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

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

- Select the occultation frequencies (& use unmodulated tones)
- Measure water vapor absorption to break the wet-dry ambiguity
- Reduce ionospheric sensitivity via use of much high frequencies to extend profiles to much higher altitudes
- Eliminate need for external boundary condition for hydrostatic integral and use/weighting of middle atmosphere climatology:
  - directly measure temperature at high altitude via Doppler line broadening
- Profile other constituents like O_3 via absorption

⇒ Cross between GPS RO and Microwave Limb Sounder (MLS)

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

⇒ Determine/Calibrate GNSS RO ionosphere error

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

Rationale: Water, Ozone & Temperature Related Climate Issues

- Water & ozone are two extremely important greenhouse gases
- Water 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 water and ozone particularly in upper troposphere/lower stratosphere (UTLS)
  - Solar variability & Earth climate may be connected through ozone
- *Temperature uncertainties*: in lapse rate adjustments with changes in vertical heating and dynamical feedbacks as well as the transition between tropospheric warming and stratospheric cooling

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.

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.

Upper Troposphere

- This issue is tied closely to deep convection and the moistening in UT that occurs when convective clouds are present.
- Therefore observations of UT region in both clear and cloudy conditions are absolutely necessary (but not presently possible).
- In addition, these convective processes have very sharply defined detrainment levels in the vertical dimension.
- To the extent that present observations can even see UT, the coarse vertical resolution of present observations averages things over thick vertical scales, which either lose the phenomena entirely or at the very least the phenomena become very much ambiguous.
- Therefore global observations of temperature and water vapor with very fine vertical resolution are a prerequisite (presently *unfulfilled*) for understanding climate, evaluating and improving climate model realism and accurately predicting the future climate state.

Observational Needs

Climate models are wrong in ways that we do not know.

When you don’t understand something, you measure it

Need observations as complete as possible and independent of models to determine what is actually happening

To understand the climate, need to measure

- Radiative energy (im)balance: Solar in and IR out
- Thermodynamic and dynamic state of the system
- Observations constrain processes and determine variability and trends

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
  - Don’t want retrievals that largely regurgitate assumptions

Observational Needs

- Precise and high vertical resolution observations are needed to
  - Measure behavior at the important scales of variability
  - Measure in and below clouds because weather forms in cloudy areas
  - Monitor trends & variability
  - Separate free troposphere behavior from that in the PBL
  - Understand the processes controlling moisture in troposphere & stratosphere and coupling to clouds and precipitation
  - Improve physical model representations for future weather and climate predictions

Some Limitations in Present Satellite Sensors

- **Vertical resolution**
  - Rule of thumb: To characterize a constituent, it should be resolved at least 3 times per scale height
    - ***Water vapor should be measured at least every 500 m vertically***
  - In ***clear*** air AIRS can retrieve water vapor with 2 km vertical resolution, 4 times worse than rule of thumb
  - Microwave nadir sounders provide 3-4 km in cloudy air only over oceans, almost an order of magnitude worse than rule.
- **All weather sensing?**
  - Cloudy areas are where severe weather develops
  - AIRS does not work in clouds
    - (90-95% of AIRS pixels are cloud contaminated)
  - MLS cannot do retrievals in clouds (=> dry biased)
  - Nadir-viewing microwave sounders are all weather but low resolution and only over ocean

Some Limitations in Present Satellite Sensors (cont'd)

- Diurnal sampling?
  - Geosynchronous IR & visible sensors sample diurnal cycle but cannot penetrate clouds
  - Eventually geosynchronous microwave radiometer will provide diurnal sampling over the oceans with poor vertical resolution
  - Each polar platform like AIRS samples 2 times per day
- All nadir-viewing passive retrievals are non-unique and contain unknown biases
  - "Unique" solutions are achieved by adding extra constraints/assumptions
  - VERY bad for climate because solution contains assumptions which can't be separated from true behavior

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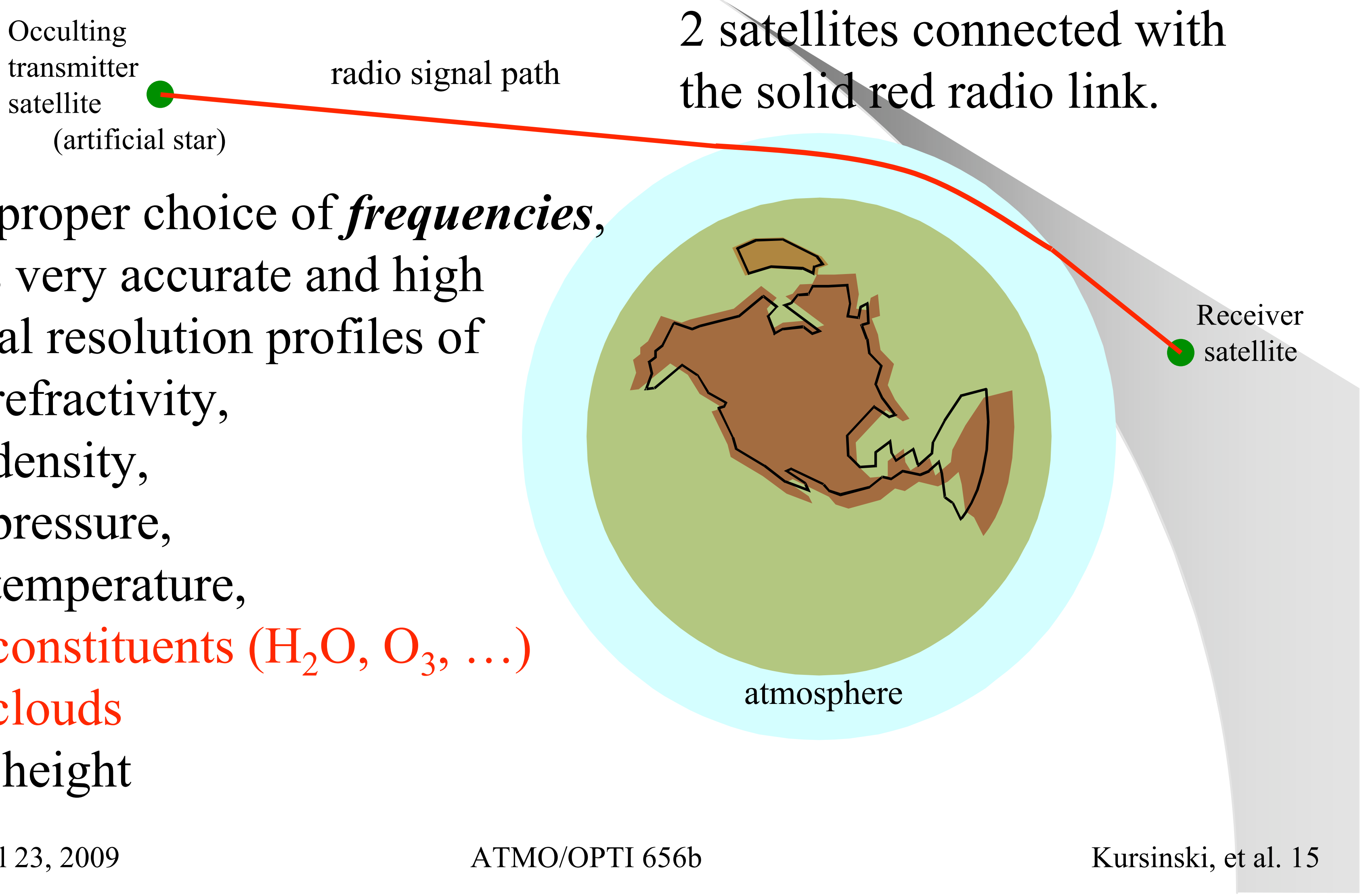
Geometry of the Active Microwave Occultation



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

With proper choice of ***frequencies***, yields very accurate and high vertical resolution profiles of

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

vs. height

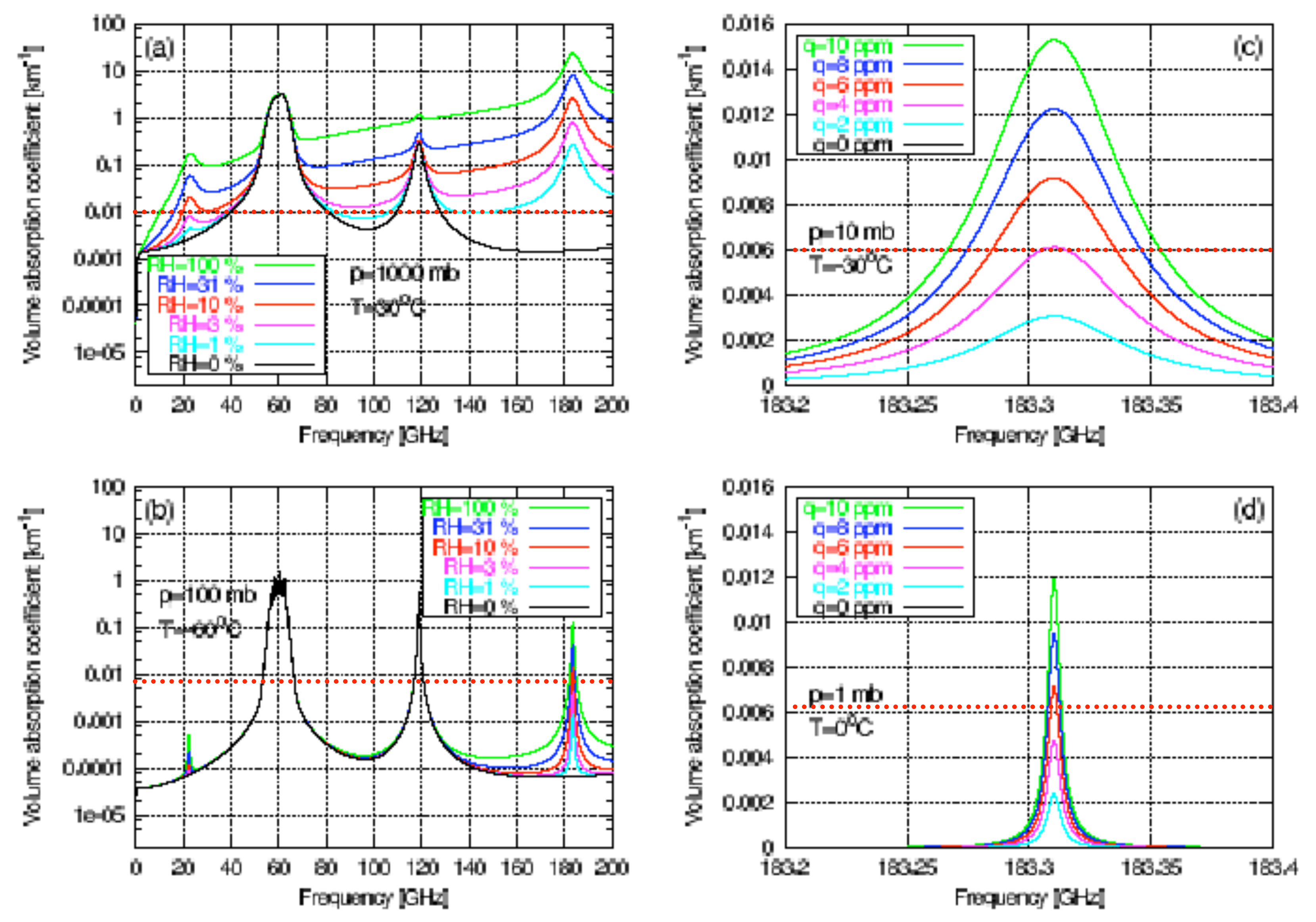
History of Satellite Occultation Observations

- 1965 first spacecraft occultation observation of Mars yielding surface pressure of ~6 mb and CO_2 as major constituent
- 1995 satellite to satellite occultations of Earth using GPS satellites as signal sources
- By 1995, every major atmosphere in the solar system probed via occultation except Pluto
- Occultations generally use signal doppler shift to derive refractivity => bulk density, pressure and temperature vs. z
- Also have used signal amplitude to characterize constituents such as NH_3 in Jupiter and Saturn and H_2SO_4 in Venus
- Historically spacecraft occultation systems have piggybacked on existing telecom/navigation systems

Incomplete History of cm/mm-wave Occultation Concept

- 1995: Possibility of 22 GHz occultations identified in U. Arizona talk
- 1997: Fall AGU talks by U. Arizona and JPL presented initial evaluation of performance of occultations near 22 GHz
- 1998: JPL, Arizona and Texas A&M developed and proposed AMORE ESSP
  - Received highest science ranking but technically embryonic (true)
- 1998: JPL, Arizona proposed and were funded to develop 22, 183 & 195 GHz concept for NASA Instrument Incubator Program (IIP)
- 2001: Funded by NASA to develop Mars Scout mission concept (MACO)
  - Figured out how to do 183 GHz occultations
- 2002: Initial assessment of concept documented
- 2004-2007: Addressed water clouds and turbulence issues
- 2005: Figured out how to do aircraft-aircraft occultations
- 2006: Proposed Mars Scout, refining science & instrument (not selected)
- 2007: NSF funded effort to demonstrate cm and mm-wave occultation concept between 2 high altitude aircraft for characterizing water vapor and ozone.

Water and O_2 Lines Below 200 GHz



Cross-Link Frequencies

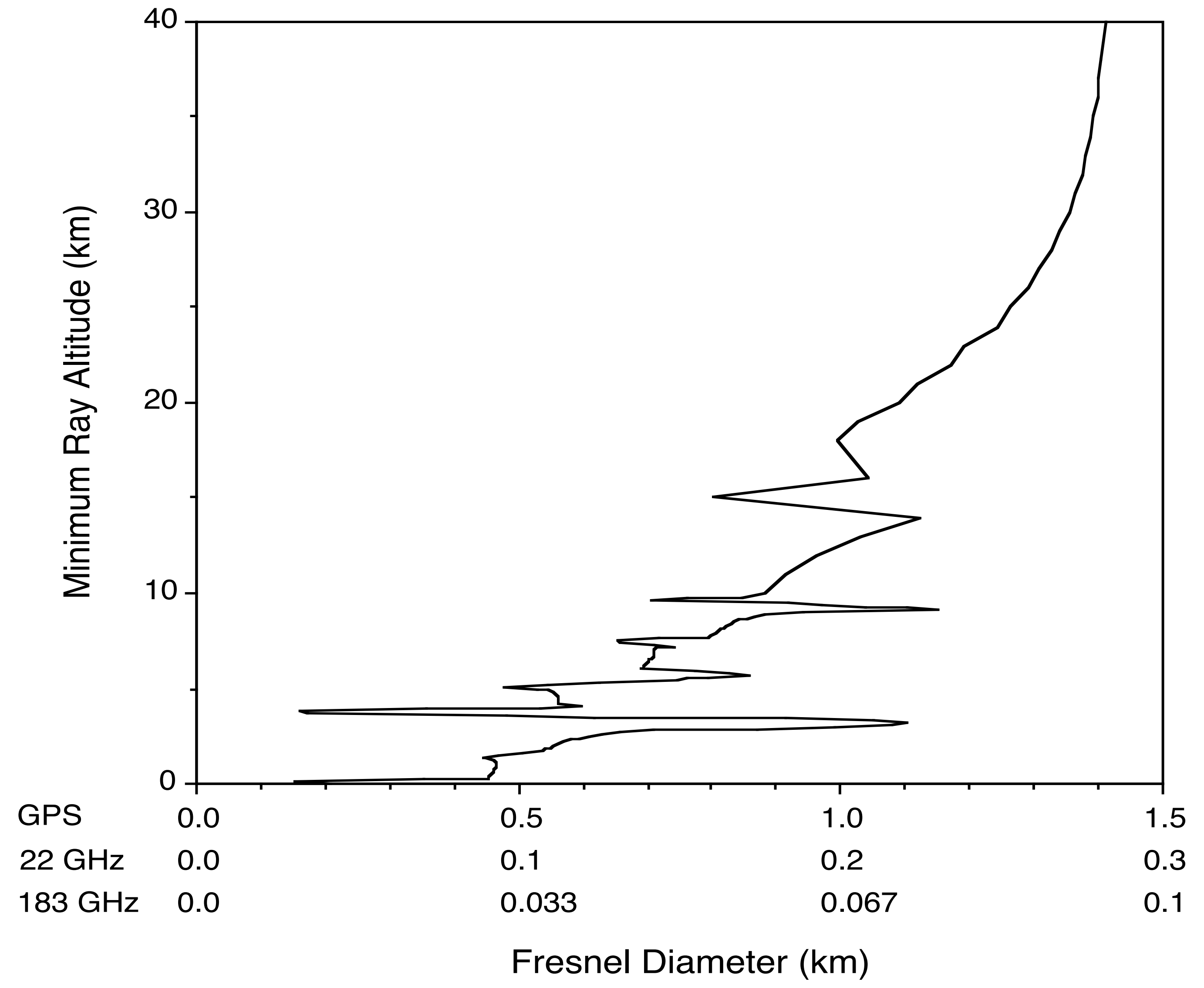
Near and below 200 GHz, there are 2 water vapor absorption lines at 22.23 and 183.31 GHz and several strong ozone lines.

(1) H_2O	22.23 GHz line ("low band")
	183.31 GHz line ("high band")
(2) Ozone	184.4 & 195.43 GHz line (high band)
(3) $H_2{}^{18}O$	203 GHz line

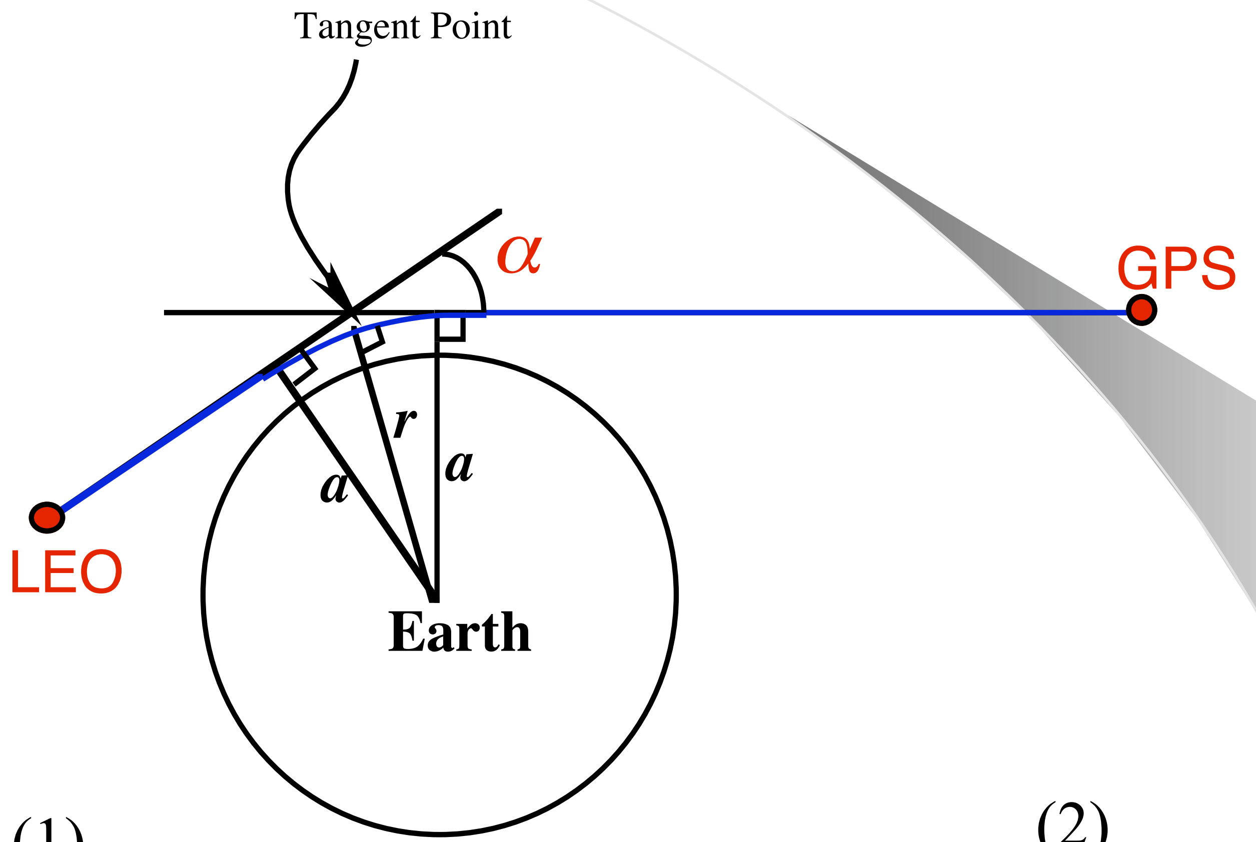
For determining *T* at high altitude for hydrostatic initialization

(4) O_2	118 GHz line
H_2O	557 GHz line

Diffraction-Limited Vertical Resolution vs. Frequency



Retrieval Overview: Deriving the Real Part of *n*



(1)

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

$$\Leftrightarrow$$

(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***)

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

$$\Leftrightarrow$$

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

Abel Transform Pair: Optical Depth & Absorption Coefficient

- The slant optical depth, τ, is the integral of the absorption coefficient, k, along the signal path through the atmosphere.

$$\tau(a) = \int k\, dl = 2\int_{x=a}^{x=\infty} k \frac{nr\, dr}{\sqrt{n^2 r^2 - n_0^2 r_0^2}} \qquad (5)$$

We measure a profile of τ but we want k. So we need to invert (5) to solve for k.

We use a similar but not identical approach to that used in the bending angle-refractivity transform pair.

First we rewrite the RHS of (5) in terms of $x = nr$ rather than r.

Abel Transform Pair: $\tau \Leftrightarrow k$

First we rewrite the RHS of (5) in terms of $x = nr$ rather than r.

$$\tau(a) = 2\int_{x=a}^{x=\infty} k \frac{x \, {dr}/{dx} \, dx}{\sqrt{x^2 - a^2}} \qquad (3)$$

Then we take (3) and perform the integral transformation that we used to get from $\alpha(a)$ to $n(r)$ using a different kernel: $a/(a^2 - a_1{}^2)^{1/2}$.

$$\int_{a=a_1}^{a=\infty} \frac{\tau \, a \, da}{\sqrt{a^2 - a_1^2}} = \int_{a=a_1}^{a=\infty} \frac{a}{\sqrt{a^2 - a_1^2}} \left[2\int_{x=a}^{x=\infty} k \frac{x \, {dr}/{dx} \, dx}{\sqrt{x^2 - a^2}} \right] da$$

$$= 2\int_{x=a_1}^{x=\infty} k \, x \frac{dr}{dx} \left[\int_{a=a_1}^{a=x} \frac{a \, da}{\sqrt{a^2 - a_1^2}\sqrt{x^2 - a^2}} \right] dx$$

$$= 2\int_{x=a_1}^{x=\infty} k \, x \frac{dr}{dx} \left[\sin^{-1} \sqrt{\frac{a^2 - a_1^2}{x^2 - a_1^2}} \right]_{a=a_1}^{a=x} dx$$

$$\int_{a=a_1}^{a=\infty} \frac{\tau \, a \, da}{\sqrt{a^2 - a_1^2}} = \pi \int_{x=a_1}^{x=\infty} k \, x \frac{dr}{dx} \, dx \qquad (6)$$

Abel Transform Pair: $\tau \Leftrightarrow k$

Now we use Leibnitz' rule to take the derivative with respect to a_1 to isolate k.

First we do an integration by parts of the LHS of (6).

$$\int_{a=a_1}^{a=\infty} \frac{\tau\, a\, da}{\sqrt{a^2 - a_1^2}} = -\int_{a=a_1}^{a=\infty} \sqrt{a^2 - a_1^2}\, \frac{d\tau}{da}\, da = \pi \int_{x=a_1}^{x=\infty} k\, x\, \frac{dr}{dx}\, dx$$

Then the derivative with respect to a_1:

$$\frac{d}{da_1}\left[-\int_{a=a_1}^{a=\infty} \sqrt{a^2 - a_1^2}\, \frac{d\tau}{da}\, da\right] = \frac{d}{da_1}\left[\pi \int_{x=a_1}^{x=\infty} k\, x\, \frac{dr}{dx}\, dx\right]$$

$$\left[\int_{a=a_1}^{a=\infty} \frac{a_1}{\sqrt{a^2 - a_1^2}}\, \frac{d\tau}{da}\, da\right] = -\pi\, k(a_1)\, a_1 \left.\frac{dr}{da}\right|_{a=a_1}$$

And k is given as

$$k(a_1) = -\frac{1}{\pi} \left.\frac{da}{dr}\right|_{a=a_1} \int_{a=a_1}^{a=\infty} \frac{d\tau}{da}\, \frac{da}{\sqrt{a^2 - a_1^2}} \qquad (4)$$

Deriving water vapor, temperature and pressure (clear sky)

Water vapor retrievals:

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

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

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

$$\textit{hydrostatic equation} \quad \frac{d(P_d + P_w)}{P_d + P_w} = -\frac{g\,dz}{R\,T}$$

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:

For lower and middle troposphere where liquid water clouds are likely present,

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

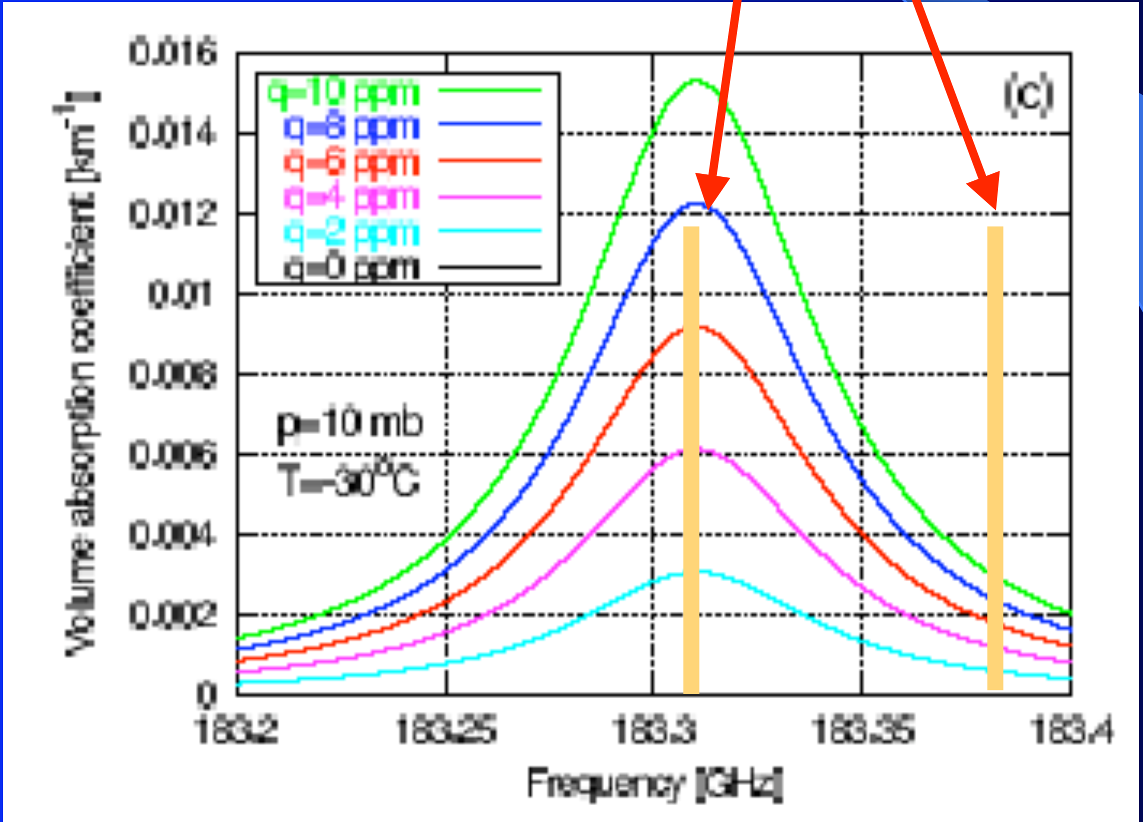
$$absorption \quad equation \quad \#1 \;\; k_1 - k_2 = F_{12}(T, P_d, P_w, L_c)$$

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

Solve these 4 closed, non-linear equations (the 2 absorption equations above, the refractivity equation, and the hydrostatic equilibrium equation) for 4 unknowns, T, P_d, P_w, and cloud liquid water content, L_c.

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:

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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,

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

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

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

Solve these 4 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

Dealing with liquid water droplets

- The absorption measured by ATOMMS can be a combination of water vapor, liquid water, molecular oxygen, ozone, ….
- At temperatures below -40°C, there is no liquid water and so we don’t need to worry about it
- At warmer temperatures, liquid water exists and has a strong absorption signature.
- In order for ATOMMS to work in both clear and cloudy weather, ATOMMS must be able to separate the absorption signatures of liquid water and water vapor
- Furthermore, one cannot assume the liquid water distribution is spherically symmetric
  - **so the Abel transform cannot be used (at least directly)**

Dealing with liquid water droplets (cont'd)

New approach is to isolate and remove the liquid water absorption spectrum along each occultation path based on its unique spectral signature.

- This approach does not assume liquid water is distributed spherical symmetrically
- Liquid water spectrum is forward modeled as liquid water amount and an average liquid water temperature

Once the liquid water is removed, we interpret the residual absorption spectrum in terms of water vapor

- This is done in a top-down process checking layer by layer to determine whether the absorption spectrum indicates liquid water is present.
- Called an "onion skin" peeling approach
- Refractivity profile and hydrostatic equilibrium are used with absorption spectrum to determine water vapor, temperature and pressure

Separating the water vapor and liquid water spectral absorption signatures requires that

- both sides of the 22 GHz water vapor line be sampled
- with a sufficient number of occultation tone frequencies to
  - The aircraft to aircraft version has 8 tones between 18 and 30 GHz

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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:	Non-spherical distributions	Horiz. average
	Uncertainty in line parameters	Spectr. cal. in space
	Correlation between vapor and liquid frequency dependence	Additional tones

ATOMMS Error Covariance

- ATOMMS observations contain sufficient information to profile the atmospheric state without an *apriori* state estimate
- We evaluate the errors in the ATOMMS' derived state estimate using a simplified error covariance equation

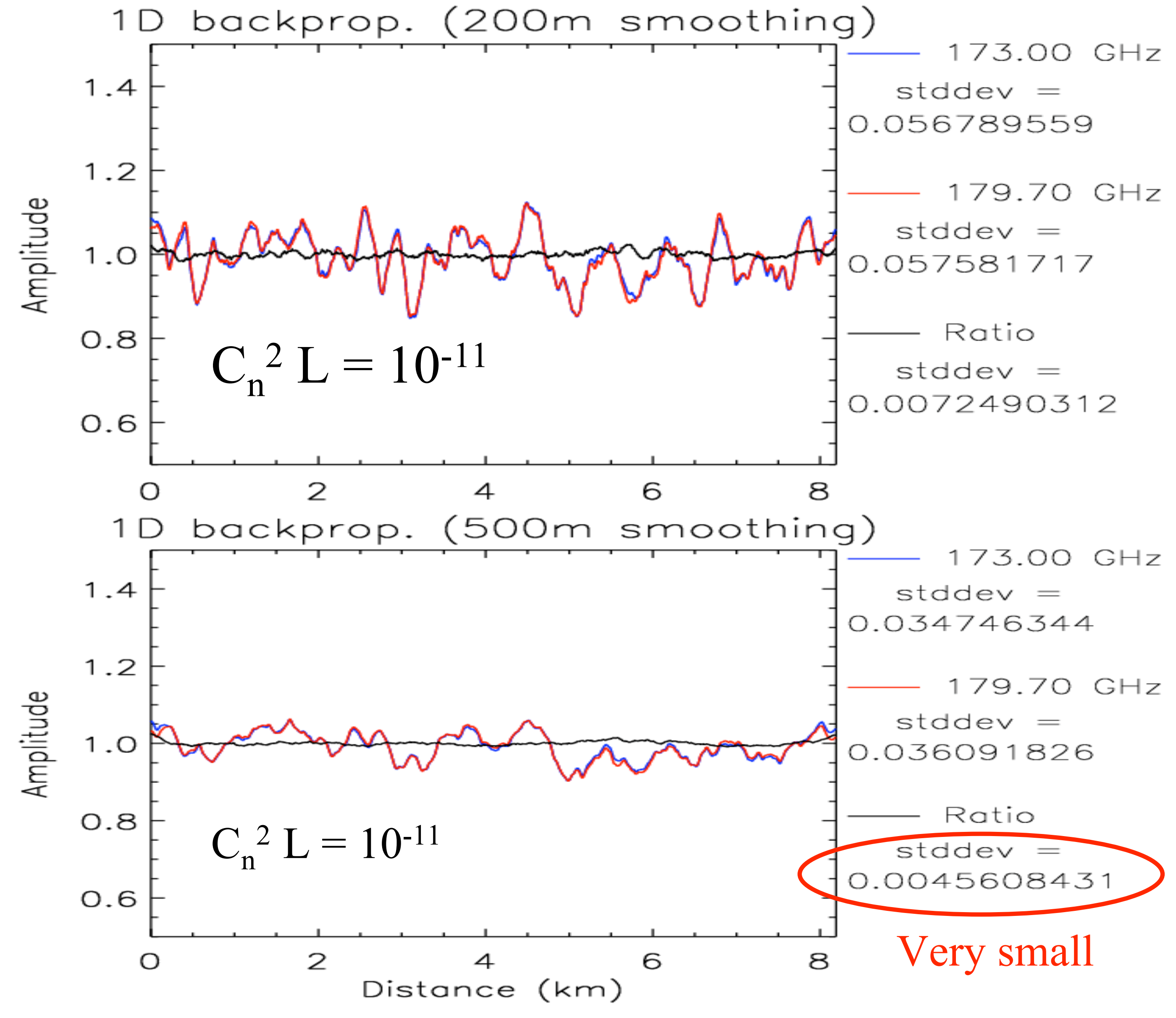
$$\hat{S}^{-1} = K^T S_\varepsilon^{-1} K$$

instead of

$$\hat{S}^{-1} = K^T S_\varepsilon^{-1} K + S_a^{-1}$$

Turbulence Scintillation Mitigation near 183 GHz

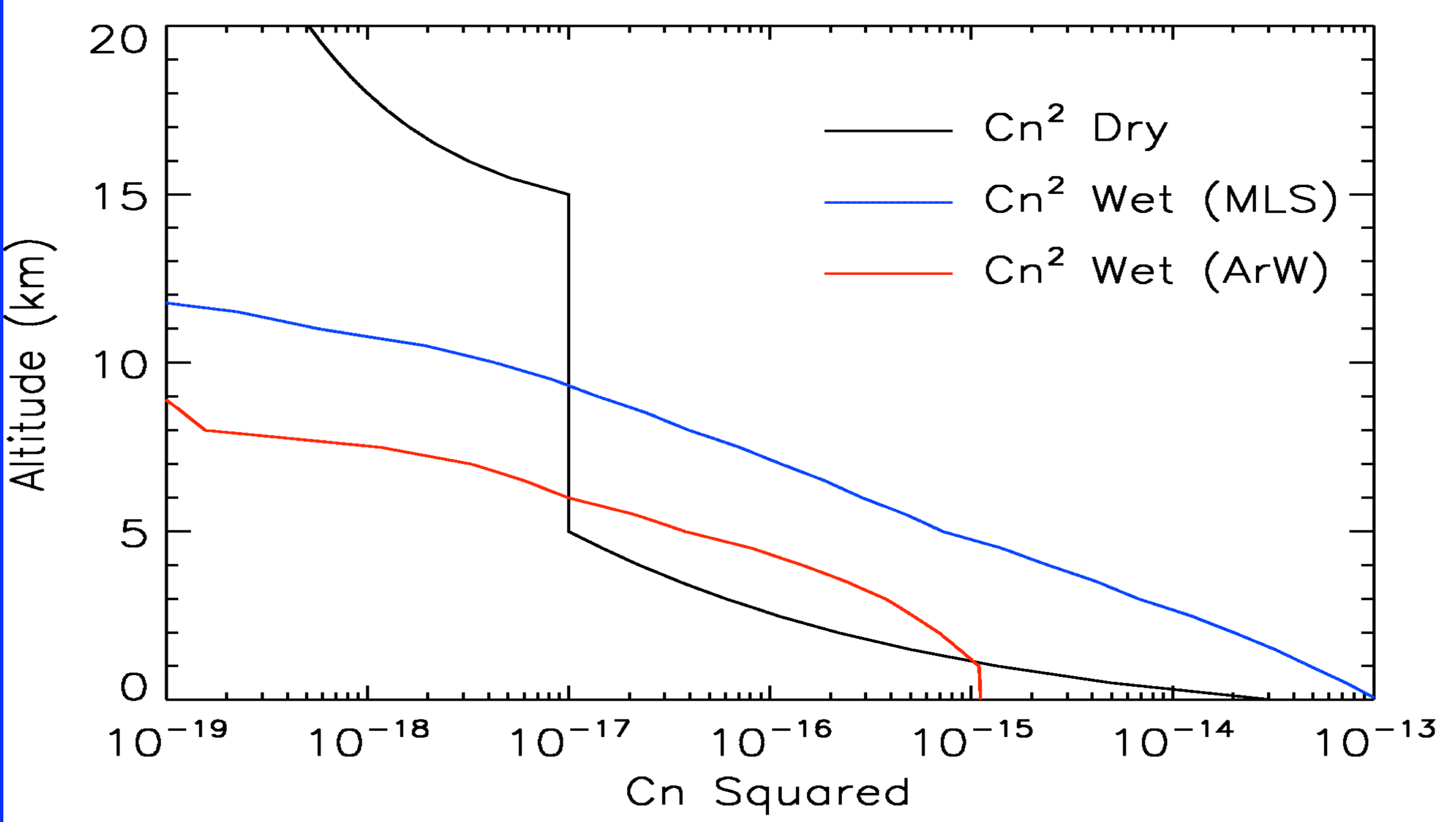
- Upper troposphere & lower stratosphere



Turbulence Impact Assessment

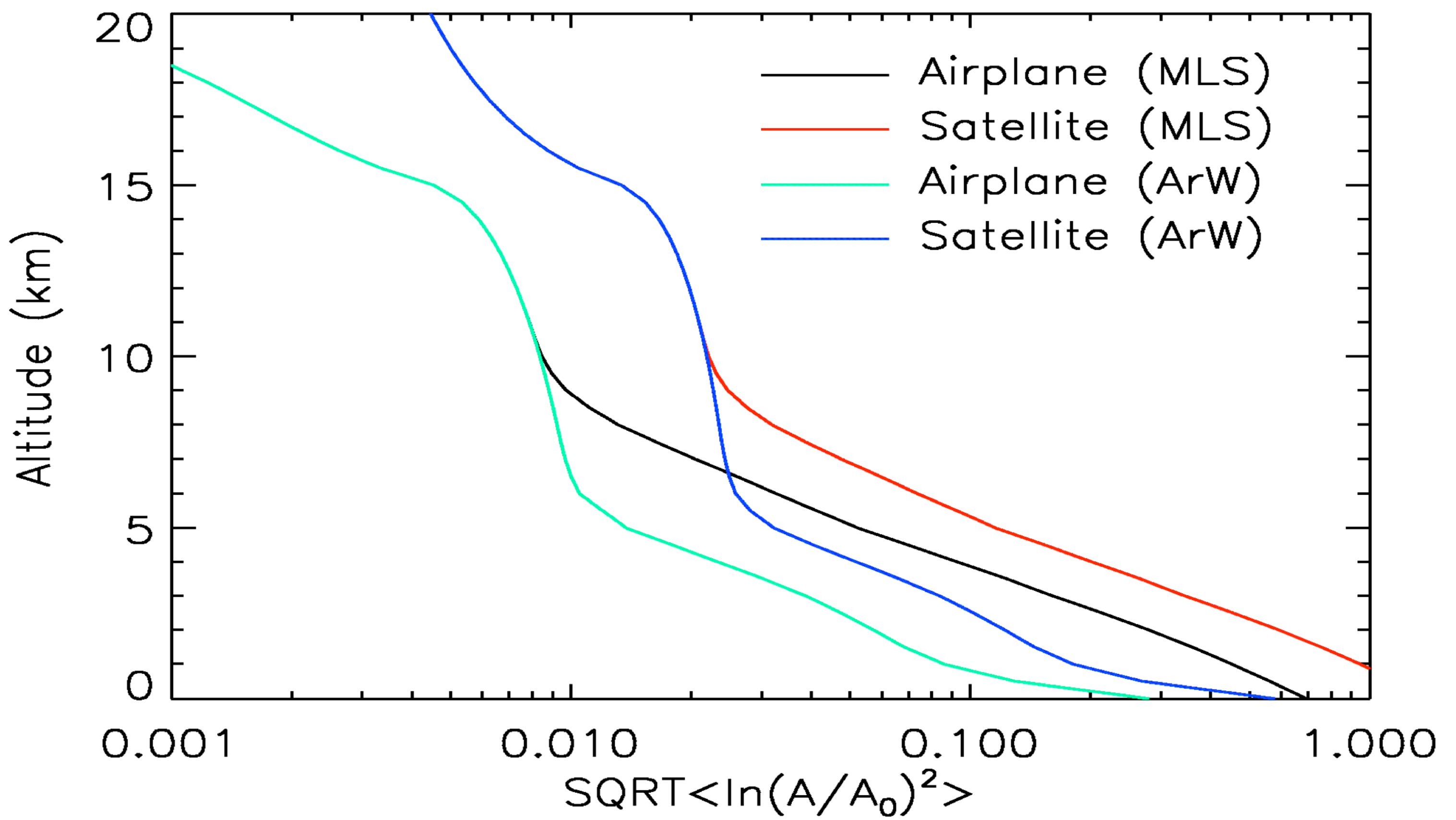
We have developed a parameterization of turbulence intensity: C_n^2

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



Estimated Amplitude Errors

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

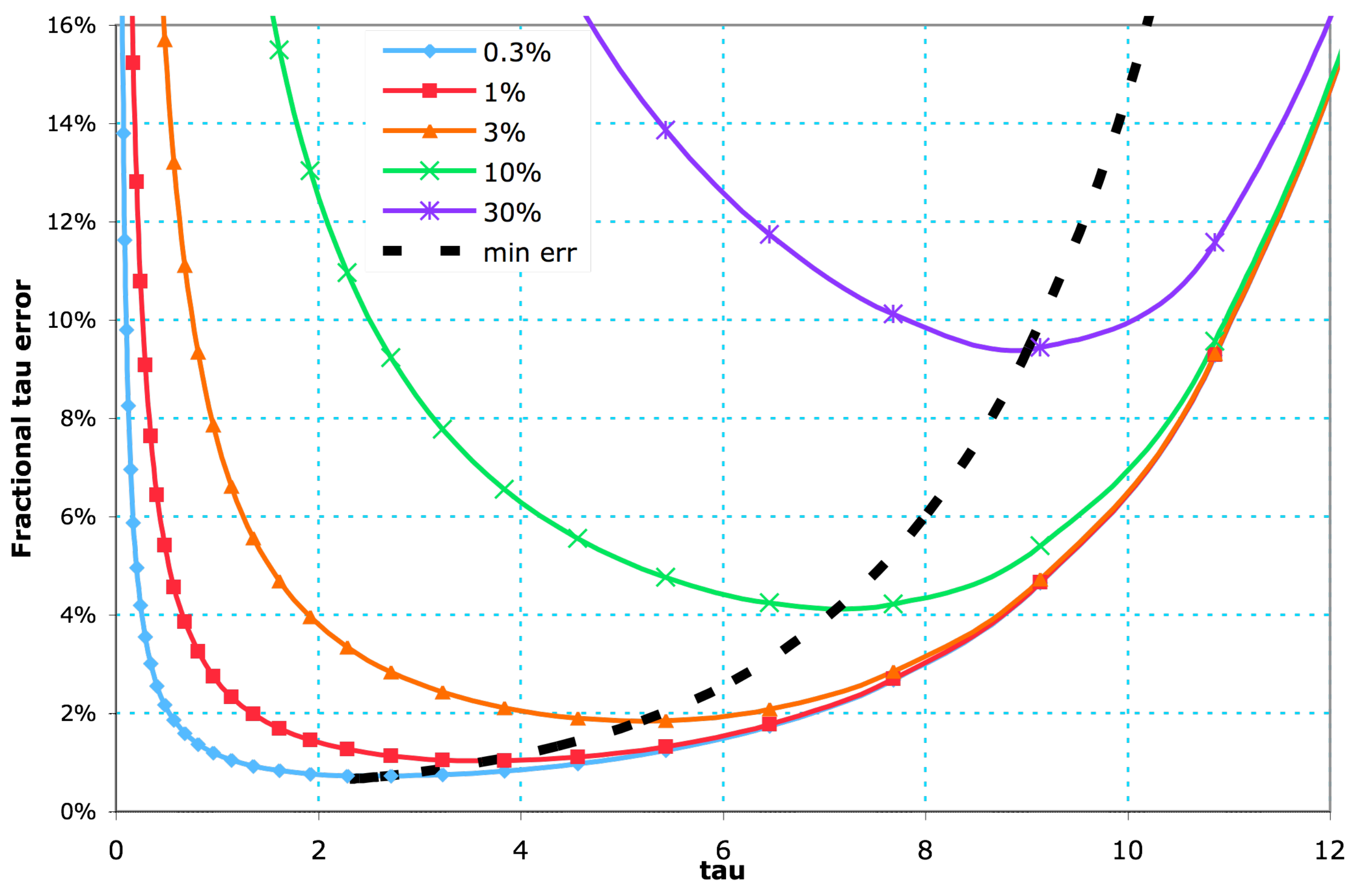


ArW: Arctic winter

MLS: mid-latitude summer

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



Turbulent Variations in Complex Refractivity

- Results in previous viewgraphs assumed turbulent variations in only the ***real*** part of the index of refraction
- A. Otarola (2008) generalized turbulence-scintillation equations to include ***imaginary*** (absorption) part

$$\left\langle \chi^2\left(\vec{R},k\right)\right\rangle = \pi^2 \cdot 0.033 \cdot L^{11/6} \cdot k^{7/6} \left\{ \begin{array}{l} C^2_{\delta n_r} \int_0^\infty ds \cdot \left(s+s_0\right)^{-11/6} \left\{1 - \frac{\sin(s)}{s}\right\} \\ -2 \cdot C_{\delta n_r \delta n_i} \int_0^\infty ds \cdot \left(s+s_0\right)^{-11/6} \frac{\sin^2\left(s/2\right)}{s/2} \\ +C^2_{\delta n_i} \int_0^\infty ds \cdot \left(s+s_0\right)^{-11/6} \left\{1 + \frac{\sin(s)}{s}\right\} \end{array} \right\}$$

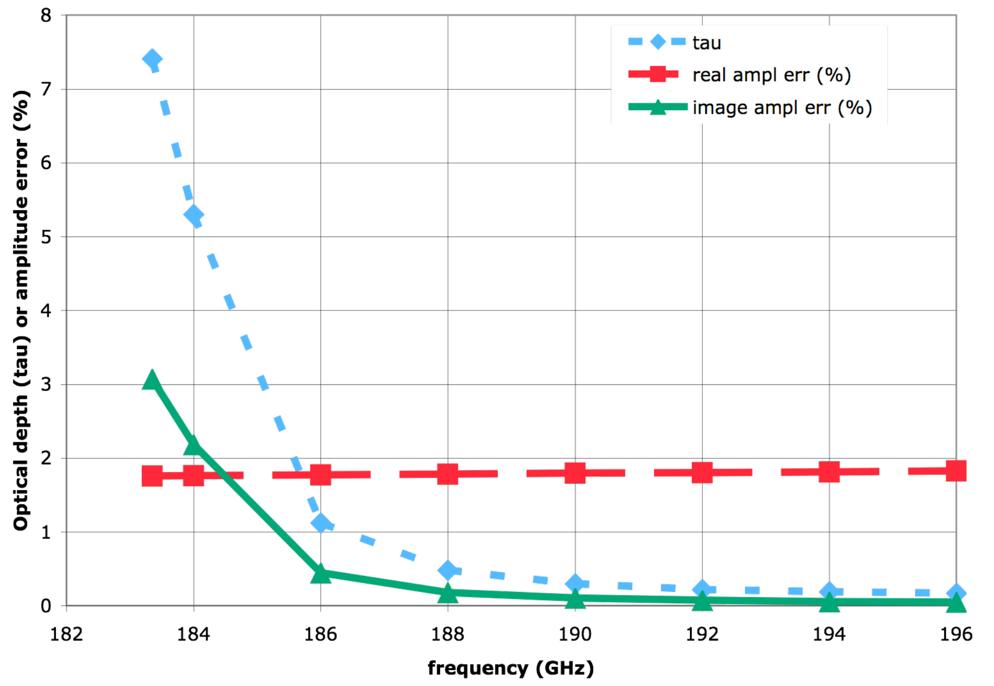
Equation determines mean square of log-amplitude variations for constant turbulence conditions over a path length, L. k is the signal wavenumber, C^2 indicate real and imaginary turbulence intensity.

$s = L\dfrac{\kappa^2}{k}$ is the scattering parameter, where κ is the spatial wavenumber of the turbulent eddies.

Similarly, $s_0 = L\dfrac{\kappa_0^2}{k}$ where κ_0 is the spatial wavenumber of the outer scale of the turbulent eddies.

Turbulent Variations in Complex Refractivity

- Dependence on signal frequency and optical depth
  - Absorption: τ
  - Turbulent fluctuations in real part: $f^{7/12}$
  - Turbulent fluctuations in imaginary part: τ
  - Scaling between τ and *f* depends on line shape and width integrated along the path



Key results about scintillations due to imaginary part

- Can dominate the scintillations
- ~ linear dependence on τ
  - Difficult to separate from τ (signal)
  - Implies fractional τ error is *independent* of τ
- Will reduce optimum performance at all τ's

Turbulent Variations in Complex Refractivity

- Prototype ATOMMS instrument:
  - 8 tones at 22 GHz: sufficient
  - 2 tones at 183 GHz: insufficient
- Follow-on proposal to increase 183 GHz to 4 tones
  - 3 tones for
    - separating real & imaginary turbulence errors
    - and turbulence characterization
  - 4th tone for assessing spectroscopic errors
  - Delay the demonstration to ~January 2010
- Will develop new theoretical optimization
- Will evaluate with ground test and then flight demonstration

ATOMMS Clear Sky Performance vs. Latitude

- Precision of ATOMMS individual temperature and water vapor profiles

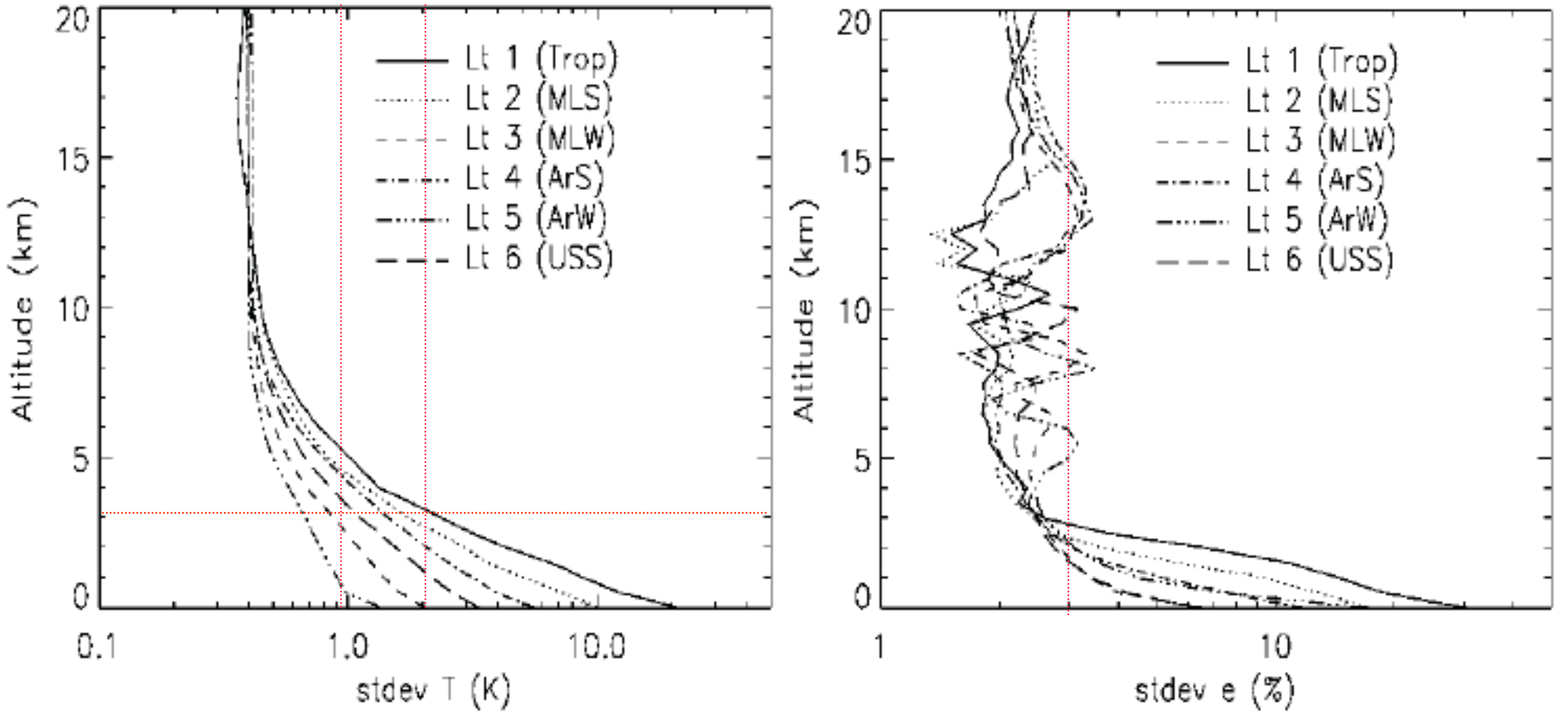
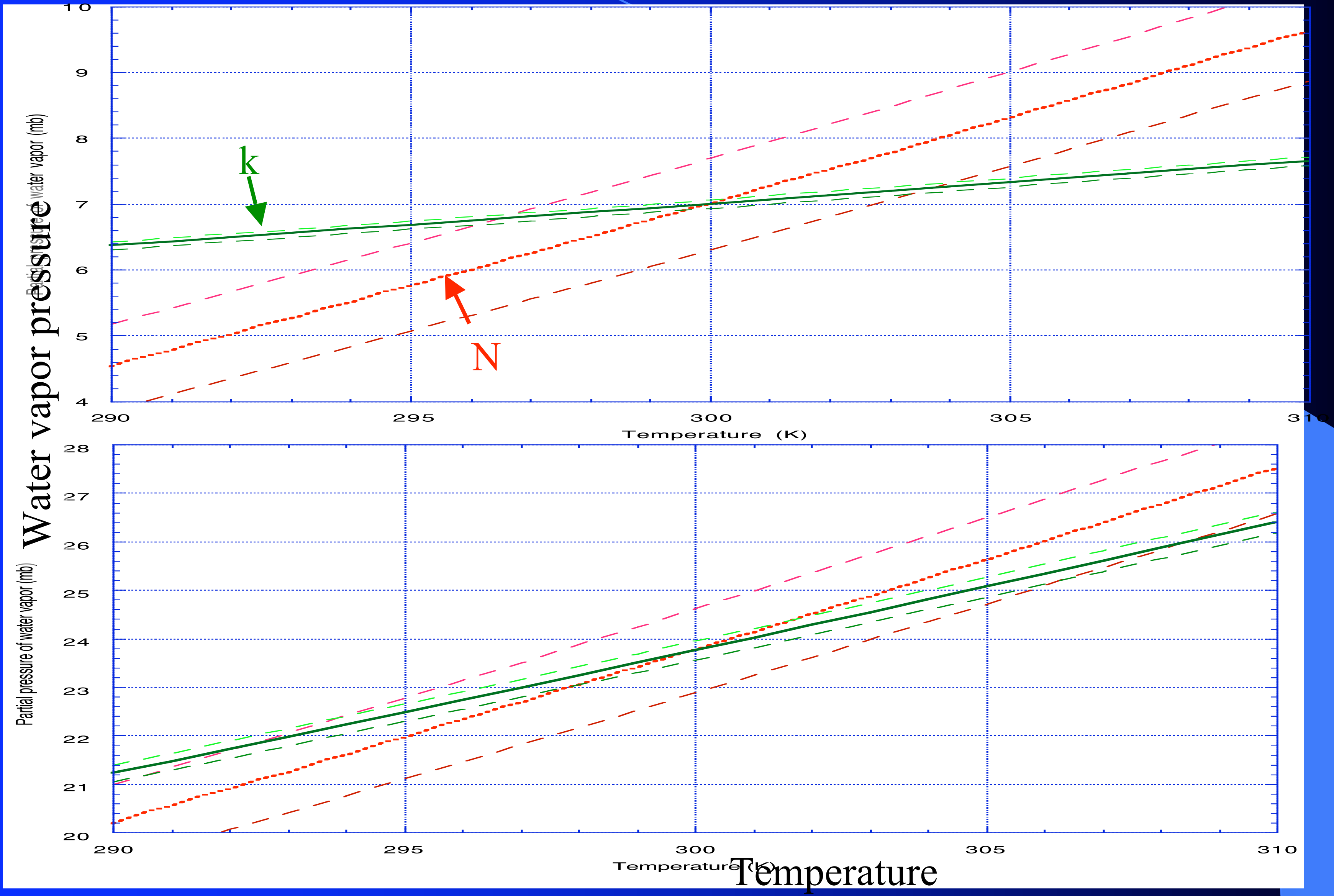


Fig. 5 Computed standard deviation of the error in the retrievals of temperature (left panel), expressed in Kelvin and water vapor partial pressure (right panel), expressed in percent, using simulated ATOMMS observations for the six labeled Lowtran atmospheres (Trop = tropical; MLS = mid-latitude summer; MLW = mid-latitude winter; ArS = Arctic summer; ArW = Arctic winter; USS = U.S. Standard).

Water Vapor Accuracy (Lower Troposphere)



T & WV Retrievals in Presence of Clouds

- Mid-latitude summer with highly asymmetric broken cloud deck between 4.5 & 5.5 km altitude

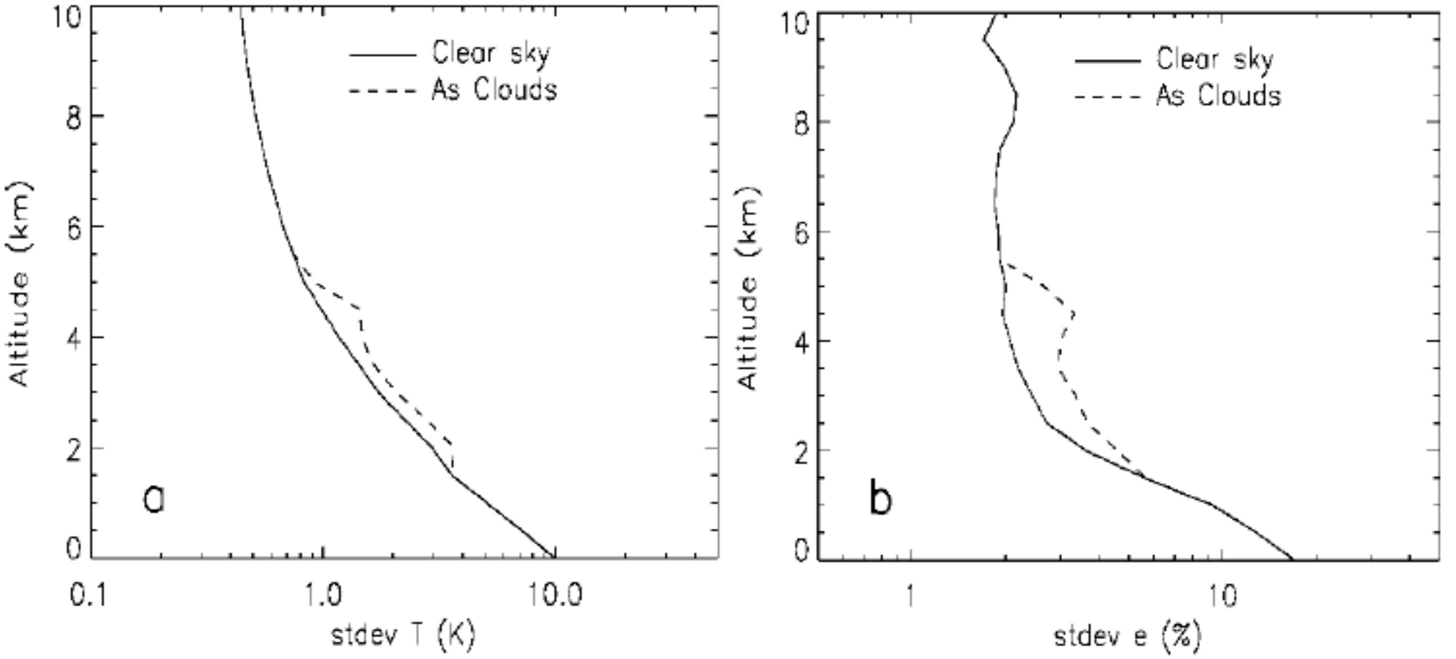


Fig. 7 Computed standard deviation of the errors in the retrievals of (a) temperature and (b) water vapor pressure using simulated ATOMMS observations. The background atmosphere is the Lowtran 2 mid-latitude summer profile. Solid lines are for clear sky conditions, while the dashed lines were computed 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}.

T & WV Retrievals in Presence of Clouds

- Highly asymmetric Arctic fog from surface to 1 km

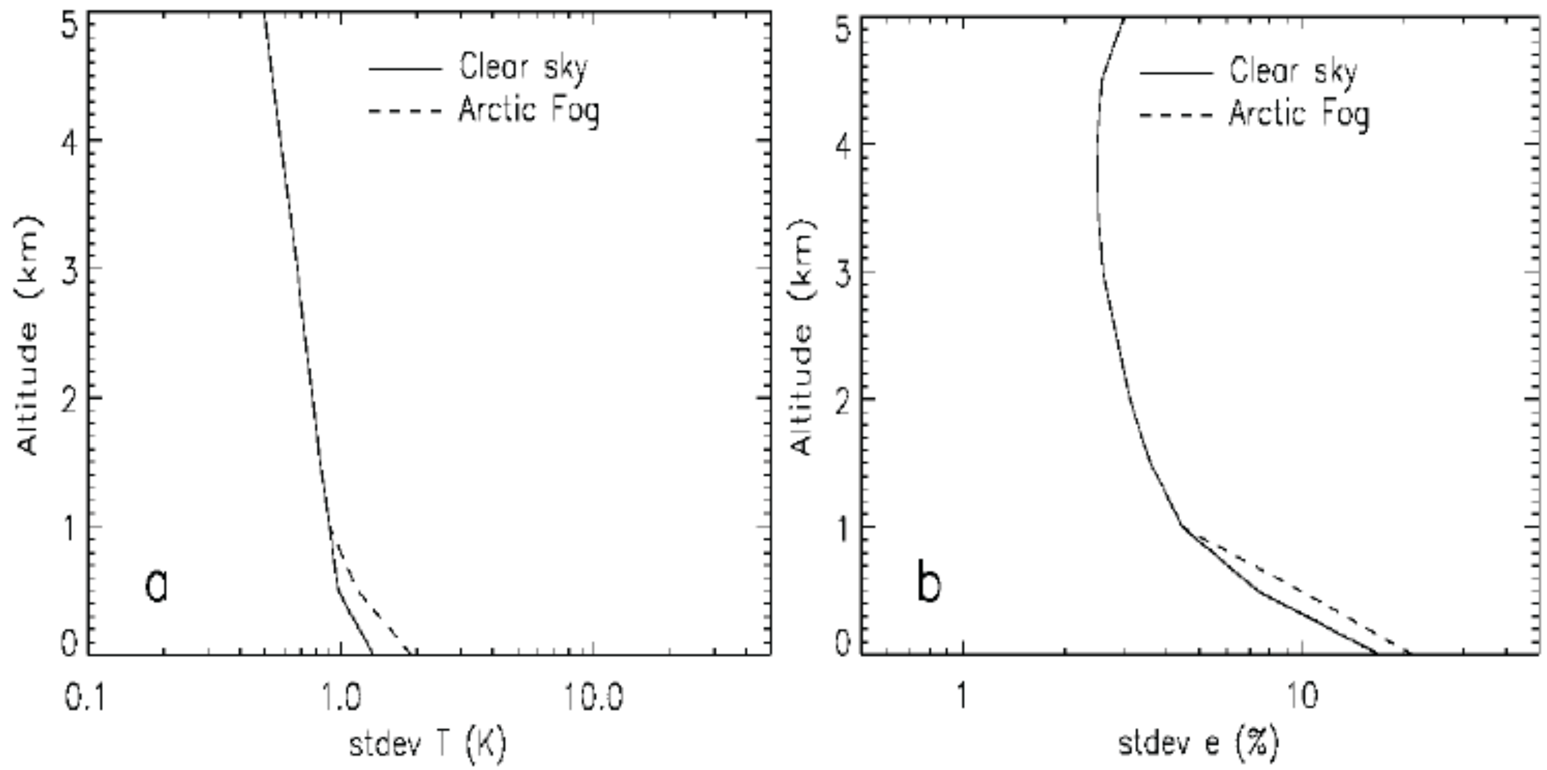
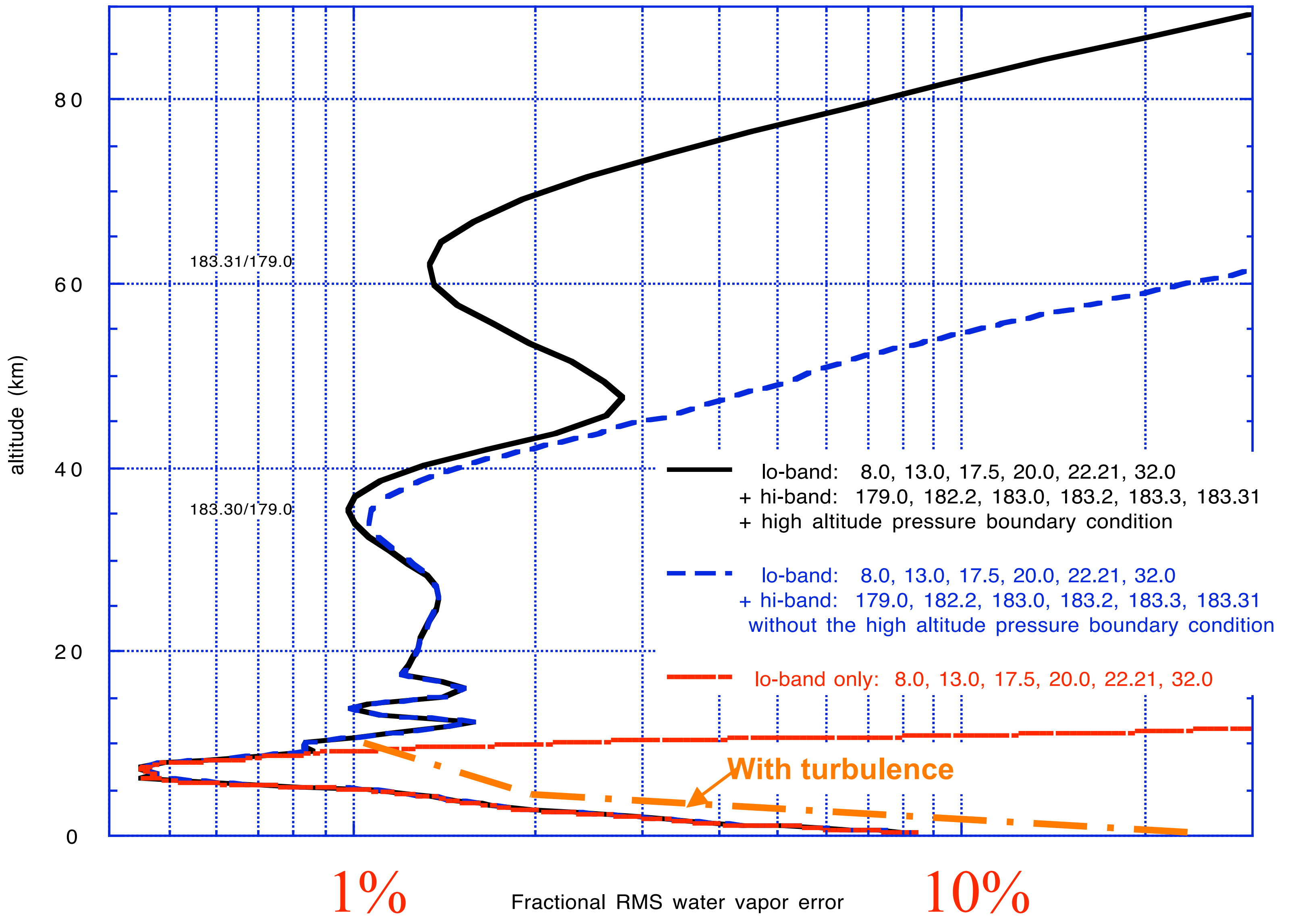
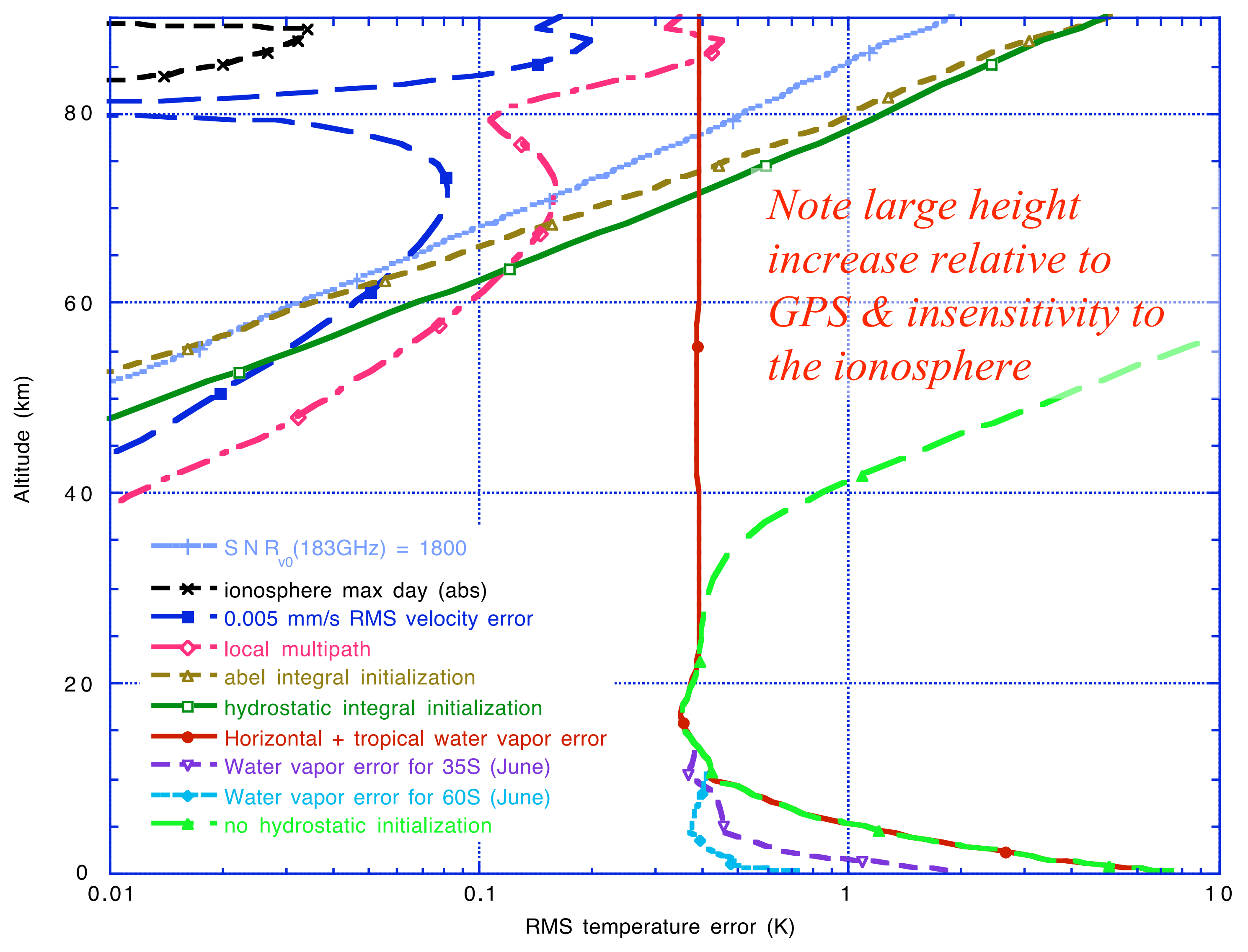


Fig. 8 Same as Fig. 7 except the background atmosphere is the Lowtran 5 Arctic Winter. For the inhomogeneous Arctic fog case, a cloud with liquid water content of 0.15 $\mathrm{g\,m^{-3}}$ extends from ground level to 1.0 km above ground.

Precision of Individual Water Vapor Profiles

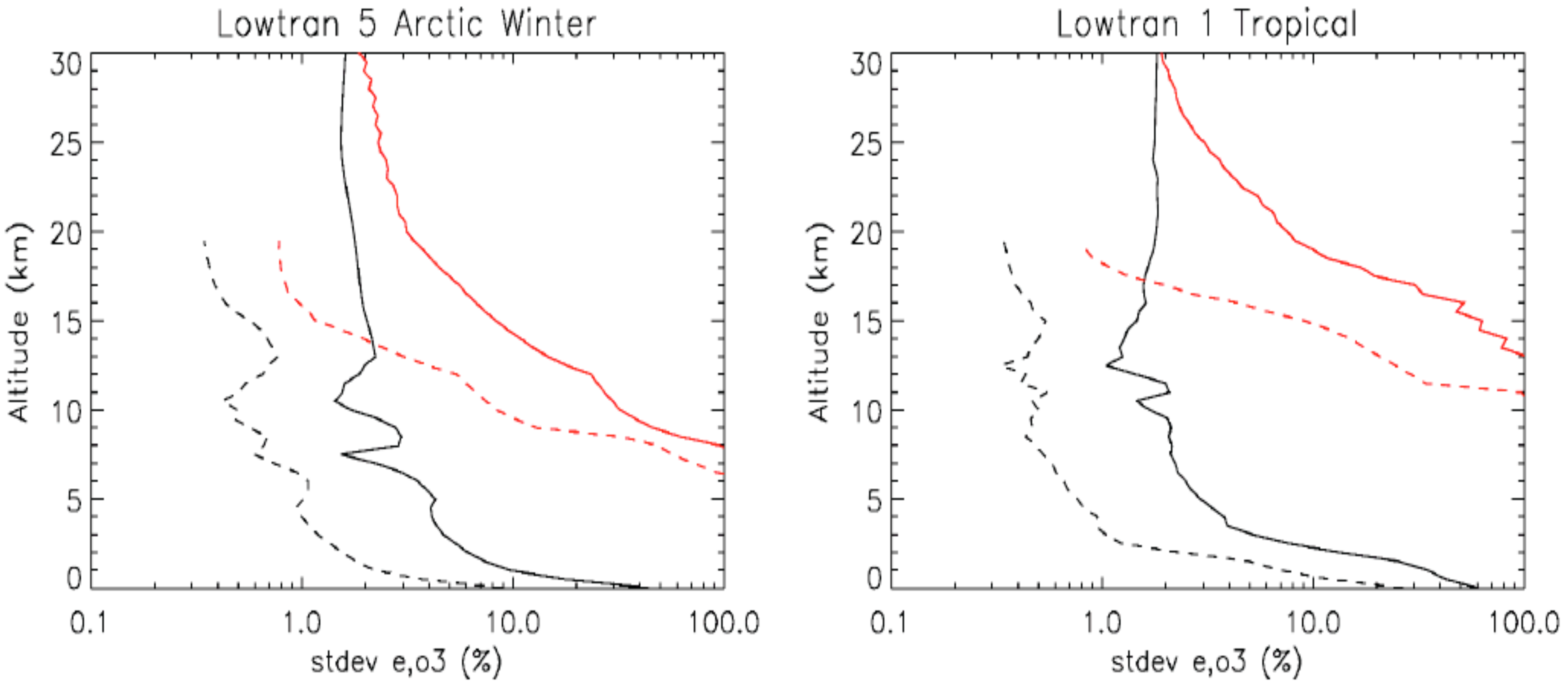


Precision of Individual Temperature Profiles



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

Ozone & Water Vapor Retrieval Precision



- Standard deviation of simulated errors of water vapor (black) and ozone (red) from satellite (solid) and aircraft occultations (dashed).
  - *Aircraft performance noticeably better than satellite performance*
- At lower altitudes, retrieval error quickly increases because ozone absorption at that altitude 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

Þ ***Excellent INSTRUMENT for CLIMATE***

Long Range Concept

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

Outline

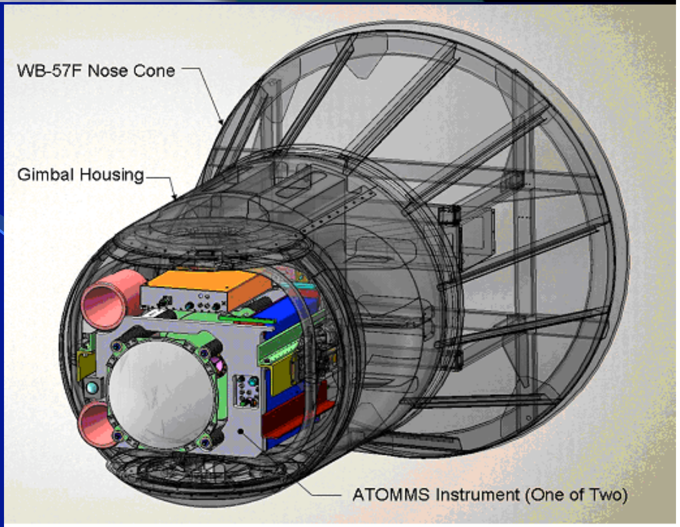
- Science drivers & observational needs
- Absorption Retrieval Theory Overview
- Accuracy of retrievals
- **Demonstration mission overview**

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 earlier this year to build and demonstrate the ATOMMS capability in 2008-2009
  - NASA will support aircraft time

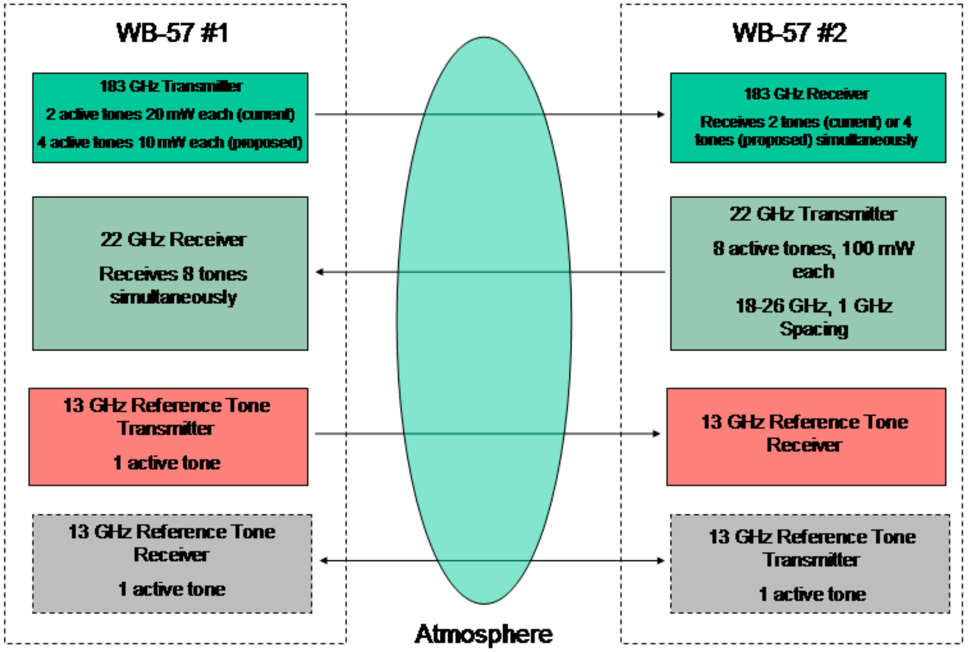
Aircraft-aircraft demonstration

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



ATOMMS MRI Proposal

Instrument Hardware



WB-57 #1

183 GHz Transmitter
2 active tones 20 mW each (current)
4 active tones 10 mW each (proposed)

22 GHz Receiver
Receives 8 tones simultaneously

13 GHz Reference Tone Transmitter
1 active tone

13 GHz Reference Tone Receiver
1 active tone

Atmosphere

WB-57 #2

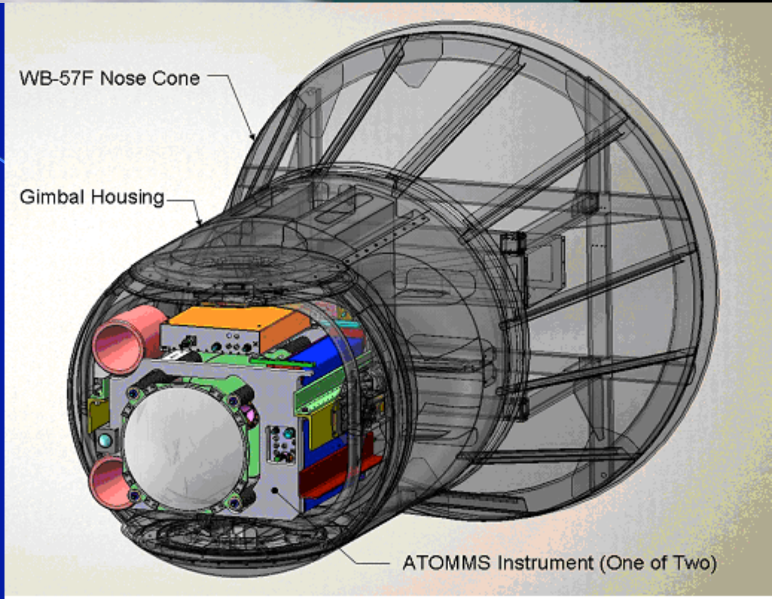
183 GHz Receiver
Receives 2 tones (current) or 4 tones (proposed) simultaneously

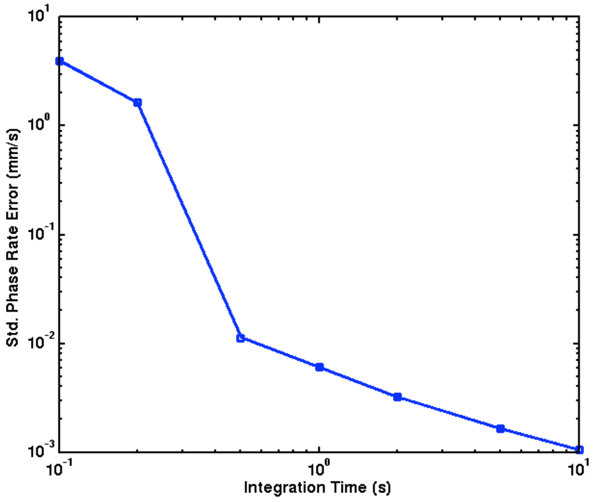
22 GHz Transmitter
8 active tones, 100 mW each
18-26 GHz, 1 GHz Spacing

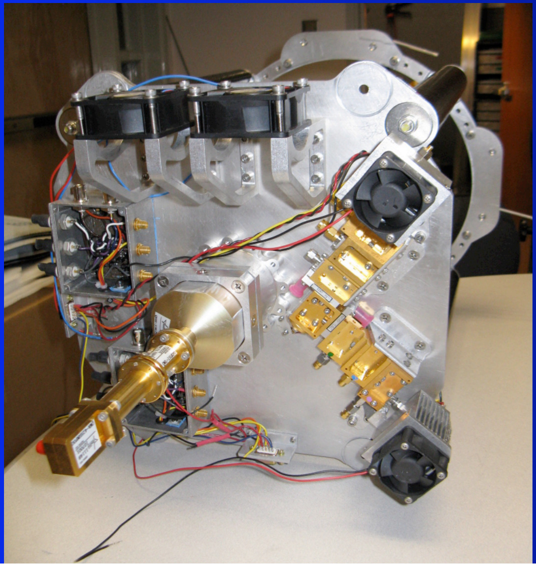
13 GHz Reference Tone Receiver

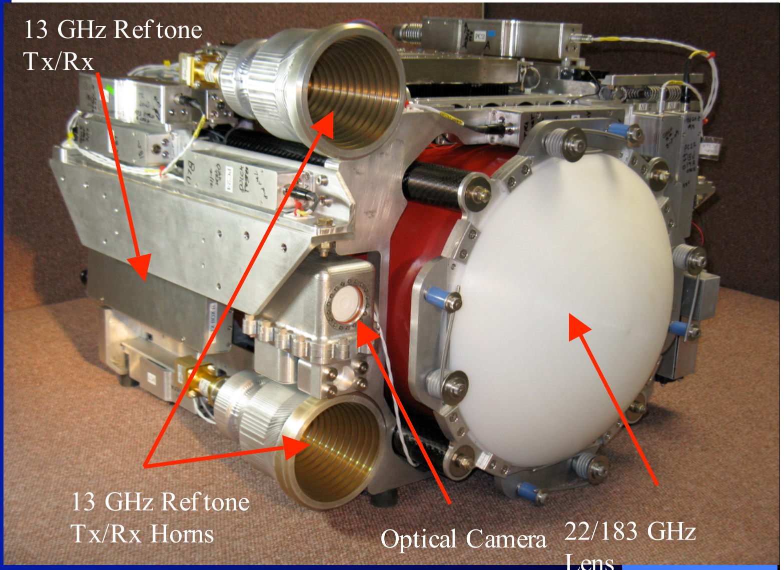
13 GHz Reference Tone Transmitter
1 active tone

System overview





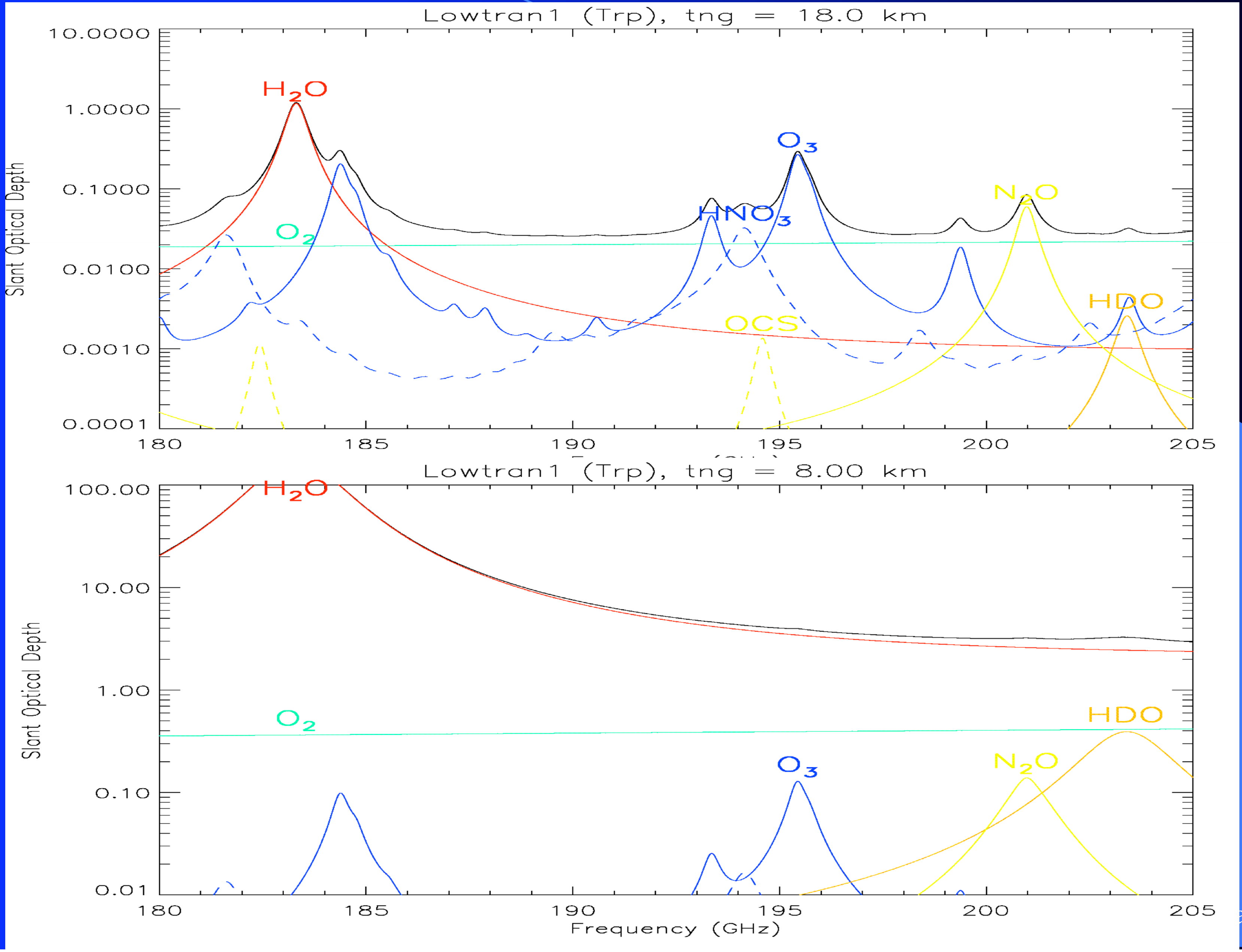




Aircraft - aircraft cm & mm-wavelength Occultation Demonstration

- Objective: Demonstrate 22, 183 & 195 GHz occultation observations ability to precisely observe
  - 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) to upper 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

ATOMMS Hi-band Spectrum at 18 and 8 km



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:

- Accuracy of near-22 & 183 GHz water vapor, temperature and pressure in clear and cloudy air
  - 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

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

Instrument Overview

- 22 GHz
  - ~8 tones between 18 and 26 GHz
  - Solve for water vapor and liquid water content
- 183 GHz water and 195 GHz ozone lines
  - 2-4 tones between 170 and 200 GHz
  - 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
- No cryogenics
- Build at UA

ATOMMS System Elements & Development

- ATOMMS instrument
- ATOMMS POD
- WAVES
- WB-57F Aircraft
- Retrieval system
- Ground truth for evaluation

Schedule

- began June 2007
- Aircraft to aircraft demonstration ~January 2010