The Active Temperature Ozone and Moisture Microwave Spectrometer (ATOMMS) Climate Observing System

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Abstract

To address fundamental climate observing needs, we are building a cm and mm wavelength satellite-to-satellite occultation instrument called the Active Temperature, Ozone and Moisture Microwave Spectrometer (ATOMMS). ATOMMS will profile atmospheric moisture to 1-3%, temperature to ~0.4K and geopotential height to 10m with 200m vertical resolution from near the surface to the mesopause in clear and cloudy air. 1-3% precision ozone and water isotope profiles will extend from the upper troposphere into the mesosphere. Accuracies with averaging will be 10 to 100 times better. We will demonstrate ATOMMS in 2009 using 2 high altitude aircraft.

1. Overview

The Active Temperature, Ozone and Moisture Microwave Spectrometer (ATOMMS) is a cross between the GPS radio occultation (RO) and the Microwave Limb Sounder (MLS) techniques. It actively probes some of the absorption lines that MLS uses via radio occultation. ATOMMS uses at least 2 frequency bands approximately 10 and 100 times higher than GPS frequencies to probe the 22 and 183 GHz water lines and 184 and 195 GHz ozone lines. A third band between 500 and 600 GHz would also be quite useful for profiling H_2O and its isotopes and initializing the hydrostatic integral.

Serious work on the ATOMMS concept began in 1998 as the Atmospheric Moisture and Ocean Reflection Experiment (AMORE) (which included the 22 GHz portion of the ATOMMS occultation concept) was proposed to NASA as an Earth System Science Pathfinder (ESSP) mission. While AMORE was technically too immature for selection, the same year NASA did fund the Atmospheric Temperature, Ozone and Moisture Sounder (ATOMS), a joint effort between the University of Arizona and JPL that included both the 22 and 183-195 GHz occultation concepts via its Instrument Incubator Program (IIP). AMORE and ATOMS also triggered parallel research and proposal efforts in Europe such as ACE+ and ACCURATE. In the US, NSF has funded the ongoing development and refinement of the ATOMMS concept since 2001 including funding in 2007 the ATOMMS aircraft to aircraft occultation demonstration that is summarized at the end of this paper. We also note the Mars Atmospheric Climate Observatory (MACO) mission concept that is focused on the Martian hydrological cycle using water occultation observations at 183 GHz supplemented by other observations. MACO was developed with seed funding from NASA in 2000 for the Mars Scout opportunity in 2002 (Kursinski et al. 2004b). While it was not selected for a Phase A study for the second Mars Scout opportunity in 2006 because it was viewed as too high risk, MACO has been recognized as a revolutionary concept for quantitatively determining the Martian hydrological cycle and climate and will hopefully become a real mission in the future.

ATOMMS is designed to address key open questions about climate such as, Is the upper troposphere warming faster than the lower troposphere and the surface, Where is the transition between tropospheric warming and stratospheric cooling and the closely related question: How are lapse rates adjusting to the changes in vertical heating and dynamical feedbacks associated with climate change. ATOMMS has a niche in the upper troposphere/lower stratosphere (UTLS) regime where water vapor and ozone are very important radiatively. 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 and the comparisons have not agreed very well, problems that can be resolved by ATOMMS. ATOMMS can answer fundamental open questions on basic behavior and trends in the UTLS regime. An overarching goal of ATOMMS has been to create an observing system capable of estimating several key climate state variables and determine how the climate system is truly evolving, *independently of atmospheric models*.

2. Estimated Precision and Accuracy

We have spent a great deal of effort on understanding the noise sources of ATOMMS (e.g. Kursinski et al, 2002, 2004a). Over the past 3 years we have focused on two areas in particular, the effects of turbulence and the ability to separate the effects of inhomogeneous liquid clouds from water vapor. Propagation of electromagnetic signals through a turbulent refractive medium creates interference through diffraction that produces phase and amplitude scintillations. From the standpoint of measuring the absorption signatures of atmospheric water vapor and ozone, turbulent amplitude scintillations are a noise source. For those interested in turbulence, ATOMMS is a planetary-scale microwave scintillometer that will provide an unprecedented global turbulence monitor. Turbulence in the troposphere can create quite large amplitude scintillations. The differential opacity measurement approach used by ATOMMS and described by Kursinski et al. (2002) is key to controlling the impact of turbulence. We have developed simulations and a parameterization of the effects of turbulent variations of dry air and water vapor that we use to estimate the errors in the ATOMMS atmospheric profiles (Otarola et al., 2008).

We have also developed a species separation inversion routine capable of handling inhomogeneous cloudiness. A manuscript describing this strategy in more detail is in preparation. In essence we sample the spectrum near the 22 GHz water line with at least 5 occultation tones which provides sufficient spectral information to separate the liquid and vapor spectral contributions.

Preliminary simulations have shown that we can separate cloud absorption optical depth from the optical depths due to water vapor and dry air based on differences in their absorption as a function of frequency. The presence of clouds generally results in slightly larger errors in the retrievals of water vapor and temperature. Based on our latest simulations, we expect to retrieve water vapor, temperature, and pressure in cloudy conditions with accuracies within a factor of two of water vapor retrievals in clear air, consistent with the prediction of Kursinski et al. (2002). Two examples showing the effects of clouds on the retrievals of temperature and water vapor are shown in Figures 1 and 2. In general, the errors in the retrievals of temperature and water vapor increase from the altitude of the cloud downward. This is expected because occultation observations corresponding to lower tangent altitudes can still pass through clouds located at higher altitudes. The seemingly strange reduction in the fractional water vapor error near 5 km in the cloud case (Figure 2) occurs because in the cloud simulation we increase the relative humidity in the cloudy layer to 95%, so even though the absolute error in the water vapor retrieval increases at 5 km, the fractional error is slightly smaller.

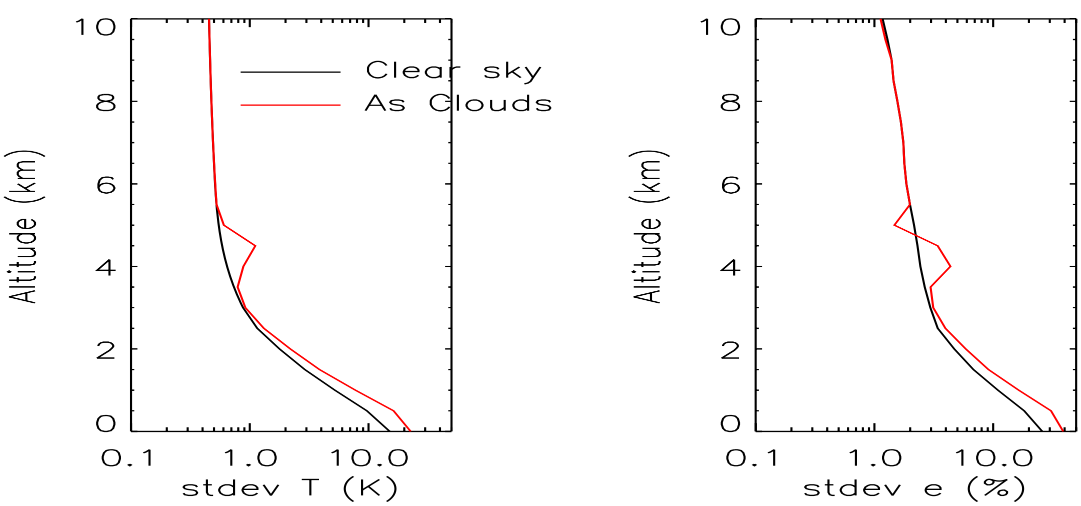

Figure 1. Computed standard deviation of the errors in the retrievals of temperature (left) and water vapor pressure (right) using simulated ATOMMS observations. The background atmosphere is Lowtran 2 mid-latitude summer profile. Black lines are for clear sky conditions, while the red lines were computed after placing a broken deck of altostratus clouds between 4.5 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 gm^{-3}.

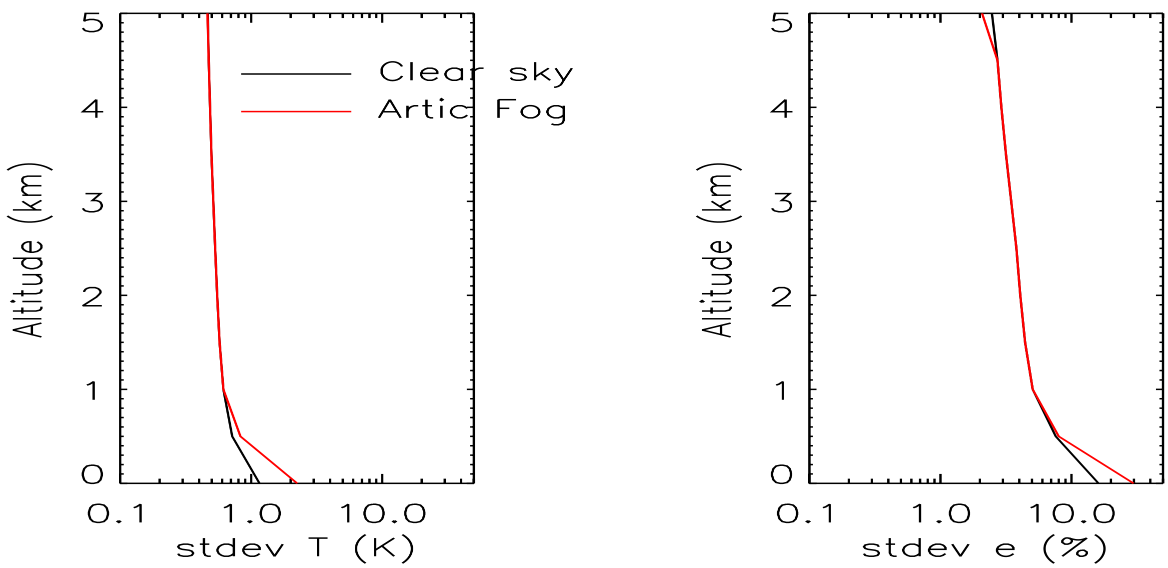

Figure 2. Same as Figure 5.2 except the background atmosphere is Lowtran 5 Arctic Winter. For the inhomogensous Arctic fog case, a cloud with liquid water content of 0.15 gm^{-3} extends from ground level to 1.0 km above ground.

The ability to estimate two additional parameters, cloud liquid water path and effective cloud temperature, along each occultation path, requires sampling the spectrum with a sufficient number of frequencies to separate the liquid water, water vapor, and dry air spectra using the slant optical depths. Beside the refractivity information derived from the phase measurements and the hydrostatic constraint, we require absorption information from at least four frequencies to isolate liquid water clouds from water vapor and unwanted variations from the instrument and turbulence.

If all goes well and our error estimates prove representative, then the accuracy (as opposed to precision) of ATOMMS will be limited ultimately by the knowledge of spectroscopy. To quantify and reduce spectroscopic uncertainty, we believe it is crucial that ATOMMS observe at least one additional frequency, bringing the minimum number to five. For this reason, the aircraft version of ATOMMS has 8 frequencies near 22 GHz and we now refer to the technique as an "Active Spectrometer". In general, it is VERY important that ATOMMS probes with a number of tones that provide sufficient information to ensure that ATOMMS observations do ***NOT*** yield an underdetermined retrieval problem (at least under the local spherical symmetry constraint).

3. ATOMMS Aircraft to aircraft occultation demonstration

In discussions with NSF in 2004 about how to make ATOMMS a reality, NSF indicated that broad support from the science community would be required for large scale NSF financial support of an eventual science mission. In subsequent discussions with key members of the climate research community it became clear that a demonstration would be needed to show that actual performance would be similar to the results of our paper studies. In 2005, discussions with Don Anderson at NASA HQ and Marty Ross at Aerospace Corporation yielded an aircraft to aircraft occultation demonstration concept using two of NASA's high altitude WB-57F aircraft. The key capability is precise antenna pointing which is critical because transmit power is limited at mm wavelengths. There are 2 WB-57F aircraft in existence with precise pointing systems (see Figure 3) developed for imaging the Space Shuttle during launch at a cost of $5M that are adequate for the ATOMMS demonstration.

Figure 3. WB-57F aircraft with WAVES nose cone. The large mirror is about the size of the ATOMMS 30 cm aperture.

In mid-2007, NSF funded our proposal to perform an ATOMMS aircraft to aircraft demonstration. NASA will provide the necessary aircraft time. The two aircraft will fly at approximately 19 km, above the tropopause, allowing atmospheric profiling from 0 to 19 km altitude, a range sufficient to demonstrate most of the key features of ATOMMS. Because the pointing systems are mounted on the front of the aircraft, the occultations will be rising occultations. The instrumentation is being developed to perform several air-air demonstrations beginning in early 2009. Key elements include demonstrating the ability to isolate the desired atmospheric absorption profiles, measure the bending angles, simultaneously profile water vapor, ozone, temperature and pressure and derive accurate retrievals in the presence of ice and liquid water clouds. Furthermore we will determine the characteristics and impact of turbulence and assess and refine the accuracy of the spectroscopy. We also hope to demonstrate water isotope profiling in the upper troposphere by measuring $H_2{}^{18}O$ via its 203.4 GHz absorption line.

The 22 GHz system transmits and receives 8 tones, that provide sufficient information to separate the vapor and liquid water spectra, assess and refine the spectroscopy and the redundancy needed to crosscheck the retrieved profiles. The 183 GHz system has a minimum of 2 independently tunable tones that we may increase to 4 tones for similar reasons.

Validation is a key part of the demonstration. Validation is challenging because ATOMMS is a state of the art system with extremely high vertical resolution but somewhat course horizontal resolution and the ability to penetrate clouds. At least one of the aircraft to aircraft occultation demonstrations is planned over the ARM site in Oklahoma to utilize the instrumentation there. A key aspect of the assessment of the retrievals is cross comparison of the 22 and 183 GHz water vapor retrievals in a 2 km altitude interval in the troposphere where both sets of profiles are very accurate.

4. Acknowledgements

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5. References

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