The Active Temperature Ozone and Moisture Microwave Spectrometer (ATOMMS)

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1. Introduction

Radio occultation has proven itself to be a powerful technique for remotely sensing Earth's atmosphere for weather prediction and climate. Its unique combination of vertical resolution, high precision, self-calibration and cloud penetration have been established in planetary science since the 1960's and on the Earth over the past decade via the GPS/MET, CHAMP and COSMIC GPSRO and other missions. While very powerful, the performance of RO missions to date has been limited by their utilization of signal sources from existing telecommunication and navigation systems designed to minimize their sensitivity to the atmosphere. On Earth, a basic limitation in using GPS wavelengths for RO is the inability to separate the wet and dry contributions to the observed atmospheric refractivity. Direct interpretation of the refractivity for temperatures warmer than about 230K in the troposphere is inherently non-unique because of significant contributions from both the wet and dry parts of refractivity. The NWP solution has been to combine GPS RO observations with other observations and a weather model and an understanding of the observational and model errors to derive unique solutions to temperature and water vapor. A solution to this ambiguity is to probe the atmosphere via RO using frequencies near water vapor absorption lines (Hajj et al., 1997; Herman et al., 1997) to profile both the speed and attenuation of microwave signals and provide the information needed to profile temperature and water vapor simultaneously, eliminating the wet-dry ambiguity that limits GPS RO.

Here we discuss an RO implementation under development called the Active Temperature, Ozone Moisture Microwave Spectrometer (ATOMMS) that will probe the absorption lines of water vapor, ozone and other constituents. ATOMMS is effectively a cross between GPS RO and the Microwave Limb Sounder (MLS) that actively probes the absorption lines used by MLS with the much higher precision and vertical resolution of GPS RO, largely retaining the best features of each observing system to yield a powerful new capability. The goal of ATOMMS is a climate observing system that estimates the atmospheric state independent of atmospheric models. Last year, we presented some of our recent ATOMMS research at the OPAC3 conference (Kursinski et al. 2008). Here, we present some new finding that were not included in that work. A key step in the process of bringing ATOMMS to fruition is the demonstration of the ATOMMS concept using two high altitude aircraft that the National Science Foundation (NSF) has funded and for which NASA is providing the aircraft time.

2. Background

Our climate is changing. Making informed decisions about how to respond to these changes requires definitive knowledge about how the climate state is evolving based on a combination of observations and models. Observations in particular must provide estimates of the climate state (1) to determine how the climate is actually evolving and (2) to assess the realism and accuracy of climate models. Furthermore, observations must (3) provide quantitative constraints from which critical processes can be deduced and correctly represented in models.

As was discussed at this conference, GPS RO provides an unusual combination of features well suited to both Numerical Weather Prediction (NWP) and the climate change problem. These include high precision and accuracy, vertical resolution to perhaps 200 m at long, cloud-penetrating wavelengths and global coverage including sampling the full diurnal cycle with a constellation of GPS RO receivers such as the 6 satellite COSMIC mission. An often underappreciated feature of GPS RO is the unique relation between the profile of the path-integrated bending angle, and the profile of the index of refraction defined by an Abel integral transform under the assumption of local spherical symmetry. This uniqueness is important because deducing the real accuracy of climate models requires estimates of the climate state that are *independent* from the models. State estimates produced by NWP data assimilation systems inherently contain model information used to fill in information lacking in the observations. Without independence, the model and state estimates will be correlated such that comparisons will yield erroneously optimistic evaluations of model realism.

In this context, ATOMMS was conceived with two closely related goals in mind, (1) overcoming the inability of GPS RO to profile temperature and water vapor simultaneously and (2) maximizing the science return from a RO system designed from scratch**.** In this context, ATOMMS is a spectrometer designed to provide sufficient information to create an over-determined remote sensing problem, independent from models, in marked contrast to the typical situation where model or climatological information must be added to convert an observationally under-determined problem into a solvable over-determined problem.

A profile of refractivity provides insufficient information to separate the wet and dry refractivity contributions (one observable to constrain two unknowns). The wet and dry contributions can be separated by combining GPS RO with a model forecast and other observations within a data assimilation framework. However, as noted, in the climate context, achieving the goal of determining the atmospheric state independently from models requires estimating the climate state directly from observations. The basic concept behind ATOMMS is to make occultation observations at frequencies sensitive to absorption by water vapor that provide profiles of both bending angle and absorption. From these, profiles of refractivity and absorption coefficient can be derived via Abel transforms or functional equivalents that provide sufficient information to profile water vapor and temperature simultaneously, independent of models, under the assumption of local spherical symmetry.

Over the past decade, with support initially from NASA and subsequently from NSF, we have worked to develop a detailed understanding of the key errors while simultaneously refining the instrument and retrieval system designs to establish the expected performance of ATOMMS and identify many of its likely scientific applications. By probing both the 22 and 183 GHz water absorption lines, ATOMMS will precisely profile water vapor and temperature from near the surface through the mesosphere yielding sensitivity to water vapor in the lower stratosphere about 10,000 higher than GPS RO. ATOMMS will also profile ozone from the upper troposphere through the middle atmosphere via the 184 and 195 GHz ozone lines. ATOMMS has a natural niche in the upper troposphere/lower stratosphere (UTLS) because of open climate questions, inconsistent observations and the accuracy of ATOMMS measurements there.

We have worked to push high accuracy measurement down to the surface. Under cool to cold conditions ATOMMS works quite well whereas under very warm tropical conditions, accurate profiles will extend down to about 3 km altitude (Kursinski et al., 2008). ATOMMS frequencies are 100 times higher than GPS, reducing sensitivity to ionosphere by 10^4 relative to GPS which allows the profiles to extend to the mesopause and essentially eliminates unwanted sensitivity of profiles in the middle atmosphere to the solar and diurnal cycles in the ionosphere. This also allows a high altitude temperature needed for the upper altitude hydrostatic constraint to be determined directly from absorption linewidths measured by ATOMMS (Kursinski et al., 2008). We are building a prototype of the ATOMMS instrumentation that will begin making ATOMMS measurements in the spring 2009 between two high altitude aircraft to demonstrate the capabilities and performance.

3. Science Applications of ATOMMS

3.1. Climate Applications

Upper Troposphere/Lower Stratosphere (UTLS)

Observations are needed in the UTLS to assess the realism of climate models in terms of their transporting heat from increasing greenhouse gases from the surface up to the upper troposphere and the climatically critical water vapor feedback above 500 mb whose response in models may be unrealistically large. Our ability to measure water vapor and temperature in the UTLS under all sky conditions has been close to nil. ATOMMS dramatically improved profiling of temperature, water vapor and ozone will determine the true evolution in the UTLS as well as provide the precise, vertically resolved all-weather sampling necessary to capture variability and constrain processes operating in this interval. For example, behavior in the UTLS is tied closely to deep convection (thunderstorms and severe weather) with the moistening in the upper troposphere occurring when convective clouds are present necessitating the ability to profile in the presence of clouds. Furthermore these convective processes have sharply defined detrainment levels in the vertical dimension. To the extent that present observations can even see the upper troposphere, their coarse vertical resolution averages things over thick vertical scales that either lose the phenomena entirely or at the very least make the phenomena ambiguous. Therefore fine vertical resolution, global observations of water vapor and temperature in both clear and cloudy conditions are a (presently *unfulfilled*) prerequisite for understanding climate, evaluating and improving model realism and accurately predicting the future climate state.

Water Vapor Trends in the Lower Stratosphere

A patchwork of observations over decades suggest stratospheric moisture concentrations have increased at an average rate of ~1%/year while at the same time the tropical tropopause has, if anything, become colder indicating stratospheric moisture control is more complex than simple gradual ascent through the tropical tropopause cold trap. Still more confusing is recent disagreement between satellite (HALOE) and balloon measured trends over Colorado. ATOMMS' precise, vertically resolved, cloud penetrating *collocated* profiles of H_2O, O_3 and temperature (and H_2O isotopes with additional frequencies (Kursinski et al., 2004)) are a powerful set of tracer constraints to determine strat-trop exchange processes and trends globally in the UTLS regime.

Atmospheric Temperature, Lapse Rates & Geopotential

While climate models predict free tropospheric temperatures will increase more rapidly than the surface, analysis of warming captured by decades of MSU radiances have ranged from little if any free tropospheric warming to tropospheric warming at least as rapid as surface temperatures (Karl et al. (Ed.), 2006). This unsatisfactory situation reflects problems in inter-calibration across multiple platforms and the inherent ambiguity of coarse vertical resolution nadir-viewing satellite observations. Furthermore, dynamically critical lapse rates are poorly observed globally and may be poorly represented in models. Gaffen et al. (2000) found decadal variations in the tropical lower tropospheric lapse rates in both radiosondes and satellite microwave radiances that could not be reproduced by models even when forced with the observed SSTs.

ATOMMS will determine temperature and lapse rates globally at the sharp vertical scales at which they vary in both clear and cloudy conditions. Over time, ATOMMS will also determine the critically important altitude at which "tropospheric warming" transitions to "stratospheric cooling" the variations of which may be contributing to the MSU warming trend discrepancies noted above (Randall and Herman, 2007). By averaging the heights of the 200 mb level to an accuracy of 1 meter, ATOMMS will determine the average tropospheric temperature to 20 mK yielding an extremely sensitive thermometer.

Cloud Feedback and Parameterizations

Coincident cloud observations and ATOMMS relative humidity in and around clouds will help to establish the relation between cloud properties and relative humidity at scales typically resolved by climate models including the frequency and amount of supersaturation and supercooled mixed phase clouds, important but poorly observed and understood phenomena sorely awaiting new observational constraints.

Tropical Water Cycle & Subtropical Dryness

As noted in the *IPCC (2007),* in the tropics, the water vapor feedback could involve changes in the water vapor content of either the convective or dry regions, as well as changes in the relative area of the two regions. Humidity in the extensive subsidence regions in the subtropics and tropics where OLR is greatest depends on saturation vapor pressure at remote points along the parcel trajectories. The water vapor feedback in the dry regions therefore depends on how the properties of these points and advection following saturation will change as the climate warms. ATOMMS will precisely determine the climatology and trends in the behavior of these saturation points, as well as tightly constrain subsequent motion of the air parcels by vertically resolving precise mixing ratios to determine how the water vapor feedback operates in the tropics. ATOMMS will also precisely determine the spatial extent and relative area of the moist and dry regions of the tropics and their trends as well as the horizontal specific humidity gradient between the upwelling and subsiding regions strongly constraining the strength of the tropical Hadley and Walker circulations.

Polar Conditions

Models predict rapid warming at high northern latitudes that seems to be at least qualitatively consistent with observations of increasing surface temperatures, reductions in summertime sea ice extent and some indications that Greenland ice sheet melting may be accelerating. Unlike present satellite observations whose sensitivity to surface conditions and clouds and poor vertical resolution have limited their application on understanding climate change, ATOMMS' unique ability to profile the atmosphere to the surface throughout the annual cycle regardless of clouds and surface conditions promises a new set of constraints to understand the evolution of climate at high latitudes, filling in gaps about what the high latitude atmosphere is doing and how it is coupled to the changing surface conditions. Furthermore, ATOMMS' determination of surface pressure at high latitudes will significantly reduce errors that limit the ability to relate the precise time dependent gravity signatures from the GRACE mission to changes in the Antarctic ice field mass and global sea level.

3.2. NWP Applications

Our goal for truly global coverage including complete diurnal sampling for climate is a LEO-LEO constellation of a dozen or more ATOMMS instruments. As John Eyre noted at the conference, because of its expense, an ATOMMS LEO-LEO constellation is probably not an efficient use of funds for NWP purposes. However, if such a constellation were implemented for climate monitoring as we hope, NWP would definitely make use of the data. Below we note a few specific NWP applications.

Bias corrections

At the workshop, Dick Dee presented indications of improvements in the quality of reanalyses that resulted when GPS RO observations were assimilated without bias correction. AMSU-A and radiosonde bias estimates were improved using only 150 CHAMP occultations per day. ATOMMS simultaneous profiling of water vapor, temperature and pressure vs. height as well as ozone at higher altitudes will likely contribute substantially to improved bias estimation of other observational data sets.

Fronts

Mid and high latitude severe weather fronts of great importance to NWP are quite difficult to sense from orbit. IR and shorter wavelength observations are limited by clouds and coarse vertical resolution limits the utility of passive microwave observations for characterizing fronts. RO can penetrate through clouds and somewhat surprisingly, the very shallow angle of the frontal surface is well matched to the RO geometry (e.g., Syndergaard et al., 2005). However, GPS RO's ability to sense fronts is limited by the relatively small refractivity contrast between the compensating wet and dry refractivity contributions on the warm and cold sides of the front (Hardy et al., 1993). In contrast, ATOMMS occultations will provide the information necessary to separate water vapor from dry density (and then temperature and pressure through the hydrostatic relation) in order to observe the temperature and water vapor contrasts across the front as the occultation tangent point crosses the frontal surface yielding an indication of the severity of the front as well as its location and, when sampled by multiple occultations, its motion. This ability to measure fronts from space should be particularly useful for forecasting as fronts over marine environment approach continental regions.

Surface pressure

ATOMMS will provide far better constraints on surface pressure than GPS RO because it directly separates the wet and dry refractivity contributions deep into the troposphere. ATOMMS should determine pressure surface heights throughout the free troposphere to about 10 to 20 m (Kursinski et al., 2002) yielding powerful dynamical and thermodynamical constraints for NWP.

3.3. Comments on the 2007 NRC Decadal Survey

The National Research Council (NRC) released a Decadal Survey report in 2007 in response NASA and NOAA requests to recommend (1) high-priority flight missions to support national research and monitoring of the Earth over the next decade, and (2) important directions that should influence planning for the decade beyond." While the Decadal Survey (2007) is overall a good input giving much requested direction to NASA and NOAA, it is also somewhat disappointing in terms of its recommendations about observations of water vapor and the limited quantitative traceability it provides between key scientific questions and its recommended set of mission solutions. Regarding water vapor, to first order it simply identifies observations that provide some measure of water vapor, but makes little distinction among observational methods with regard to the resolution, precision, accuracy and ability to sample in clouds and over land. Regarding the capabilities of GPS RO, the Decadal Survey indicates somewhat misleadingly that GPS RO can profile both water vapor and temperature. It would be more correct to state that GPS RO can profile water vapor **OR** temperature but not both simultaneously. At a simple level, we think of GPS RO as profiling temperature and pressure above the 230 K level in the troposphere and water vapor at altitudes below the 240 K level in the troposphere. The Decadal Survey correctly points out the ability of a microwave sounder in geosynchronous orbit to penetrate clouds and sample the diurnal cycle, but it also understates the limitations of the inherently poor vertical resolution of downward-looking passive microwave observations and the ambiguities associated with variable surface emissivity over land that will significantly limit its ability to characterize the boundary layer.

Little traceability is provided that would allow one to determine the effectiveness of the Decadal Survey's recommended mission suite in answering the open questions about climate change. This is a bit surprising in light of the science traceability matrices that NASA requires be included in its Mars Scout and Discovery class mission proposals.

Our suggestion is that a document like the Decadal Study can be improved upon by defining a set of key scientific objectives and goals and associated desired observational performance, *independent of present observational capabilities*. This would then be used to develop a conceptual design of an observing system capable of addressing as many of these objectives as possible. A key result of this design exercise would be identifying the set of objectives that ***cannot*** be met at present that would require development of new instrumental capabilities. The set of unmet objectives would be used in defining the observational R&D program of NASA for instance, tightly coupling this program to unfulfilled scientific objectives critical to climate.

4. ATOMMS Retrieval Theory Overview

Here we summarize some key aspects of the ATOMMS retrievals. ATOMMS measures differential absorption by measuring the strength of signals at two or more frequencies simultaneously. This differential approach attenuates unwanted effects that are largely common to both frequencies such as antenna gain and turbulent scintillations and eliminates requirements about absolute intensity that can be very challenging to achieve in orbit. ATOMMS will sample the spectrum near the 22 GHz water line with at least five frequencies in order to separate the effects of liquid water from water vapor as well as refine the spectroscopy while in orbit (Kursinski et al., 2008). The Abel integral for transforming profiles of slant path optical depth to extinction coefficient is given in Kursinski et al. (2002). Kursinski et al. (2008) summarizes a more general method of deriving the extinction coefficient profile in the presence of clouds that isolates and removes the effects of inhomogeneously distributed liquid water clouds.

Turbulence impact and removal

Propagation of electromagnetic signals through a turbulent refractive medium creates diffractive interference that produces phase and amplitude scintillations ("twinkling of a star"). As a result, ATOMMS acts as a planetary-scale scintillometer to measure turbulence globally. In the context of profiling water vapor and ozone, these turbulent amplitude scintillations are a noise source that will be reduced significantly via the differential opacity measurement approach used by ATOMMS.

We have spent considerable effort developing an understanding of the effects of turbulence on the ATOMMS measurements summarized to some degree in Kursinski et al., (2008). Angel Otarola's dissertation to be complete by December 2008 focuses on the impact of turbulence including a parameterization of the wet contribution of refraction, the spectral characteristics of turbulence in the horizontal and vertical directions and the impact of turbulent variations in the imaginary part of the refractivity.

Figure 1 shows estimates of the impact of turbulence on measurement accuracy based upon our parameterization of turbulent fluctuations in the dry and wet contributions to the real part of atmospheric refractivity. Kursinski et al. (2008) describes how we estimate the partial cancellation of turbulence-induced amplitude scintillations through a differential opacity approach. Figure 1 shows simulated fractional errors in measuring the difference optical depth for a single frequency pair (22.0 GHz minus 20.0 GHz) as a function of altitude for several conditions: instrumental errors only, i.e., no turbulence effects, instrumental errors plus dry turbulence effects, and instrumental errors plus dry and we turbulence effects. Measurements of the optical depth difference for selected frequency pairs are inputs for the final species retrieval inversion.

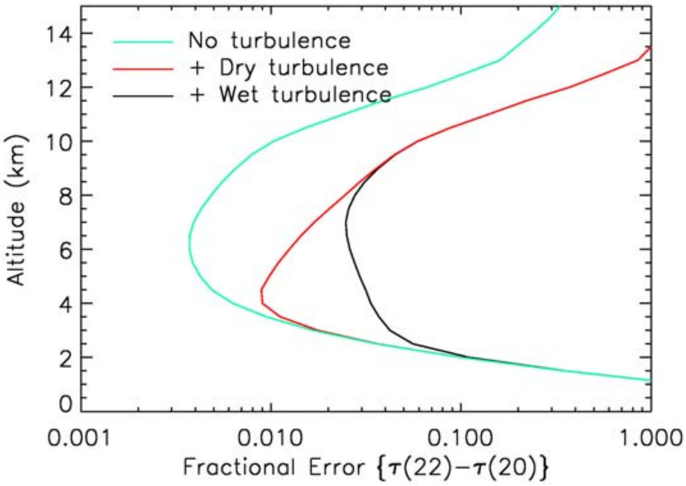

Figure 1: Simulated fractional errors in estimating the difference optical depth (via ATOMMS occultations) for a single, representative frequency pair (22.0 minus 20.0 GHz) made by ratioing the simulated, measured amplitudes. The atmosphere is the Lowtran 2 mid-latitude summer profile. The green line includes expected instrumental performance errors such as signal to noise ratio but does not include turbulence. The red line includes the effects of dry turbulence. The black line includes both wet and dry turbulent effects.

Optimizing the Fractional Error in $\tau(f_1)-\tau(f_2)$ as a Function of Scintillations and $\tau(f_1)$

We discuss the errors and conditions for optimal performance given our refined understanding of turbulence. Kursinski et al (2002) presented the differential absorption measurement approach where the amplitudes of signals at 2 nearby frequencies are measured simultaneously and used to derive the differential optical depths from the logarithm of the ratio of the two signal amplitudes. The resulting optical depth difference is

$$\Delta\tau_{12} = \tau_1 - \tau_2 = 2\ln\left[\frac{A_{10}}{A_1}\frac{A_2}{A_{20}}\frac{F_1}{F_2}\left(\frac{G_1}{G_2}\right)^{1/2}\right] \qquad (1)$$

where A_{10} and A_{20} are the signal amplitudes measured above the atmosphere, A_1 and A_2 are the two signal amplitudes measured during an occultation, F_1 and F_2 are amplitude scintillations due to turbulence and diffraction at the two frequencies and G_1 and G_2 are instrumental gain variations at the two frequencies. The accuracy to which we can estimate τ_{12} depends on how accurately we can measure A_{10}, A_1, A_{20}, and A_2, estimate F_1/F_2 and control or calibrate G_1/G_2. Kursinski et al. (2002) show that assuming the errors are independent, the fractional error in $\Delta\tau_{12}$ is given by (their equation 11).

$$\frac{\left\langle \varepsilon^2_{\tau_{12}} \right\rangle}{\Delta\tau^2_{12}} = \frac{4}{\left(1-a_{12}\right)^2 \tau_1^2} \left[\begin{array}{l} \dfrac{\delta_0}{S^2_{v_{10}}\delta_{10}} + \dfrac{\delta_0 V_0}{S^2_{v_{10}} Z_R}\dfrac{e^{\tau_1}}{F_1^2 G_1} + \dfrac{\delta_0 V_0}{S^2_{v_{20}} Z_R}\dfrac{e^{a_{12}\tau_1}}{F_2^2 G_R} + \dfrac{\delta_0}{S^2_{v_{20}}\delta_{20}} \\ + \dfrac{\left\langle \varepsilon^2_{F_1/F_2}\right\rangle}{\left(F_1/F_2\right)^2} + \dfrac{1}{4}\dfrac{\left\langle \varepsilon^2_{G_1/G_2}\right\rangle}{\left(G_1/G_2\right)^2} \end{array}\right] \qquad (2)$$

where <x> denotes expected value of x, $a_{12} = \tau_2/\tau_1$, S_{v10} is the voltage signal to noise ratio in the absence of any atmospheric effects for an integration time of δ_0 (typically 1 second), δ_{10} and δ_1 are the integration times over which the f_1 signal is measured above the atmosphere and during the occultation respectively with δ_{20} and δ_2 being defined analogously, V_0 is the vertical velocity of the ray path in the absence of the atmosphere and Z_R is the vertical resolution. The dominant errors in (2) are the SNR during the occultation (the two e^{τ}/S_{v0}^2 terms) and the F_1/F_2 errors.

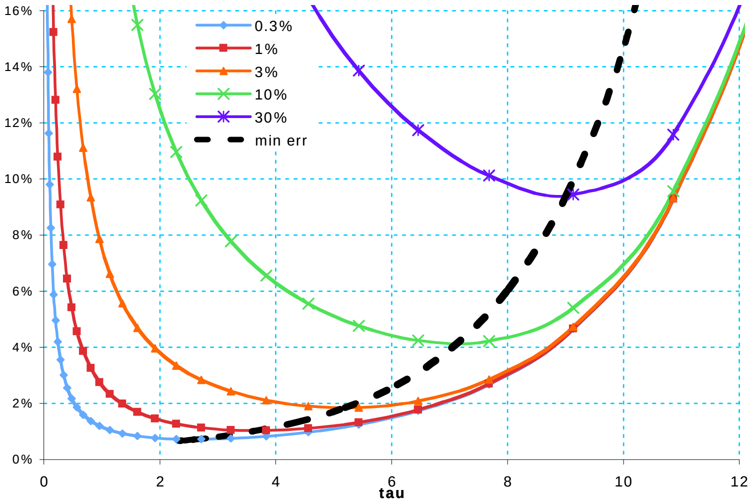

Figure 2: The fractional error in measured $\Delta\tau_{12}$ versus τ_1 for turbulence-induced, amplitude ratio errors (after amplitude ratioing) ranging from 0.3% to 30%, for $S_{v10}= S_{v20}=2000$, a_{12} =0.2, 200 m vertical resolution and V_0 = 2.5 km/sec. The black dashed line defines the curve of minimum fractional $\Delta\tau_{12}$ error

Figure 2 shows how the standard deviation of the fractional error in $\Delta\tau_{12}$ depends on the residual amplitude error and the optical depth, τ_1. In Fig. 2, errors to the left of the minimum fractional $\Delta\tau_{12}$ error curve (dashed curve) are dominated by amplitude scintillation errors whereas errors to the right are dominated by the decreasing SNR as optical depths become large. The minimum fractional $\Delta\tau_{12}$ error occurs at the transition between these two regions. So, as the scintillation error increases, the minimum fractional $\Delta\tau_{12}$ error is achieved by choosing frequencies closer to line center to measure higher optical depth or by switching to a more opaque line. So, for relatively small turbulence-induced amplitude scintillation errors of 0.3%, comparable to those considered by Kursinski et al. (2002), the optimum optical depth is around 2.5 whereas for a large turbulence-induced amplitude error of 30%, the optimum optical depth is 8 to 9 assuming 1 second voltage SNRs in the range of 1000-2000. By measuring at such high optical depths, the 30% residual amplitude error can yield a fractional error in $\Delta\tau_{12}$ of less than 10%. We note that the dashed curve in Fig. 2 shows that the optimum error grows slowly at smaller scintillation errors such that the optimum error increases by about a factor of 2 as the scintillation error grows from 0.3% to 3%. However at larger 30% scintillation errors, the minimum error grows far more rapidly.

Therefore, large SNRs are important (1) for minimizing amplitude errors when turbulent scintillations are small and (2) for minimizing the fractional error in $\Delta\tau_{12}$ when turbulent scintillation errors become sufficiently large that large optical depths must be probed to minimize errors.

183, 22 GHz Overlap Interval

Figure 3 shows how we can utilize both the relatively strong 183.31 GHz and relatively weak 22.21 GHz water absorption lines to achieve accurate measurements of differential optical depth from near the surface upward into the stratosphere. The solid lines show simulated fractional errors in the measurement of difference optical depth for several representative pairs of frequencies near the 183.31 GHz water absorption line, while the dashed lines show fractional errors for a few representative pairs of frequencies near the 22.21 GHz water absorption line. Note that we will use pairs of frequencies closer to the 183.31 GHz line to obtain fractionally more accurate estimates of difference optical depth at altitudes above 15 km (not shown in figure). A major challenge in retrieving water vapor is that its concentration increases over several orders of magnitude in moving downward from the upper stratosphere to the surface. We can achieve a nice altitudinal overlap in minimum fractional error between the 183 GHz and 22 GHz channels by selecting 183 GHz pairs further away from line center as the tangent altitude of the measurements approach the upper and middle troposphere. This will allow us to make cross comparisons of the 183 GHz-derived and 22 GHz-derived water vapor retrievals in the overlap region. These cross comparisons will be an important test of the accuracy of our entire retrieval system. As such we are planning to critically study this in the ATOMMS aircraft demonstration.

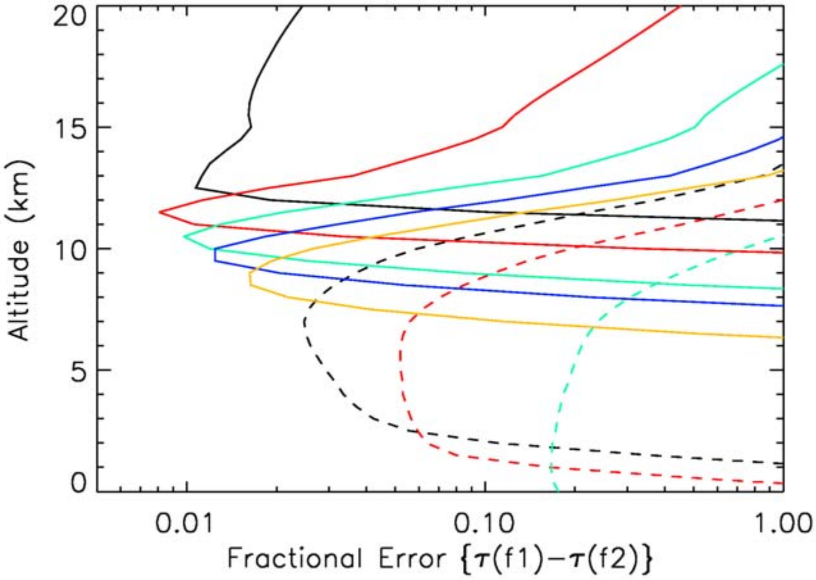

Figure 3: Simulated fractional error in measuring the difference in optical depth for selected pairs of frequencies as a function of altitude. The background atmosphere is the Lowtran 2 mid-latitude summer profile. Fractional errors take into account expected measurement uncertainty, atmospheric absorption and defocusing, and the effects of turbulent variations in both dry and wet real refractivity. Solid lines are 183 GHz pairs (Black: 183.0, 179.0 GHz; Red: 181.7, 179.0 GHz; Green: 180.0, 176.0 GHz; Blue: 179.0, 165.0 GHz; Orange: 176.0, 165.0 GHz) and dashed lines for 22 GHz pairs (Black: 22.0, 20.0; Red: 21.0, 18.0 GHz; Green: 19.0, 16.0 GHz).

4.1. Isolating the impact of clouds

We have developed a new method for isolating and removing the effects of ice and liquid water clouds that we summarized in Kursinski et al (2008). For clmate, it is critical that the ATOMMS observations provide sufficient information to ensure this is an overdetermined rather than underdetermined problem. We have found that the spectral shape and magnitude of cloud liquid water absorption near 22 GHz can be satisfactorily reproduced with two fitting parameters, cloud liquid water path and cloud temperature, thus requiring the retrieval algorithm to estimate two additional parameters. Overdetermination is accomplished by increasing the number of signal tones used simultaneously during the occultation observations. A key feature in our approach to clouds is that we attempt to isolate and remove the frequency dependent cloud absorption signature from the slant path absorption measurements before passing the slant path absorption measurements through the Abel transform or equivalent. This is because clouds are often far from spherically symmetric with respect to an occultation observation and ignoring this will lead to rather poor retrievals of water vapor.

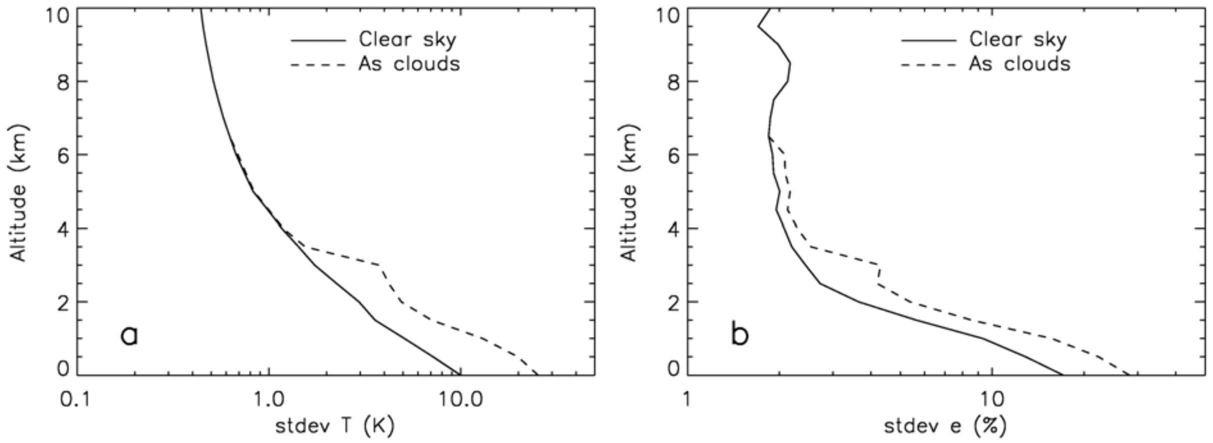

Figure 4: Computed standard deviation of the errors in the retrievals of (a) temperature and (b) water vapor pressure using simulated ATOMMS observations. The background atmosphere is the Lowtran 2 mid-latitude summer profile. Solid lines are for clear sky conditions, while the dashed lines were computed after placing two broken decks of altostratus clouds between 3 - 3.5 and 6 - 6.5 km altitude with liquid water contents of 0.3 and 0.2 gm^{-3} respectively. The cloud fields are highly non-symmetric about the local tangent point.

Sensitivity to Cloud Temperature

The presence of multiple cloud decks is a challenging problem for ATOMMS retrievals since the algorithm has to determine a single cloud temperature that best fits the observations. (While it is possible to solve for multiple cloud temperatures, this would require additional frequency pairs). Fortunately, the temperature sensitivity to liquid water absorption is relatively small, though not small enough that it can be ignored compared to other expected errors. Also the dependence at intermediate temperatures looks like an average of the dependence at high and low temperatures, based on our present understanding of the supercooled spectroscopy. Both of these points likely help in isolating the effects of multiple cloud decks. An example showing the effects of two non-symmetric cloudy layers on the simulated retrievals for temperature and water vapor are shown in Figure 4. In general the errors in the retrievals of temperature and water vapor increase from the altitude of the clouds and below. This is expected because the occultation observations corresponding to lower tangent altitudes can still pass through clouds located at higher altitudes. The clouds at 6 km have little impact on the temperature retrieval because at that altitude the temperature is highly constrained by the refractivity, while at lower altitudes where water vapor concentrations get large, a larger fraction of the temperature retrieval information comes from the absorption measurements. Based on our latest simulations, we believe that we can retrieve water vapor and temperature with accuracies within a factor of 2-3 of the retrievals made under clear sky conditions. These error estimates are dependent upon on our understanding of the liquid water absorption spectrum; however, it is clear that the supercooled liquid water spectrum needs to be determined better as it is very difficult to observe super cooled liquid water in the laboratory. To quantify and observe spectroscopic uncertainty, we believe it is crucial that ATOMMS observe at least one additional frequency pair beyond the minimum required for cloudy retrievals. For this reason, the ATOMMS aircraft demonstration has 8 frequencies near 22 GHz.

Cloud-related Biases?

At the workshop, Peter Bauer of ECMWF raised a question about whether any remaining, residual biases exist after removing the effects of ice and liquid water clouds. In theory the ATOMMS technique can provide the information necessary to eliminate biases to the extent that the spectroscopy is correct. Peter’s question does point out the need to run simulations of a variety of cloud distributions to assess whether any subtle residual bias will remain after applying our method. It seems likely that removing subtle residual biases after eliminating the first order effects of clouds or turbulence will require sampling on both sides of a gaseous absorption feature.

The ATOMMS occultations could include still more information by adding 2 measurements of polarization which could open the possibility of determining more about ice crystals: size distribution, facets, etc. Voyager radio occultations of Saturn's rings were able to constrain the ring particle sizes.

Spectral Availability Issues John Eyre raised the question of whether an active system like ATOMMS can operate within the spectral protection allocations in or near passive emission bands. For signals near 22 GHz, ATOMMS will probe the atmosphere at frequencies where transmission is allowed. At frequencies near183 GHz, the ATOMMS transmission levels are so low that the signals are below the detection specifications defined for radio astronomy and passive radiometry. ATOMMS achieves very high signal to noise ratios because the ATOMMS detection bandwidths are only a few Hz whereas the passive radiometry and radio astronomy bandwidths are MHz and above.

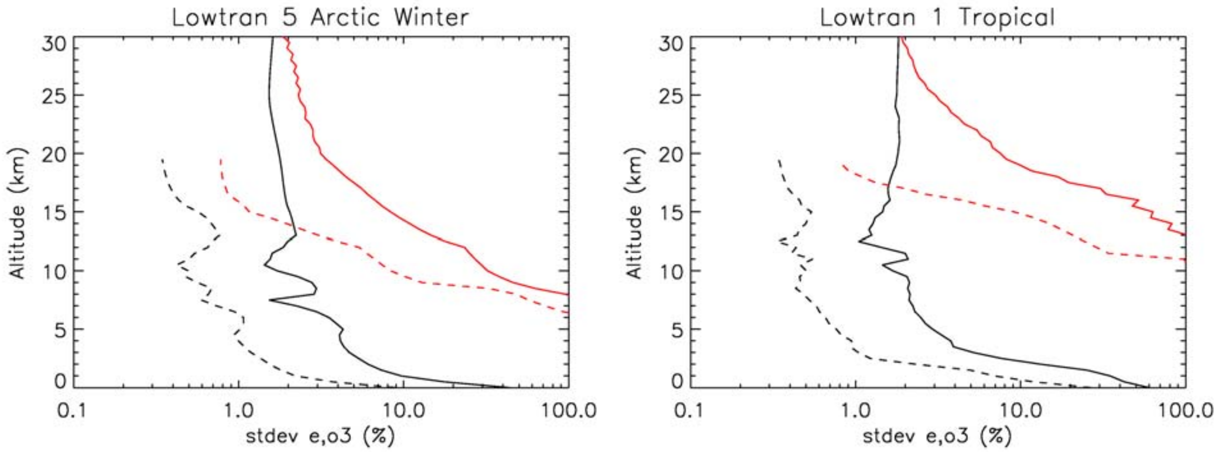

Figure 5: Standard deviation of simulated errors of water vapor (black) and ozone (red) from satellite (solid) and aircraft occultations (dashed). Panel a is for arctic winter conditions and Panel b is for tropical conditions.

Accuracy of Ozone Profiles

Ozone is critical to Earth through its absorption of UV and as a key greenhouse gas. Ozone is being modified by human activity. Tropospheric ozone is a key greenhouse gas forcing for the future and has been suggested as a possible culprit in the warming at high northern latitudes (e.g. Hansen et al., 2005). ATOMMS will profile ozone using the 184 and 195 GHz ozone lines. Figure 5 indicates predicted precisions for individual profiles will be 3% or better above the altitude of maximum mixing ratios in the lower portion of the middle atmosphere. This altitude varies from approximately 20 km in the tropics down to 14 km under high latitude winter conditions. Performance decreases at altitudes below the altitude range where ozone mixing ratios are maximum. In both of the cases shown, the altitude at which the error is approximately 10% coincides approximately with the altitude where the O_3 mixing ratio is 1 ppm. The altitudes where the errors are 30% are 10 km and 16 km respectively in the winter and the tropics. The aircraft to aircraft occultations will provide significantly better performance in the UTLS than the satellite observations because the air-air occultations do not sample and are not affected by the overlying O_3 layer in the stratosphere.

5. Aircraft to Aircraft Occultation Demonstration

With funding from the National Science Foundation (NSF) we are building a prototype of the ATOMMS instrumentation at the University of Arizona to demonstrate the ATOMMS concept between two high altitude WB-57F aircraft (see Fig. 6) beginning in Spring 2009 near Houston. This is a critical step required before ATOMMS can move into space. Water vapor, ozone, temperature and pressure will be profiled from near the surface to about 19 km altitude. We may also profile N_2O and $H_2{}^{18}O$ absorption lines that fall within the prototype instrument's spectral range. Evaluating the performance of the ATOMMS aircraft-aircraft occultations will be accomplished in part by comparing the 22 and 183 GHz water vapor profiles that overlap in the upper troposphere (Fig. 3). We hope to have another aircraft like HIAPER instrumented to make in-situ measurements of water vapor, ozone, temperature and pressure along the occultation path at the height where the 22 GHz and 183 GHz profiles overlap and perhaps with dropsondes to measure the occultation path at still lower altitudes. We plan to make measurements coincident with an overflight of MLS and perhaps GPS RO for cross-comparisons and evaluating the accuracy of GPS-derived humidity profiles. We may also make measurements over the Southern Great Plains (SGP) Atmospheric Radiation Measurement (ARM) site in Oklahoma for cross comparison with the instruments there.

Figure 6: Left hand panel: WB-57F aircraft with gymbal nose cone. Right hand panel: ATOMMS instrument mounted in the nose cone gymbal.

6. References

Decadal Survey (2007), *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future, Space Studies Board, Division on Engineering and Physical Sciences, National Research Council of the National Academies, The National Academies Press, Washington, D.C. www.nap.edu

Gaffen, D.J., B.D. Santer, J.S. Boyle, J.R. Christy, N.E. Graham, and R.J. Ross, Multidecadal Changes in the Vertical Temperature Structure of the Tropical Tropopause, *Science*, **287**, 1242-1245, 2000.

Hajj, G.A., E R Kursinski, and S. J. Walter, Examining the Appropriate GPS Science Signal Suitable for Radio Occultation Measurements of Atmospheric Water Vapor, *Fall AGU* 1997, G22C-04.

Hansen, J., et al. 2005. Efficacy of climate forcings. *J. Geophys. Res.* **110**, D18104, doi:10.1029/2005JD005776.

Hardy, K.R., G. A. Hajj and E. R. Kursinski, Accuracies of atmospheric profiles obtained from GPS occultations, *ION-GPS 93*, Salt Lake City, Utah, Sep.22-24, 1993.

Herman, B., D. Feng and X. Xun, GPS Remote Sensing Using a Third Frequency for Water Vapor Profiles of the Atmosphere, Fall AGU 1997, G22C-05.

IPCC (2007) *Climate Change 2007 - The Physical Science Basis*, Contribution of Working Group I to the Fourth Assessment Report of the IPCC (ISBN 978 0521 88009-1 Hardback; 978 0521 70596-7 Paperback

Karl, T.R., et al., “Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differenced” in A Report by the Climate Change Science Program and the Subcommittee on Global Change Research, Washington, D.C., 2006.

Kursinski, E. R., D. Feng, D. Flittner, G. Hajj, B. Herman, S. Syndergaard, D. Ward and T. Yunck, A microwave occultation observing system optimized to characterize atmospheric water, temperature and geopotential via absorption, *J. Atmos. Oceanic Technol.,* **19**, 1897-1914, 2002.

Kursinski, E. R. et al., An Active Microwave Limb Sounder for Profiling Water Vapor, Ozone, Temperature, Geopotential, Clouds, Isotopes and Stratospheric Winds, in *Occultations for Probing Atmosphere and Climate (OPAC-1),* Springer-Verlag, Berlin, p. 173-188, 2004.

E. R. Kursinski, D. Ward, A. Otarola, R. Frehlich, C. Groppi, S. Albanna, M. Shein, W. Bertiger, H. Pickett and M. Ross, (2008) The Active Temperature Ozone and Moisture Microwave Spectrometer (ATOMMS), in *Occultations for Probing Atmosphere and Climate (OPAC-3)*, Springer-Verlag, Berlin, *in press*, also available at http://www.atmo.arizona.edu/~kursinsk/NextGenOccEarth.htm

Randall, R. M., and B. M. Herman (2008), Using limited time period trends as a means to determine attribution of discrepancies in microwave sounding unit–derived tropospheric temperature time series, *Journal of Geophysical Research-Atmospheres*, **113**, D05105, doi:10.1029/2007JD008864.

Syndergaard, S., E. R. Kursinski, B. Herman, E. Lane and D. Flittner (2005) A Refractive Index Mapping Operator for Assimilation of Occultation Data, *Mon. Weath. Rev.*, **133**, No. 9, p. 2650–2668, doi: 10.1175/MWR3001.1