Development and demonstration of a new global climate sensor: The Active Temperature, Ozone and Moisture Microwave Spectrometer (ATOMMS)

E. R. Kursinski[1], D. Ward[1], A. Otarola[1], C. Groppi[1], M. Schein[1], R. Frehlich[2], W. Bertiger[3], H. Pickett[3], D. Rind[4], M. Ross[5], S. Al Banna[1], K. Sammler[1], M. Stovern[1], B. Wheelwright[1]

[1]*University of Arizona, Tucson, AZ, 85721, USA, kursinsk@atmo.arizona.edu*
[2]*National Center for Atmospheric Research, Boulder CO, 80307, USA, frehlich@ucar.edu*
[3]*Jet Propulsion Laboratory, Pasadena, CA, USA, 91109, willy.bertiger@jpl.nasa.gov*
[4]*NASA Goddard Institute for Space Science, NYC, NY, 10027, USA, drind@giss.nasa.gov*
[5]*Aerospace Corporation, El Segundo, CA, 90245, USA, martin.n.ross@aero.org*

ABSTRACT

To assess and improve climate models, precise and accurate measurements of the climate state are needed that must be as independent from the models as possible. We are addressing these fundamental observational needs as they relate to water vapor, ozone, temperature and pressure with a new remote sensing technique called ATOMMS. ATOMMS combines many of the best features of GPS Radio Occultations (RO) and NASA's Microwave Limb Sounder (MLS) by actively probing via satellite-to-satellite occultations the absorption lines that MLS probes passively.

ATOMMS overcomes several limitations of GPSRO by profiling bending angle simultaneously with absorption to provide enough information to profile water and temperature independent of other observations and climatologies. Probing via occultation offers several advantages over passive emission including an order of magnitude better vertical resolution, simple and unique retrievals, very high SNR and precision to capture variability and signatures of processes, all-weather sampling eliminating clear sky-only biases and self-calibration eliminating long term drift.

ATOMMS profiles of temperature, geopotential height and moisture will extend from the lower troposphere to the mesopause with typical precisions over much of this altitude range of ~0.4 K, 10 m and 1-3%. With additional signal frequencies, other trace constituents such as water isotopes can be measured in the upper troposphere and above with similar performance. ATOMMS will profile line of sight winds above the 10 mb level. ATOMMS also profile turbulence.

With funding from NSF and aircraft time from NASA, we are building a prototype instrument to demonstrate the ATOMMS concept and performance using two NASA high altitude WB-57F aircraft in 2010. The long term goal is a microsatellite constellation that will provide full global and diurnal cycle coverage.

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 since 1995 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. Removing this ambiguity can be achieved by probing the atmosphere via RO using frequencies near water vapor absorption lines 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 [1],[2]. [3] described ATOMMS as a differential absorption approach achieved by probing the atmosphere simultaneously at multiple frequencies. Conceptually two occultation tones are sent through the atmosphere where one is tuned to be on the absorption line and the other is tuned to be off the line such that when the ratio of the two amplitudes is formed it largely eliminates common noise like antenna gain while retaining most of the desired absorption signature.

2. CLEAR SKY PERFORMANCE

The first systematic error analysis of the ATOMMS concept for clear sky conditions was provided in [3] which revealed the potential of the technique. In that analysis, the dominant error was the finite signal to noise ratio (SNR) due to the finite transmitter signal strength, the distance between the transmitter and receiver and the finite noise temperature of the receiver. Since then we have come to realize that atmospheric turbulence and the scintillations ("twinkling of a star") that they produce will be a key source of error as well [4]. We continue to refine our understanding of the impact of turbulence and several manuscripts are in preparation based largely on [5]. The simple 2 tone amplitude ratioing is quite effective in reducing the impact of turbulent variations in the real part of the index of refraction such that scintillations at 183 GHz will be reduced down to a few percent of the original scintillations [4]. Four frequencies are required to separate turbulent fluctuations in the real and imaginary parts of the index of refraction. Fig. 1 shows the estimated clear sky accuracy of the ATOMMS temperature and water vapor profiles for several latitudes and seasonal conditions that includes the effects of amplitude

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scintillations due to turbulent fluctuations of temperature and water vapor.

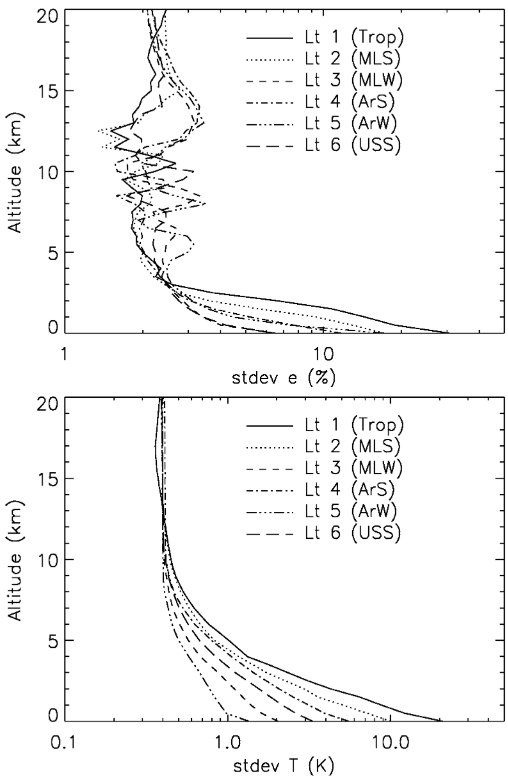

Figure 1. *Computed standard deviation of the error in the retrievals of temperature (upper panel) and water vapor pressure (lower panel), expressed in percent, using simulated ATOMMS observations for the six labeled Lowtran atmospheres (Trop = tropical; MLS = mid-latitude summer; MLW = mid-latitude winter; ArS = Arctic summer; ArW = Arctic winter; USS = U.S. Standard)*

3. ISOLATING THE EFFECTS OF CLOUDS

ATOMMS will probe the 22 and 183 GHz water lines. Because absorption by *liquid* water in clouds is very large at frequencies near 200 GHz, the occultation signals near 22 GHz will be used to probe through liquid water clouds. Under these conditions, observations near 200 GHz will be limited to altitudes above the freezing level (~ 5 km and above in the tropics and lower altitudes at higher latitudes).

We have developed a method for isolating and removing the effects of ice and liquid water clouds summarized in [4]. For climate, 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 using two fitting parameters: cloud liquid water path and cloud temperature, requiring that the retrieval algorithm estimate these two additional parameters. Overdetermination is accomplished by increasing the number of signal tones used simultaneously during the occultation observations to at least 5. A key feature in our approach to minimizing the effects of clouds is that we 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 necessary because clouds are often far from spherically symmetric with respect to an occultation observation and ignoring this would lead to rather poor retrievals of water vapor. Fig. 2 provides an example of the estimated performance for 2 inhomogeneously distributed cloud decks.

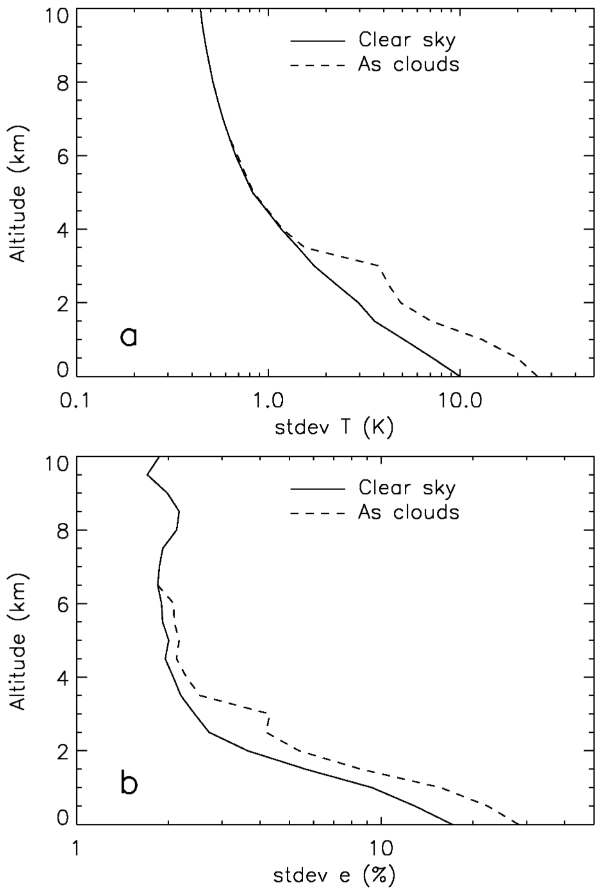

Figure 2. *Computed standard deviation of the errors in the retrievals of (a) temperature and (b) water vapor pressure using simulated ATOMMS observations. The background atmosphere is the Lowtran 2 mid-latitude summer profile. Solid lines are for clear sky conditions, while the dashed lines were computed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

Ice clouds will attenuate the ATOMMS signals via scattering which depends on the particle size distribution. Ratioing the amplitudes of two tones will eliminate most of this effect. However, a small, systematic residual error will remain. The example in Fig. 3 assumes measurements made at 180.5, 183.5 and 186.5 GHz. For a two channel water vapor retrieval, the differential extinction coefficient would be either (W2 - W1) or (W2 - W3). However, in the presence of the cirrus cloud, the quantity that is actually measured is (T2 - T1) or (T2 - T3). For the simulated conditions, (T2 - T1) is about 2% larger than (W2 - W1) and (T2 - T3) is about 2% smaller than (W2 - W3). Thus, if ATOMMS were to measure at only two tones and the calibration tone were on the low frequency side of the absorption line, the water vapor content in the presence of cirrus clouds would be systematically overestimated. If the caltone were on the high frequency side of the line, the water vapor content would be systematically underestimated. Using three tones this cloud bias can be largely eliminated by removing linear trends in extinction vs. frequency. For this reason, the ATOMMS demonstration must therefore measure at least 3 tones to quantify the two tone cloud bias and its reduction using 3 tones. For climate monitoring, any such systematic errors must be identified and eliminated whenever possible. This is one of the key reasons why the portion of the portion of the ATOMMS prototype instrument that operates near 183 GHz will be upgraded from its current 2 channels to 4.

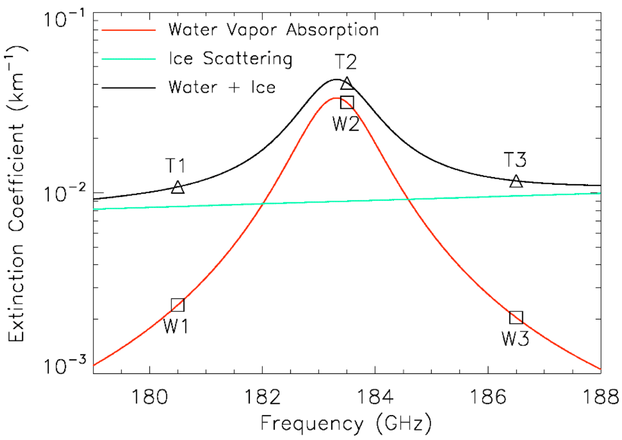

Figure 3. *Representative example showing extinction coefficient vs. frequency for water vapor absorption, ice scattering for a typical cirrus cloud, and their sum calculated for mid-latitude summer conditions at an altitude of 12 km.*

4. 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 and changes in stratospheric ozone concentrations are very difficult to predict because ozone depends on a number of factors that are also being modified anthropogenically. ATOMMS will profile ozone using the 184 and 195 GHz ozone lines. Fig. 4 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 roughly 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. Fig. 4 shows that 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 thus not affected by the overlying O_3 layer in the stratosphere. This suggests the aircraft to aircraft occultation capability will have utility for supporting scientific field campaigns. A peer-reviewed manuscript on the ozone performance is near submission [6].

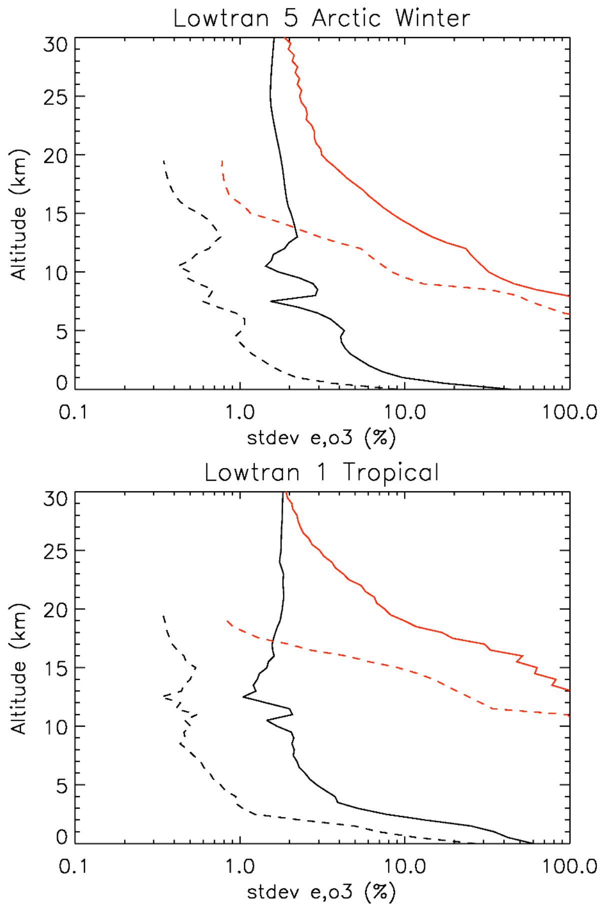

Figure 4. *Standard deviation of simulated errors of water vapor (black) and ozone (red) from satellite (solid) and aircraft occultations (dashed). Panel a is for arctic winter conditions and Panel b is for tropical conditions.*

4. ATOMMS AT MARS

The ATOMMS concept actually works better at Mars because of the low surface pressure which allows a number of trace species as well as line of sight winds via the Doppler shift to be accurately profiled right to the surface. A white paper on the Mars concept is available at the planetary decadal survey web site: http://www8.nationalacademies.org/ssbsurvey/publicview.aspx.

5. ATOMMS AIRCRAFT DEMONSTRATION

NSF has funded our group to build a prototype of the ATOMMS instrument at the University of Arizona to perform an aircraft to aircraft occultation demonstration in 2010. The temperature, water vapor and pressure profiles will extend from the surface to near the 19 km altitude of the aircraft. The prototype instrument has 8 channels between 18 and 26 GHz and 2 tunable channels in the 180 to 203 GHz range that we have requested funds to upgrade to 4 channels in the near future. With this capability, we can profile water vapor and ozone as well as N_2O and $H_2{}^{18}O$ in the upper troposphere and lower stratosphere. The instrument also uses 13 GHz to precisely measure the phase shift associated with atmospheric bending of the signal path from which profiles of refractivity are derived.

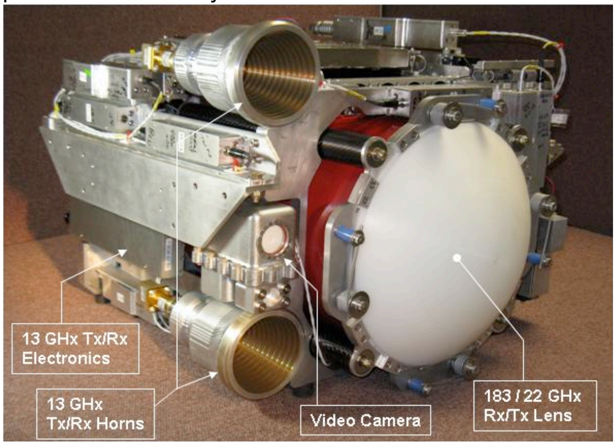

Figure 5. *One of the two ATOMMS prototype instruments. Visible components are labeled. The 183 GHz Transmitter and 22 GHz Receiver modules are not visible.*

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