A Laboratory System for Simulation of Extreme Atmospheric Conditions in the Deep Atmospheres of Venus, Jupiter, and Beyond

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ABSTRACT

A new atmospheric simulator, in operation and developed at Georgia Tech, now offers a flexible platform for simulating deep planetary atmospheres. In its current configuration, the laboratory system has been designed to simulate the deep Jovian atmosphere, and measure the microwave opacity of key atmospheric constituents. A 30 liter pressure vessel has been designed to withstand a pressure up to 100 bars of hydrogen, and helium with trace amounts of either ammonia or water vapor. A high temperature chamber along with the pressure vessel allows for simulations with a temperature ranging from 295-616°K. Within the pressure vessel a cylindrical microwave cavity is used to measure the microwave opacity of ammonia and water vapor. Two custom built feedthroughs allow us to excite, and measure absorption inside the simulator, while keeping a network analyzer (measuring wavelengths between 5 to 25 cm) at room temperature. The primary motivation for this system is to provide reliable microwave opacity models for use in interpreting data from the Juno microwave radiometer (MWR).

The Juno-MWR will be capable of sensing centimeter-wavelength emission from the very deep atmosphere of Jupiter at pressures exceeding 100 Bars (Janssen et al., 2005, Icarus 171, 447-453). In order to accurately retrieve the abundances of microwave absorbing constituents such as ammonia and water vapor from measurements of the centimeter-wave emission from these deep layers, precise knowledge of the absorptive properties of these gases under deep atmospheric conditions is necessary. To date, only a very limited number of measurements have been made of the microwave absorption of ammonia or water vapor at such high pressures, and none of these measurements were conducted at wavelengths greater than 3.3 cm.

While our primary motivation is to provide this critical information, this is not the only function our system may perform. In the future this system could easily be adapted to provide a test platform for instrumentation and hardware that must withstand some of the harshest atmospheric conditions, including those of Venus which has a surface pressure up to 100 bars. While the Venus surface temperature exceeds our maximum simulator temperature (616°K), it would certainly be a sufficient test platform for a variety of entry probe hardware for Venus, Jupiter or any other planetary atmosphere which reaches 100 bars pressure.

1.0 Introduction

The atmospheres of Venus and Jupiter are among the most extreme in the solar system. The temperatures of both planets reach temperatures below 300°K, and approach extremely high temperatures above 600°K near the 90 bar level of each planet. The extremes of temperature as a function of pressure are revealed in the temperature pressure profile shown in Figure 1. Any mission which requires information from the deep atmosphere of either planet requires either a very precise model, or a simulator to understand the phenomenon associated with such extreme conditions. Our ultimate goal in this work is to develop precise models for H_2O and NH_3 absorption in the presence of H_2 and He for the Juno Micorwave Radiometer (MWR). One can clearly see in viewing Figure 2, that the Juno MWR will sense contributions from the 100 bar level (and deeper) for its lowest frequency channels (0.6, 1.25, 2.6, and 5.2 GHz). The Juno MWR team will require an accurate model based upon laboratory measurements to allow for interpretation of the thermal emission sensed by the Juno MWR as it orbits Jupiter with a perijove on the order of 4500 km. The close approach at perijove allows for the Juno MWR to sense below the synchrotron radiation belts which to date have prevented radio astronomers from accurately measuring the thermal emission from Jupiter's deep atmosphere. Accurate laboratory measurements of trace gases under Jovian conditions have been accurately measured (eg. Hanley and Steffes, 2007[1]) , however, no measurements have been conducted under the desired conditions, or frequency range required for accurate interpretation of results from the Juno MWR. Here we present in detail a system built and tested at Georgia Tech for simulating deep Jovian conditions. In addition we show that while the system has been designed for simulation of deep Jovian conditions, this system could easily be adapted to simulate conditions in the Venus atmosphere using CO_2 and N_2 replacing H_2 and He as used in the current Jovian condition simulator.

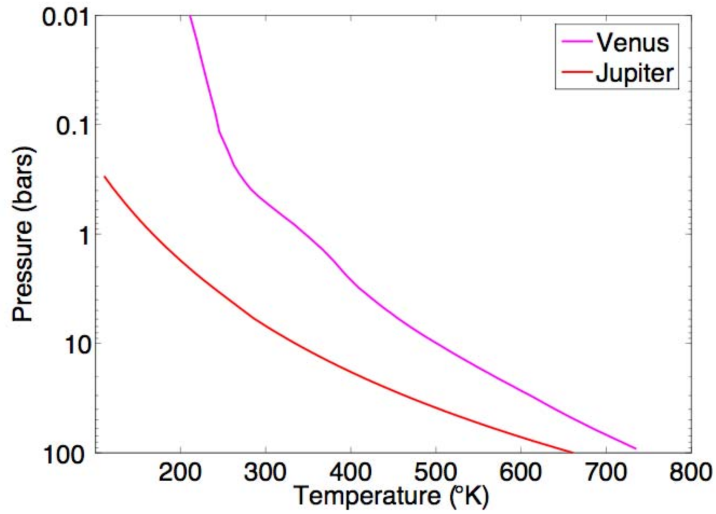

Figure 1: The temperature pressure profiles of Venus (magenta) and Jupiter (red).

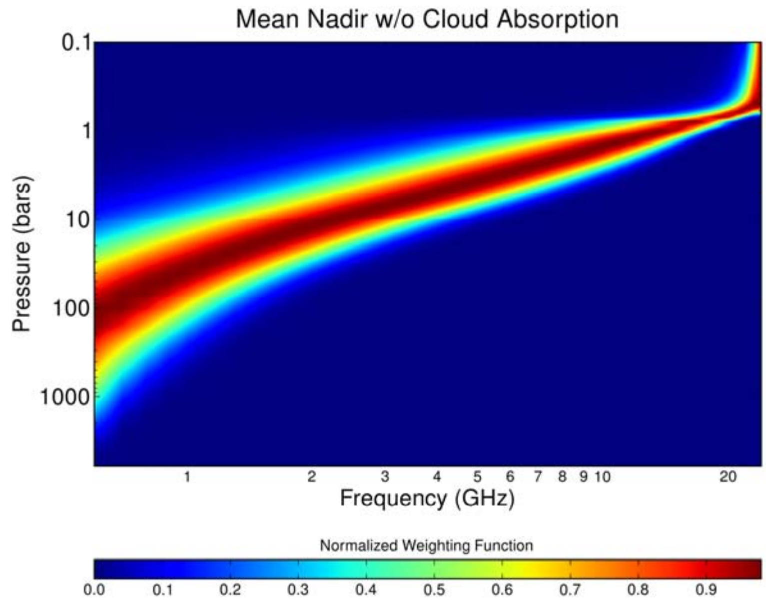

Figure 2. Normalized Weighting (contribution) functions from Jupiter's Atmosphere as Calculated by Georgia Tech's Radiative Transfer model

2.0 The Ultra-High Temperature Pressure System

The Ultra-High Pressure System is shown in schematic form in Figure 3. The system is composed of a pressure vessel custom built by Hays Fabrication and Welding located in Springfield, Ohio, a water reservoir made of a 304 stainless steel pipe 18" long and 1.5" in diameter, a used Grieve industrial oven model AB-650 (maximum temperature 650ºF), two Matheson 3030 regulators (580 for Ar, and 350 for H_2), an AirGas Y11215F580 regulator for He, two Omega DPG7000 pressure gauges (one rated from 0-15 psi, the other rated to 300 psi), a PX1009L0-1.5KAV pressure transducer capable of measuring up to 1500 psi at 600°F, and an Omega ¼" NPT thermocouple probe (TC-T-NPT-G-72). All the valves shown in Figure 3 with a blue dot are high temperature valves made by Swagelok (SS-1RS6-PK) rated to 315°C at a maximum pressure of 215 bars, otherwise valves are rated to 93°C at a maxium pressure of 295 bars (SS-1RS6) .

The custom pressure vessel was designed with two ½" NPT input ports for gas delivery, one ¼" NPT port for the thermocouple, and two CF-1.33" Flanges for microwave feedthroughs. The pressure vessel was hydro-tested by Hays Fabrication and Welding with all input flanges, and feedthroughs at a pressure of 1450 psi. In place of a standard rubber or viton O-ring a composite (glass fiber/NBR) KLINGERsil C-4430 is used to seal the pressure vessel along with 20 nuts 2 3/8" in diameter torqued to 1300 lb-ft of torque using a hand torque wrench (325 ft-lbs) and a 4x torque multiplier. The vessel is constructed out of a 12" section of schedule 100 pipe which is 14" in diameter (outer dimension). On one end an elliptical head is welded to the bottom giving the vessel a maximum interior height of 18 1/8". The top is a ANSI class 900 flange 4" thick, with a top plate which is 3 5/8" thick The vessel has a volume of 29.9 liters, and weighs approximately 1200 lbs.

The two most critical (and heaviest) elements of the Ultra-High Temperature Pressure System (the pressure vessel and oven) are shown in Figure 4. The weight of the pressure vessel (1200 lbs) and the shipping weight of the oven (1630 lbs) far exceeded the load capacity of the laboratory floor. Therefore, it was necessary to hire a civil engineer (Bob Goodman of TRC Worldwide Engineering) to evaluate a location on the Van Leer 4th floor roof (adjacent to the 5th floor Laboratory). After careful analysis it was determined that a concrete pad on which a decommissioned crane once stood, would be the ideal location for a load far exceeding 2800 lbs. Once the equipment was procured, it was lifted onto the 4th floor roof via a crane rented from Southway Crane. After delivery of the pressure vessel to the 4th floor roof, a steel shed (Arrow EZEE Shed 86) was erected to protect the oven. A photograph of the system in assembly is shown in Figure 5. In addition to the EZEE shed, a 1 Ton capacity gantry crane (Harbor Freight Model 41188), and a 1 chain lift (Harbor Frieght/ Central Machinery Model 00996) was procured and assembled. This enabled one person to disassemble the pressure vessel (remove the top) and insert the microwave resonator. After the microwave resonator was inserted, the top was replaced along with the 20 nuts each fastened with an applied torque of 1300 lb-ft.

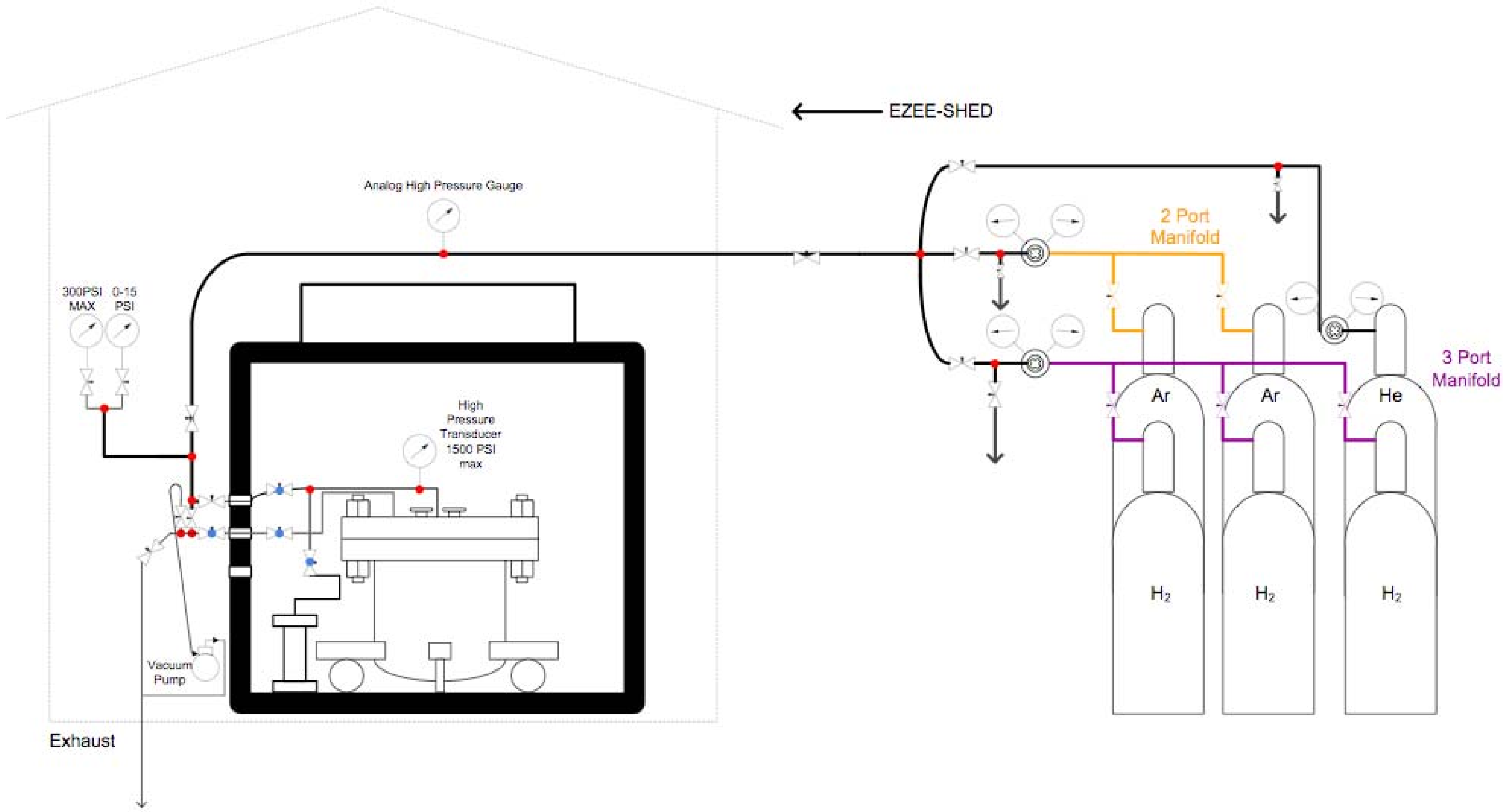

Figure 3. The Georgia Tech Ultra-High Pressure System

Figure 4. The Grieve oven (AB-650) and the Custom Hays Fabrication and Welding Pressure Vessel

Figure 5. The Ultra-High Pressure system in assembly.

3.0 The Data Acquisition/Microwave Measurement System

While developing the data acquisition, and microwave system for the atmospheric simulator, two major factors were considered: pressure, and temperature ratings. A schematic of the cables, and measurement devices used is shown in Figure 6. The microwave resonator shown in Figure 6 has been used in several studies, most recently it has been used in studies by *Hanley, 2008*[2] and *Hanley and Steffes,2007*[1] . The resonator is a cylindrical cavity resonator with a height of 25.75 cm, and a radius of 13.12 cm. The resonator is connected to feedthroughs within the pressure vessel, by SiO_2 microwave cables (Times Microwave). They were selected to withstand the highest temperatures possible 600ºC (1000ºC without the connector). This was done to minimize the need to replace the cables within the pressure vessel (applying 1300 lb-ft of torque to 20 bolts is quite labor intensive). On the exterior of the pressure vessel two SMA Ceramtec feedthroughs (16545-01-CF) both rated to 103 bars and 350ºC are used. Both Ceramtec feedthroughs are backed by fully annealed copper gaskets made by Kurt J. Lesker Company (Part # VZCUA19). While it would have been ideal to use SiO_2 cables within the oven, we found this to be cost prohibitive. Instead two 4' sections of CobraFlex cables rated to 250ºC from Astrolab were used to connect the microwave feeedthroughs to the SMA to type N panel mounts to the outside of the oven. Two sections of 80' length of Andrews CNT 600 microwave cable are connected to the type N bulkheads on the oven back to the Agilent E5071C network analyzer. The CNT 600 cable is not exposed to an extreme environment, thus its maximum operating temperature of 85ºC is sufficient for our application. Use of the long microwave cable extension is required to ensure temperature stability of the Agilent E5071C network analyzer within the laboratory environment. The S parameters measured by the network analyzer are read in via GPIB to the data acquisition computer.

In addition to the microwave measurement system, there are the pressure and temperature measurement systems. Both systems make use of an extended USB bus which allows the data acquisition computer to remain inside the laboratory. The temperature measurement system is composed of an Omega HH506RA temperature reader connected to two type T thermocouples (one connected inside the pressure vessel, one on the pipes for ambient temperature). The temperature reader is connected to an RS-232/USB converter which is then connected to the USB bus within the EZEE shed. The pressure DPG7000 pressure gauges are read via two USB webcams connected to the USB bus. Finally the voltage from the high pressure transducer is read in via a shielded twisted pair back into the laboratory where the voltage is read in by an HP 34401A multimeter. The data acquisition computer reads in the voltage from the multimeter via GPIB. For calibration purposes a Davis Weather Station II, with a barometer is also located within the EZEE shed, and connected to the USB bus via an RS232/USB converter.

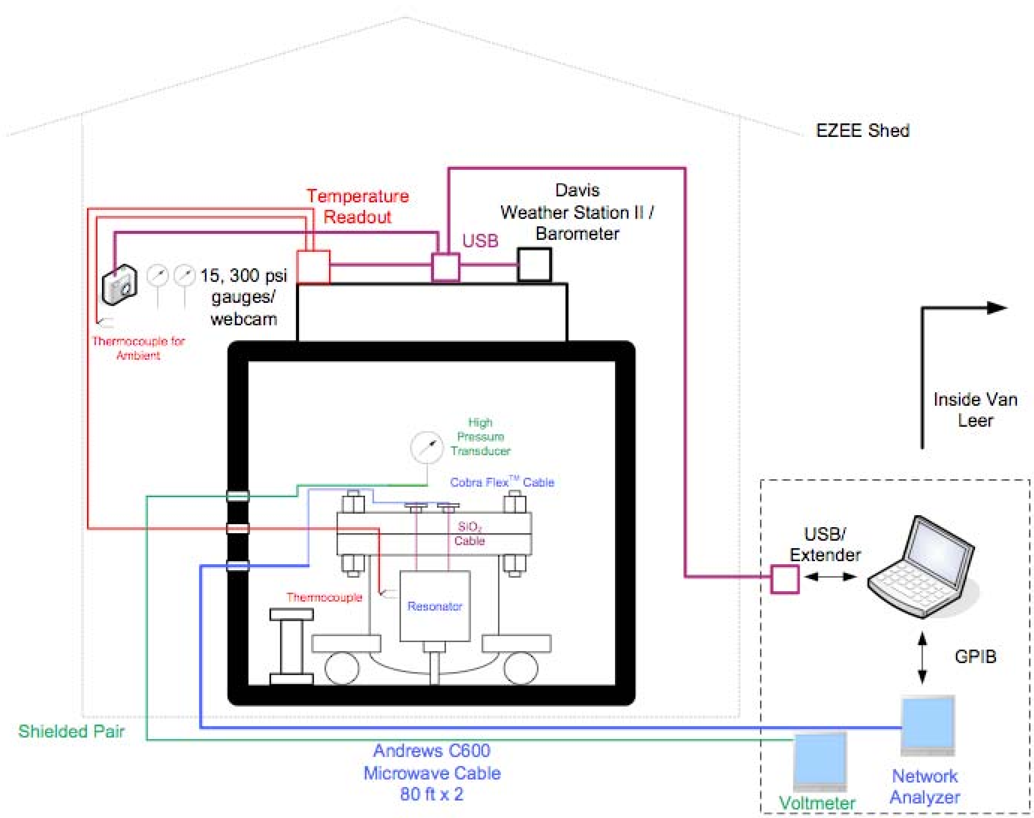

Figure 6. The microwave and data acquisition system.

4.0 System Performance

Initial tests have been performed on all systems including the pressure, microwave and temperature systems. In Figure 7 the results of the 90 bar pressure test over a period of 34 hours are shown, without controlling the temperature of the vessel (the oven is powered off during the test). The test indicates that no gas is lost, however, a drop in pressure occurs due to thermal expansion of the pressure vessel, and restores once the pressure vessel cools in the evening. This phenomenon is clear when viewing Figure 8, a plot of temperature over the same 34 hours.

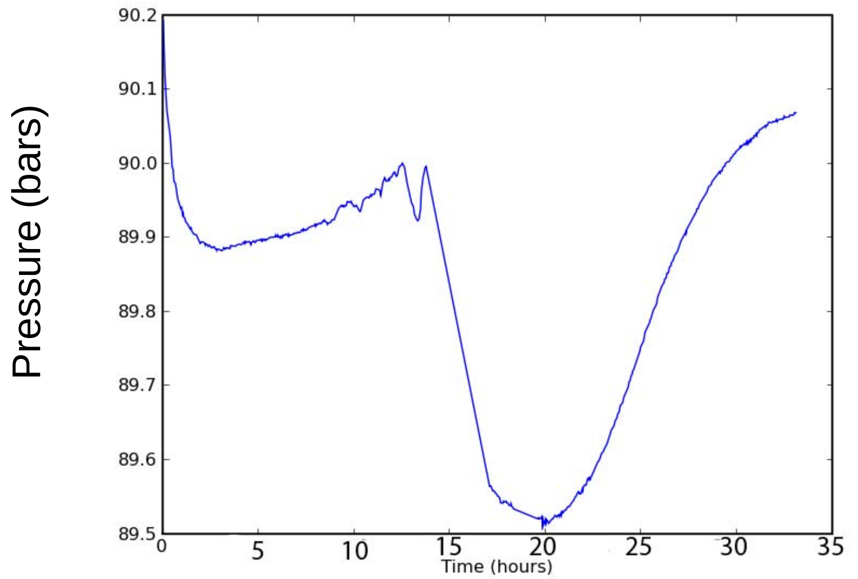

Figure 7. A plot of pressure versus time for a 34 hour period.

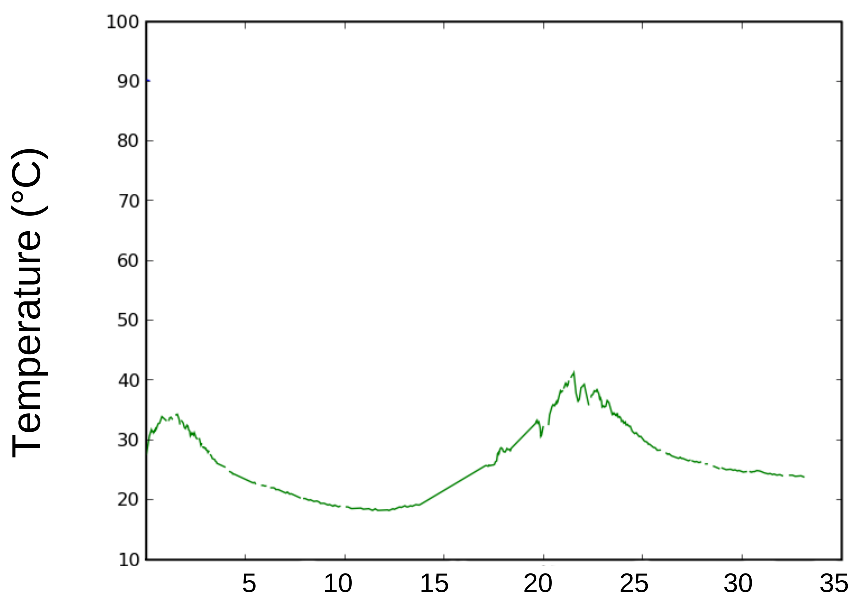

Figure 8. A plot of temperature versus time for a 34 hour period.

In Figure 9 a sample response of the transmission response (S_{21}) the microwave resonator is shown. The spectrum is clean and symmetric indicating the resonator is functioning properly at the given resonance. Other resonances were measured, and the transmission response was quite similar to that prior to the system upgrade.

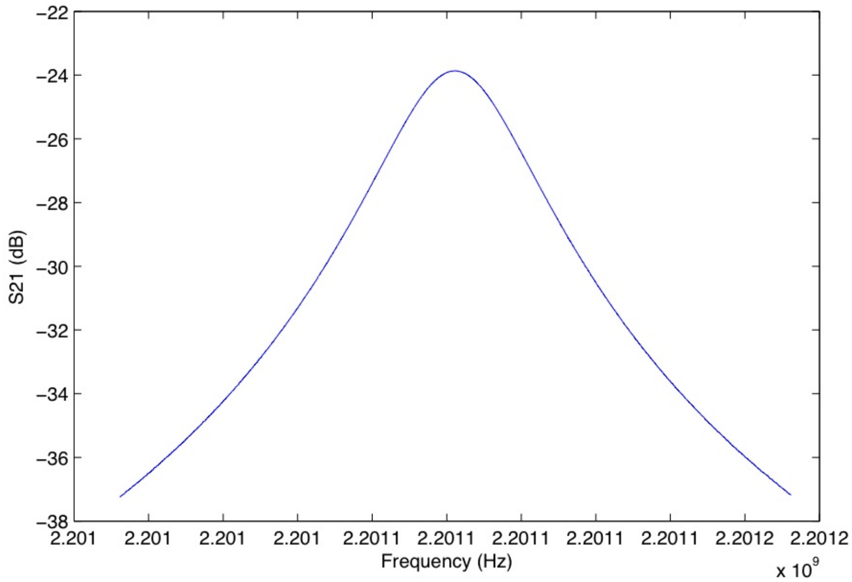

Figure 9. Transmission response of the cavity resonator at a resonance centered near 2.2011 GHz.

The temperature performance of the Grieve oven seems to be satisfactory, however, further test are needed. The oven can hold a temperature of 200°F, however, if one set the thermostat higher than this, the circuit breaker in the lab will trip. This is no surprise given the oven will require approximately 40 amps at full load to operate, whereas the lab only has a capacity of 20 amps. A higher current service will be installed prior to conducting the higher temperature experiments. Once the higher current service is installed, the experiment temperature will be limited by the maximum temperature of the oven (650°F). This limitation is not a concern for simulating Jupiter's atmosphere, however, if one desires to simulate the surface of Venus, it may be necessary to upgrade or replace the Grieve 650-AB with a higher temperature oven.

5.0 Summary

An overview of the Ultra-High temperature pressure system currently in use at Georgia Tech has a wide range of flexibility in that in can simulate a wide range of temperatures and pressures applicable to both Jupiter and Venus. To simulate the Venus atmosphere, two main upgrades may be necessary: first the CobraFlex cables are only rated to 250°C, however, these cables might withstand up to the melting point of the dielectric (PTFE with a melting point of 327°C). Second, the Grieve Oven is only rated to 650°F, to simulate the deep atmosphere of Venus it is likely that an upgrade, or replacement will be necessary.

Over the next few months, experiments will be conducted to support the Juno mission over the temperature and pressure range shown in Figure 10. Experiments will first be conducted with H_2O in an H_2/He atmosphere, followed by measurements of NH_3 in an H_2/He atmosphere. Once the experiments are completed, the most precise model of the microwave opacity of H_2O and NH_3 to date will allow the Juno MWR to accurately retrieve H_2O and NH_3 abundances deep within Jupiter's atmosphere.

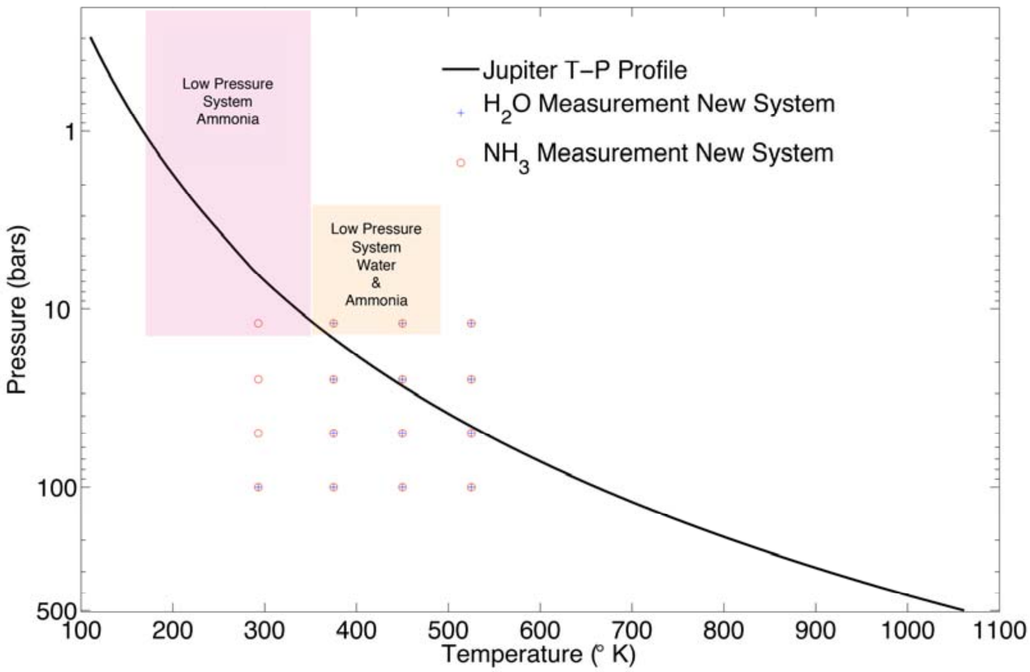

Figure 10. The measurement space for planned experiments ovelayed on top Jupiter's temperature pressure profile

Acknowledgments

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References

[1]Hanley, T. R. and P.G. Steffes.``A high-sensitivity laboratory system for measuring the microwave properties of gases under simulated conditions for planetary atmospheres," *Radio Science*, Vol. 42, doi:10.1029/2007RS003693, 2007.

[2]Thomas Ryan Hanley. *The Microwave Opacity of Ammonia and Water Vapor: Application to Remote Sensing of the Atmosphere of Jupiter*. PhD thesis, Georgia Institute of Technology, 2005.