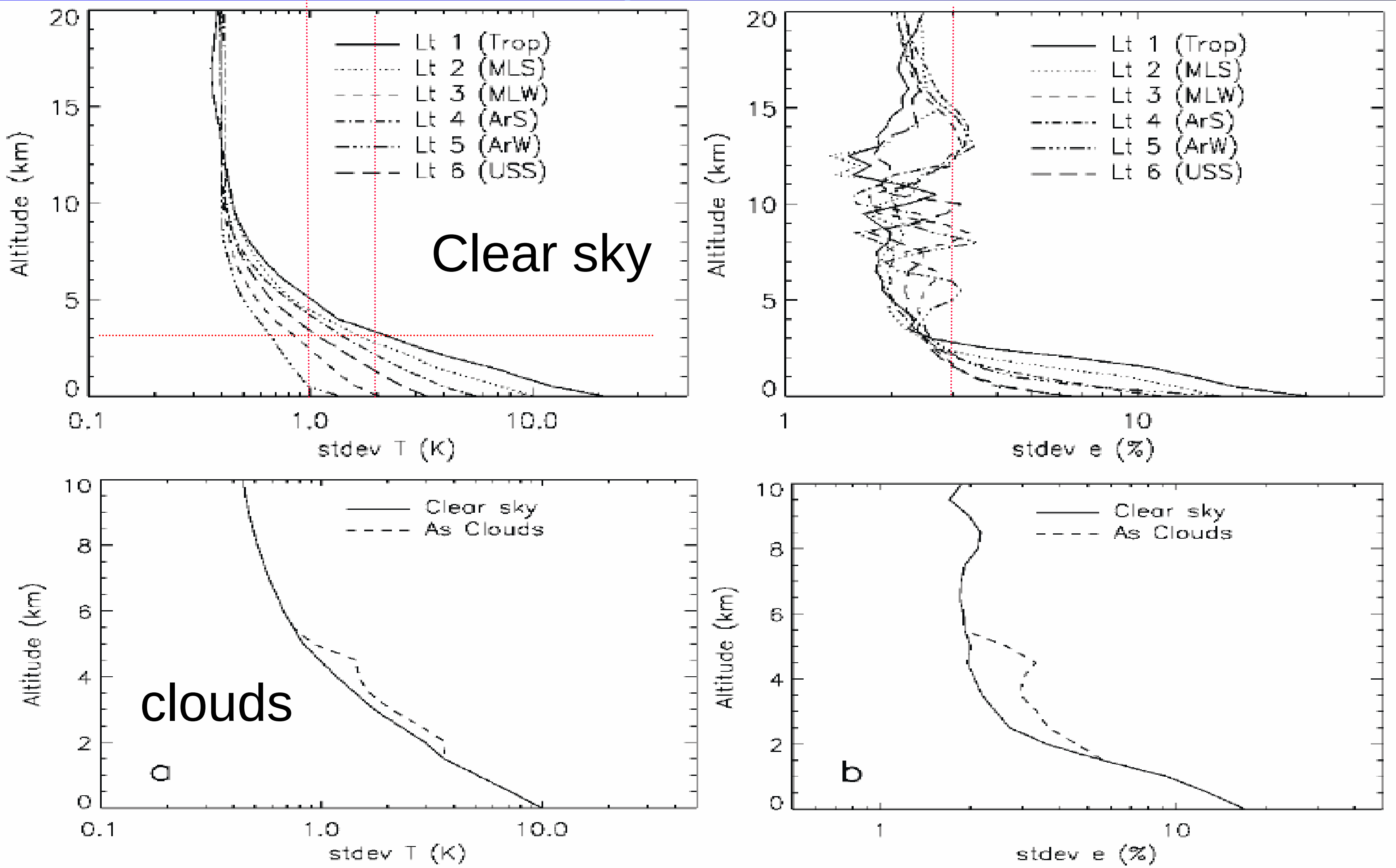
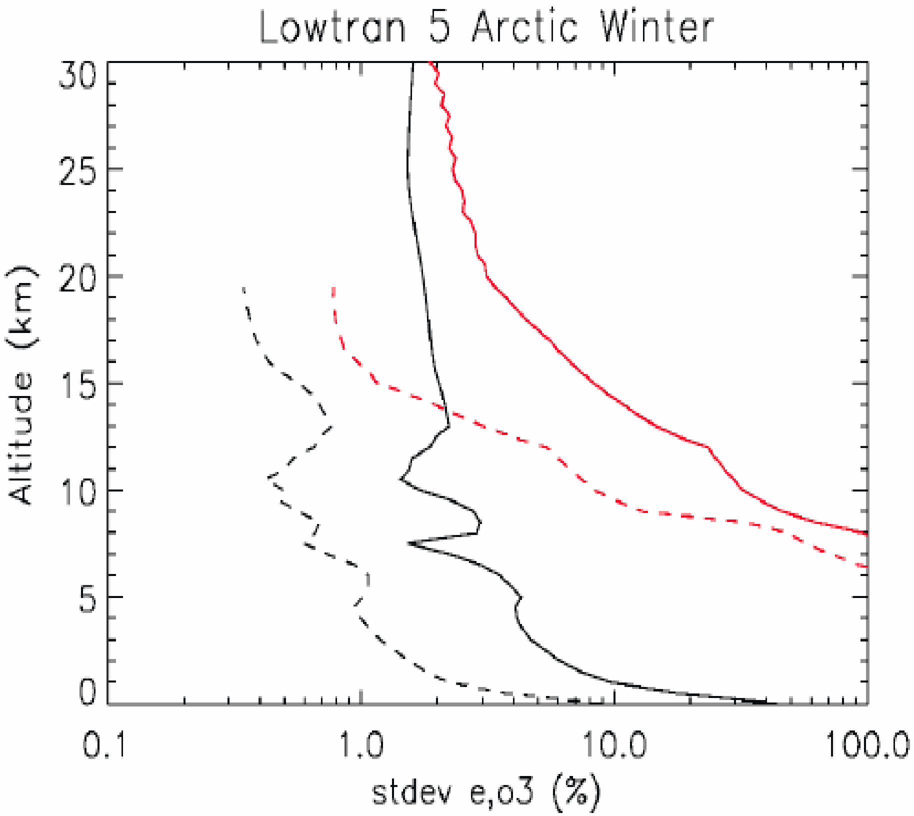
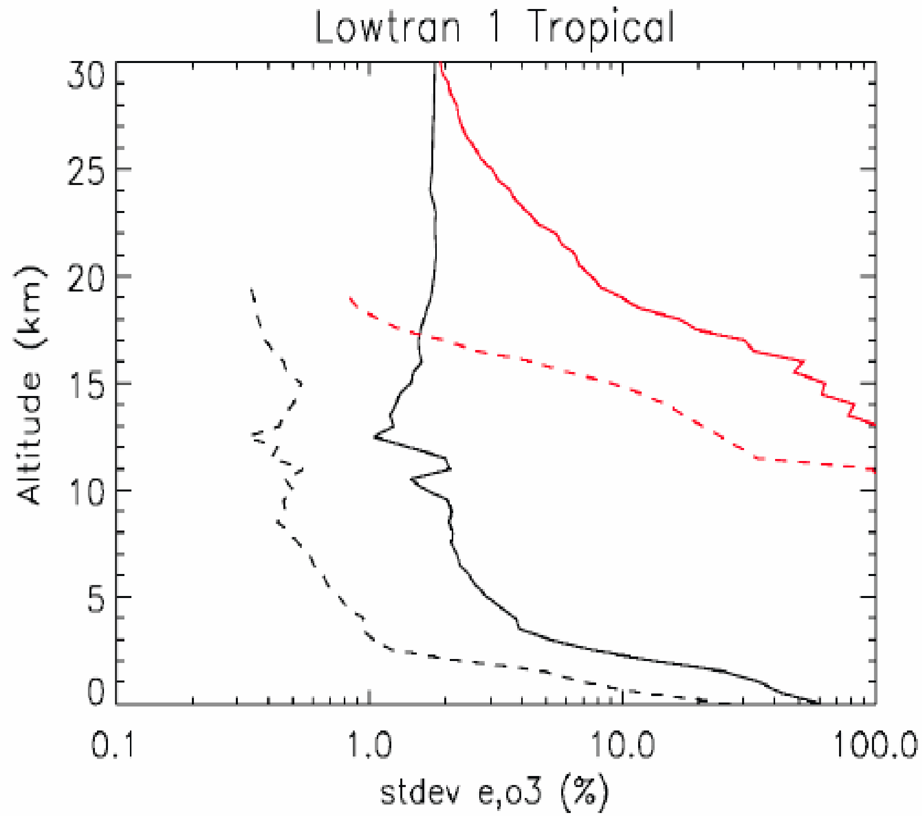


Fig. 7 Computed standard deviation of the errors in the retrievals of (a) temperature and (b) water vapor pressure using simulated ATOMMS observations. The background atmosphere is the Lowtran 2 mid-latitude summer profile. Solid lines are for clear sky conditions, while the dashed lines were computed after placing a broken deck of altostratus clouds between 4.5 km and 5.5 km altitude. The cloud field is highly non-symmetric about the local tangent point. Cloud elements have liquid water contents of 0.3 g m^{-3}.

Ozone & Water Vapor Retrieval Precision

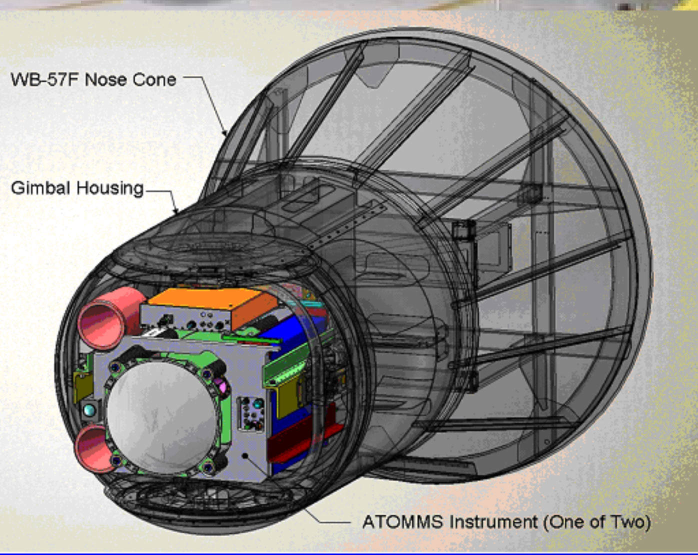


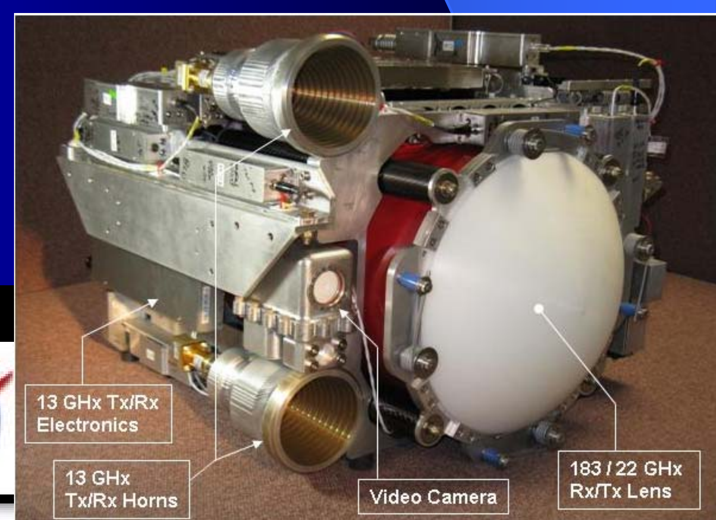


- Standard deviation of simulated errors of water vapor (black) and ozone (red) from satellite (solid) and aircraft occultations (dashed).
- At altitudes below ozone peak, ozone retrieval error quickly increases
- Aircraft retrievals are more accurate than satellites & will be quite useful

Aircraft-aircraft demonstration

- Occultation between 2 WB-57F aircraft flying near 19 km altitude
- Perform series of rising occultations
- Measure phase and amplitude at several wavelengths
- POD: GPS + accelerometers
- Pointing via WAVE





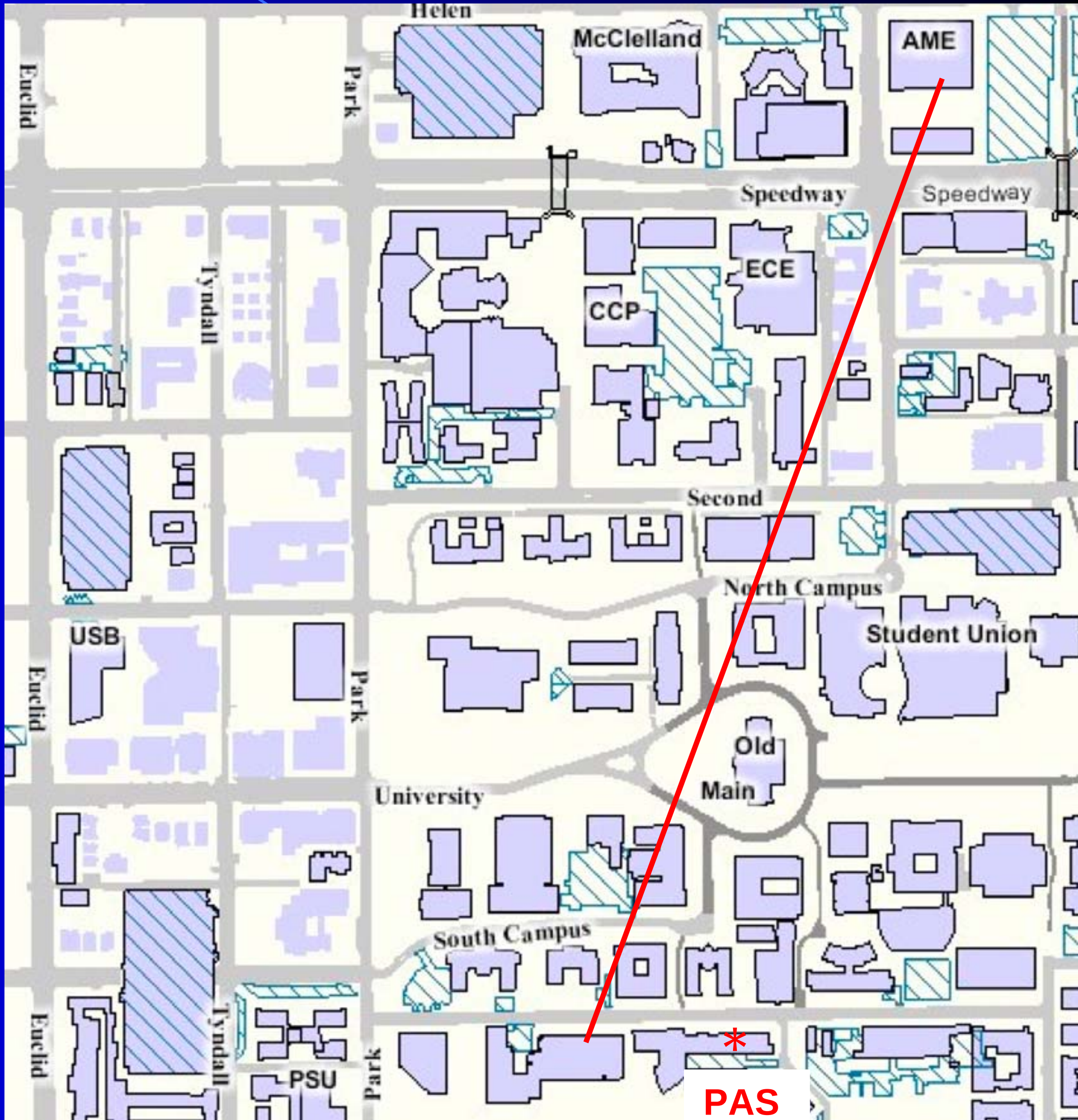
ATOMMS System Elements & Development

- ATOMMS occultation instrument (UA)
- ATOMMS precise positioning system (JPL)
  - < 0.1 mm/sec via GPS and seismic accelerometers
- WAVES pointing system (SRI)
- WB-57F Aircraft (JSC)
- Retrieval system (UA)
  - extended from JPL GPS RO
- Ground truth for evaluation (ARM SGP + A-Train + ….)

Rooftop measurements at University of Arizona

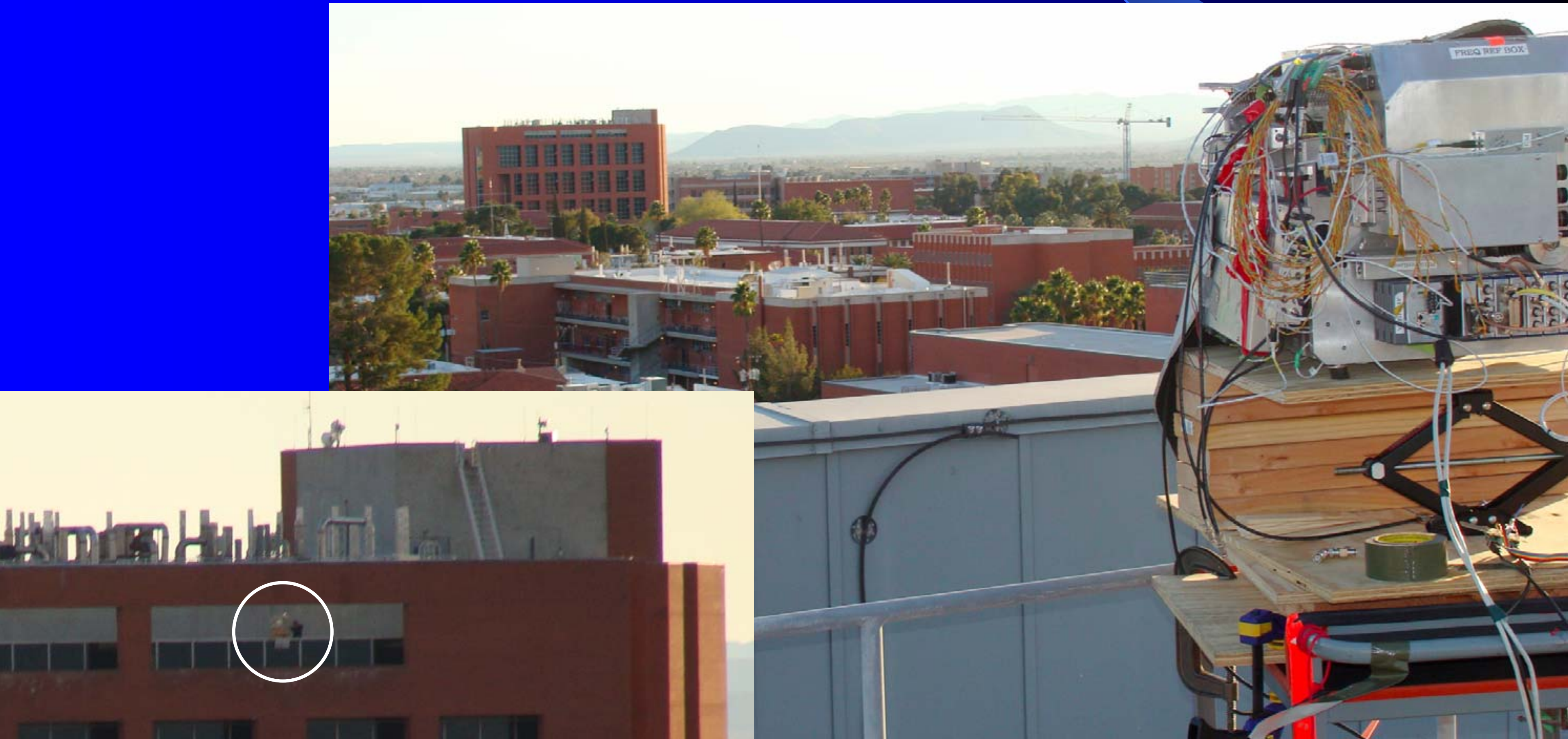
In spring 2010, we made measurements using 183 GHz portion of ATOMMS instrument

- Transmitter on AME building
- Receiver on Gould Simpson Building
- Separated by about 800 m
- * shows location of hygrometer on PAS building that was compared against



Rooftop measurements at University of Arizona

- View from AME building
- Simple Az-El instrument mount



Rooftop measurements at University of Arizona

- View of AME building from Gould Simpson

Problems with Calibration for Ground Measurements

To measure water vapor etc., one must calibrate out the instrument response to see and interpret the signal attenuation

- Easy in space: measure instrument response above the atmosphere a minute before or after each occultation,
- Harder in aircraft,
- Difficult on the ground
  - Can't evacuate the air before or after the measurement

APPROACH

- Measure instrument response in anechoic chamber w/o hi gain antenna
- Scale in antenna vs. frequency response & $1/R^2$ is independent of freq
- **PROBLEM**: local multipath. (Surprising given directionality of antenna)

SOLUTIONS

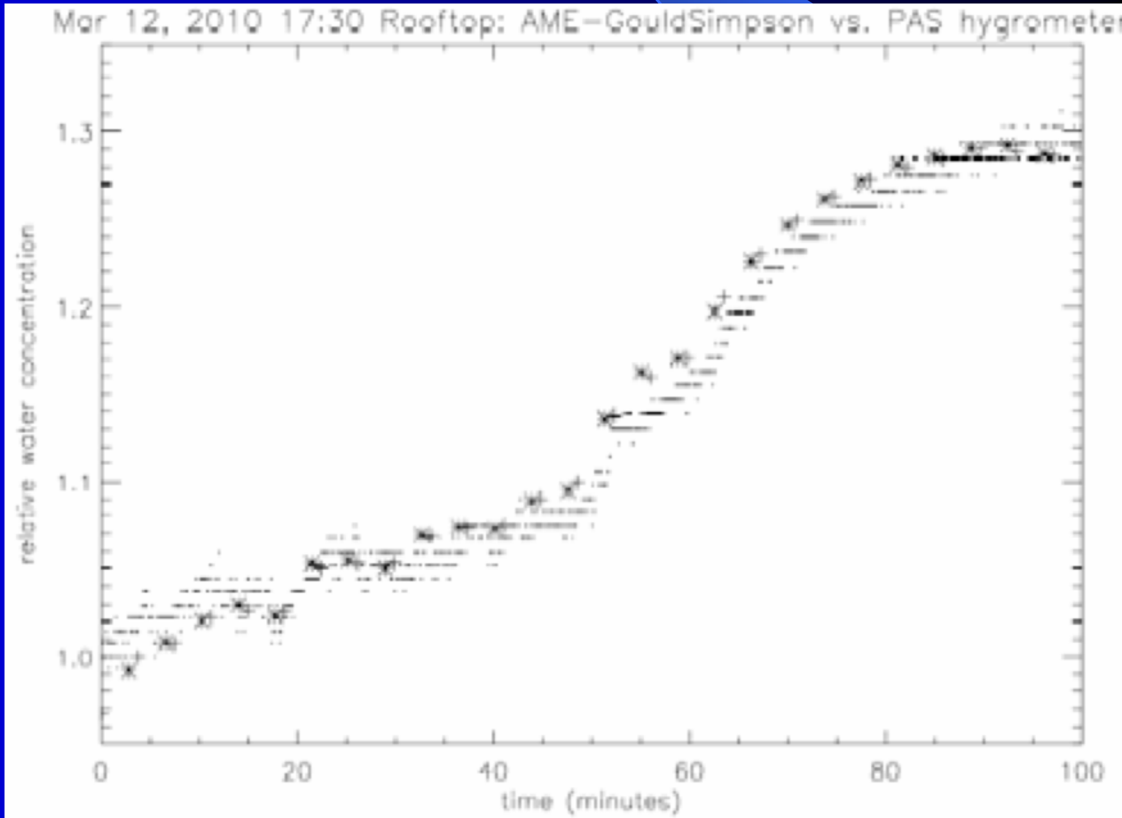
- To date, we have been calibrating by ratioing spectral data at min to max water vapor
- Developing method to isolate multipath effect that will allow use of anechoic chamber calibration

Initial Water Vapor Results

- Measure **change** in water vapor
- Asterisks: ratios of ATOMMS optical depths
- Dotted lines: ratio of PAS capacitive hygrometer vapor pressures.
- Close agreement between two data sets from very different measurement techniques.
- Some differences due simply to very different spatial sampling of the two techniques.

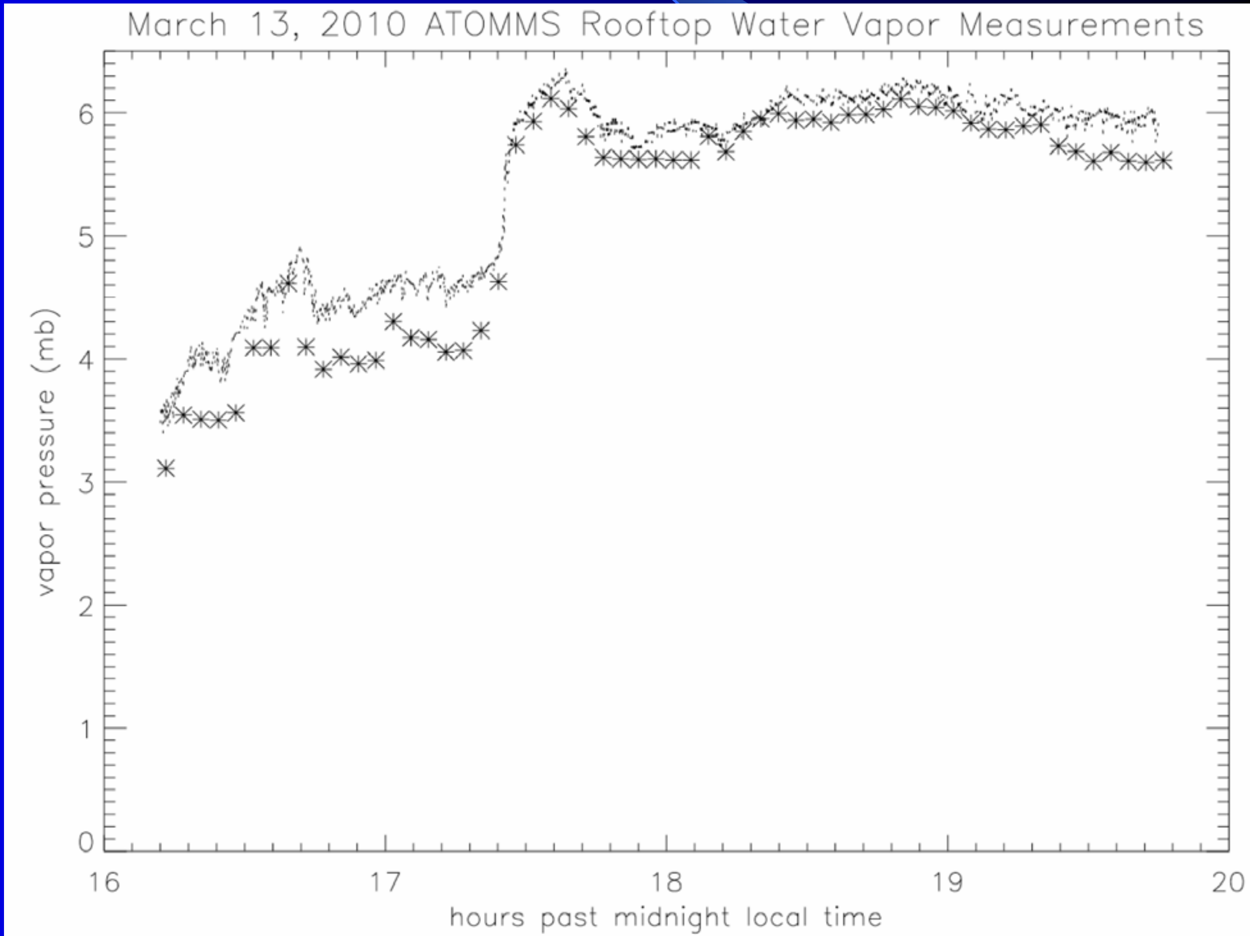
  - PAS hygrometer is time integrated, point measurement via changes in dielectric of a moisture sensitive capacitor

  - ATOMMS measurements are path integral measurements along an 800 m path.



Absolute water vapor estimates

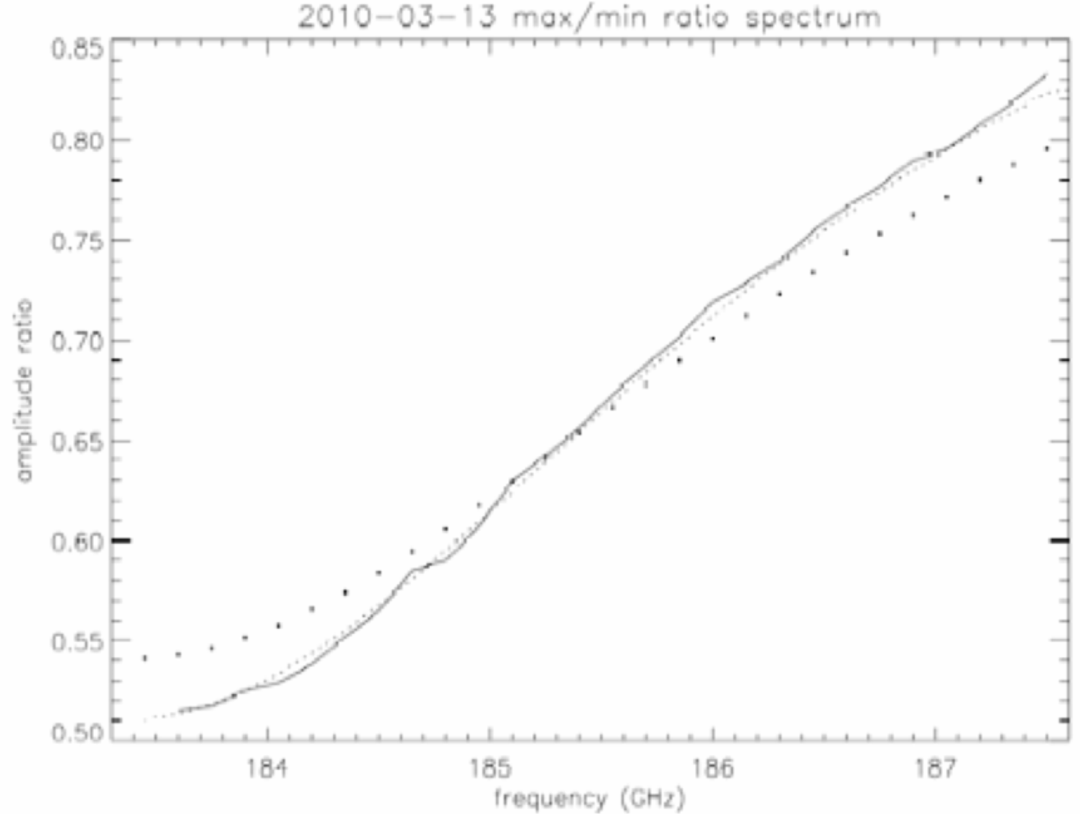
- Asterisks: water vapor derived from ATOMMS.
- Fine dots: 5 second partial pressure derived from the capacitive hygrometer on roof of PAS building east of Gould-Simpson building.



Rooftop 183 GHz Absorption Spectra

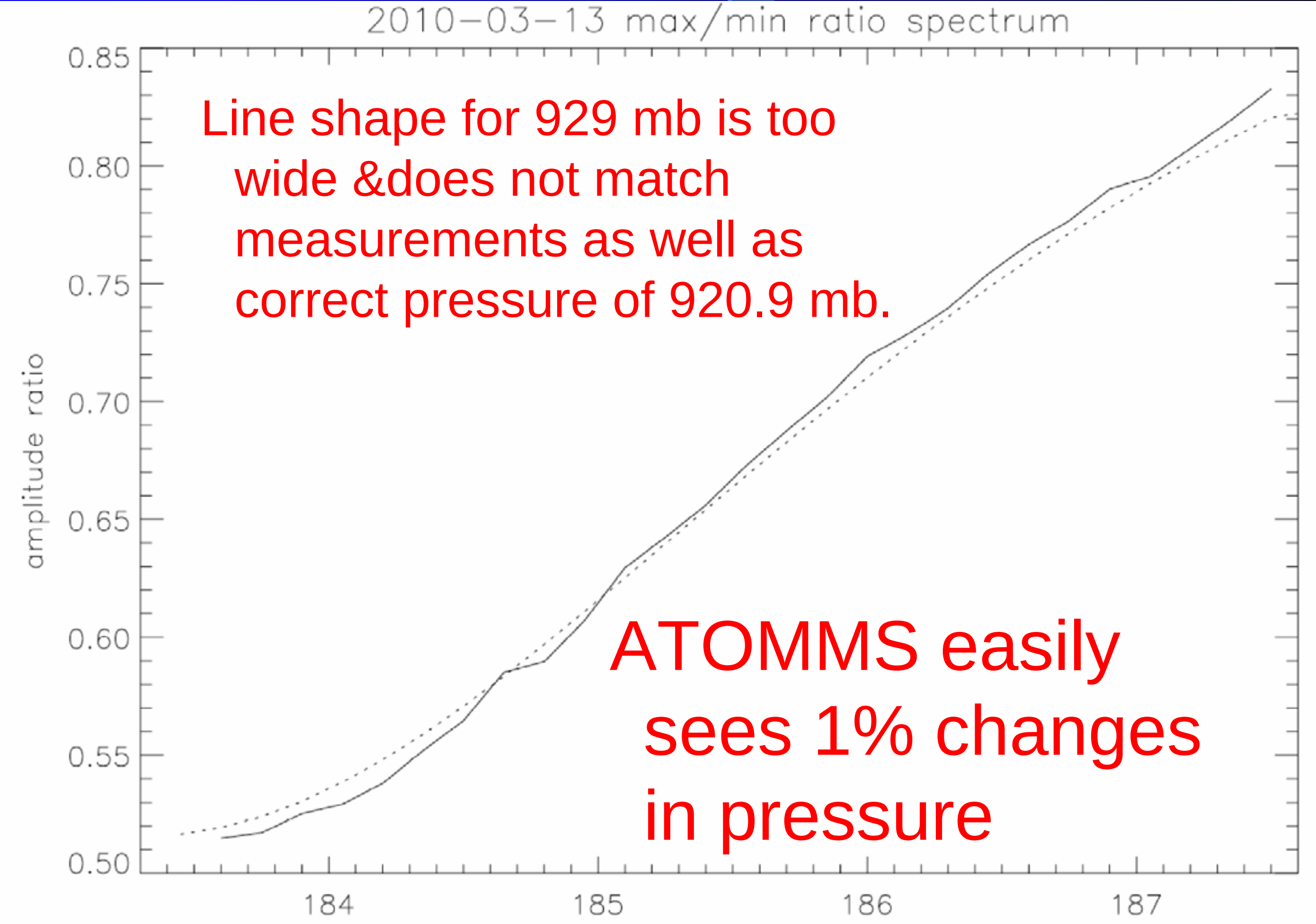
- Ratio of minimum/maximum amplitude spectra from ATOMMS and from two spectroscopic models, AM5.2 & MPM93.
- The spectra are for 920.9 mb surface pressure and 21ºC.
- Solid line: ratio of min/max amplitude spectra from ATOMMS.
- Fine dotted line: AM-5.2 spectra ratio for e_{max}-e_{min} = 2.64 mb.
- Large dotted line: Liebe spectrum for e_{max}-e_{min} = 2.2 mb.

- AM-5.2 spectra fits ATOMMS results quite well.
- Line shape in Liebe MPM93 code does NOT match measurements very well.

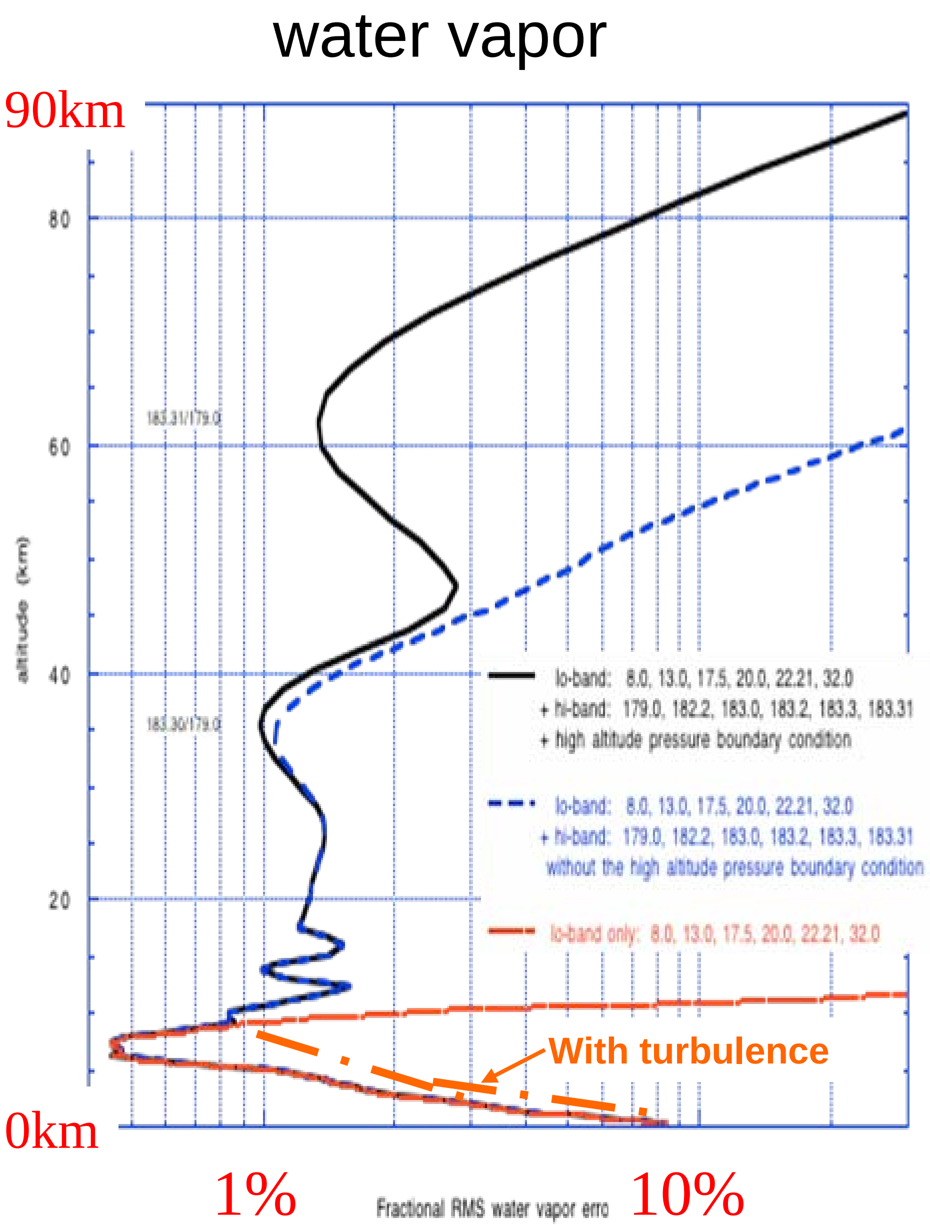


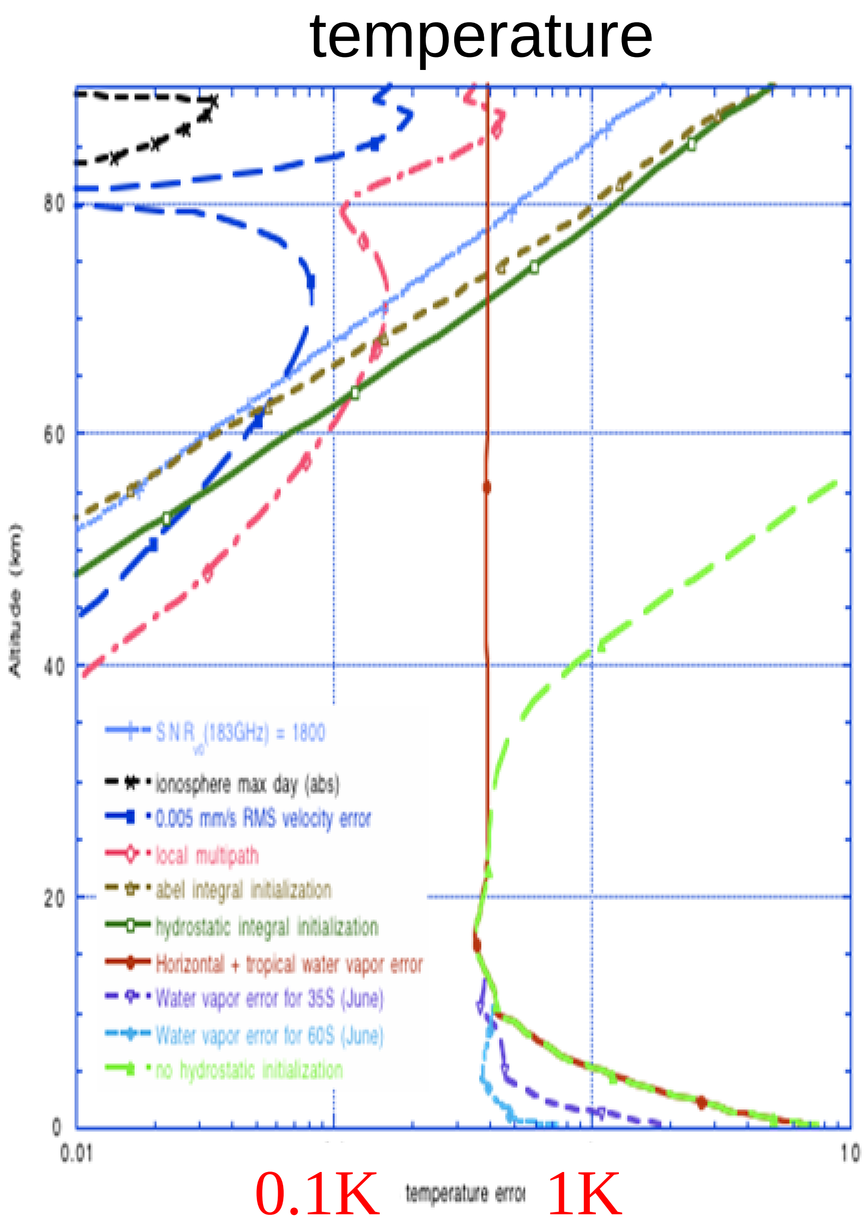
Lineshape Sensitivity to Pressure

- Solid line: same ATOMMS data as in previous figure.
- Dotted line: AM-5.2 spectra ratio for e_{max}-e_{min} = 2.5 mb for 929 mb
  - 8.1 mb (0.9%) higher than the actual pressure.



Precision of Individual ATOMMS Profiles





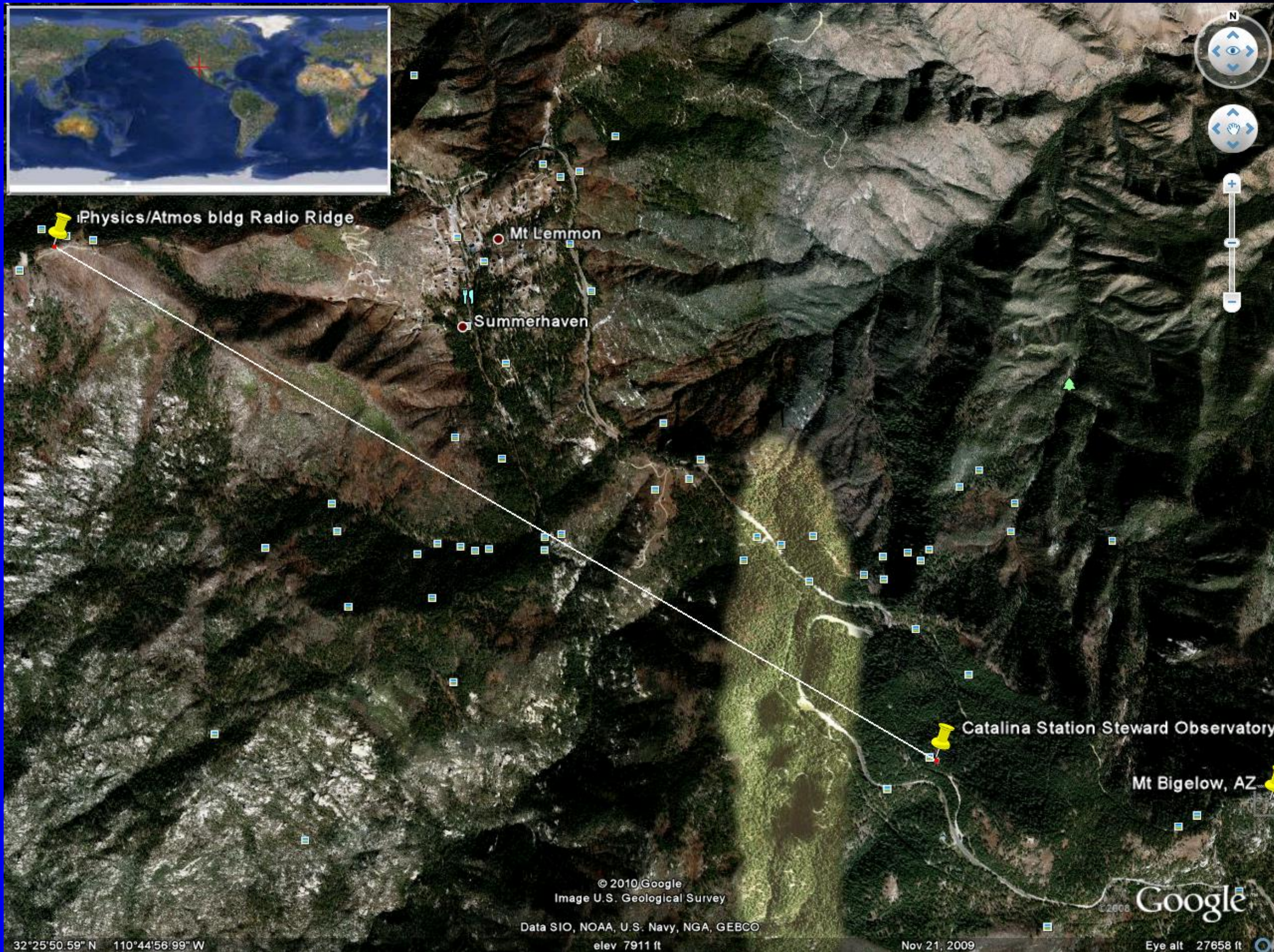
Mountaintop Tests

- Test while PWV is high over SE AZ (our monsoon)
- Geometry: Mt Lemmon to Mt. Bigelow 1 hr N of Tucson

5.4 km separation

Lemmon: 2753 msl

Bigelow: 2504 msl



Mountain Sites

Mt Lemmon

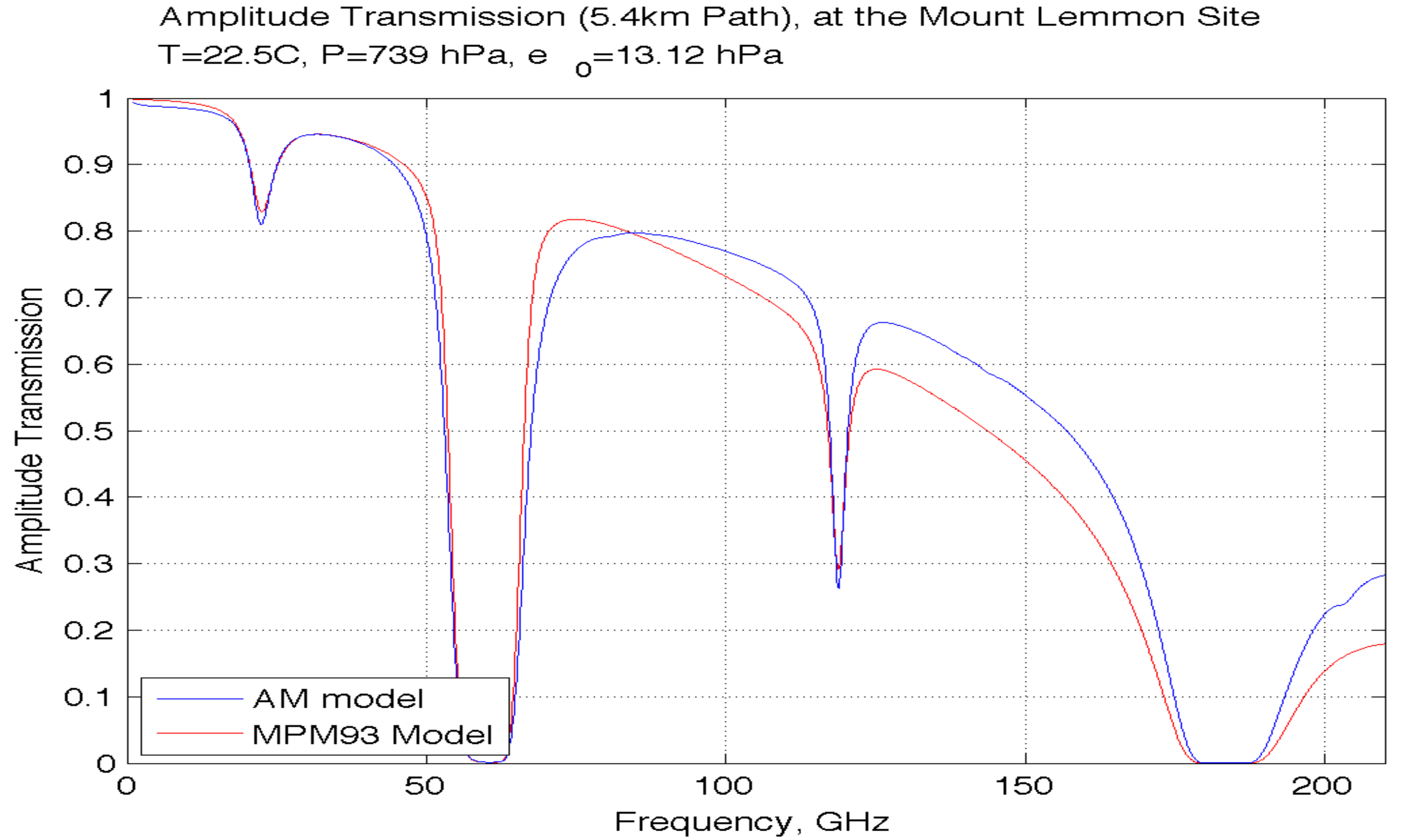
Mt Bigelow

View of Lemmon from Bigelow

September 10, 2009

Expected Spectrum

- Enough to measure at 22.
- 183 opaque at line center
- Note differences between MPM93 and AM6.2

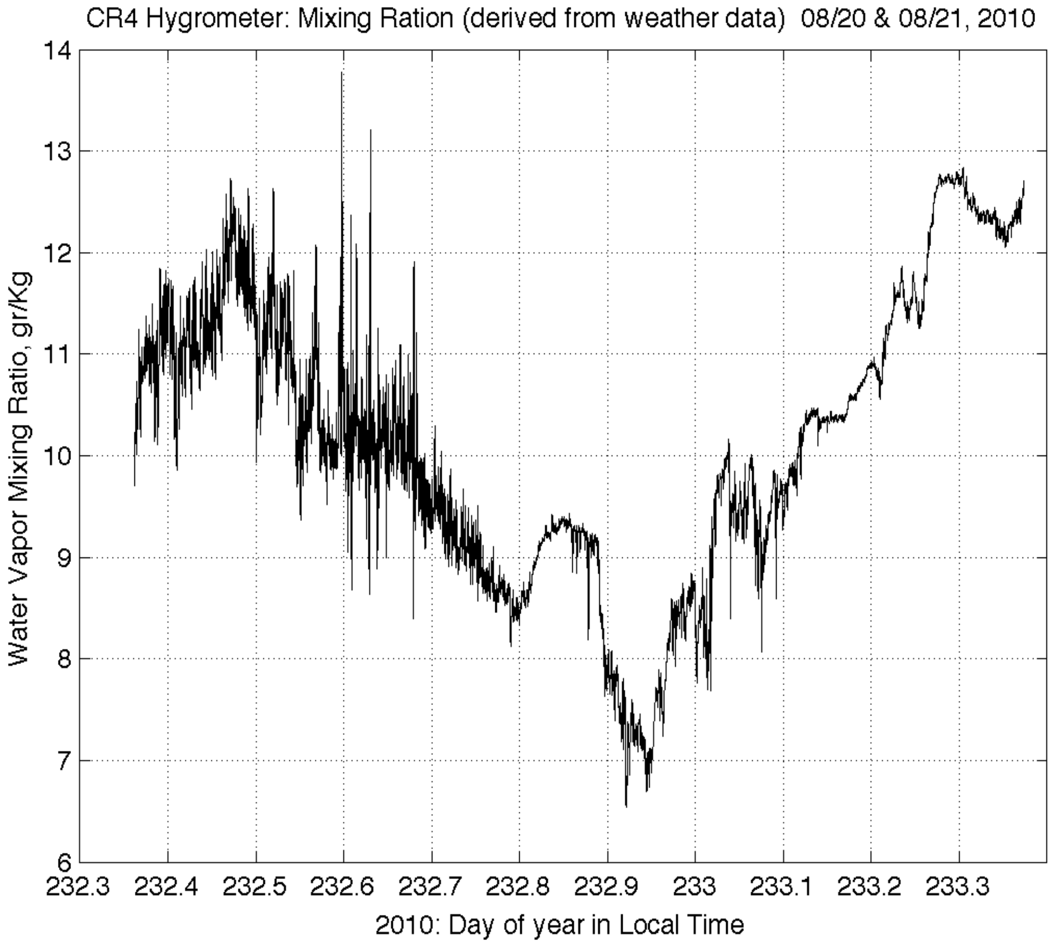


BIGELOW

LEMMON

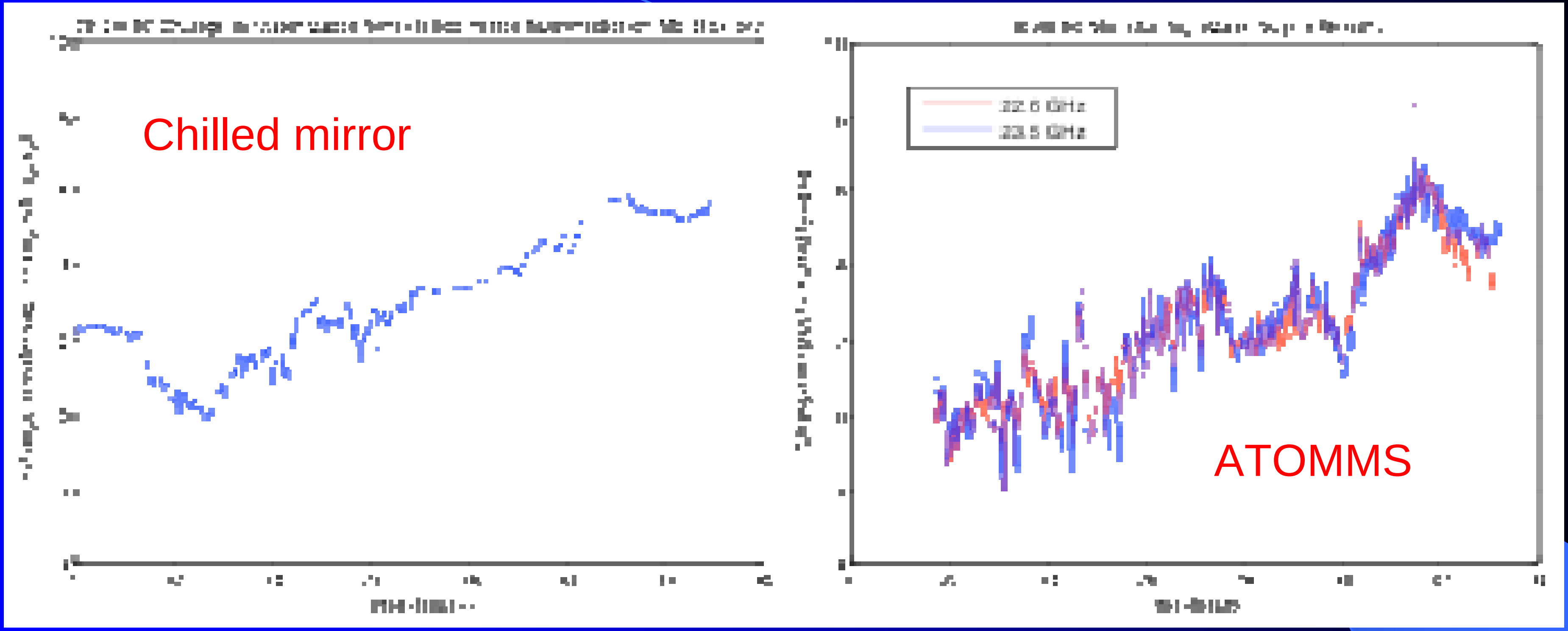
First Test: August 19 & 20

- Almost factor of 2 change in water vapor over 24 hours
- Measured by chilled mirror hygrometer at Mt. Bigelow



- 6 of 8 channels near 22 GHz worked
- 183 GHz system did not work due to synthesizer controller malfunction

Measured Change in Water Vapor

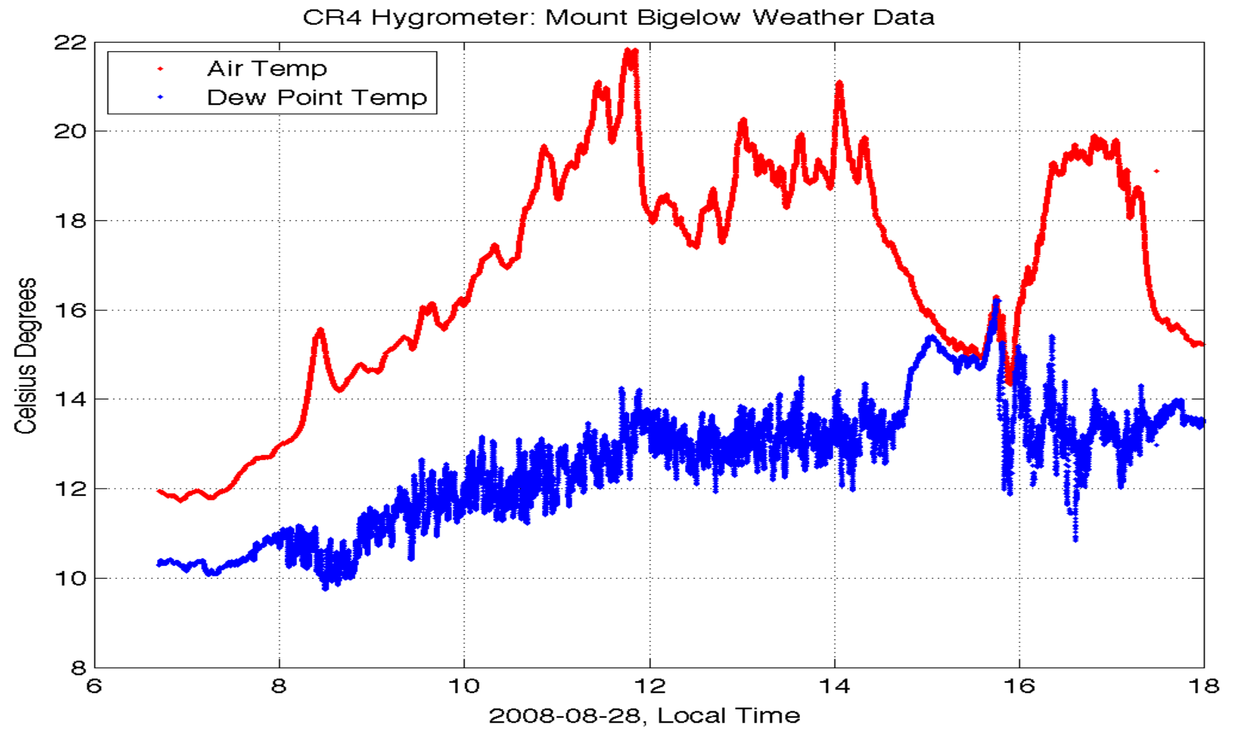


- Chilled mirror & ATOMMS observe similar increase of about 6 g/kg over 9 hours (9:40 pm Aug. 19, to 9:30 am Aug. 20).
- Agreement between two ATOMMS channels
  - Detailed differences between chilled mirror point meas. on Mt. Bigelow and ATOMMS meas. along 5.4 km path between Lemmon & Bigelow are real
  - Not dominated by measurement error.

2nd mountain test August 28, 2010

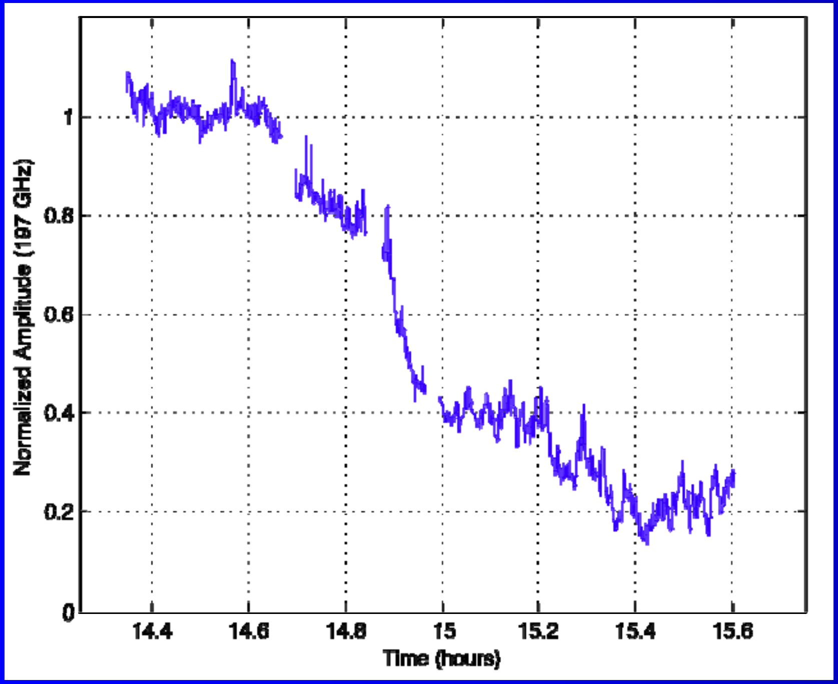
- 7 of 8 channels worked near 22 GHz
- Both 183 GHz channels worked
- Acquired data from noon to 5:30 PM
- Storm passed thru 3 to 3:45 PM

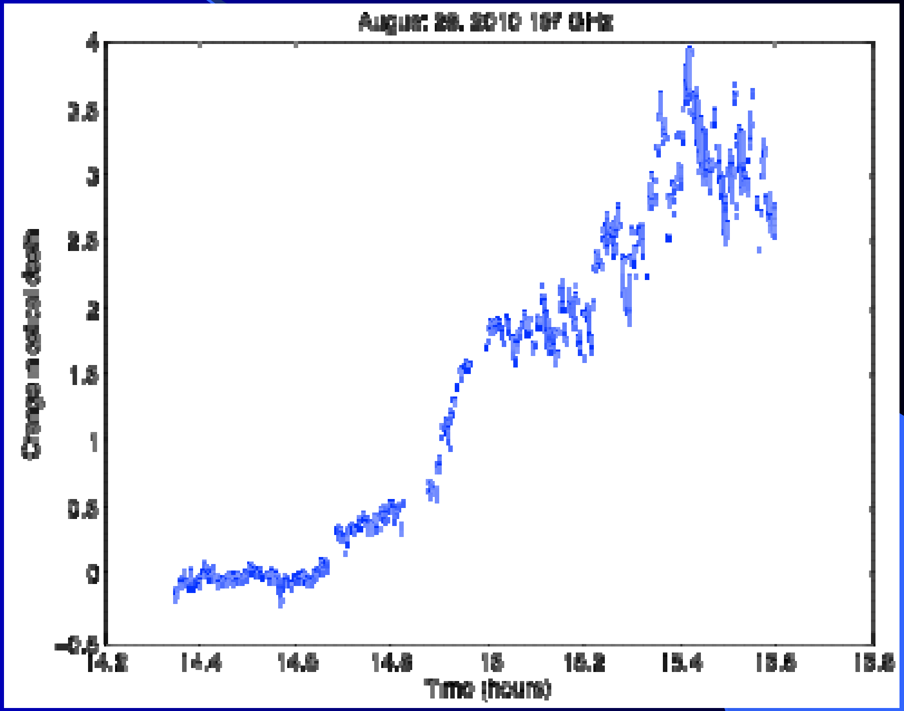
Chilled mirror temperature & dew point



Changes in Optical Depth at 197 GHz

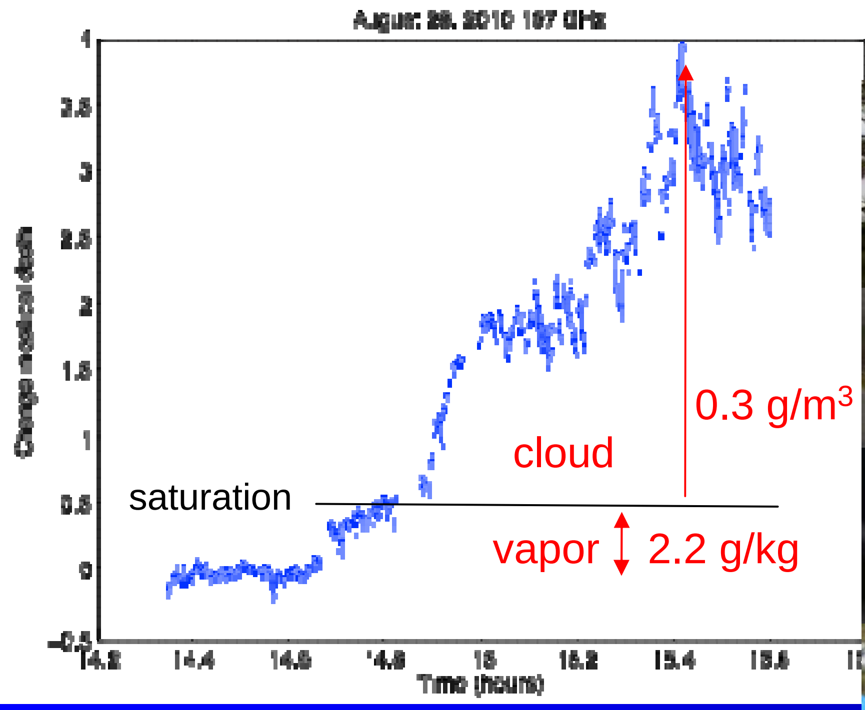
- Changes in normalized signal level and optical depth as storm passed through





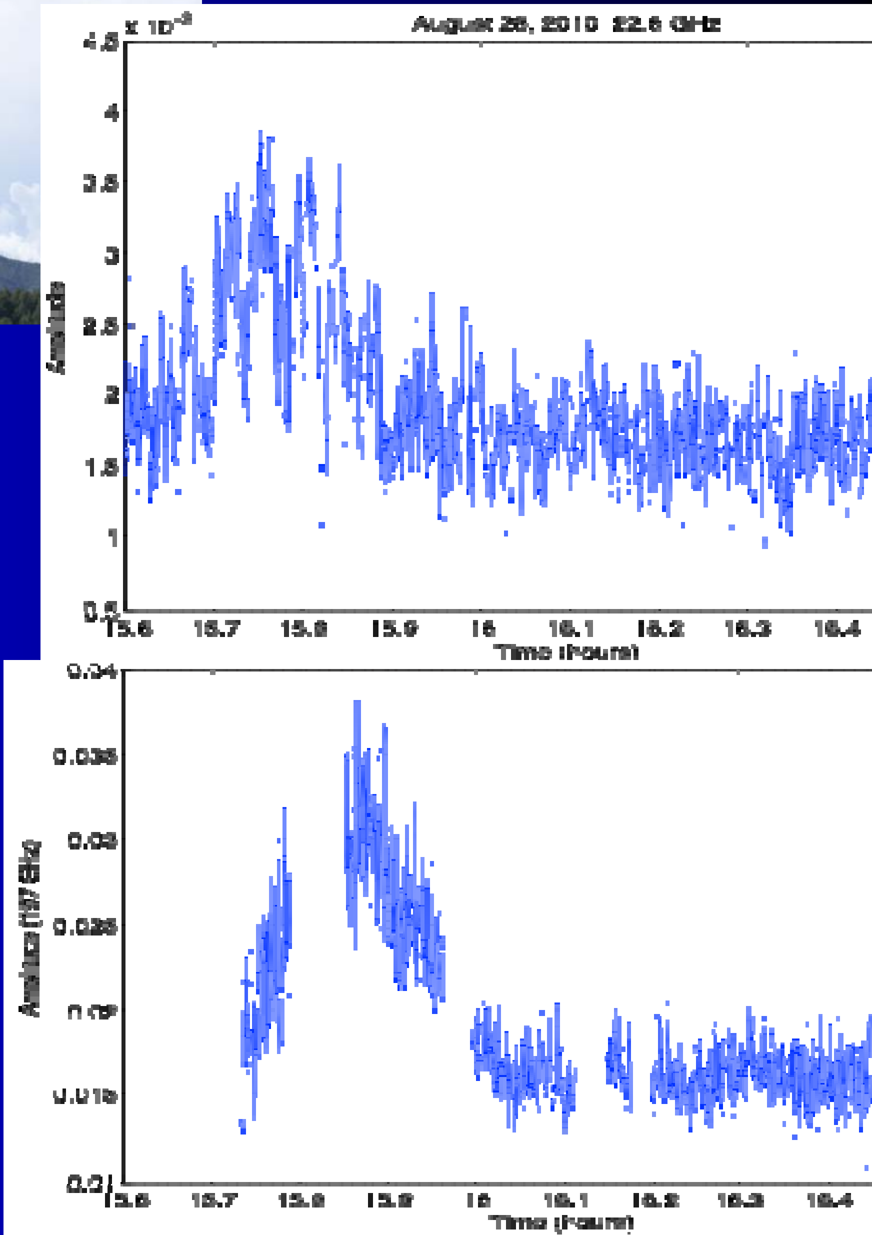
Changes in visible & 200 GHz optical depth during storm

- WV Increase to saturation
- Followed by Increase in cloud extent and LWC



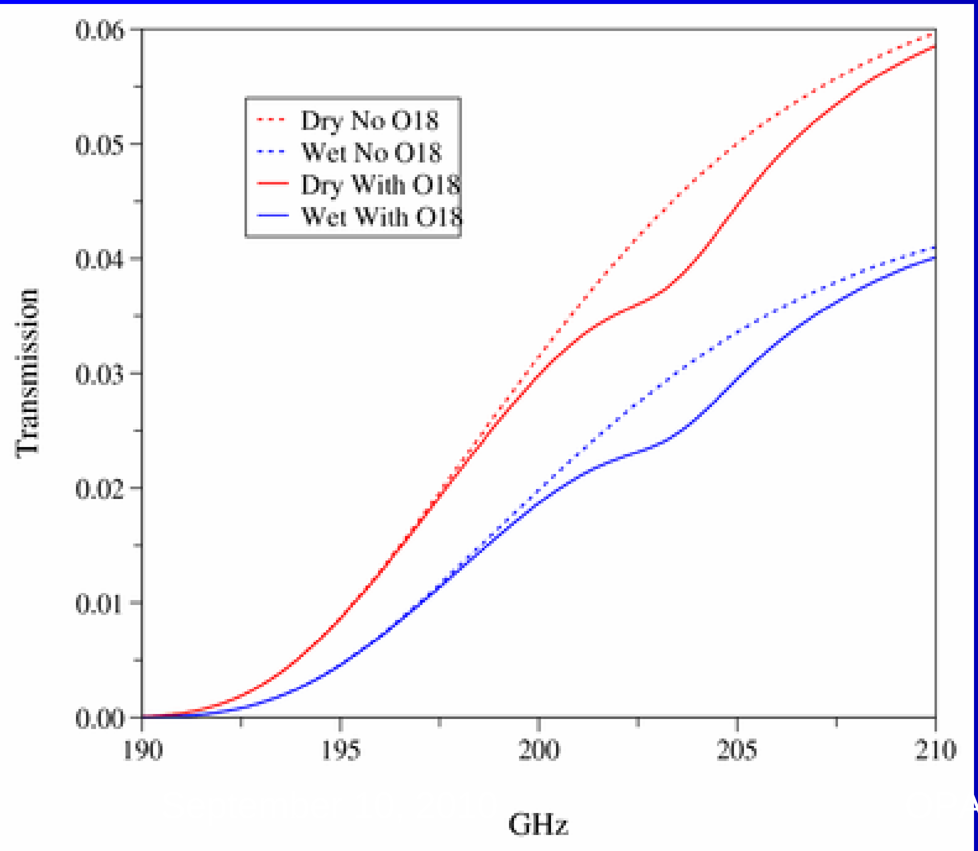
Post Storm

- Storm cleared out at 15:45, followed by …
- Unexpected increase in signal levels
- 22 went up first, followed by 197, then 22 went down, followed by 197
- Forward scattering off enhanced turbulence as it decays and cascades to smaller scales?



Isotope Detection ?

- ATOMMS is designed to profile $H_2^{18}O$ at 203.4 GHz in upper troposphere
- Mountains offer first opportunity to detect it via ATOMMS
- May be seeing it?
- Need fast tuning & more moisture contrast to really see it



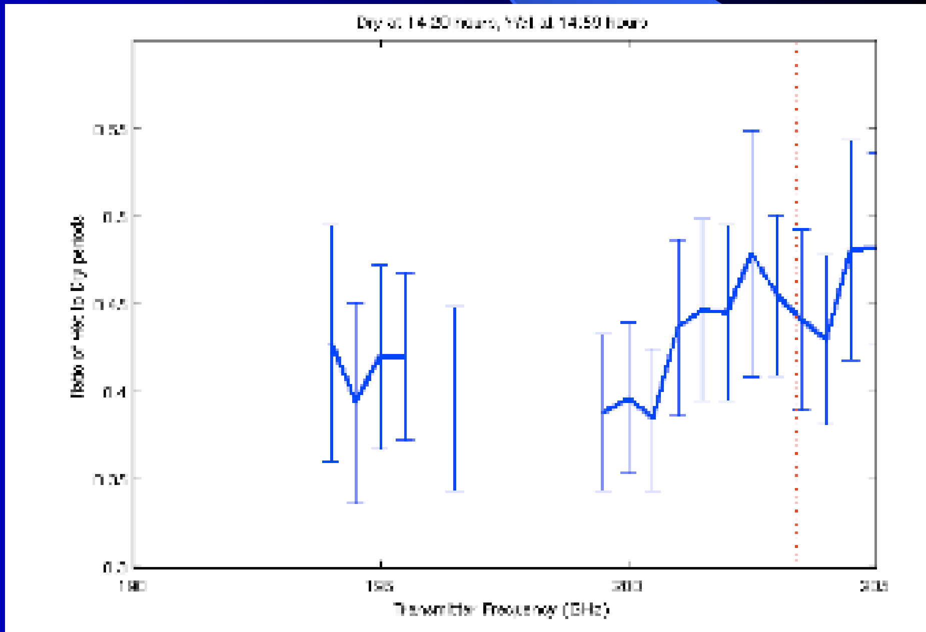


Illustration 4: Ratio of two selected tunes with error bars.