The Active Temperature, Ozone, and Moisture Microwave Spectrometer (ATOMMS)
A LEO-LEO Occultation Observing System

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Outline

- **Science drivers & observational needs**
- Absorption Retrieval Theory Overview
- Accuracy of retrievals
- Aircraft-aircraft occultation Demonstration

Why do we another satellite remote sensing system?

- Last year, we received $1.6 M funding from NSF to build and demonstrate a new atmospheric remote sensing system that will eventually fly in space if all goes well
- Here's why

Rationale: Water, Ozone & Temperature Related Climate Issues

- H_2O & O_3 are extremely important greenhouse gases
- H_2O vapor is directly coupled to clouds and precipitation, two other very important & uncertain climate variables
- The future concentrations and feedbacks of these water variables are uncertain
- Fundamental questions exist on basic behavior and trends of H_2O & O_3 particularly in upper troposphere/lower stratosphere (UTLS)
  - Solar variability & Earth climate may be connected through ozone

Science Issues in UTLS

UTLS is VERY important regime for climate

- Water vapor and ozone are very important radiatively in this regime
- Fundamental questions exist on basic behavior and trends of water and ozone in this regime
- Our ability to measure vertically resolved water vapor in the upper troposphere under all sky conditions has been close to nil.
- Existing observational techniques have very different types of uncertainties, errors and resolutions.
  - *Comparisons have not agreed very well.*

Temperature Uncertainties

- Is the upper troposphere warming faster than the lower troposphere and the surface as climate models predict?
- Where is the transition between tropospheric warming and stratospheric cooling and how does it vary with location?
- How are lapse rates adjusting to the changes in vertical heating and dynamical feedbacks?

Upper Troposphere (UT)

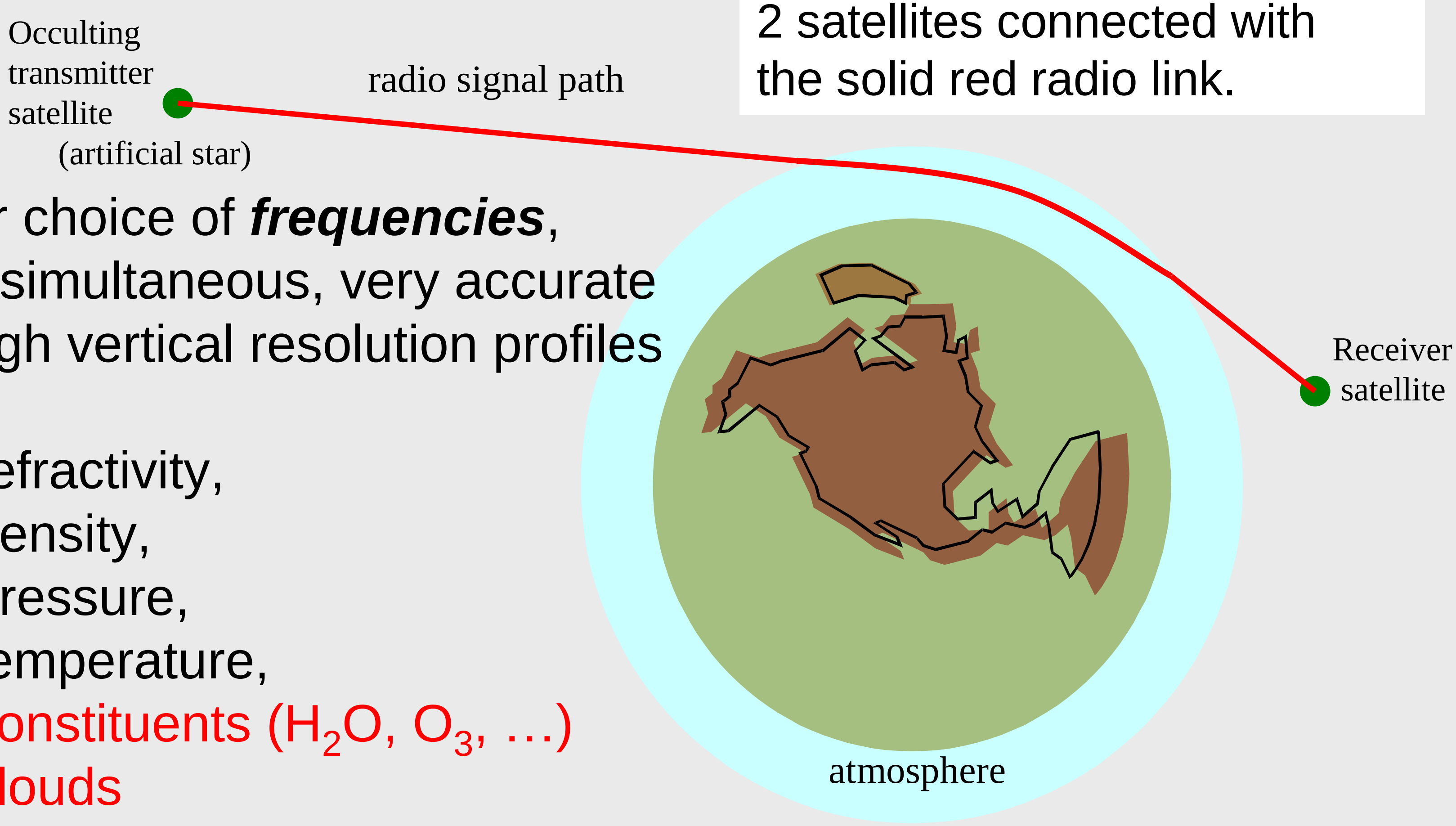
- UT is critical for climate because temperature changes in this region will produce very large changes in the outgoing long wave radiation that cools the Earth.
- Temperature changes in this region are indicative of model realism in transporting added heat from additional greenhouse gases from the surface up to the upper troposphere.
  - Are model simulations of surface-free troposphere coupling realistic?
- A primary feedback is water vapor above 500 mb.
- Climate models *may* produce more water vapor in the upper troposphere in response to increased greenhouse gas concentrations and warming at the surface than reality.
- *Don’t know whether or not this is true* because the water vapor and temperature observations in the UT are not good enough.

Observational Needs

- Global 4D coverage (at least statistically),
- All-weather sensing,
- Seasonal and diurnal coverage,
- High spatial resolution
- Sufficient sampling density
- High precision and absolute accuracy without biases & drifts,
- Independence from assumptions and models

Geometry of the Active Microwave Occultation

An occultation occurs between 2 satellites connected with the solid red radio link.



Proper choice of ***frequencies***, yields simultaneous, very accurate and high vertical resolution profiles of

- refractivity,
- density,
- pressure,
- temperature,
- constituents (H_2O, O_3, …)
- clouds
- winds

vs. height

What can we achieve if we optimize a RO system by designing it from scratch

- Select the occultation frequencies (& use unmodulated tones) to measure absorption of interesting constituents:
  - H_2O absorption to break wet-dry ambiguity of (real part of) refractivity
    - *Simultaneously* profile H_2O, T & P vs. altitude
  - Profile other constituents like O_3 via absorption
- Extend profiles to much higher altitudes
  - by reducing ionospheric sensitivity of GPSRO using much higher frequencies
- Eliminate need for external boundary condition for hydrostatic integral and use/weighting of middle atmosphere climatology:
  - directly measure high altitude temperature via Doppler broadening
- Direct profiling of LoS winds at pressures < 10 mb

What can we achieve if we optimize a RO system by designing it from scratch (cont'd)

- No sensitivity to surface emissivity
  - Avoids nadir sensor problems over land
- Clear and cloudy conditions
  - Accuracy in clouds within factor of 2 of clear
  - Avoids dry bias of other sensors
- (Diffraction-limited) Vertical resolution of ~200 m
  - Reveals new scales of H_2O and stability behavior
- Full diurnal sampling with $\geq$ 12 satellite constellation
  - First vertically-resolved sampling of troposphere in clear & cloudy conditions

What can we achieve if we optimize a RO system by designing it from scratch (cont'd)

- Self calibrating
  - Calibrate against signals measured above atmosphere before or after each occultation and against calibration signals during occultation
- Sufficient information to create over-determined data set:
  - Independent of models avoiding model & climatology-based biases in other retrievals and analyses
    - Critical for assessing climate models
  - Relies on spherical symmetry, knowledge of spectroscopy and refractivity and hydrostatic equations

What can we achieve if we optimize a RO system by designing it from scratch (cont'd)

The result is …

⇒ A cross between GPS RO and Microwave Limb Sounder (MLS)

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

Side benefit:

⇒ Determine/Calibrate GNSS RO ionosphere error

⇒ Anchor data set for NWP bias correction

Long Range Concept

- Constellation of microsatellites for climate and NWP
  - Satisfy (NOAA) climate monitoring needs
  - Provided by NASA, NSF, ESA, eventually NOAA, …

Challenges:

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

Outline

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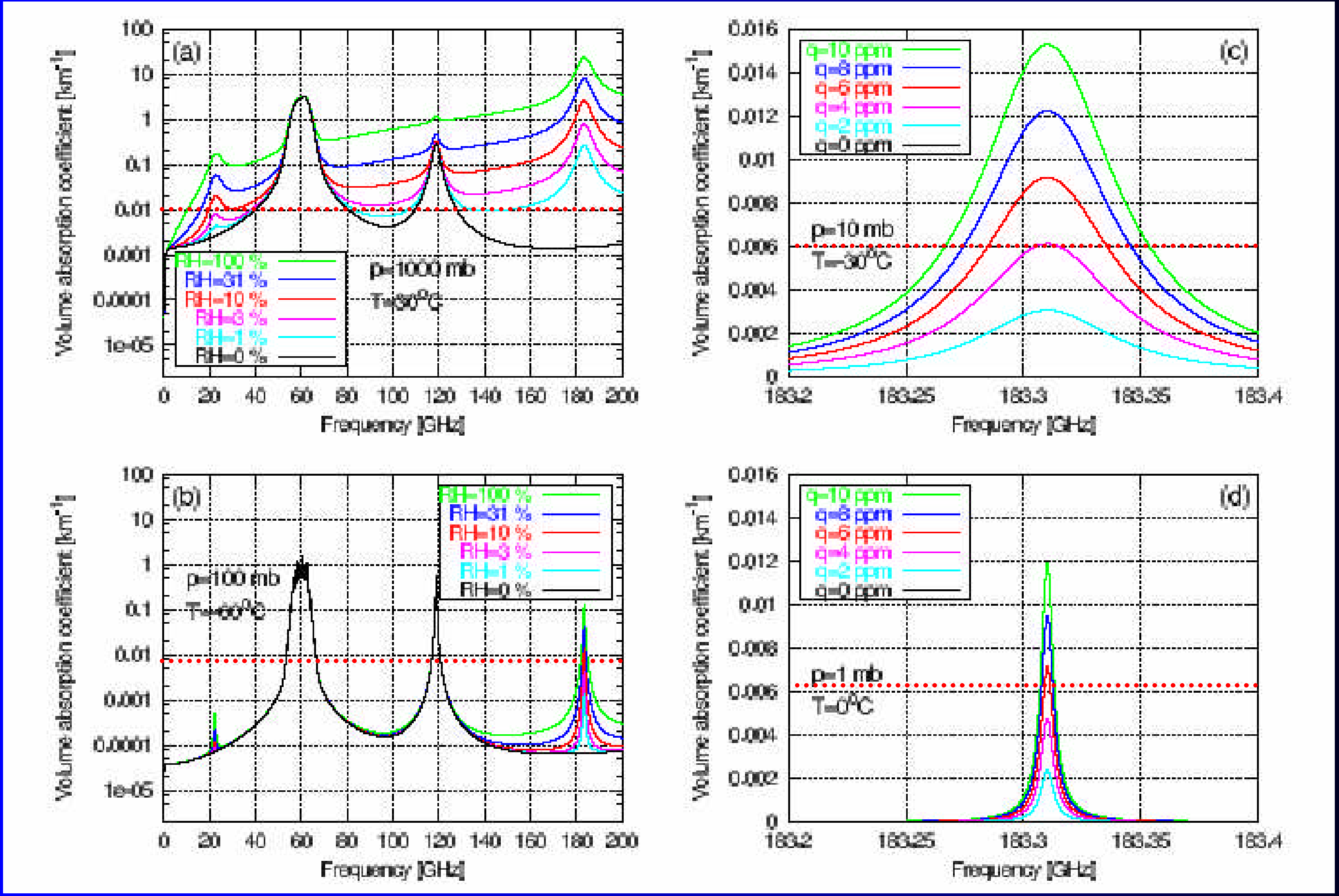
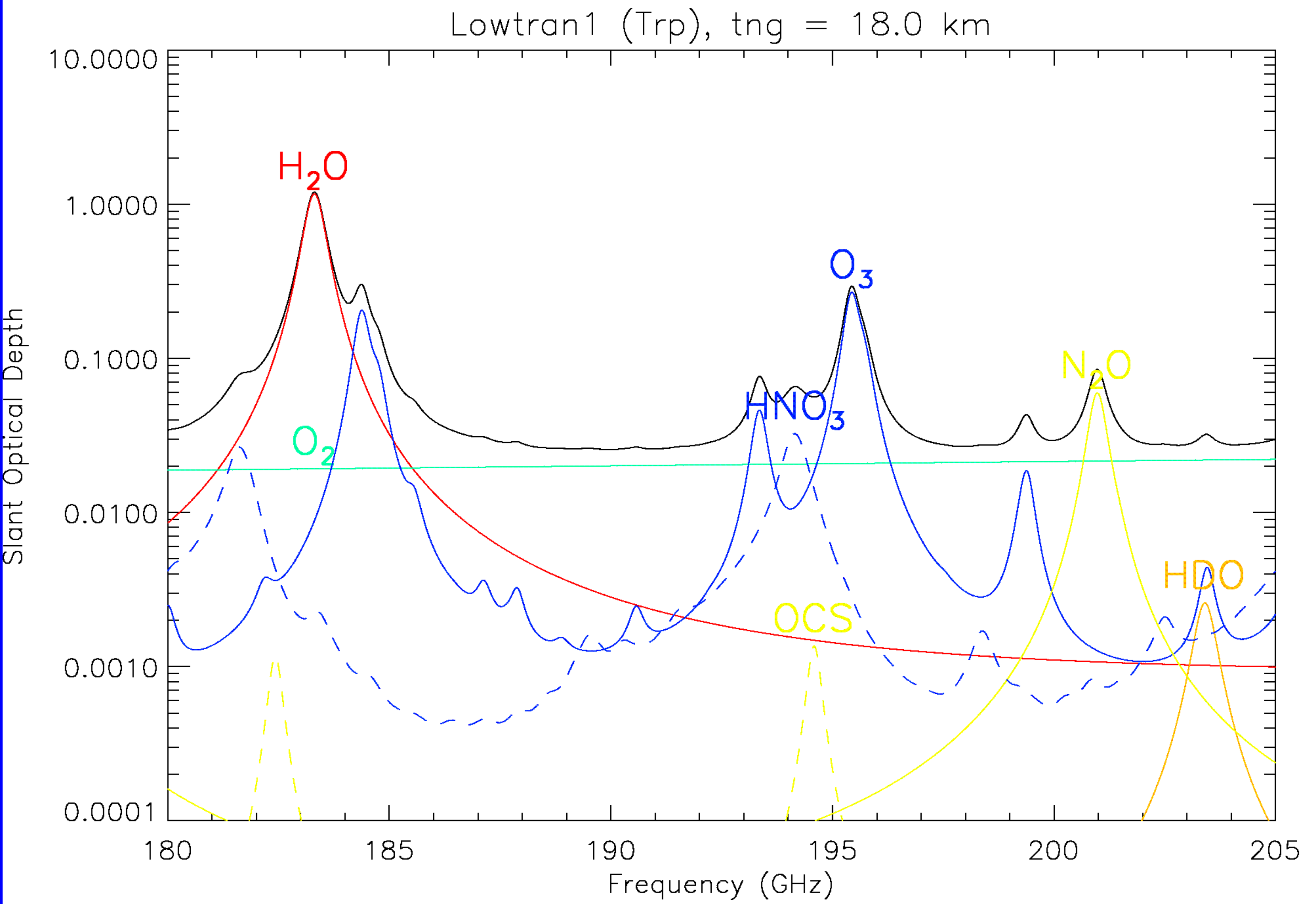
- **Absorption Retrieval Theory Overview**
- Accuracy of retrievals
- Demonstration mission overview

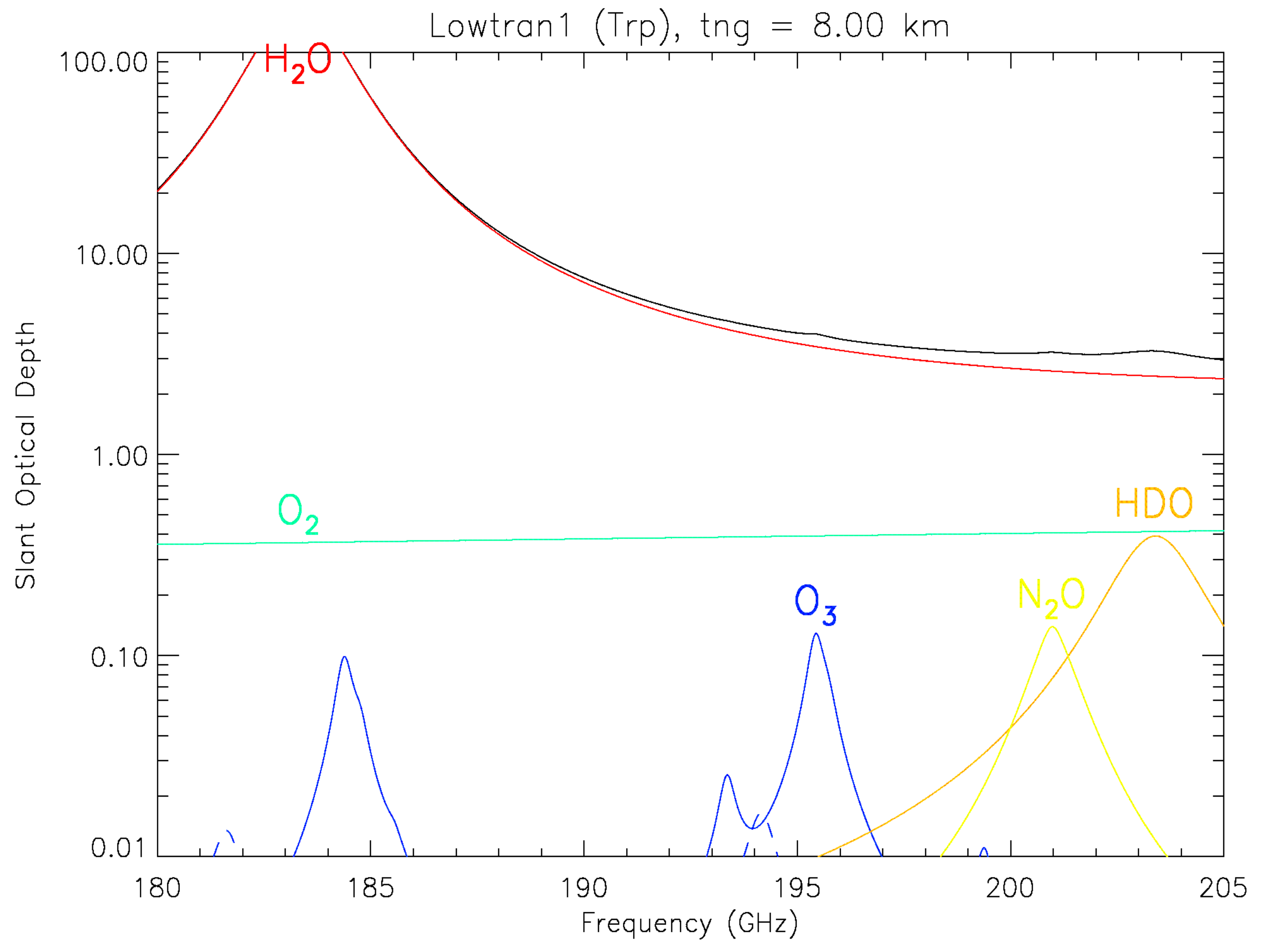
Water and Oxygen Lines Below 200 GHz



ATOMMS Hi-band Spectrum at 18 km



ATOMMS Hi-band Spectrum at 8 km



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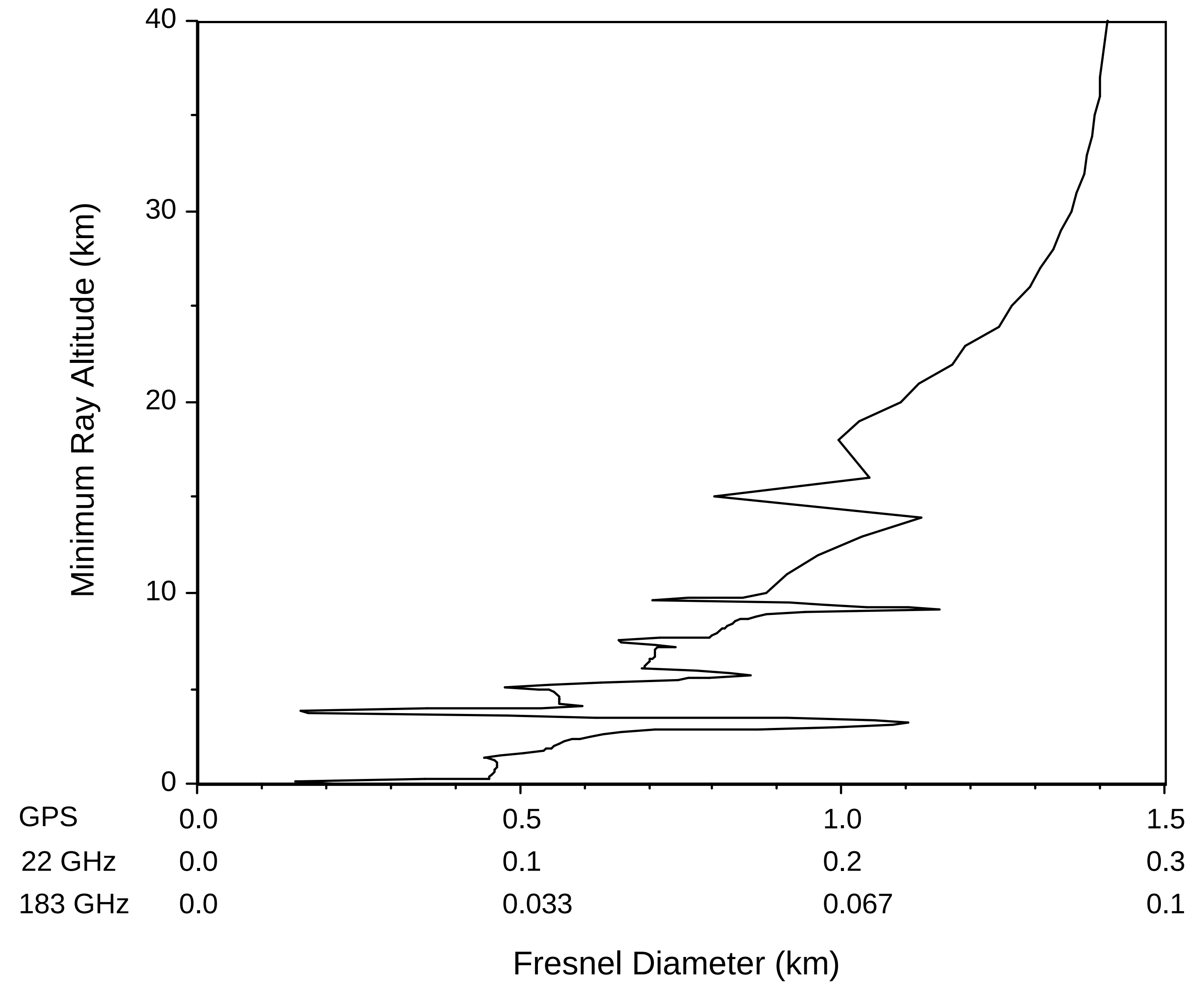
Cross-Link Frequencies

Near and below 200 GHz, there are 2 water vapor absorption lines at 22.23 and 183.31GHz and several strong ozone lines.

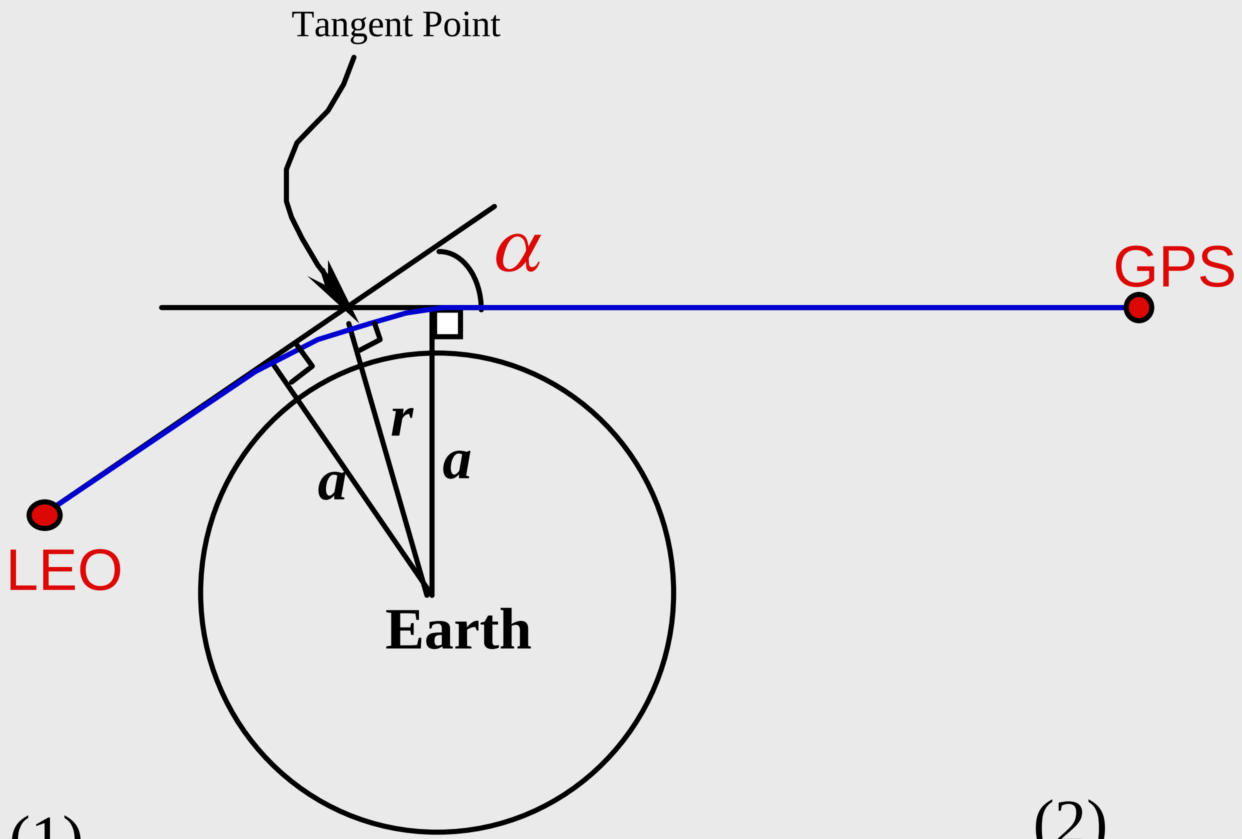
(1) Water vapor	22.23 GHz line (low band)
	183.31 GHz line (high band)
	557 GHz line (higher band)
(2) Ozone	184,4 & 195.43 GHz line (high band)
(3) $H_2^{18}O$	203 GHz line
(4) O_2	118 GHz line

(For determining T at high altitude for hydrostatic initialization)

Diffraction-Limited Vertical Resolution vs. Frequency



Retrieval Overview: Deriving the Real Part of *n*



(1)

$$\alpha(a) = 2a \int_{r_t}^{\infty} \frac{1}{\sqrt{r^2 n^2 - a^2}} \frac{d\ln(n)}{dr} dr$$

$\Leftrightarrow$

(2)

$$n(r) = \exp\left[\frac{1}{\pi} \int_{a_1}^{\infty} \frac{\alpha}{\sqrt{a^2 - a_1^2}} da \right]$$

Retrieval Overview: Deriving Extinction Coefficient Profiles

- Signal intensity is reduced by absorption along the signal path as

$$\mathrm{d}I = -I\ k\ \mathrm{d}l$$

where *k* is the volume absorption coefficient.

- For each wavelength, the observed intensity, *I*, equals the vacuum intensity (signal intensity with no atmosphere), I_0, times $e^{-\tau}$ where τ is the optical depth.

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

- The measured optical depth is along the signal path whereas we want a ***radial*** profile of the extinction coefficient
- The simplest solution is an abel integral transform pair for opacity and extinction coefficient: **(Note: *x = nr*)**

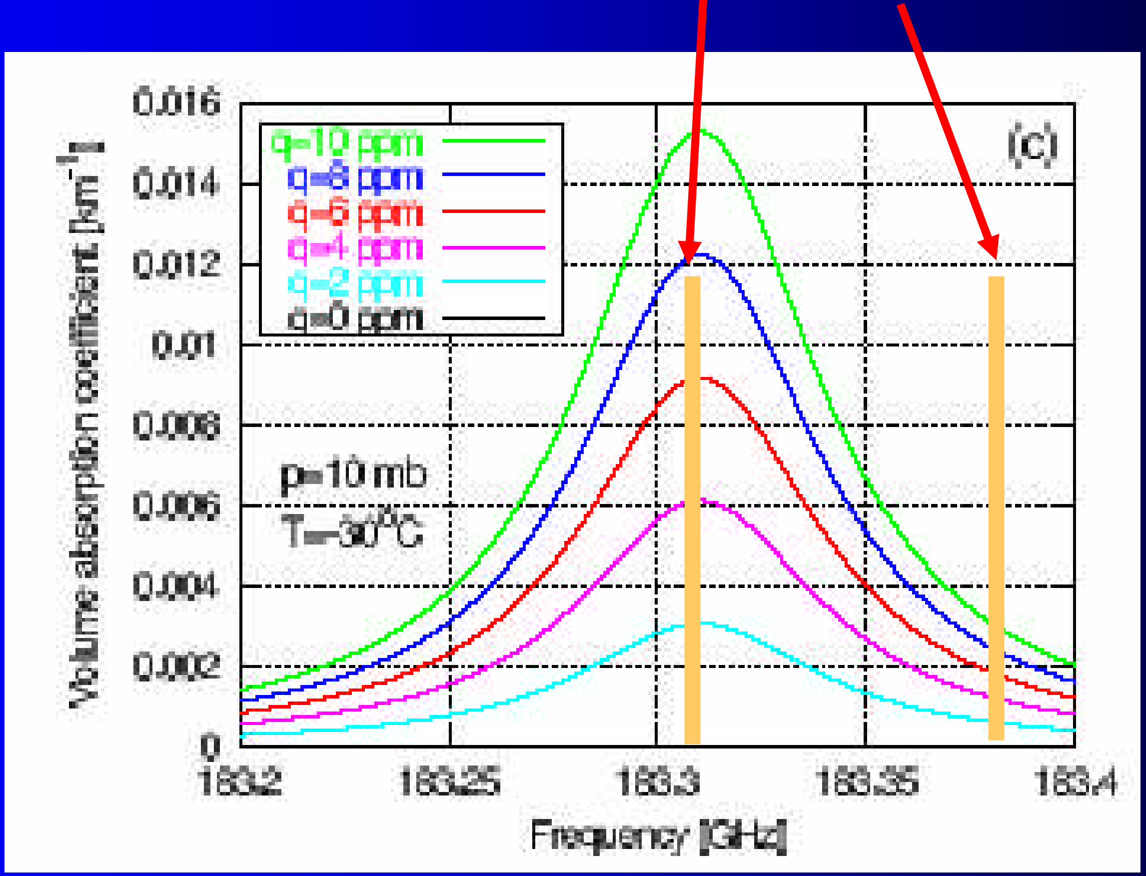
$$\tau(a) = \int k\ dl = 2\int_{x=a}^{x=\infty} k \frac{x \, {}^{dr}\!/_{dx} \, dx}{\sqrt{x^2 - a^2}} \tag{3}$$

$$\Leftrightarrow$$

$$k = -\frac{1}{\pi}\frac{da}{dr}\bigg|_{a=a_0} \int_{a=a_0}^{a=\infty} \frac{d\tau}{da}\frac{da}{\left(a^2 - a_0^2\right)^{1/2}} \tag{4}$$

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



Deriving Water Vapor, Temperature and Pressure

(Clear Sky)

Water vapor retrievals:

Using frequency ***pairs*** (frequencies #1, #2) close to the water vapor absorption lines

$$\text{absorption equation} \quad k_1 - k_2 = F(T,\, P_d,\, P_w)$$

$$\text{refractivity equation} \quad N = 77.6\frac{P_d}{T} + 71.7\frac{P_w}{T} + 3.75\times 10^5\frac{P_w}{T^2}$$

$$\text{hydrostatic equation} \quad \frac{d(P_d + P_w)}{P_d + P_w} = -\frac{g\,dz}{RT}$$

At each altitude, solve these 3 closed, non-linear equations for 3 unknowns, T, P_d, and P_w. (P_d – dry pressure; P_w – water vapor pressure)

Deriving Water Vapor, Temperature, Pressure ***& Clouds***

Lower Troposphere Water vapor retrievals:

Near & below freezing level liquid water clouds are present,

Use the 22 GHz water vapor line and add 3 absorption equations at frequencies #1, #2 and #2, #3, and #3, #4

$$absorption\ equation\ \#1\quad k_1 - k_2 = F_{12}(T, P_d, P_w, L_c, T_c)$$

$$absorption\ equation\ \#2\quad k_2 - k_3 = F_{23}(T, P_d, P_w, L_c, T_c)$$

$$absorption\ equation\ \#3\quad k_3 - k_4 = F_{34}(T, P_d, P_w, L_c, T_c)$$

Solve these 5 closed, non-linear equations (the 3 absorption equations above, the refractivity equation, and the hydrostatic equilibrium equation) for 4 unknowns, T, P_d, P_w, cloud liquid water content, L_c and cloud temperature, T_c

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- **Accuracy of retrievals**
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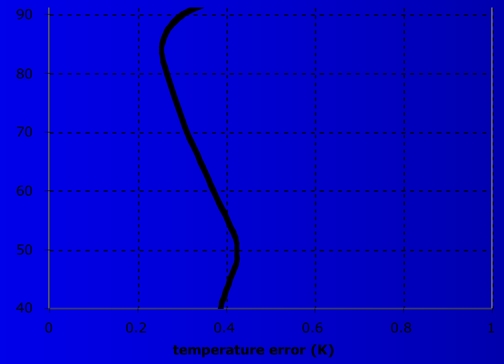
Sources and Mitigation of Error

Instrumental effects:	Finite signal to noise ratio,	Directional antenna
	Antenna gain and pointing,	Calibration tone
	Transmitter power fluctuations,	Monitor/Cal. tone
	Receiver gain fluctuations,	Cal. tone
	Local multipath	Directional antenna
Atmospheric effects:	Molecular oxygen absorption	Est. from T & P
	Defocusing	Cal.tone/Diff Corr
	Diffrac./M.P. from layering	Cal.tone/Diff Corr
	Scintillations from turbulence	**Cal.tone/Diff Corr**
	Liquid water clouds	**Spect. Separation**
Retrieval errors:	**Hydrostatic boundary condition**	**Doppler linewidth**
	Non-spherical distributions	Horiz. average
	Uncertainty in line parameters	Spectr. cal. in space

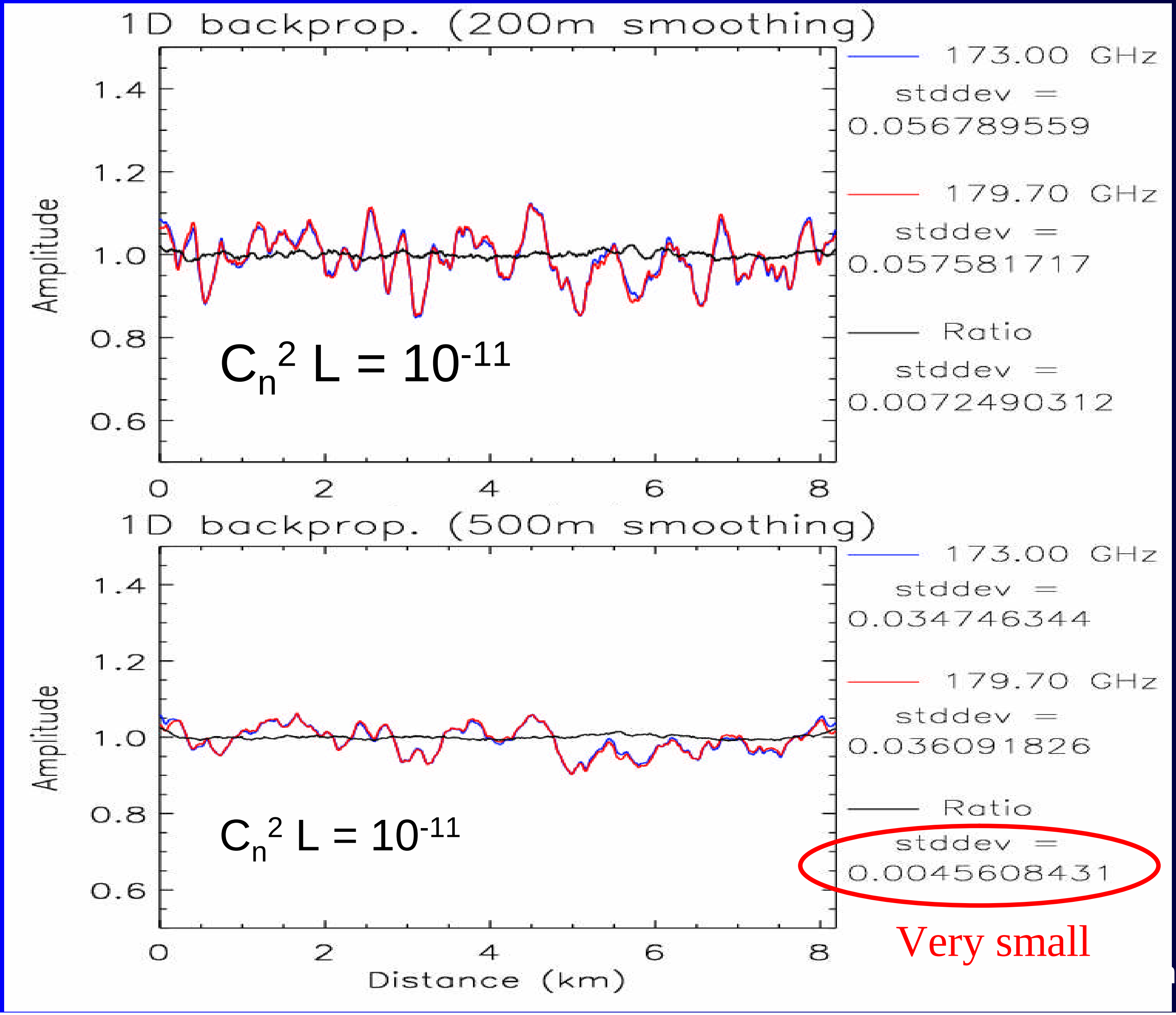
Hydrostatic initialization

- High frequencies much less sensitive to ionosphere so profiles extend to much higher altitudes than GPS
- At high altitudes, Doppler linewidth provides direct measure of temperature
- Combining temperature with refractivity (proportional to density) yields the needed hydrostatic constrain directly from observations



Turbulence Scintillation Mitigation near 183 GHz

- Upper troposphere & lower stratosphere



$C_n^2\,L = 10^{-11}$

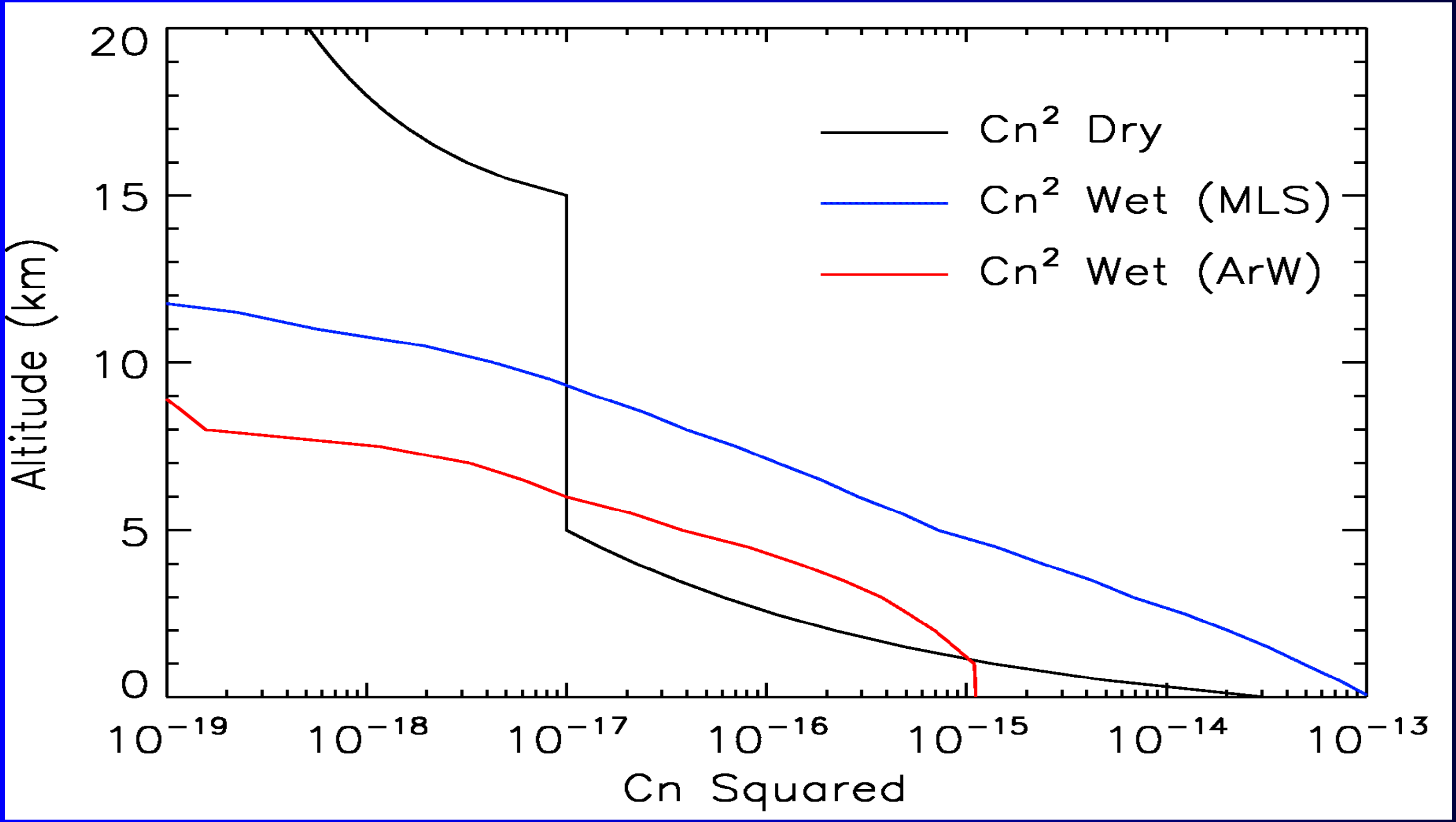
$C_n^2\,L = 10^{-11}$

Very small

Turbulence Impact Assessment

We have developed a nominal parameterization of turbulence intensity: C_n^2

- C_n^2 Dry is from literature and simulations,
- C_n^2 Wet is from A. Otarola thesis research



Reduction of Scintillation Errors via Ratioing

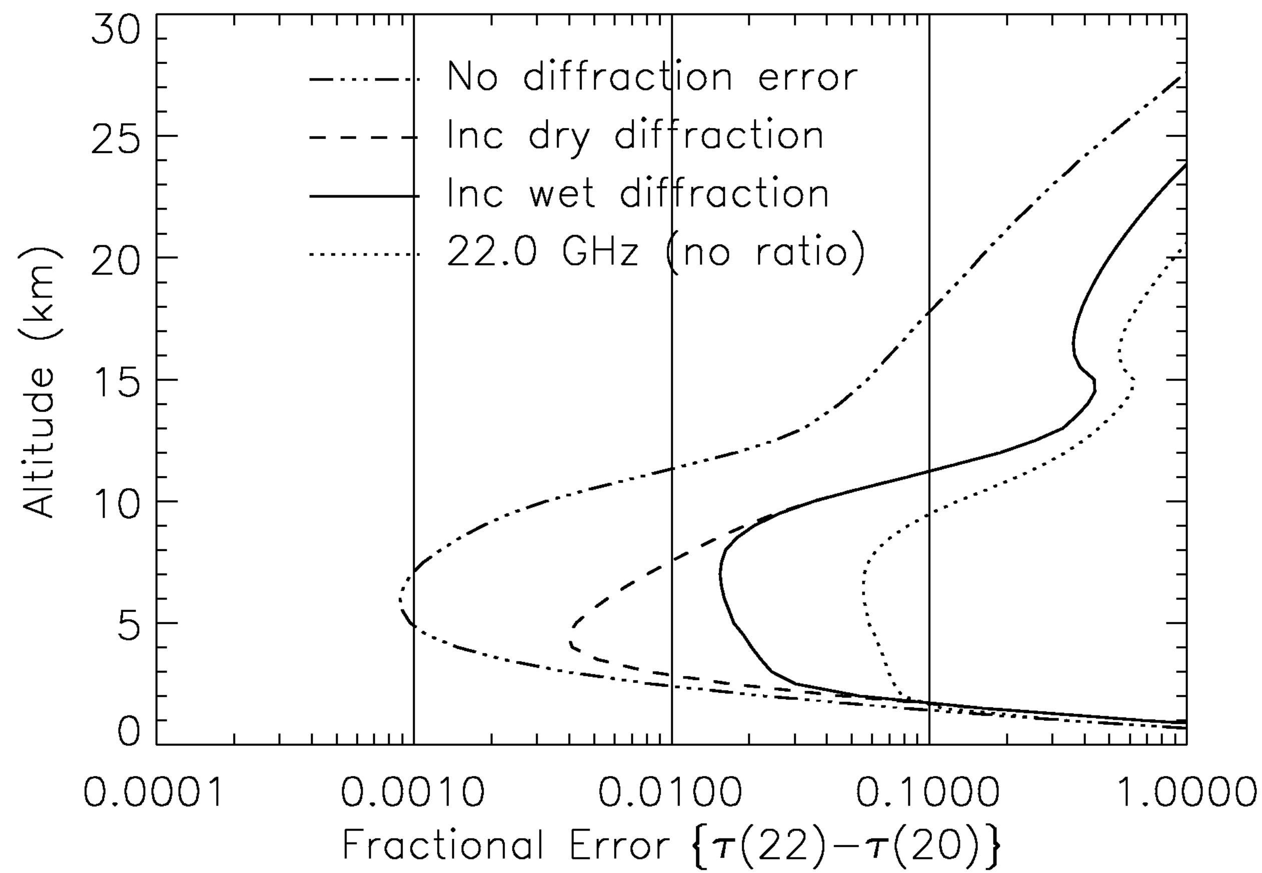
4 errors shown for ratioing 22 and 20 GHz amplitudes:

(1) Finite SNR (no scintillations) after ratioing,

(2) Scintillations due to dry turbulence after ratioing,

(3) Scintillations due to wet & dry turbulence after ratioing,

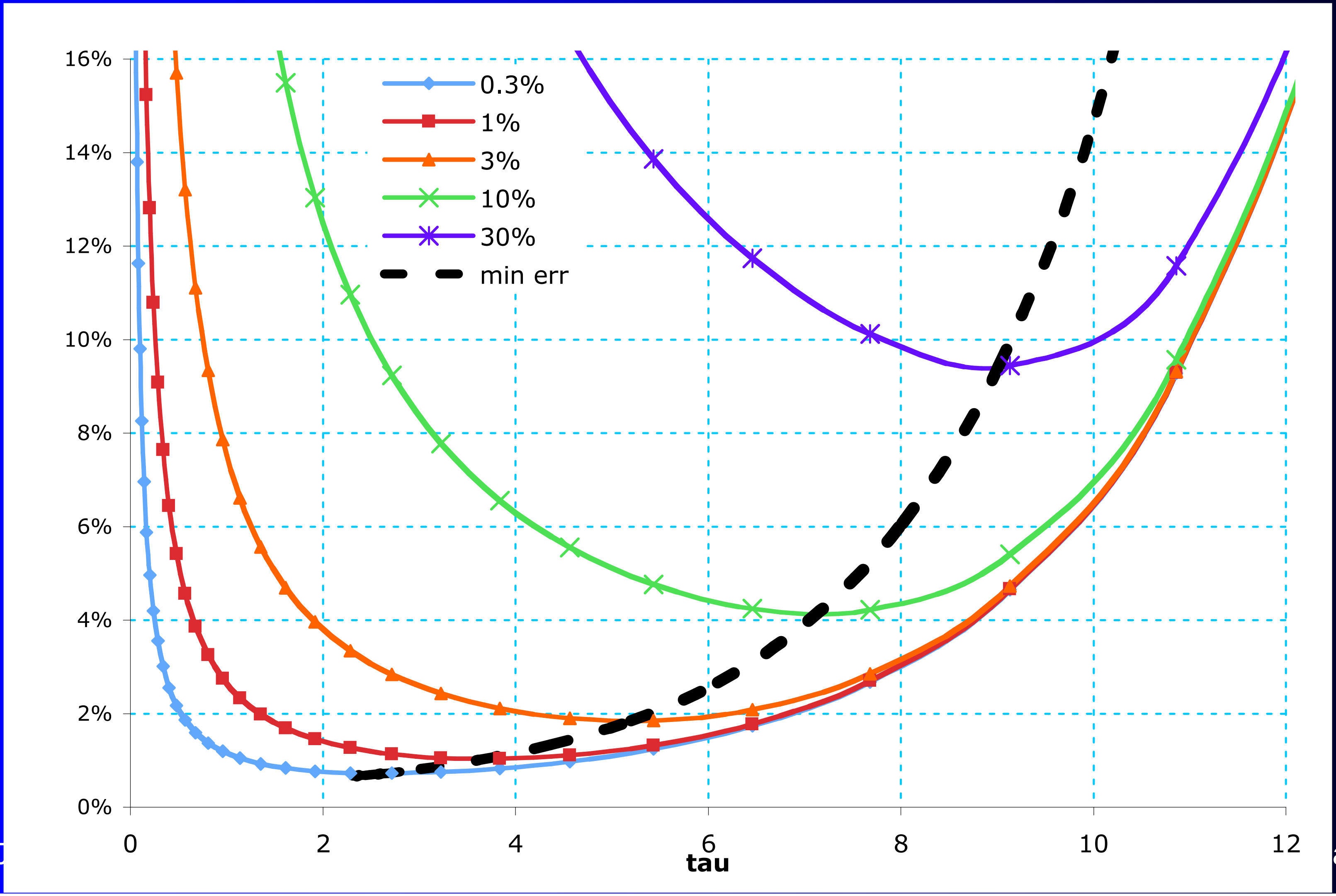
(4) Raw scintillations without ratioing



Notice scintillation error is reduced by about a factor of 4 with ratioing

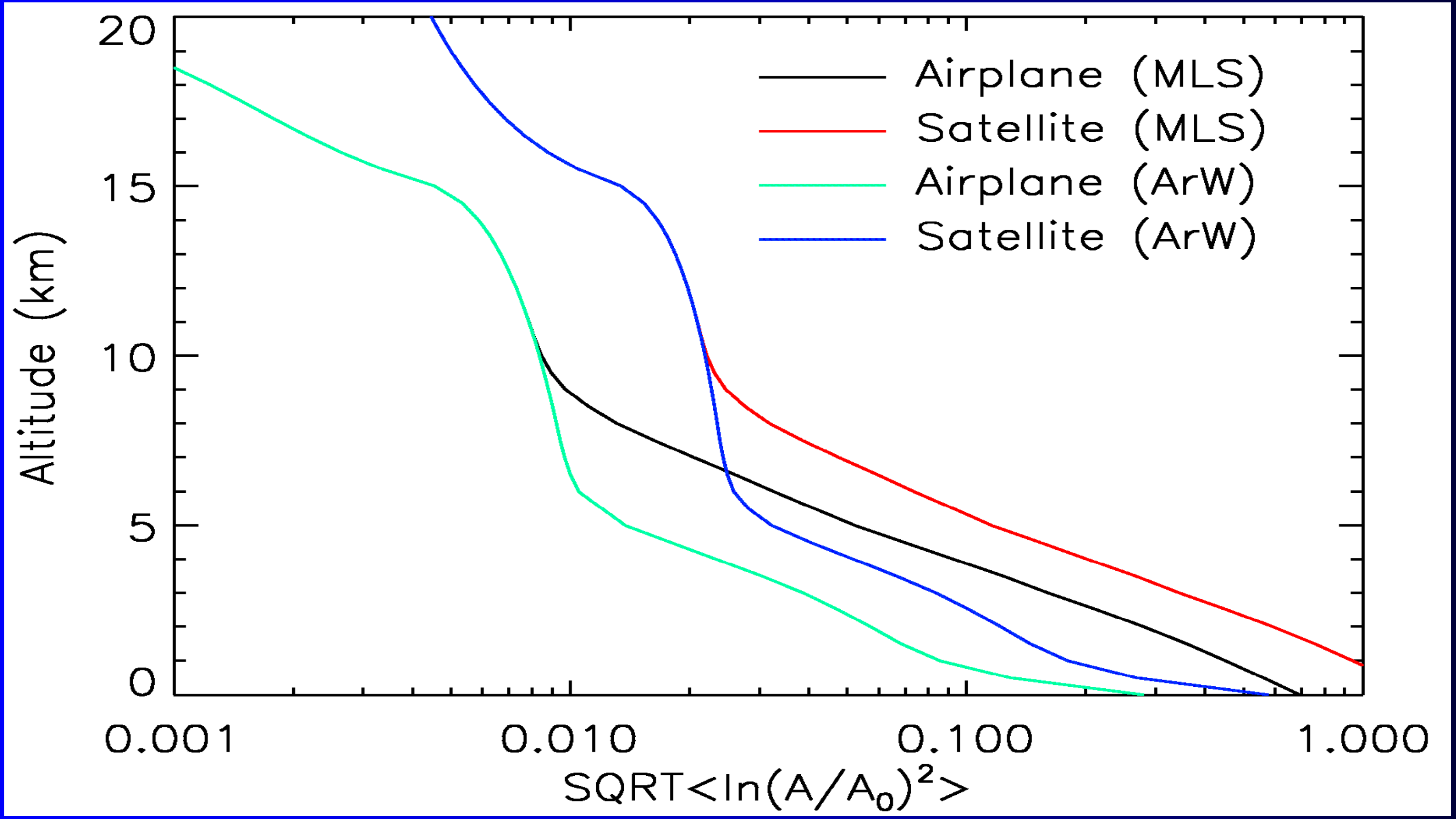
Optimum Optical Depth (tau) vs SNR

- In troposphere, errors dominated largely by turbulence rather SNR
- Optimum performance occurs at higher taus (> 6) than the tau ~ 2-3 estimated by Kursinski et al. 2002



Estimated Amplitude Errors

- Includes SNR and turbulence
- Results similar in magnitude to cases explored by Gorbunov and Kirchengast (2007)



ArW: Arctic winter

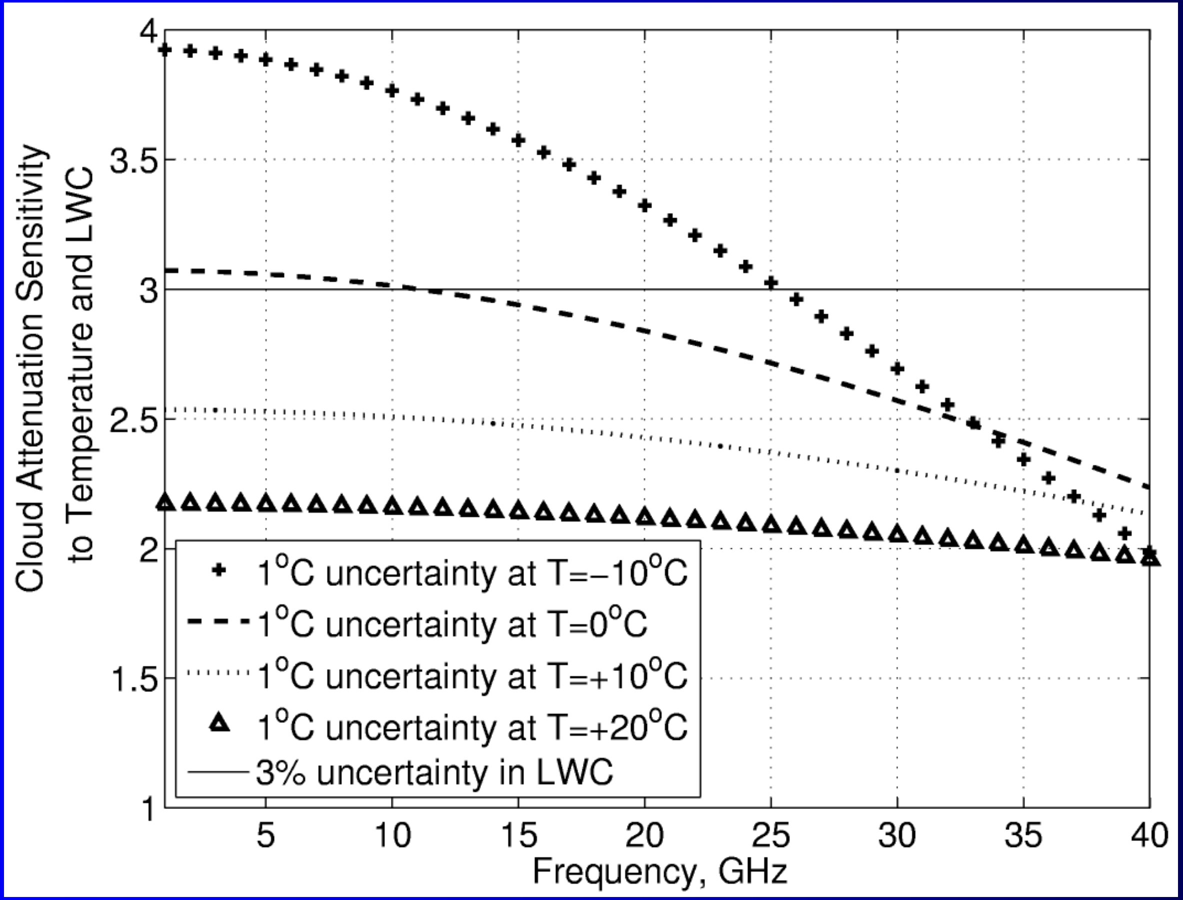
MLS: mid-latitude summer

New Approach for Isolating Inhomogeneous Liquid Water Clouds

- How do we isolate the condensed water attenuation
  - Attenuation due to ice cloud scattering is largely removed by amplitude ratioing ***prior to*** the abel transform
    - Works regardless of cloud's spatial distribution
  - Simple ratioing does not work well for liquid water whose absorption spectrum is more complex than ice
- We have developed an analogous approach for liquid water clouds
  - We sample the near-22 GHz spectrum (*both sides of line*) with $\geq$ 5 tones to separate the liquid and vapor spectra
    - 5 constraints for cal. tone, vapor, liquid amount & *T*, spectroscopy
      - Liquid spectrum depends on liquid water amount & temperature
  - At each altitude, retrieval tries to match measured spectrum with a dry + water vapor spectra *without liquid water spectrum*
  - If residuals are too large, then liquid water spectrum is included

Sensitivity of Liquid Water Spectrum to Temperature

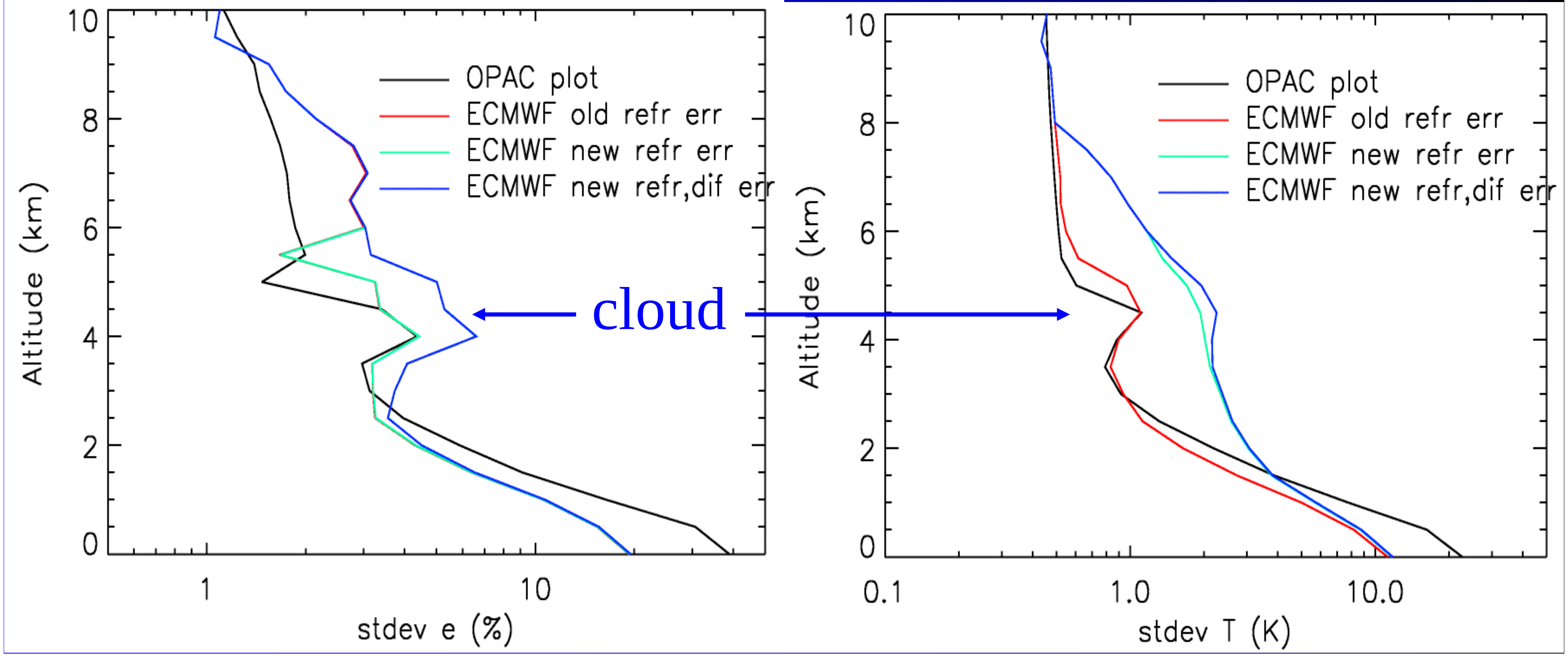
- Compensating for the temperature dependence by adding or deleting liquid water leaves residual water absorption after amplitude ratioing
  - particularly at lower temperatures



- Another problem: *uncertainty in super-cooled spectrum*

Estimated Water Vapor & Temperature Precision: cloudy, mid-lat summer

- Single inhomogeneous cloud layer near 4 km
- Different refractivity errors considered affect temperature accuracies

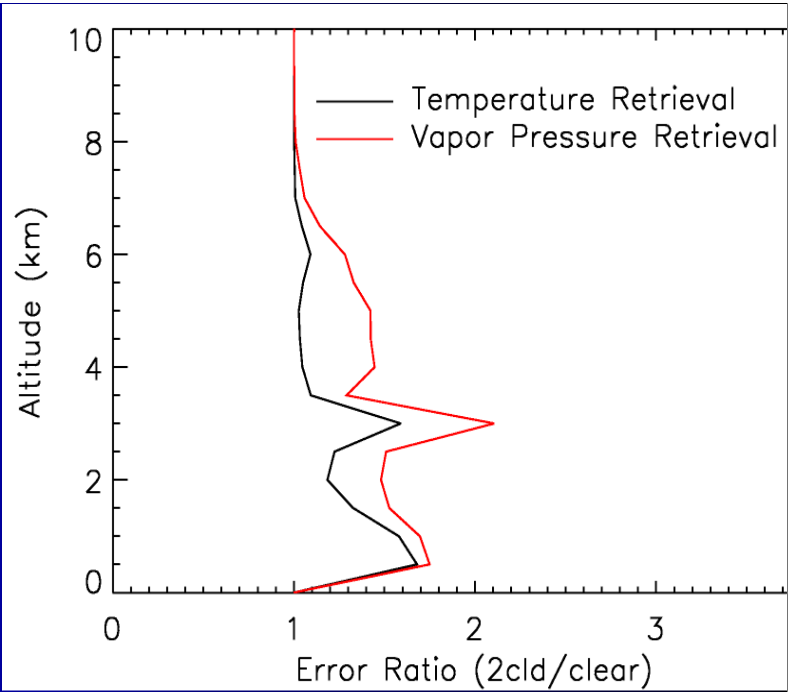


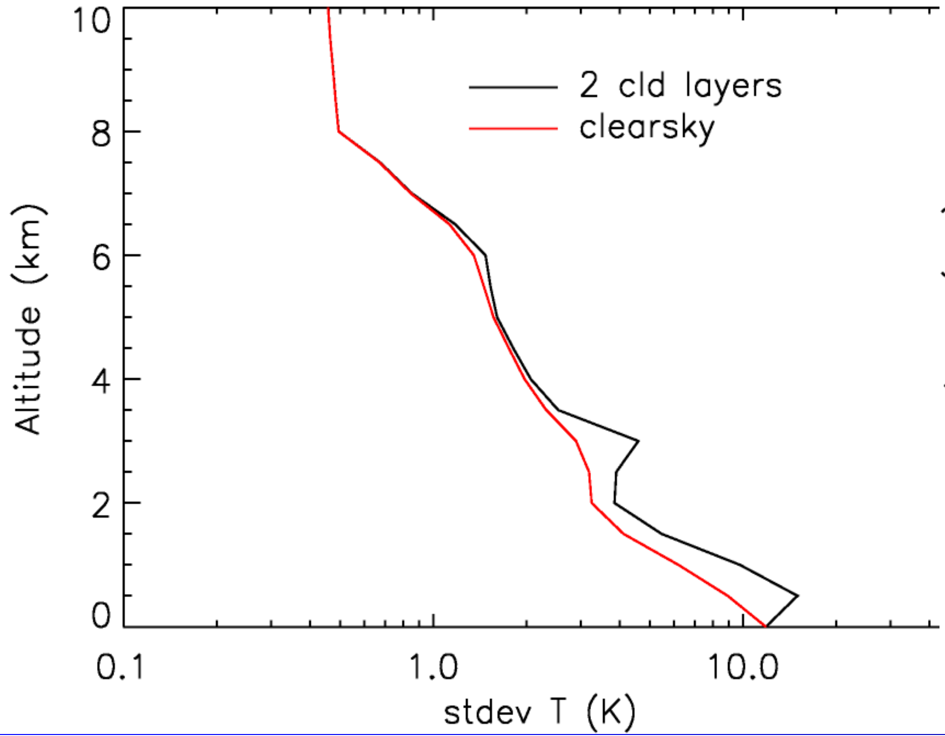
Errors for 2 cloud layers at 2 heights and temperatures

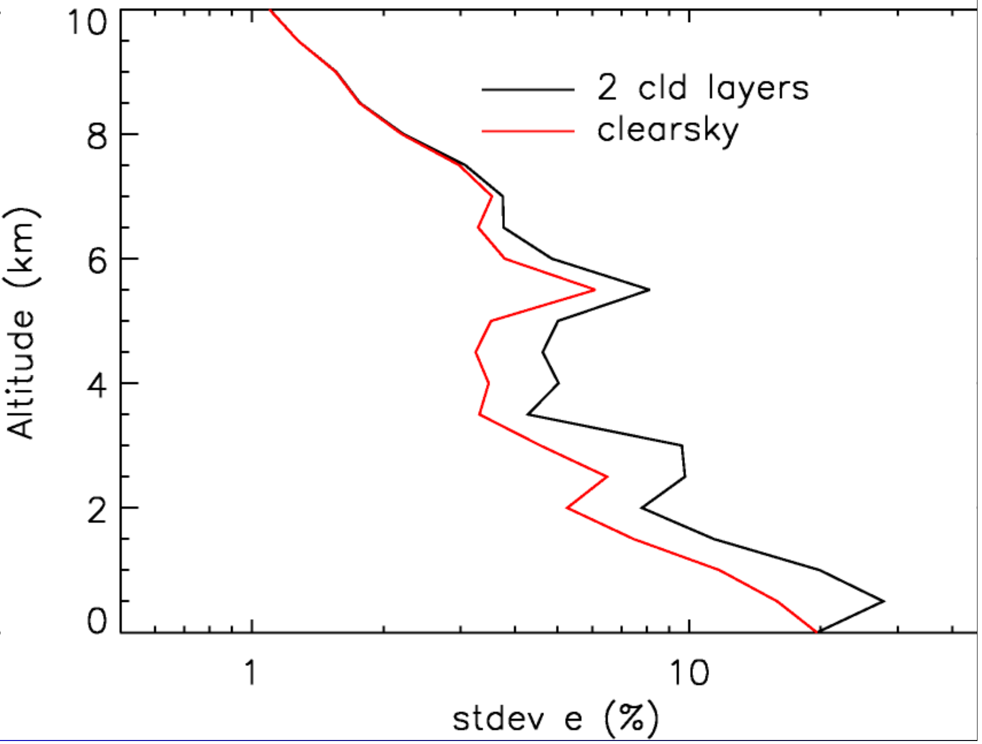
Mid-lat summer

1: lwc 0.2g/m^3, 6-6.5 km, 259.6 K

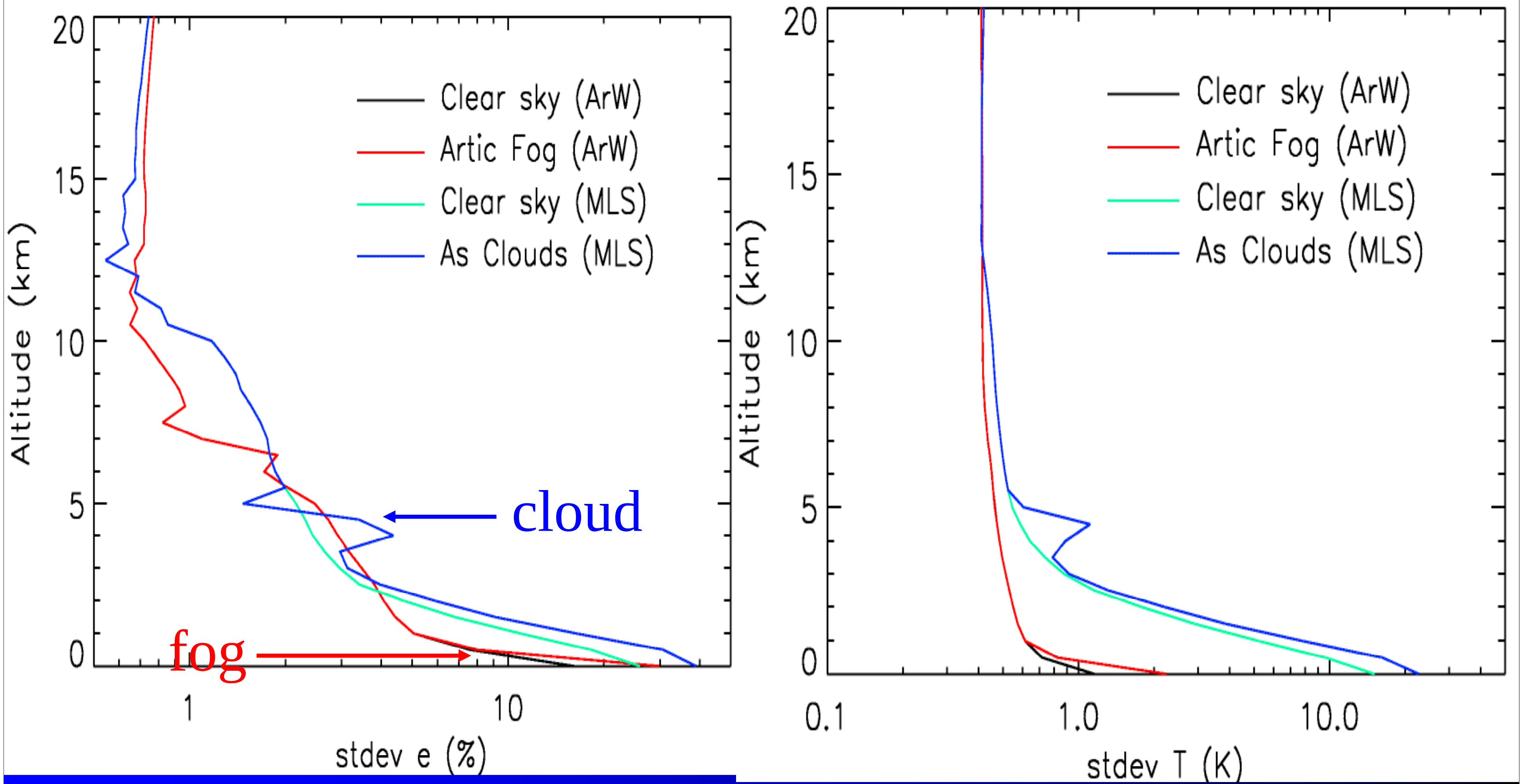
2: lwc 0.3g/m^3, 3-3.5 km, 277.8 K







Estimated Water Vapor & Temperature Precision: clear & cloudy

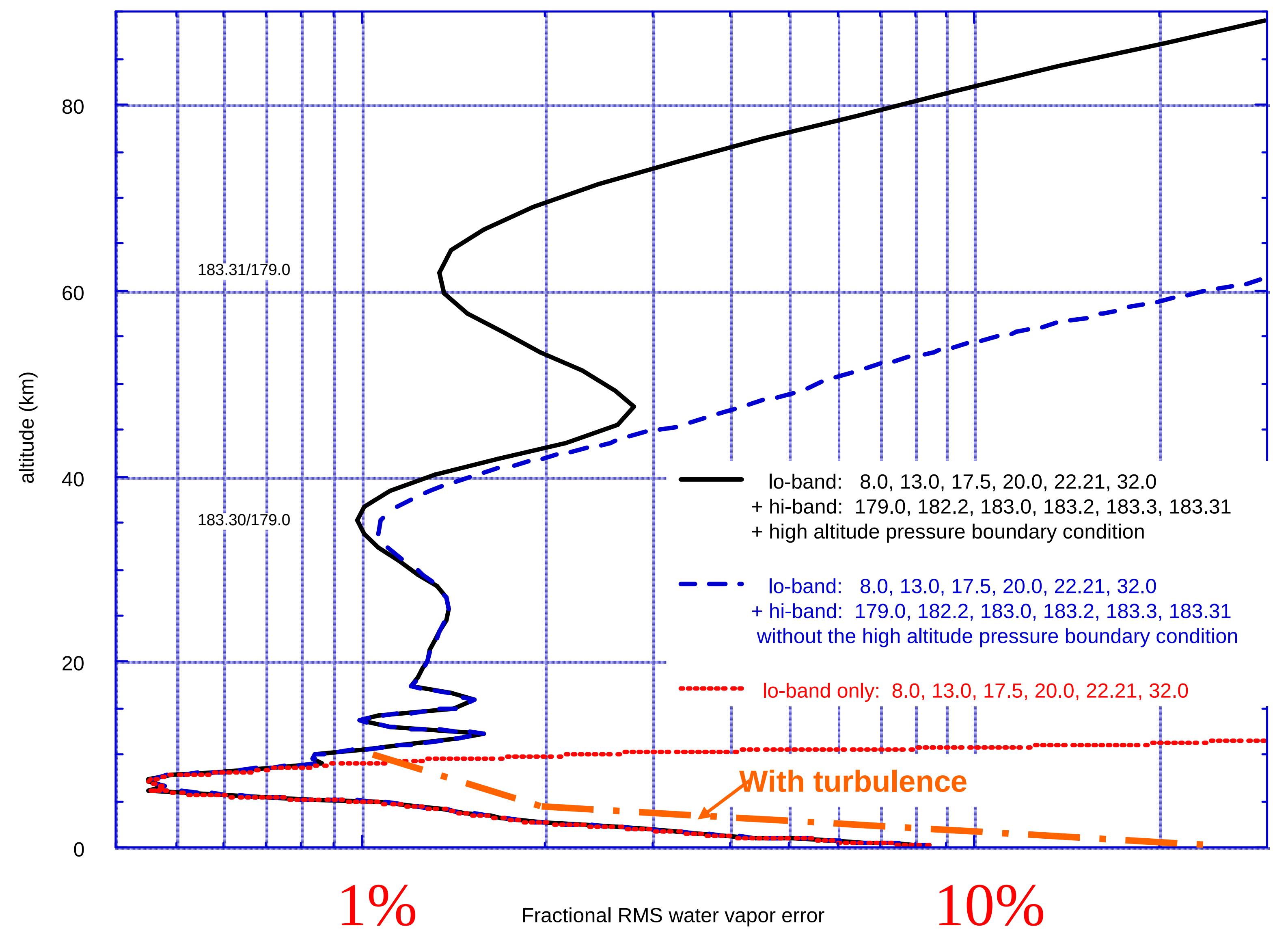


- ArW: Arctic winter MLS: mid-latitude summer

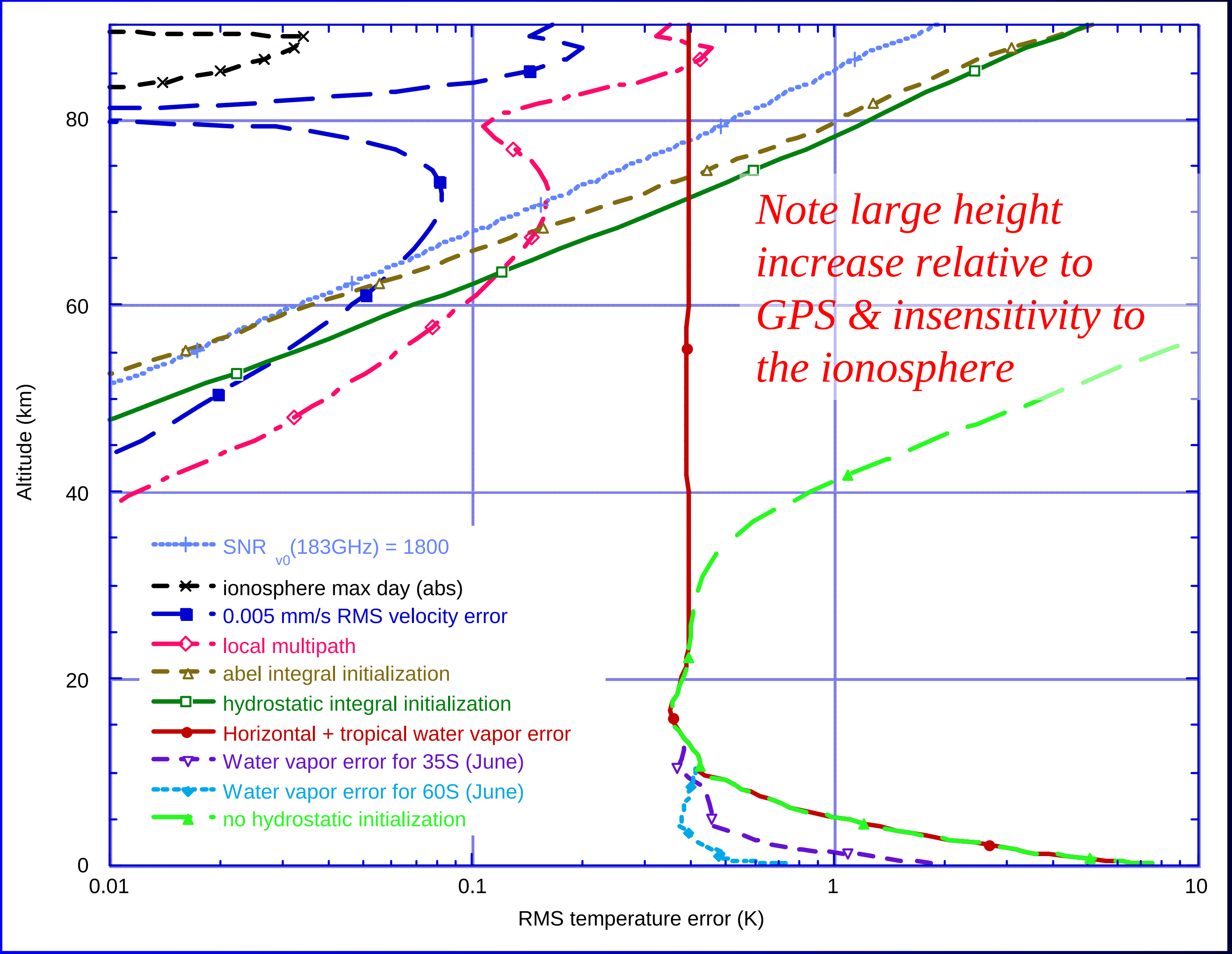
Boundary Layer Accuracy with ATOMMS

- Accuracy in tropical boundary layer will be limited by
  - Larger horizontal refractivity gradients
  - Limited orthogonality between absorption coefficient and refractivity information under wet conditions
  - High optical depth on the high side of 22 GHz
  - Wet turbulence
- Accuracy in colder boundary layers will be better,
  - the colder the more accurate

Precision of Individual Water Vapor Profiles

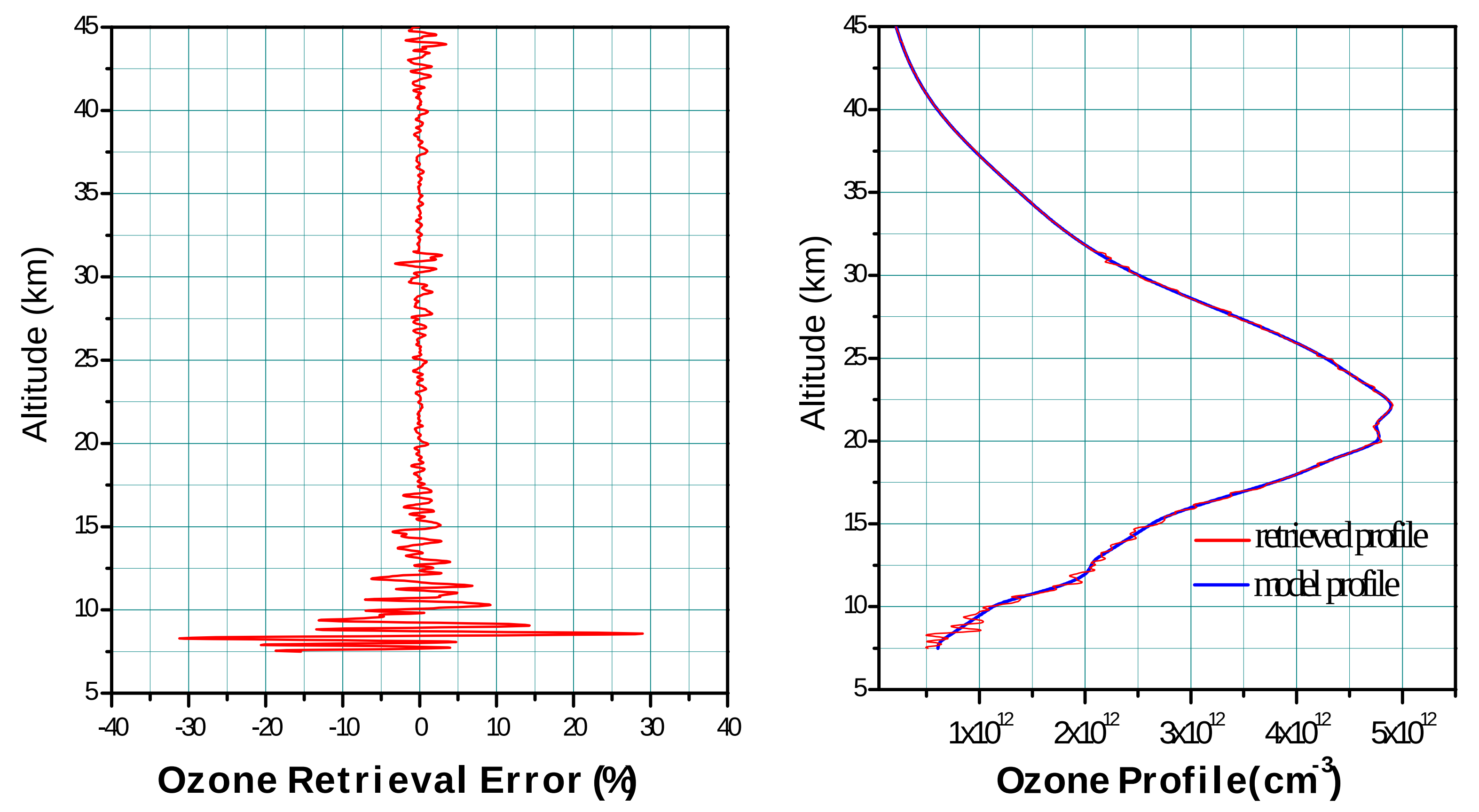


Precision of Individual Temperature Profiles



Note large height increase relative to GPS & insensitivity to the ionosphere

Ozone Retrieval Precision near 195 GHz



- Ozone r.m.s. retrieval error ~ 2 % (15- 40 km)
- Below 10 km, the ozone retrieval error quickly increases because ozone absorption becomes small fraction of total absorption
- Retrievals work in ice clouds

Observing System Features

Very high precision (1-3%) water vapor and ozone profiles at very high vertical resolution (100-500m)

- AIRS claims 10% at 2 km vertical resolution in clear air

Self calibrating technique => Very high accuracy

Simple and direct retrieval concept

- Retrievals are independent of models and initial guesses

Microwave system

- Retrievals degraded only slightly in cloudy conditions
- Sees into and below clouds to see cloud base and multiple cloud layers
- Yields all weather global coverage with high precision, accuracy and vertical resolution

⇒ ***Excellent INSTRUMENT for CLIMATE***

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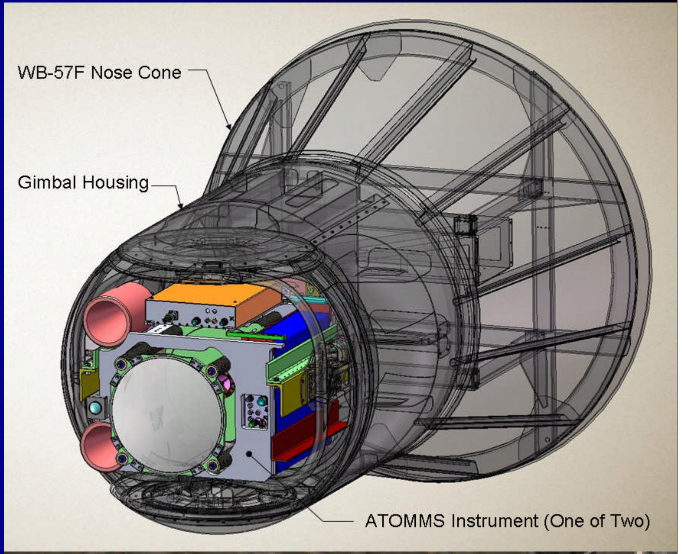
- Accuracy of retrievals
- **Demonstration mission overview**

How Do We Get There from Here? ATOMMS Aircraft-aircraft Demo:

- To proceed to orbiting mission requires an actual demonstration of ATOMMS performance
- Full demonstration requires expensive LEO transmitter & receiver
- Intermediate solution: High altitude aircraft - aircraft demo?
  - Provides occultation geometry below the altitude of the aircraft
  - Relatively inexpensive
- Key problem is antenna pointing
  - Achieving high SNR with low transmit power => Directional Antennas
  - ⇒ Directional antennas require precise pointing in aircraft
  - In 2005, brainstorming with Don Anderson (NASA HQ) identified NASA-developed capability to image Shuttles during launch: WAVES ($5M investment)
- Basis for MRI proposal to NSF selected in 2007 to build and demonstrate the ATOMMS capability in 2009
  - NASA is supporting the aircraft time

Aircraft-aircraft demonstration

- Occultation between 2 WB-57F aircraft flying near 20 km altitude
- Perform a series of rising occultations
- Measure phase and amplitude at several wavelengths
- POD: GPS + accelerometers
- Pointing via WAVES



Aircraft - aircraft cm & mm-wavelength Occultation Demonstration

- Objective: Demonstrate 22, 183 & 195 GHz occultation observations ability to precisely observe in clear & cloudy air
  - Water vapor from aircraft altitude (~19 km) to near surface
  - Temperature from aircraft altitude (~19 km) to near surface
  - Geopotential from aircraft altitude (~19 km) to near surface
  - Ozone from aircraft altitude (~19 km) into troposphere
- Possibly
  - $H_2{}^{18}O$ in mid to upper troposphere (203 GHz)
  - N_2O in lower stratosphere (201 GHz)
- Also relevant to next Mars mission opportunity

WB-57F Aircraft- Aircraft Demonstration Objectives

Demonstrate ability to:

- Measure phase & amplitude accurately near 10-32 & 170-200 GHz
- Isolate absorption signatures from other unwanted amplitude effects
- Derive accurate bending angle profiles from surface to the aircraft altitude

Good test conditions

- High SNR
- Somewhat reduced turbulence
- Slower time evolution of occultation

WB-57F Aircraft- Aircraft Demonstration Objectives

Assess retrieval accuracy and performance vs. expectation including:

- Compare 22 and 183 GHz water retrievals in altitude overlap interval
- Assess impact of turbulence on retrieval accuracy
- Performance in cloudy vs. clear conditions
- Accuracy versus altitude in the lowermost troposphere
- Accuracy of ozone retrievals and how deep into the troposphere can the ozone retrievals can penetrate

Secondary Objectives

- Tradeoff between number & spacing of tones and retrieval accuracy
- Ability to remotely sense and characterize turbulence
- Feasibility and accuracy of spectroscopic refinement using occultation measurements

Instrument Overview

- 22 GHz
  - 8 fixed tones between 18 and 26 GHz
  - Solve for water vapor and liquid water content
- 183 GHz water and 195 GHz ozone lines
  - 2 tones between 183 and 203 GHz
  - Solve for water vapor in upper troposphere & above
  - Solve for ozone in upper troposphere and above
- 13 GHz phase tones
  - Provide phase in lower troposphere where 183 GHz cannot penetrate
- No cryogenics
- Build at UA

ATOMMS System Elements & Development

- ATOMMS instrument (UA)
- ATOMMS Precise Positioning System (JPL)
- WAVES pointing system (SRI)
- WB-57F Aircraft (JSC)
- Retrieval system (UA)
- Ground truth for evaluation (NOAA + ….)

Schedule

- Began June 2007
- 2 years of development, 1 year of demos
- Begin air to air demos in early 2009

ATOMMS Beyond the Aircraft Demos

A note in the Decadal Survey (DS) CLARREO Workshop Report Edited by: Donald E. Anderson NASA, MAP Program Manager October 10, 2007 (science.hq.nasa.gov/earth-sun/docs/Volz4_CLARREO.pdf):

Potential NSF participation Rob Kurczinski for U. of Arizona attended the meeting. He was recently awarded a large NSF grant, ATOMMS: Active Temperature, Ozone, Moisture Microwave Spectrometer (ATOMMS) is LEO-LEO Occultation Observing System. Rob moved from JPL a few years ago. NASA has interacted with Rob and is providing a platform for flight tests. NASA will provide an opportunity to instrument the two NASA WB57s with ATOMMS instruments. *ATOMMS development may be accelerated as a result of the CLARREO workshop. NSF may well become a partner, if ATOMMS is developed on schedule and satisfies CLARREO measurement requirements.*