ATOMMS: the Active Temperature, Ozone and Moisture Microwave Spectrometer

Christopher Groppi, E. Robert Kursinski, Dale Ward, Angel Otarola, Kate Sammler, Michael Schein, Sarmad Al Banna, Brian Wheelwright, Steve Bell, Willy Bertiger, Mark Miller, Herb Pickett

Abstract— ATOMMS represents a new class of active, airborne, limb-viewing spectrometer that is a cross between Global Positioning System (GPS) occultations (e.g [1]) and NASA's Microwave Limb Sounder. ATOMMS will characterize atmospheric constituents by actively probing their cm and mm wavelength absorption lines. Two instrument packages are being constructed for NASA's WB-57F high altitude research aircraft, now equipped with precise WAVES gimbaled pointing systems. One aircraft will generate multiple tones near the 22 GHz water line and 183 GHz to 204 GHz absorption lines and transmit them across the Earth's limb through the atmosphere to receivers on a second aircraft. Flight paths of the two aircraft begin over the horizon, with the two aircraft flying at 65 kft altitude. This creates a rising occultation geometry as the aircraft fly towards each other. ATOMMS provides the sensitivity, resolution and accuracy needed to satisfy key monitoring needs for temperature, pressure, moisture and ozone. The 100 to 200 m ATOMMS vertical resolution will far surpass the 1 to 4 km vertical resolution of present state-of-the-art satellite radiometers opening a window into atmospheric scales previously inaccessible from space. Predicted precisions of individual ATOMMS temperature, pressure and moisture profiles are unprecedented at ~0.4 K, 0.1% and 1-3% respectively, extending from near the surface to the flight altitude of ~20 km. ATOMMS ozone profiles precise to 1-3% will extend from the upper troposphere well into the mesosphere. Other trace constituents such as water isotopes can be measured with performance similar to that of ozone. The ATOMMS experiment is a pathfinder experiment for eventual implementation on a constellation of satellites. Space observations from multiple satellites in precessing orbits will allow for global spatial coverage and increased altitude coverage. Our long term goal is a constellation of approximately a dozen small spacecraft making ATOMMS measurements that will provide dense, global coverage and complete cloud-penetration and diurnal sampling every orbit. The ATOMMS instrument packages are now being tested and assembled, with expected flight series in spring and early summer, 2009.

***Index Terms*—Remote Sensing, Terrestrial atmosphere, Microwave receivers, Microwave transmitters**

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I. INTRODUCTION

ATOMMS is a new remote sensing system that combines features of GPS RO with the Microwave Limb Sounder (MLS). It is an active limb viewing occultation system that promises performance that will make it a key observing system in the Global Climate Observing System (GCOS). We are building a prototype of the instrument for an aircraft to aircraft occultation demonstration of its performance. A high-level ATOMMS instrumental configuration is depicted in Figure 1.

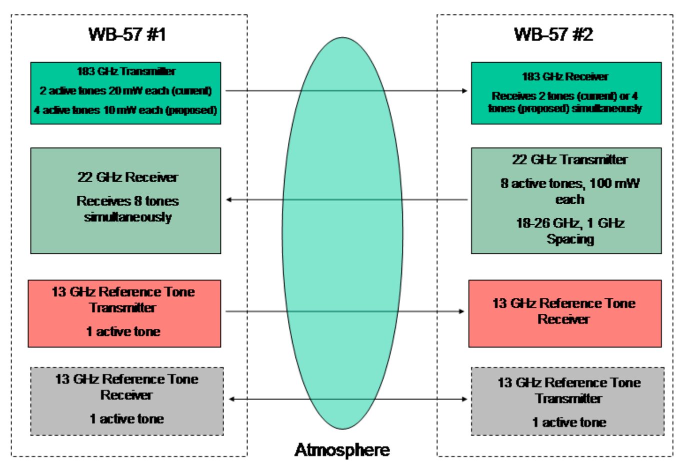

Figure 1: ATOMMS experiment configuration. The two payloads are referred to as ATOMMS-A and ATOMMS-B.

Figure 2 shows the key elements of the ATOMMS instrumentation demonstration on one of the two aircraft: (1) ATOMMS microwave instrument 13 GHz, 22 GHz and 183 GHz transmitters and receivers, (2) ATOMMS precise positioning system hardware consisting of a GPS receiver a 3 axis precision accelerometer system on each aircraft, (3) the WB57F aircraft and (4) the WAVE gimbal built by SRI for NASA that points the ATOMMS microwave instrument. Not shown are the ATOMMS retrieval system and the precise positioning system software.

During an occultation, each ATOMMS microwave transmitter radiates several monochromatic signal tones that pass through the atmosphere to the receiver on the opposite side of the atmosphere (as shown in Figure 1) which digitizes and records the signals. We have designed the ATOMMS transmitters and receivers to simultaneously sample water vapor at both the 22 and 183 GHz lines to create the dynamic range needed to profile water vapor from the surface into the mesosphere as well as measure ozone at 195 GHz in the upper troposphere and middle atmosphere. The ATOMMS retrieval system later derives the phase and amplitude of the signals and combines them with the precise knowledge of the transmitter and receiver positions (estimated by the ATOMMS precise positioning subsystem) to derive profiles of atmospheric moisture, ozone, temperature and pressure.

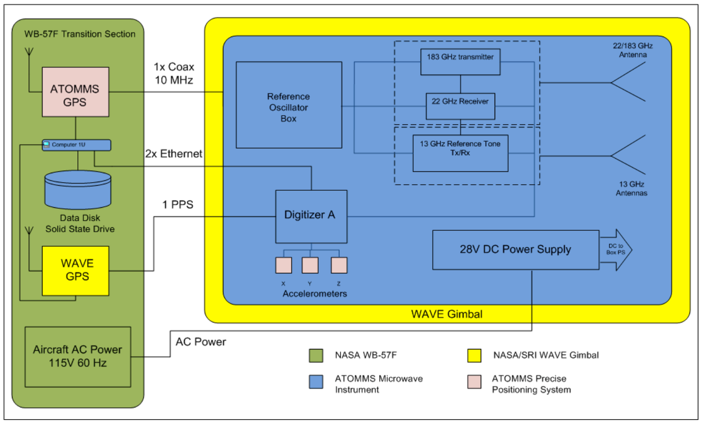

Figure 2: Block diagram of the ATOMMS A aircraft. With the exception of the science tone complement, ATOMMS B is identical.

The ATOMMS system has a unique set of strengths for monitoring climate and climate change as well as strongly constraining physical processes in the atmosphere, which are unmatched by any current or planned satellite-borne water vapor sensors. Some of the research benefits afforded by ATOMMS observations are briefly summarized in this section. A more complete description of the potential research benefits of ATOMMS can be found in [2].

II. Scientific Motivation

A. *Accuracy and Vertical Resolution of Temperature and Water Vapor Profiles*

Considering that average scale height for tropospheric water vapor is about 1.5 km, it is imperative that its vertical structure be resolved by measurements to a vertical resolution of 500 m or less. The recent GPS occultation experiments (GPS/MET [10], CHAMP[11], SAC-C[12], and COSMIC [13]) have demonstrated the ability of radio occultations to probe the atmosphere with a vertical resolution of ~200 m. ATOMMS retains this characteristic; a level of vertical resolution is simply not possible using a passive, nadir-viewing system (e.g., AIRS, IASI, AMSU). The highest vertical resolution claimed for these systems is on the order of 2 km. MLS also has 2-3 km vertical resolution. Thus, ubiquitous layering of water vapor in the troposphere with typical vertical scales of a few hundred meters [3] will remain invisible to passive sensors.

Only radio occultation can globally determine temperature and lapse rates at the sharp vertical scales at which they vary in both clear and cloudy conditions. However, accurate GPS RO temperatures are limited to the upper troposphere (limited by moisture) through the mid-stratosphere (limited by the ionosphere). In contrast, ATOMMS temperature and stability will extend throughout the free troposphere through the mesosphere under any conditions. Another key point is GPSRO measures temperature OR water vapor, not both. GPSRO has shown some of the potential for RO observations in the warmer regions of the lower and middle troposphere with accuracies of 0.2 – 0.5 g/kg [4]. ATOMMS will extend the dynamic range by orders of magnitude to precisely profile water from the 1-4% levels in the lower troposphere to the ppm levels in the mesosphere with 1-10% individual profiles and absolute accuracies with averaging perhaps an order of magnitude better (depending on spectroscopy), while simultaneously profiling temperature to sub Kelvin accuracy over the same range.

B. *Upper Troposphere / Lower Stratosphere Retrievals*

ATOMMS offers a remarkable improvement in our ability to measure temperature, water vapor and ozone behavior in the climatically critical upper troposphere and lower stratosphere (UTLS). Despite the critical roles this region plays in determining how our climate will change in the future, its behavior has been and continues to be very poorly observed. To place ATOMMS in context, a basic conundrum for understanding and predicting climate change has been that our ability to measure water vapor and temperature in the upper troposphere under all sky conditions has been close to nil. The existing observational techniques all have very different types of uncertainties, errors and resolutions. When comparisons have been made, the comparisons have not agreed very well. For instance, the observations assimilated (radiosondes and radiances from several remote sensing sensors) in the ECMWF 40-year reanalysis (ERA-40) database [15] shows ERA-40 water mixing ratios are considerably larger in the tropical upper troposphere than measurements from the MOZAIC (Measurements of Ozone and Water Vapor by Airbus In-Service Aircraft) program, while in the upper stratosphere ERA-40 has about 5% to 10% more ozone and 15% to 20% less water vapor than inferred from the Halogen Occultation Experiment and the Microwave Limb Sounder onboard the Upper Research Satellite [16].

This region 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 also indicative of how realistic models are in transporting added heat from additional greenhouse gases from the surface up to the upper troposphere. There has been an issue for quite some time as to whether model simulations at the surface visa vis the free troposphere are realistic. One component is that a primary feedback is water vapor above 500 mb. It appears climate models have a tendency to produce more water vapor in the upper troposphere in response to increased greenhouse gas concentrations and warming at the surface than may be occurring in the real world. Unfortunately we don't really know whether or not this is true because the water vapor and temperature observations in the upper troposphere are simply not good enough.

C. *Retrievals can be made in the presence of most clouds*

Earth is at least two-thirds cloud covered [5] creating a fundamental sampling problem for remote sensing systems that are unable to penetrate clouds, which includes all IR probing systems (e.g., AIRS, IASI) and limits MLS. Long-term data sets derived from these systems will be incomplete and dry-biased, which limits the ability to measure and understand processes that control climate and aid in weather prediction as well as making detection of climate change difficult. Again GPS occultation experiments have demonstrated the ability of radio occultations to make observations and retrievals in both clear and cloudy conditions. Coincident cloud observations and ATOMMS relative humidity in and around clouds will establish the relation between cloud properties and relative humidity at scales typically resolved by models including the frequency and amount of supersaturation, supercooled mixed phase clouds, all important but poorly observed and understood phenomena sorely waiting for new critical observational constraints. One can see from these discussions that with its global coverage once deployed in orbit, ATOMMS will provide something approaching a global field campaign for studying convection at the scales of GCMs.

III. ATOMMS Development Status

A. *ATOMMS Microwave Instrument*

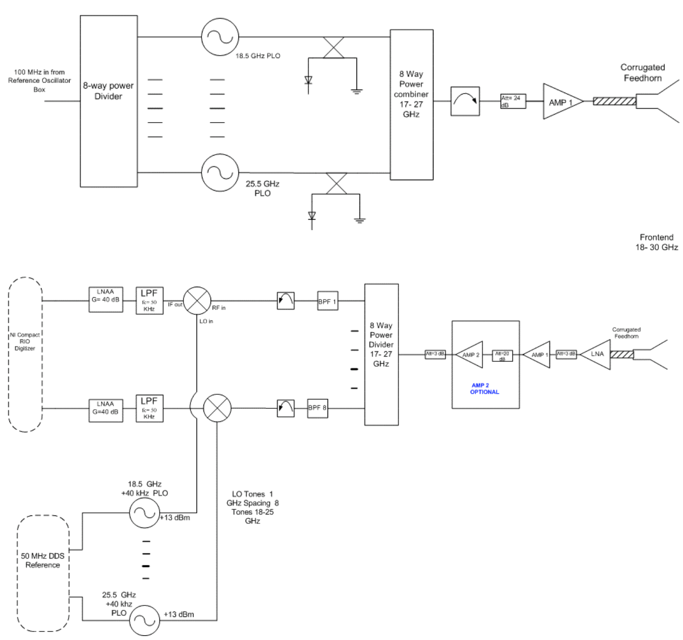

Figure 3: The ATOMMS 22 GHz transmitter (top) and receiver (bottom) subsystems. Two of the eight channels are shown in each block diagram for clarity.

The ATOMMS microwave instrument has been designed to take advantage of off-the-shelf telecommunications technology whenever possible, particularly for the 22 GHz channel. The basic instrument design uses very similar circuits for all channels. Figure 3 shows the block diagram of the 22 GHz transmitter and receiver. The transmitter uses eight separate phase locked YIG oscillators to generate the tones. These tones are individually power-monitored before they are power combined. A single amplifier then amplifies these eight tones to a level of ~100 mW per tone. Since ATOMMS measurements are effected by differential amplitude noise, a common power amplifier is used for all tones to attenuate differential amplitude fluctuations. The receiver amplifies all eight received tones simultaneously for the same reason. The amplified signal is then power divided into eight channels. Bandpass filters in each channel isolate a single received tone. These tones are then mixed with LO signals generated by YIG phase locked oscillators fed with a reference from a DDS synthesizer. This synthesizer is used to offset the frequency of the LO, generating a ~ 40 kHz IF frequency. The low frequency IF is then low pass filtered and amplified with a low noise audio frequency amplifier. The IF is then fed into a National Instruments Compact RIO real-time data acquisition system, where the time domain waveform is digitized and recorded. This data acquisition system has been shown to operate at ambient pressure in the WB-57F in previous experiments. The 13 GHz reference tone transmitter and receiver are identical to the 22 GHz system, but with a single transmitted and received tone rather than eight.

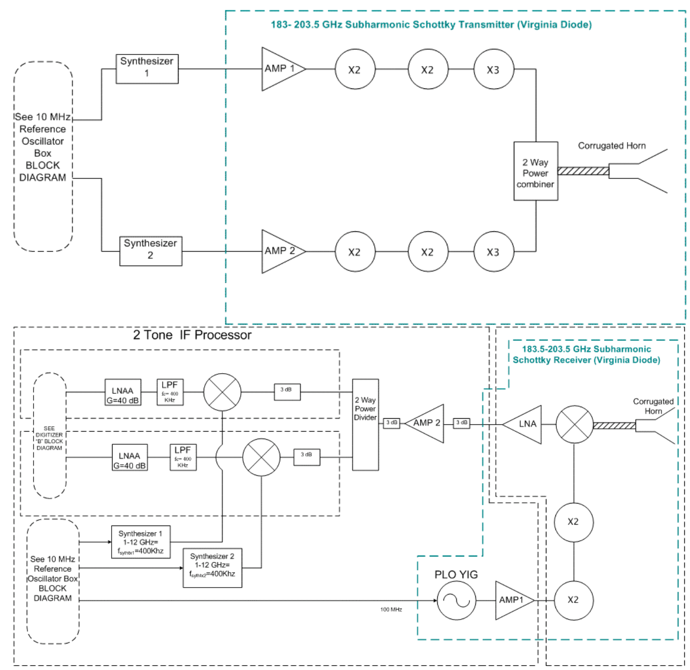

Figure 4: The ATOMMS 183 GHz transmitter (top) and receiver (bottom) system block diagrams.

The 183 GHz subsystem is based on a two tone transmitter and subharmonically pumped Schottky mixer receiver front end from Virginia Diodes. The transmitters each provide 40 mW of power from 180-203.5 GHz, and are power combined using a waveguide magic tee. Power monitoring diodes before the magic tee record the transmitted power level of each channel, for later removal of differential amplitude effects. After power combining, the transmitted power is ~20 mW per tone. The subharmonically pumped Schottky receiver has a measured noise temperature of ~1100K, and is flat across the band. A low noise amplifier with a 1-12 GHz bandwidth relays the IF signal to a downconverter module. The receiver IF downconverter is identical in architecture to the 22 GHz receiver system with the exception that tunable synthesizers are used to generate the LO signals rather than fixed tuned oscillators. Block diagrams of the 183 GHz subsystem are shown in figure 4. Figure 5 shows the 183 GHz transmitter system mounted to the ATOMMS-A rear plate.

The ATOMMS antenna system uses a pair of coaxially mounted feedhorns to illuminate a single 30 cm diameter high density polyethylene lens, anti-reflection grooved for operation at 183 GHz. The design and fabrication of this optical system is covered in another paper in these proceedings [6].

A detailed link budget simulated the performance of the instrument using realistic antenna parameters and estimated losses. This link budget was used to specify all the components of the ATOMMS transmitter and receiver systems. The final configuration of both aircraft is shown in Figure 1 and 2. Transmitter and receiver pairs are mounted in opposite aircraft, with each aircraft containing a transmitter for one band and the receiver for the other band. This balances both the data acquisition and power needs for each instrument.

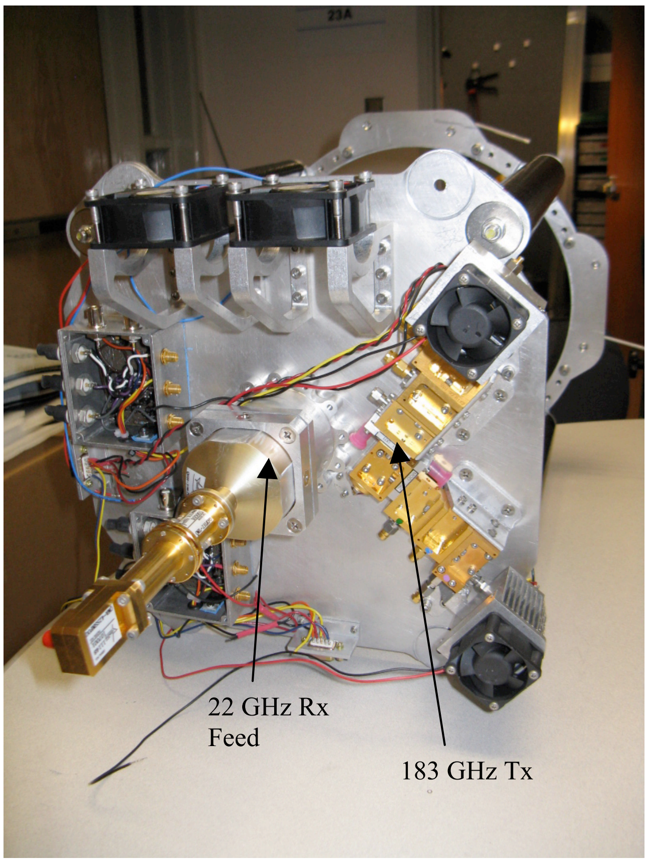

Figure 5: The ATOMMS 183 GHz transmitter system and 22 GHz receiver feed.

The ATOMMS instrument package mechanical aspects are as highly engineered as the electronics. Past experience in flying complex research instruments in the WB-57F aircraft have shown that a fairly sophisticated minimum level of integration of structure, power, thermal, vibration, low pressure and various other design factors are required to build a successful instrument. The ATOMMS instrument design, shown in figure 6, was engineered down to the level of fasteners, connectors and wiring using 3D Computer Aided Drafting (CAD) software before any manufacturing. Figure 7 shows the ATOMMS-A instrument, completely assembled and awaiting system testing.

With fully assembled electronics modules, we have completed testing of the electronics systems at the box level, and we are now verifying that instrument performance meets the specifications necessary to accomplish the scientific mission.

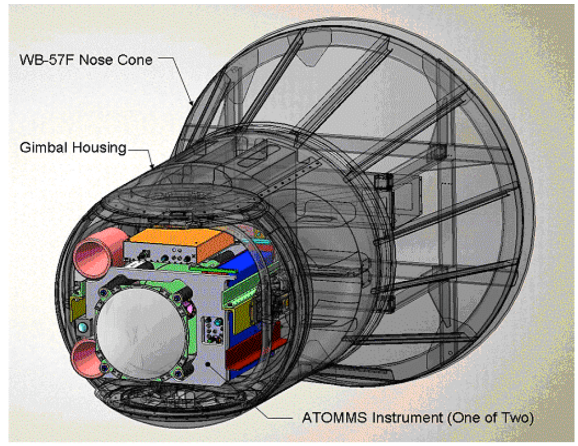

Figure 6: A 3D CAD model of one of the ATOMMS instruments in the SRI WAVE gimbal. The ATOMMS instrument was completely built in CAD before any fabrication took place.

Data acquisition duties are handled by National Instruments Compact RIO systems. These small chassis can be loaded with up to eight multifunction interface modules to handle science signal and housekeeping digitization, digital I/O and accelerometers readout. Each Compact RIO system communicates with a PC over two dedicated Ethernet cables. These PCs are mounted in a partially pressurized part of each aircraft, just behind the moving portion of the gimbal. Each PC is equipped with large capacity solid state hard drives, and runs Labview Realtime OS. These computers receive the data collected by the Compact RIO system mounted directly on the ATOMMS instruments and record the data to disk. They also are responsible for collecting the GPS observables from the JPL provided GPS receiver used as part of the Precise Positioning System.

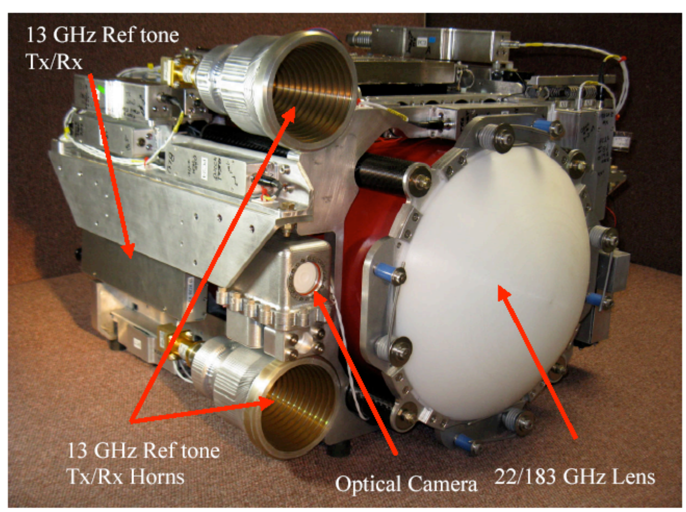

Figure 7: The fully assembled ATOMMS A instrument. Visible components are labeled. The 183 GHz Tx and 22 GHz Rx modules are not visible.

B. Precise Positioning System

The ATOMMS system will profile atmospheric temperature and pressure. This is derived from a profile of refractivity that is derived from a profile of bending angle derived in turn from a profile of Doppler shift versus time. In the aircraft to aircraft occultations, the atmospheric Doppler shift is much smaller than for the spacecraft occultation case because the aircraft move much slower (~200 m/sec) than the spacecraft (several km per second). At the uppermost altitudes, just below the altitude of the aircraft, the atmospheric bending angle is quite small. Therefore the atmospheric Doppler shift is quite small. In order to precisely determine atmospheric temperature and pressure, the ATOMMS system must measure very small bending angles at high altitudes. The system goal is to estimate the motion of the aircraft to an accuracy of 0.1 mm/sec.

Over the course of the experiment design, we refined our understanding of the necessity of this goal and how to achieve this small error. The ATOMMS Precise Positioning System consists of accelerometers and GPS receiver on each aircraft. Positions can be estimated very accurately from the GPS receiver data about every 100 seconds. In profiling the atmosphere via the ATOMMS occultations, we determined that we will use integration times of ~10 seconds or less. To achieve the high vertical resolution and performance over these short intervals, we determined that very accurate accelerometers must be used. Essentially the precise reconstruction of the time-varying aircraft positions and velocities will integrate the acceleration measured by the accelerometers to obtain the velocities of the two ends of the ATOMMS instrument. The GPS receiver data will essentially be used to estimate the bias and scale factor of the accelerometers. Extremely low-noise accelerometers (Endevco Model 86), developed for seismic research, were selected for the ATOMMS experiment after extensive analysis by the ATOMMS team at the University of Arizona and JPL.

High performance GPS receivers have been selected that could satisfy the ATOMMS requirements that were also familiar to JPL. The receivers already in the WB-57F aircraft were deemed insufficient to deliver the quality of phase data needed. JPL suggested a high performance Ashtech receiver that they use for other applications.

C. WB-57F Aircraft

NASA is providing the WB-57F aircraft time for the ATOMMS experiment. ATOMMS presently holds two flight slots in the WB-57F schedule, and a third is planned to be added. Currently, the first flight slot is a combination engineering test flight, followed immediately by an air to ground RF testing flight series. The second is a full up air to air, two aircraft flight test series. A minimum of 3 flights are anticipated for each flight series. As a risk reduction measure, we plan to separate the engineering test flights and air-to-ground single aircraft test flights, allowing more time to address any issues identified in the engineering test flights.

Figure 8: The WAVE system mounted on the nose of a WB-57F. ATOMMS will replace the optical telescope in this system. A microwave transparent radome will replace the front skin and optical window.

In support of these flight tests, Southern Research Institute and the University of Arizona have been defining the desired flight plans for each flight series, along with the task load for the WB-57 flight backseat operator (FBO).

D. NASA/Southern Research Institute (SRI) WAVE Gimbal Pointing System

The ATOMMS experiment takes advantage of NASA's WB-57F Ascent Video Experiment (WAVE) system, designed to optically image the space shuttle during launch. This system is a complete replacement nose for the WB-57F, containing a 2-axis gimbaled pointing system capable of 0.25 degree pointing accuracy (see figure 8). The system also contains an optical telescope with a high definition video camera and recorder. The ATOMMS microwave sensors replace this optical imaging package, but still use the replacement nose and gimbal.

ATOMMS does present several challenges for pointing and integration with the WAVE system. The ATOMMS instrument must be adequately balanced, and within weight limits for the gimbal. More importantly, ATOMMS is not an imaging detector, so pointing cannot be done with image recognition. In addition, the atmospheric attenuation effects we wish to measure will not allow pointing based on feedback from the microwave signal strength. Any atmospheric fluctuations would be interpreted as a pointing error, and would cause the pointing loop to become unstable. We have therefore developed, jointly with Southern Research Institute (SRI) a pointing system based on GPS coordinates. As a development effort with NASA, SRI has already proven the capability to point and track a known GPS coordinate to far better than 0.25 degree accuracy in level flight. This accuracy has been demonstrated by SRI on several WB-57 test flights with the WAVE optical sensor. Using an optical camera co-mounted with the ATOMMS instrument, we can calibrate this GPS pointing system using SRI's existing algorithm to allow ATOMMS to also point to within 0.25 degrees of a known GPS coordinate. The ATOMMS microwave beam will be measured in the lab relative to the center of this optical camera to compensate for any fixed pointing offset.

The next challenge was to predict the GPS coordinate for each aircraft, and provide that information to the other aircraft to allow them to point at each other. This will be done with a combination of a pre-computed flight plan based on GPS waypoints and times, and pseudo-real time updates of position provided by an Iridium phone data link between aircraft. Because of the slow speed and unreliability of the Iridium link, the primary location information will be the flight plan, which the pilots will attempt to fly as accurately as possible. Meeting the waypoint locations accurately is not a large challenge for the pilots, but timing arrival at those waypoints is a significant challenge. Therefore, the Iridium link will be used to provide time shifts along the flight path rather than for full position and time information. The code for this implementation has been written by SRI and is now undergoing testing.

Another requirement was the need for RF transparent nose skins in the SRI gimbal system. The windows and skin material in the existing gimbal nose skins is effectively opaque at microwave and millimeter wavelengths. They are presently in fabrication at Cobham Defense / Nurad Division in subcontract to SRI, and are scheduled for delivery in the early February 2009 time frame.

E. ATOMMS Retrieval System

1) Retrieval Software

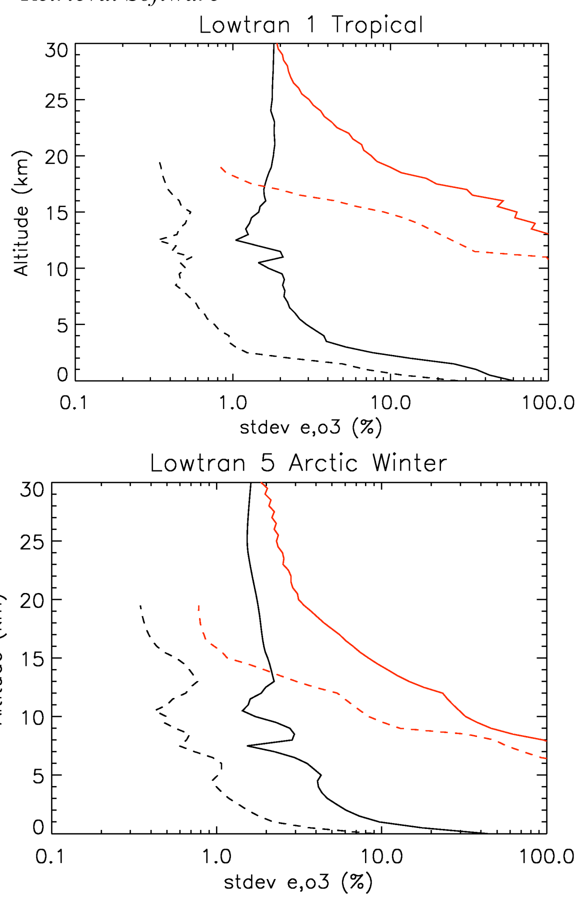

Figure 9. Standard deviation of simulated errors of H2O vapor (black) and O3 (red) from satellite (solid) and aircraft occultations (dashed). top: arctic winter conditions. bottom: tropical conditions. From [9].

Prior to this project, we developed simulations to investigate the accuracy of retrievals for an ATOMMS-type instrument in a satellite-to-satellite geometry. We have been adapting this code to perform retrievals in the MRI aircraft to aircraft geometry. We have used this code to understand how instrumental parameters, such as SNR and antenna gain pattern, will affect retrieval accuracy. We have also developed an improved method to deal with liquid water clouds distributed inhomogeneously along the occultation signal path. We developed a two relaxation dielectric model of liquid water for simulating ATOMMS retrievals when liquid clouds are present [14].

ATOMMS will retrieve the atmospheric profile of index of refraction using the method proven to work for GPS occultations, modified for the aircraft geometry. JPL has agreed to provide the JPL GPS occultation processing software to the UA that we will modify for the ATOMMS processing. Simulated errors based on this retrieval technique for water and ozone are shown in figure 9.

2) Atmospheric Turbulence

Amplitude scintillations ("twinkling of a star") are an unwanted source of amplitude variation that reduces the accuracy of how well we can isolate the absorption on the ATOMMS signals. To better understand this error, Angel Otarola's recently defended dissertation research [7] focused on atmospheric turbulence and its impact on the ATOMMS observations. We have coupled this effort to the retrieval system development to understand the impact these variations will have on the accuracy of the ATOMMS retrievals.

We have developed a relation between the scintillations due to the real part of the wet refractivity variations that allows us to estimate the magnitude of the scintillations due to water vapor knowing the average water vapor concentration. A paper is in preparation. Using high resolution radiosonde data, we have developed an understanding of the spectrum of turbulent variations in the vertical coordinate in particular the spectral transition from homogeneous turbulence at smaller scales to a different spectral dependence of turbulence at larger scales.

Prior to this work, the impact of turbulent variations in the imaginary component of refractivity has thus far been ignored by the radio occultation community. We are working towards generalizing the equations that describe the impact of turbulence variations in the real part of the index of refraction to include the contributions of the imaginary variations. This work is important because we now realize that the simple two tone amplitude ratioing method described by [8] will not work as well for the imaginary contributions. The two tone method cancels the real contributions well because of their weak frequency dependence, but does not perfectly cancel the contributions due to the imaginary component. Based on this new understanding, we feel that it is essential that we simultaneously measure more than two tones at our high band frequencies (180 – 203 GHz) to diagnose and minimize the effects of turbulence on our retrievals.

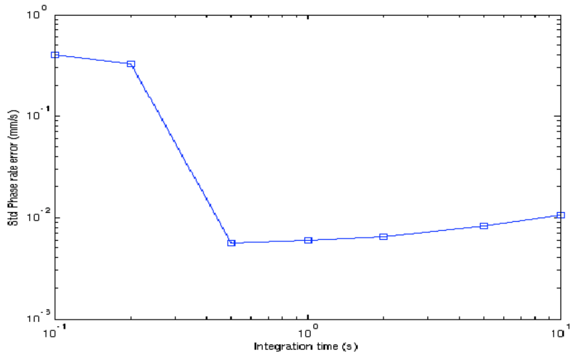

Figure 10: Standard deviation of the phase rate error for a 13 GHz signal generated and transmitted from one ATOMMS device, then received and digitized by the second ATOMMS device before processing

3) System Testing Support

We have been developing codes and testing strategies to support preliminary instrument tests: laboratory tests, ground based tests, and air to ground tests. Since each test has its own unique implementation and interpretative challenges, we have been developing separate software for each. With the hardware partially completed, we have begun to process and analyze signals recorded by the ATOMMS instrument in the lab. As an example, the ATOMMS MRI will utilize the 13 GHz channels to determine the atmospheric Doppler shift from which we will retrieve the atmospheric refractivity. To meet our accuracy goals, the 13 GHz signals need to be extremely phase stable. We expect the limiting error in determination of the atmospheric Doppler shift to be due to uncertainty in the estimation of the line of sight velocities of the aircraft, which is specified to be 0.1 mm/s or less. Digitized laboratory measurements from one of the 13 GHz transmit-receive chains has been analyzed for phase stability as a function of the signal integration time as shown in figure 10. The phase error has been translated into units of mm/s. The figure shows that for integration times greater than 0.5 s, the instrument performance is an order of magnitude better than the expected error in the line of sight velocity determination. As we plan to use integration times of 1-10s for signal extraction, the phase error of the 13 GHz signals is well within specification.

IV. Conclusion

ATOMMS offers a unique and unprecedented capability for measuring key atmospheric variables fundamental to climate independently from models and other climatological assumptions. The planned aircraft to aircraft occultations offer the only way to demonstrate and assess the ATOMMS concept and its performance without the very costly step of placing at least one if not both of the instruments in orbit. Assuming the aircraft demonstrations prove successful, they will pave the way for support from the larger science community for the ATOMMS concept and a NSF/NASA/NOAA spacecraft mission and a major new global research instrument for atmospheric science.

Acknowledgements

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