I. INTRODUCTION AND SUMMARY

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments, entry probe radio signal absorption measurements, and earth-based or spacecraft-based radio astronomical (emission) observations can be used to infer abundances of microwave absorbing constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or the use of laboratory measurements of such properties taken under environmental conditions that are significantly different than those of the planetary atmosphere being studied, often leads to significant misinterpretation of available opacity data. Additionally, even if laboratory measurements have previously been conducted, improvements in the sensitivity of new space-based and earth-based microwave sensors may require higher precision laboratory measurements to achieve their basic science goals.

With improved laboratory capability, it has been possible to achieve a wider range of environmental conditions in the laboratory, which are similar to those actually being probed by microwave sensors. For example, an upgrade to one of our laboratory systems was completed recently by Steffes et al. (2014) under our predecessor Planetary Atmospheres grant (NNX11AD66G, 1/15/11-1/14/15), and was used to conduct measurements of the 3.7-20 cm opacity of sulfur dioxide in a carbon dioxide atmosphere under simulated conditions for the Venus boundary layer (92 Bars pressure). The 300 data points taken using this new system and a new millimeter-wavelength system, which measured the 2-4 mm opacity of sulfur dioxide in a carbon dioxide atmosphere under simulated conditions for the upper troposphere of Venus, have been used to verify models for SO_2 opacity which will allow for accurate retrieval of spatial and temporal variations in SO_2 abundances from both centimeter-wavelength and millimeter-wavelength observations of the Venus atmosphere.

The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by radio occultation experiments, entry probe radio link experiments, and radio astronomical observations, and over a range of frequencies which correspond to those used in both spacecraft experiments and in radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It is the goal of this investigation to conduct such measurements *and* to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identity and abundance profiles of constituents in those planetary atmospheres.

In the 3-year program proposed, key activities will include applying results from our recently-completed laboratory measurements of the microwave and millimeter-wave properties of sulfur dioxide to recently-completed observations of Venus conducted by our group at the NRAO Very Large Array (3.6 cm images) and at the Combined Array for Millimeter Astronomy (CARMA, 2.6-3.0 mm images), and to recently-published observations of Venus conducted with the Atacama Large Millimeter/submillimeter Array (ALMA, see e.g. Moreno et al, 2013). Additionally, new laboratory measurements of the millimeter-wavelength absorption of gaseous sulfuric acid will be conducted over an extended range of frequencies (30-40 GHz, or 7.5-10mm, and 75-150 GHz, or 2-4 mm) under simulated conditions for the atmosphere of Venus. While measurements have been made of a number of the over 42,000 centimeter-, millimeter-, and submillimeter-wavelength lines of sulfuric acid vapor (see, e.g., Cohen and Drouin, 2013), no laboratory measurements of the millimeter-wavelength continuum spectrum of sulfuric acid vapor have ever been conducted. Since the weighting functions at these wavelengths generally peak from just below the lower cloud base to the top of the middle cloud (pressures 0.3-2 Bars), measurements will be taken in that pressure range. These measurements will make it possible to interpret the source of variations in Venus millimeter-wavelength emissions reported in previous radio astronomical observations and those recently completed, by using a new radiative transfer model which will employ our new lab measurements. The 7.5-10 mm measurements will also directly support Ka-Band radio occultation measurements, which will likely be conducted in the next generation of Venus missions. These measurements will be conducted using a new millimeter-wavelength laboratory system specifically developed for measurement of sulfuric acid vapor under our predecessor grant (NNX11AD66G, 1/15/11-1/14/15).

II. RELEVANCE TO THE SOLAR SYSTEM WORKINGS PROGRAM

An aggressive program of laboratory measurements of the millimeter-wave properties of gaseous sulfuric acid under simulated Venus conditions is proposed. These measurements are directly relevant to the Solar System Workings Program in that when they are applied to our radiative transfer models and to observations of Venus from both earth-based and spacecraft-based instruments, important new insights into the composition and dynamics of the Venus atmosphere will be obtained.

Specifically, the millimeter-wavelength radiative transfer studies proposed (employing our recently completed laboratory measurements of sulfur dioxide pertinent to the atmosphere of Venus and the proposed measurements of gaseous sulfuric acid) will be applied to earth-based millimeter-wavelength observations of Venus so as to provide planetary maps of sulfuric acid vapor and sulfur dioxide abundance at and immediately below the main cloud layer. Interpretation of such observations will complement the study of the long-term variations of SO_2 abundance at the 70 km altitude level measured over the duration of the Pioneer-Venus and Venus Express missions using the UV instruments, and give insight into the processes driving this noteworthy temporal variation. Such work can directly support proposed Discovery-Class missions to Venus by providing contextual images of cloud-related gases, and by enabling the interpretation of Ka-Band (9.2 mm-wavelength) radio occultation experiments, which are being considered by several proposing teams. Moreover, the new laboratory measurements of the millimeter-wavelength properties of sulfur-bearing gases under simulated Venus conditions and their application to currently available millimeter-wavelength maps of Venus using our radiative transfer model will help "*Determine the abundances and altitude profiles of reactive atmospheric species (OCS, H_2S, SO_2, H_2SO_4, S_n, HCl, HF, ClO_2, and Cl_2), greenhouse gases, H_2O, and other condensables, in order to characterize sources of chemical disequilibrium in the atmosphere and to understand influences on the current climate.*" which is identified as a priority investigation in *Goals, Objectives, and Investigations for Venus Exploration: 2014* (VEXAG, 2014).

III. RECENTLY COMPLETED LABORATORY MEASUREMENTS AND OBSERVATIONS: *CENTIMETER-WAVELENGTH LABORATORY MEASUREMENTS OF CARBON DIOXIDE AND SULFUR DIOXIDE UNDER SIMULATED CONDITIONS FOR THE DEEP ATMOSPHERE OF VENUS*

It is well understood that the microwave emission spectrum of Venus reflects the abundance and distribution of constituents such as carbon dioxide, sulfur dioxide, and sulfuric acid vapor (see, e.g., Steffes et al., 1990), but there are a number of factors that limit the accuracy of this approach for microwave remote sensing of these constituents. The most critical of these is the knowledge of the microwave absorption properties of these constituents under Venus atmospheric conditions. While the *centimeter-wavelength* absorption properties of both gaseous sulfuric acid vapor and sulfur dioxide in a carbon dioxide atmosphere have been measured and modeled at pressures up to 6 bars (Kolodner et al., 1998, Suleiman et al., 1996, Fahd and Steffes, 1992), no measurements of the centimeter-wavelength properties of any Venus atmospheric constituent had been conducted under conditions characteristic of the deep atmosphere (pressures from 10-92 Bars and temperatures from 400-700 K), excepting a single measurement campaign conducted at a single wavelength (3.2 cm) over 40 years ago (Ho et al., 1966). At altitudes below 35 km, H_2SO_4 thermally dissociates, forming H_2O and SO_3, both of which exhibit very small amounts of microwave absorption at the abundance levels present in the Venus atmosphere. Thus, in the deep atmosphere, only SO_2 and CO_2 have the potential to affect the observed microwave emission.

Microwave observations of Venus were conducted in 1996 at 4 wavelengths using the NRAO Very Large Array (Butler *et al*., 2001). Maps of emission from Venus were made at two of the wavelengths (1.3 cm and 2.0 cm), which indicated dark (~3%) polar regions consistent with increased sulfuric acid vapor abundance due to vaporization of cloud condensate from the downwelling characteristic of Hadley cell circulation (Jenkins *et al*., 2002). Over the disk of Venus, the weighting functions at these wavelengths peak well above the surface or boundary layer (Jenkins *et al*., 2002). Even at the disk center (nadir), with the deepest possible weighting functions, the emission at wavelengths of 2 cm and shorter largely originates from altitudes above the boundary layer, which exists from 0-10 km. At 3.6 cm, emission from both the boundary layer and surface are present. Supported by our predecessor grant (NNX11AD66G, 1/15/11-1/14/15), (Devaraj (2011) made maps of the 3.6 cm emission from Venus based both on the 1996 observations (Butler *et al.,* 2001) and from subsequent observations conducted in 2009 from the NRAO Very Large Array. Since variations in 3.6 cm emission are due both to variations in surface emissivity and potentially from variability in the abundance of SO_2 in the boundary layer, accurate interpretation of such data requires accurate models of the microwave opacity of constituents in the boundary layer (Figure 3).

Under the predecessor grant (NNX11AD66G, 1/15/11-1/14/15), we conducted laboratory measurements of the microwave properties of SO_2 and CO_2 at wavelengths from 3.7-20 cm under simulated conditions for the deep atmosphere of Venus, using a new high-pressure system. Results from this measurement campaign conducted at temperatures from 430 K to 560 K and at pressures up to 92 Bars indicate that the model for the centimeter-wavelength opacity of pure CO_2 (developed over 40 years ago -- Ho et al., 1966 – see Figure 1), is valid over the entire centimeter-wavelength range under simulated conditions for the deep atmosphere of Venus. Additionally, the laboratory results (example in Figure 2) indicate that the models for the centimeter-wavelength opacity of SO_2 in a CO_2 atmosphere from Suleiman et al. (1996) and from Fahd and Steffes (1992) can reliably be used under conditions of the deep atmosphere of Venus. (These results were submitted to the journal *Icarus* in June 2014: Steffes *et al.*, 2014.)

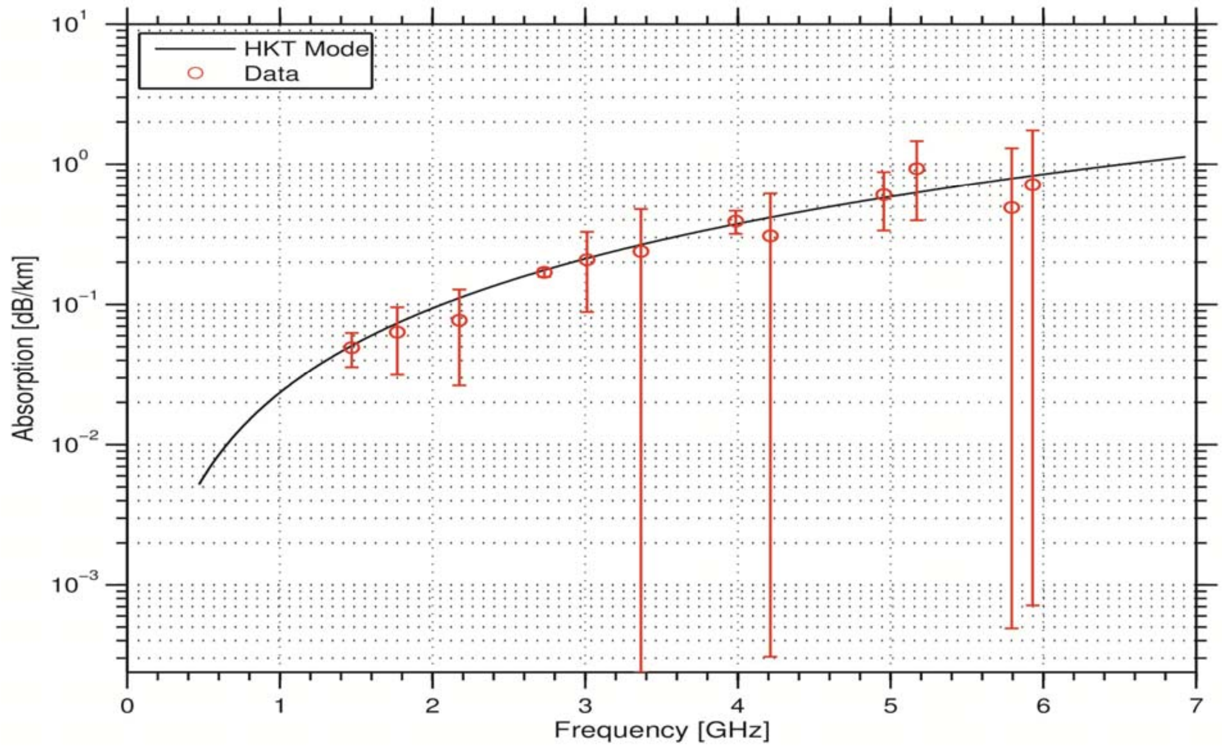

Figure 1: Measured microwave opacity of pure CO_2 at pressure 78.05 bars and 495.4 K compared with model from Ho et al. (1966).

When our radiative transfer model for Venus (using these models for constituent opacity and a nominal abundance of 75ppm for SO_2 from the boundary layer up to the base of the clouds) is used as a reference, the residual brightness variations shown in Figure 3, map to deep atmospheric abundances variations of SO_2 of up to 60 ppm in the boundary layer. However, since the statistical variation of the maps using the original VLA configuration is relatively large (standard deviation of 3.6 cm emission measured across Venus disk is approximately 2 K), higher precision measurements, such as could be obtained by a spacecraft-borne 3-cm radiometer (proposed by some previous Discovery class missions) or by new observations with the more sensitive NRAO-EVLA (Expanded Very Large Array) will provide improved sensitivity at this wavelength and can be used to detect potential sources of elevated SO_2 in the boundary layer.

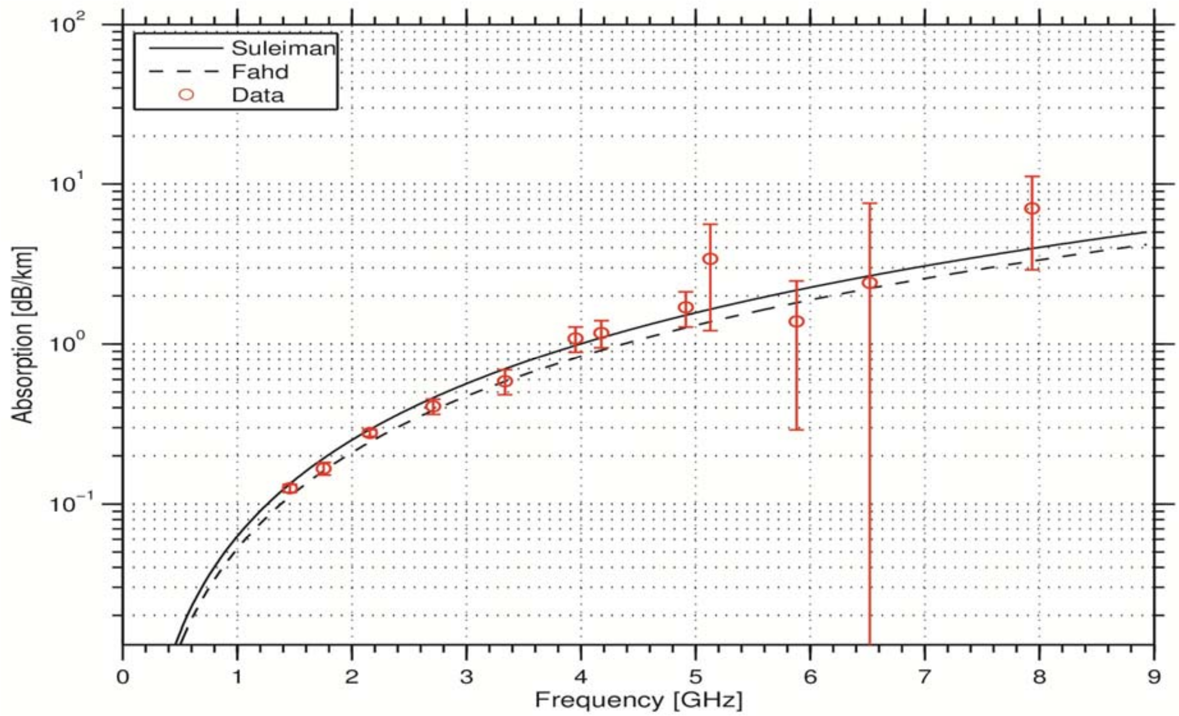

Figure 2: Measured microwave opacity of SO_2 (0.250 Bars, or 0.240% by mole fraction, corrected for compressibility) in a CO_2 atmosphere at 435.3 K and 92.002 Bars pressure compared with models from Suleiman et al. (1996) and from Fahd and Steffes (1992).

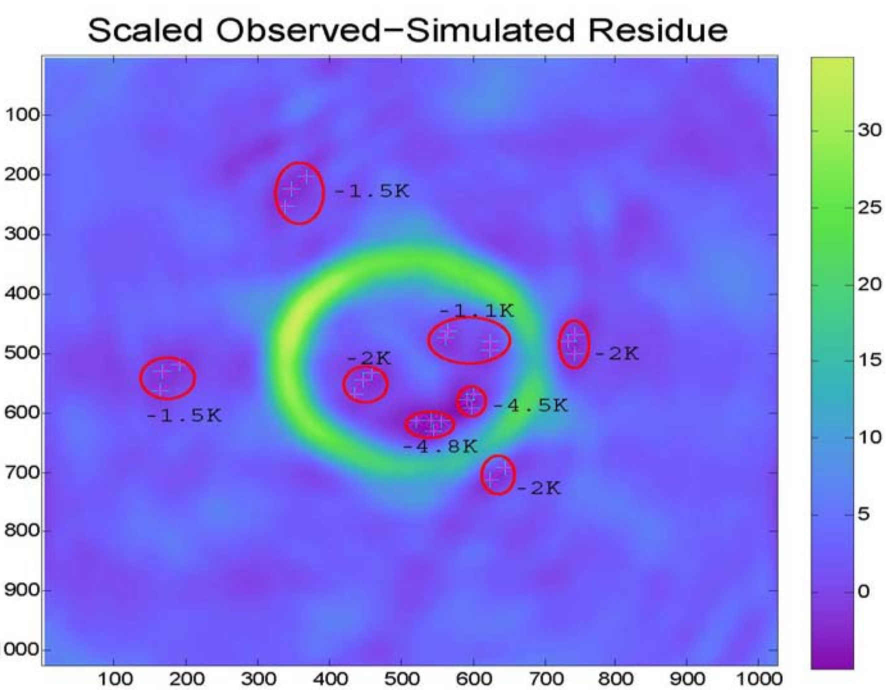

Figure 3: Residual map of microwave Venus microwave emissivity at 3.6 cm (8.4 GHz). The residual is relative to a modeled atmosphere containing 75 ppm of SO_2 in a CO_2 atmosphere. Variations in the surface emissivity measured at the 12.6 cm wavelength by the Magellan mission have been extrapolated to 3.6 cm and subtracted from the emission (Steffes et al., 2013).

IV. PROPOSED LABORATORY MEASUREMENTS AND APPLICATION TO OBSERVATIONS: *LABORATORY MEASUREMENTS OF THE MILLIMETER-WAVELENGTH OPACITY SPECTRUM OF GASEOUS SULFURIC ACID UNDER SIMULATED CONDITIONS FOR THE ATMOSPHERE OF VENUS*

For over 30 years, sulfuric acid vapor (H_2SO_4) has been recognized as a major source of the microwave absorption in the atmosphere of Venus (Steffes and Eshleman, 1982). Through radio occultation measurements from both the Pioneer-Venus and Magellan, it has been possible to retrieve abundance profiles of gaseous H_2SO_4 in the atmosphere of Venus (Jenkins and Steffes, 1991 and Jenkins *et al.*, 1994). Laboratory measurements of the *centimeter-wavelength* opacity of gaseous H_2SO_4 in a CO_2 atmosphere (Kolodner and Steffes, 1998) dramatically increased the precision of retrievals from both radio occultation experiments (conducted at 3.6 and 13 cm) and from radio emission measurements conducted at 1.3 and 2.0 cm (Jenkins *et al.*, 2002). Recently, observations of Venus with the Nobeyama millimeter-wave array conducted at 103 GHz (~3mm) showed substantial variation (~25%) in the millimeter-wave brightness with position on the disk (Sagawa, 2008). While maps of the 1.3 and 2.0 cm emission from Venus have indicated dark (~3%) polar regions consistent with increased sulfuric acid vapor abundance due to vaporization of cloud condensate from the downwelling characteristic of Hadley cell circulation (Jenkins *et al.*, 2002), the 3 mm maps show much stronger variations over a range of different locations, with some indication of diurnal variation. de Pater *et al.* (1991) also reported significant variations (10%) in the 2.6 mm emission maps of Venus made with the Hat Creek Interferometer. Recent maps of Venus made by our group from 100-116 GHz (2.6-3.0mm) under our predecessor grant (NNX11AD66G, 1/15/11-1/14/15) using the CARMA (Combined Array for Research in Millimeter-wave Astronomy) show the same types of variation. (See, e.g., Figure 4.)

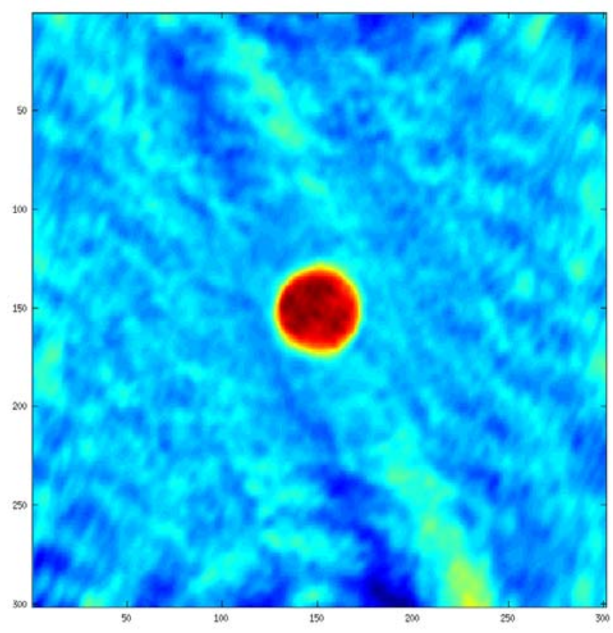

Figure 4: 100.7 GHz Venus emission residual as measured (Fall 2013) using the Combined Array for Research in Millimeter-Wave Astronomy (CARMA) array.

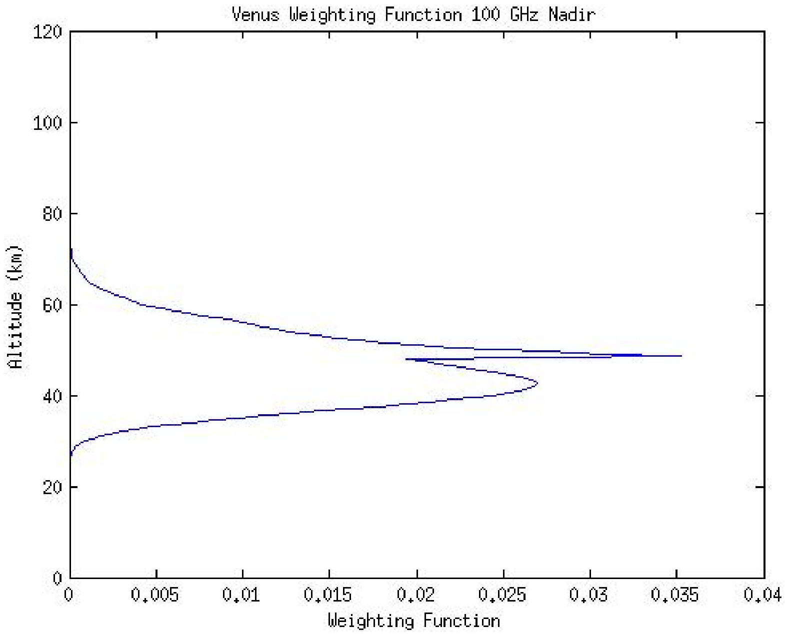

Figure 5: Altitude weighting function for Venus emission at 100 GHz computed using Georgia Tech Venus Radiative Transfer Model (GT-VRTM) developed under our predecessor grant.

Sagawa (2008) attributes the Venus millimeter-wavelength continuum brightness variations to spatial variations in the abundances of both gaseous H_2SO_4 and SO_2 in a range of altitudes from just below the lower cloud base to the top of the middle cloud (pressures 0.3-2 Bars). This is consistent with the weighting functions calculated using our (Georgia Tech) Venus radiative transfer model (see Figure 5). However his attribution involves use of models for the millimeter-wavelength opacities of these constituents which were extrapolated from previous centimeter-wavelength measurements. Additionally, Sagawa has suggested that the effects of the two constituents could be distinguished based on differences in frequency (wavelength) dependencies of the millimeter-wave absorption from both constituents, but those wavelength dependencies were uncertain. Under our predecessor grant (NNX11AD66G, 1/15/11-1/14/15), we recently completed measurements of the millimeter-wave absorption from SO_2 at these pressures under simulated Venus conditions (CO_2 atmosphere with temperatures from 307-343 K). One example of our laboratory results is in Figures 6 (below). Our laboratory measurements conducted in the 2-4 mm wavelength range verify the accuracy of both the Fahd and Steffes (1992) and Suleiman et al. (1996) models for use at millimeter-wavelengths. [Note that these laboratory results are part of a Master's thesis being completed by graduate student Amadeo Bellotti (Bellotti, 2014) and will also be the basis for a paper being prepared for submission to *Icarus* (Bellotti and Steffes, 2014).]

In addition to *gaseous* H_2SO_4 and SO_2, some minor contributions to the emission spectrum in the 2-4 mm wavelength range are made by collisionally-induced absorption from CO_2 (Ho et al., 1966) and absorption from the sulfuric acid cloud (Fahd and Steffes, 1991). Both are included in our radiative transfer model, but have effects on the millimeter-wavelength emission spectrum that are significantly lower than those from *gaseous* H_2SO_4 and SO_2.

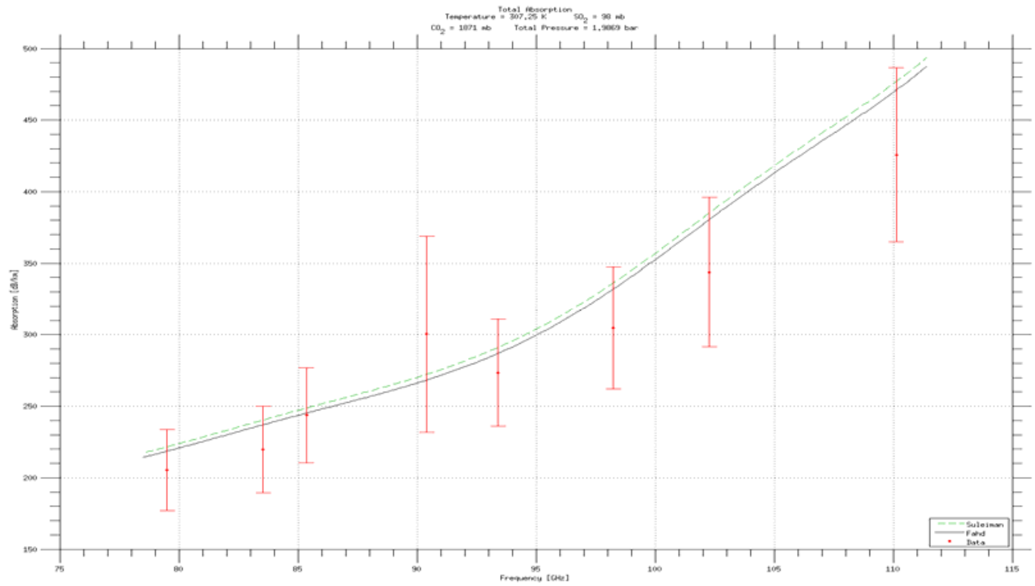

Figure 6: Measured absorptivity from SO_2 (partial pressure 98 mBars) in a CO_2 atmosphere (total pressure 1.87 Bars) at 307 K in the 78-110 GHz (2.7-3.8 mm) range. Also shown are calculated opacities from models by Fahd and Steffes (1992) and Suleiman et al. (1996). This profile is one of several measured in the 75-150 GHz (2-4 mm) range, and from 307-345 K at pressures from 0.05-2 Bars.

To date, determination of the millimeter-wavelength absorption from gaseous H_2SO_4 has been speculative. While measurements have been made of a number of the line center *frequencies* of the over 42,000 centimeter-, millimeter-, and submillimeter-wavelength lines of sulfuric acid vapor (see, e.g., Cohen and Drouin, 2013), a much smaller number of line *intensities* have ever been directly measured. Moreover, no laboratory measurements of the millimeter-wavelength continuum spectrum of sulfuric acid vapor broadened by carbon dioxide have ever been conducted. High-accuracy laboratory measurements of the *centimeter-wavelength* (1.3-13 cm) continuum opacity of gaseous H_2SO_4 in a CO_2 atmosphere (Kolodner and Steffes, 1998) were conducted in our lab, but even with a wide range of possible lineshapes, it is not possible to match those measurements with the current line catalog. This led Kolodner and Steffes to develop best-fit multiplicative expressions which served well in interpreting *centimeter-wavelength* radio occultation data (Kolodner and Steffes, 1998) and *centimeter-wavelength* radio astronomical observations (Jenkins et al., 2002). However, extrapolation of the Kolodner and Steffes (1998) model to *millimeter-wavelengths* (such as suggested in Sagawa, 2008) may lead to significant errors in interpretation of such observations.

A. Approach for Measurements of Millimeter-Wavelength Opacity of Sulfuric Acid Vapor

The highly-successful measurements of the millimeter-wavelength opacity spectrum of sulfur dioxide in a carbon dioxide atmosphere described above were originally planned to be conducted by using a simple pressurized transmission cell containing a test atmosphere contained within a temperature chamber (oven) along with highly stable swept signal sources and detectors placed with their antennas outside the oven (Devaraj and Steffes, 2011). However, due to the short path length (less than 1 meter) the sensitivity of such a system was found lacking, and in order to achieve the required sensitivity, use of a Fabry-Perot resonator (providing path lengths in excess of 200 meters) was required. As shown in Figure 7, the test system actually used for the measurements of SO_2 in a CO_2 atmosphere employed a Fabry-Perot resonator and its accompanying pressure envelope (originally developed for measurements of ammonia under Jovian conditions, see Devaraj and Steffes, 2011) placed within the temperature chamber (oven) into which was added the gas mixture under test. The resonator in its accompanying glass pressure vessel is shown in Figure 8.

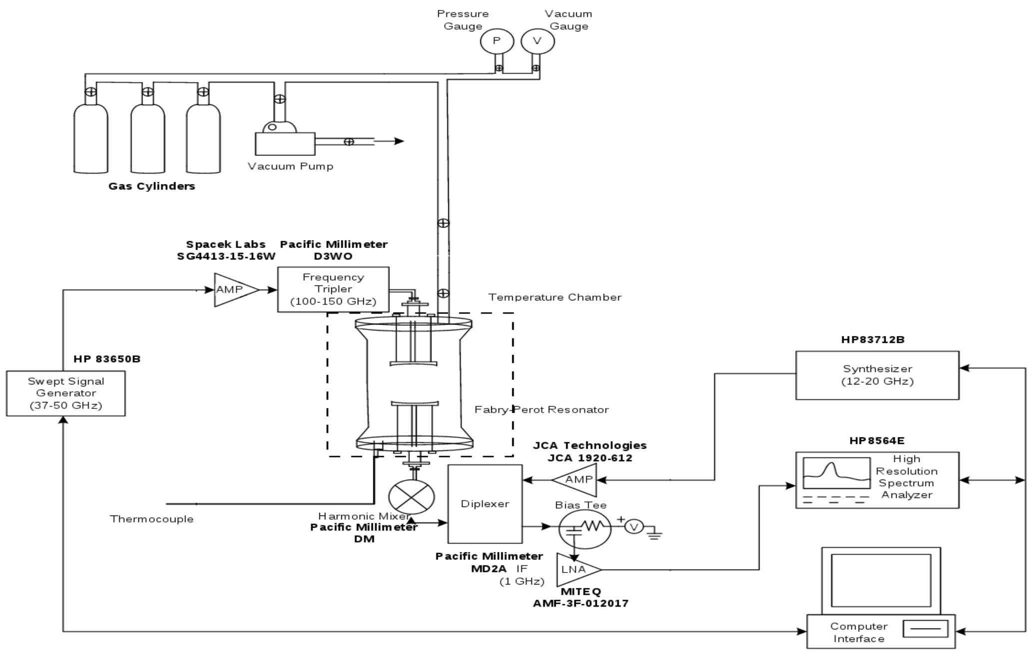

Figure 7: System used for measurement of SO_2/CO_2 mixture in the 2-3 cm (100-150 GHz) wavelength range (F-Band). The same resonator was used for W-Band (75-110 GHz, or 3-4mm) measurements using a different set of frequency multipliers and harmonic mixers.

As can be seen in Figure 8 (below), all components within the resonator pressure envelope are exposed to the gas mixture under test and are maintained at the temperature under test. While this was appropriate for measurements of SO_2/CO_2 mixtures at temperatures below 400 K, significant damage would occur if a mixture of highly corrosive gaseous H_2SO_4 in a CO_2 atmosphere were introduced at temperatures above 450 K. (Note that because of its low vapor pressure, sulfuric acid measurements must be conducted at temperatures above 450 K so that enough vapor will be present in the test mixture so as to be measurable with our resonator system.) As a result, we have recently begun development of Fabry Perot resonator system wherein the gas mixture under test is located in a glass cylinder within the temperature chamber (oven), but the mirrors and all electronics are located external to the oven. (See Figure 9.)

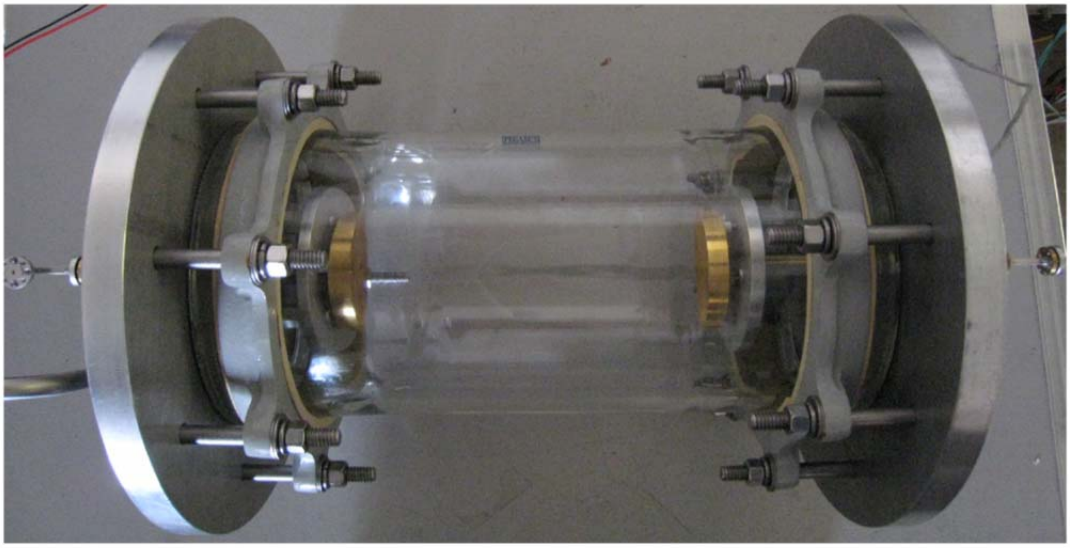

Figure 8: Fabry-Perot resonator used within oven for measurement of SO_2/CO_2 mixtures(oven),

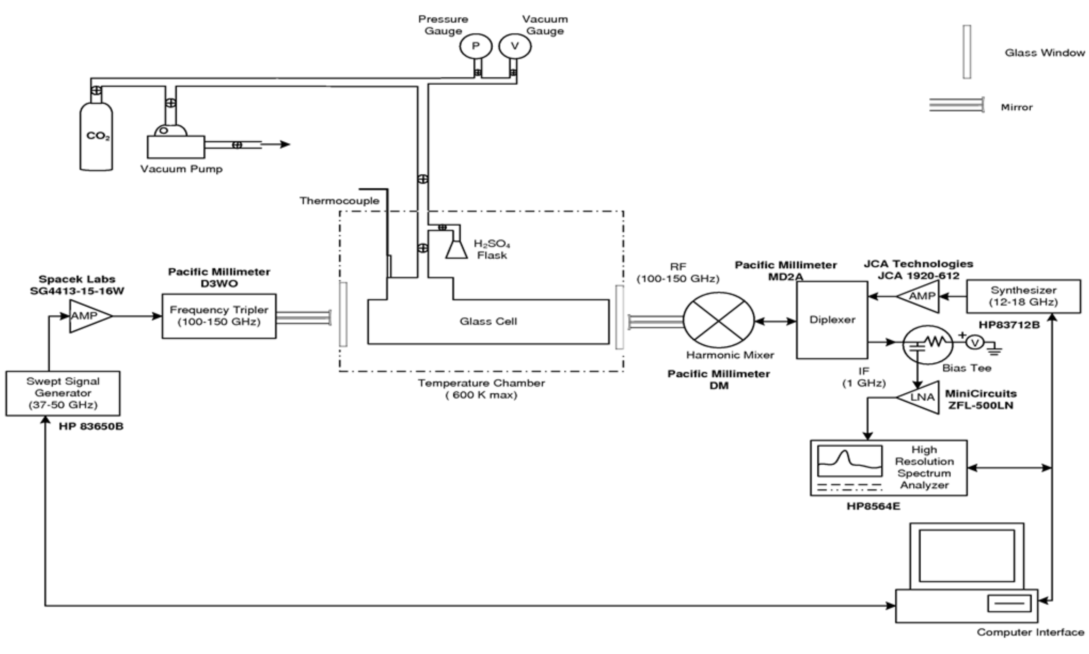

Figure 9: System to be used for measurement of $H_2SO_4(g)/CO_2$ mixture in the 2-3 cm (100-150 GHz) wavelength range (F-Band). The same resonator will be used for W-Band (75-110 GHz, or 3-4mm) measurements, using a different set of frequency multipliers and harmonic mixers. Measurements in Ka-Band (30-40 GHz) will be conducted using the same glass cell, but a different set of mirrors.

As shown in Figures 10 and 11, high-temperature glass windows are mounted in the oven walls allowing the microwave signals to propagate through the windows and to the mirrors. As with the previous system described above (Figures 7 and 8), the absorptivity and refractivity of the test mixtures are measured based on changes to the center frequency and quality factor (or Q) of the individual resonances (Devaraj and Steffes, 2011). However, because there will be portions of the resonator system not containing the test gas, a correction for "equivalent path length through the gas mixture under test" must be developed.

Figure 10: Glass cell mounted within temperature chamber (oven), with glass widow (rear) providing access to the externally mounted resonator mirror.

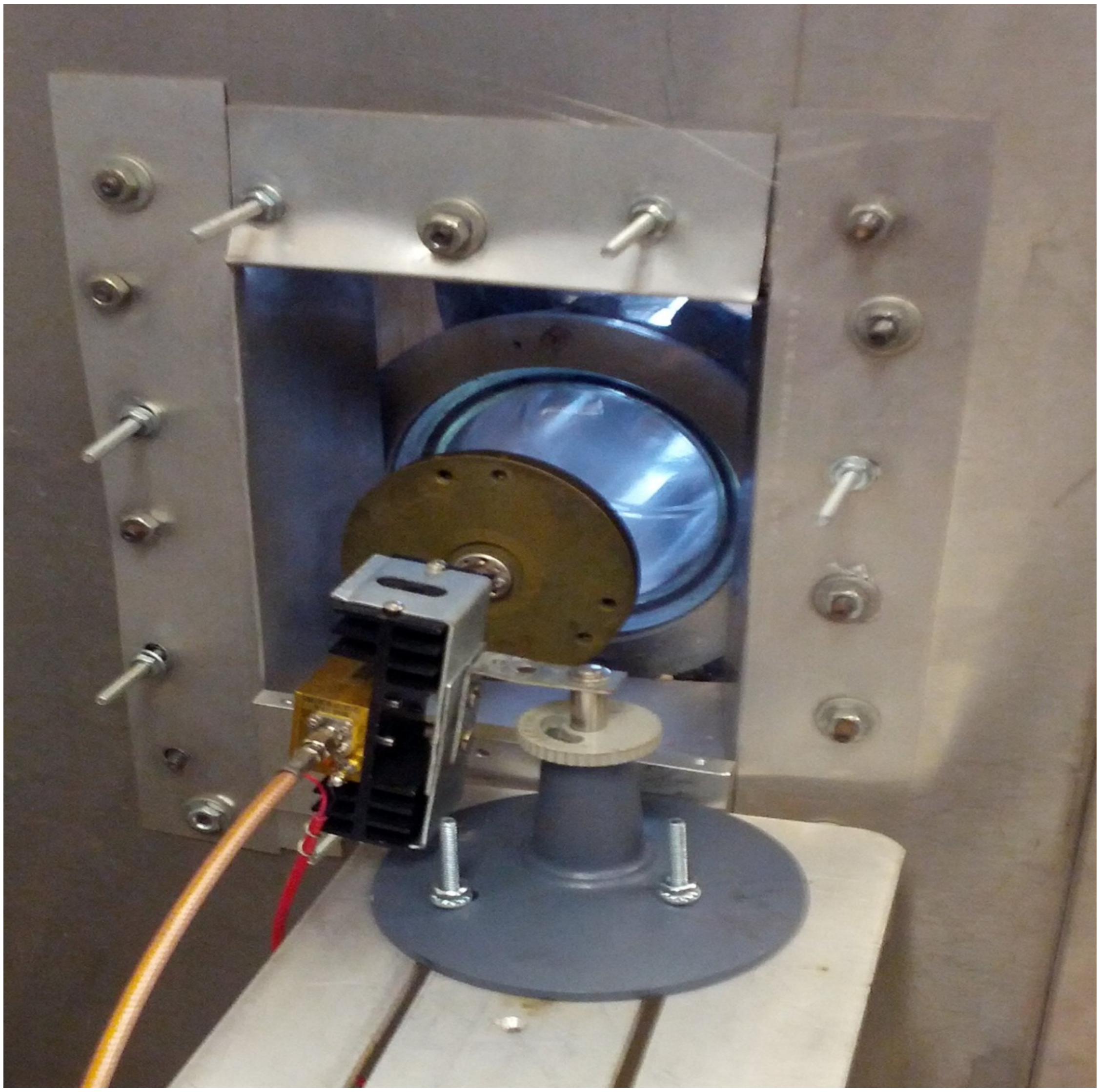

Figure 11: Glass cell mounted within temperature chamber (oven), with glass widow (rear) providing access to the externally mounted resonator mirror and signal source.

In our "traditional" Fabry-Perot resonator measurements where the entire resonator is exposed to the test gas mixture, the relationship between the quality factor, or Q, of each resonance and the absorptivity (or extinction coefficient) at each resonant frequency is given by the equation (Devaraj and Steffes, 2011):

$$\alpha = 8.686\,\frac{\pi}{\lambda}\left(\frac{1-\sqrt{t_{loaded}}}{Q^{m}_{loaded}} - \frac{1-\sqrt{t_{matched}}}{Q^{m}_{matched}}\right) \qquad (dB/km) \qquad (1)$$

where the quality factor, Q, of each resonance is directly measured by dividing the measured center frequency (f_o) by the measured half-power bandwidth (HPBW) with both the gas mixture under test present (loaded) and with a lossless reference gas with the same refractive index (matched)

$$Q = \frac{f_0}{HPBW} \tag{2}$$

The quantity t is the linear insertion loss at the resonance peak (a value between 0 and 1) which is measured both with the gas mixture present and with the lossless reference gas and λ is the wavelength (in km) with the test gas present. The effective path length (EPL) through the test gas in the resonator (when the entire resonator is exposed to the test gas mixture) is (Devaraj and Steffes, 2011)

$$\mathrm{EPL(km)} = Q^{m}_{loaded}\, \lambda/2\pi \tag{3}$$

It is also possible to relate the path length to the change in insertion loss and the measured absorptivity at the resonant frequency:

$$\mathrm{EPL\ (km)} = 10 \log_{10}(t_{matched}/t_{loaded}) \,/\, \alpha\ \mathrm{(dB/km)} \tag{4}$$

While the results from equations (3) and (4) are normally identical, they will deviate in our new system since the EPL given in equation 4 is reduced due to the resonator ray path only being partially through the test gas. Thus to derive an accurate extinction coefficient, we will scale the results from equation (1) by the ratio of the ideal effective path length (given by equation 3) and the modified effective path length (shown in equation 4), thus giving

$$\alpha_{\mathrm{corrected}}\ \mathrm{(dB/km)} = [\alpha\mathrm{(dB/km)}]^2\ Q^{m}_{loaded}\, \lambda \,/\, [20\pi \log_{10}(t_{matched}/t_{loaded})] \tag{5}$$

B. Application of Measurements of Millimeter-Wavelength Opacity of Sulfuric Acid Vapor

As shown below in Figure 12, the current range of models for the millimeter-wavelength opacity of gaseous sulfuric acid in a carbon dioxide atmosphere is very broad. When applied to our radiative transfer model, the resulting uncertainty in the retrieved abundance of sulfuric acid vapor derived from our observations of Venus using the CARMA observatory, or from other observations using the ALMA or Nobeyama observatories would be nearly an order of magnitude. However, with the laboratory measurements proposed here, it will be possible to develop a new model (or verify an existing one) to a precision of better than 20%. When applied to our radiative transfer model and the various multi-frequency millimeter-wavelength observations, the new model will provide the capability to accurately retrieve spatial variations in the abundances of both gaseous H_2SO_4 and SO_2 in a range of altitudes from just below the lower cloud base to the top of the middle cloud (pressures 0.3-2 Bars), as suggested by Sagawa (2008).

Additionally, results for the 7.5-10 mm opacity from sulfuric acid vapor will be incorporated both into our radiative transfer model *and* provided to radio science teams of perspective (or selected) Venus missions, which will be able to employ these results in planning and interpreting radio occultation experiments using the Ka-band telecommunications systems now being integrated into the NASA-DSN for the next generation of NASA missions.

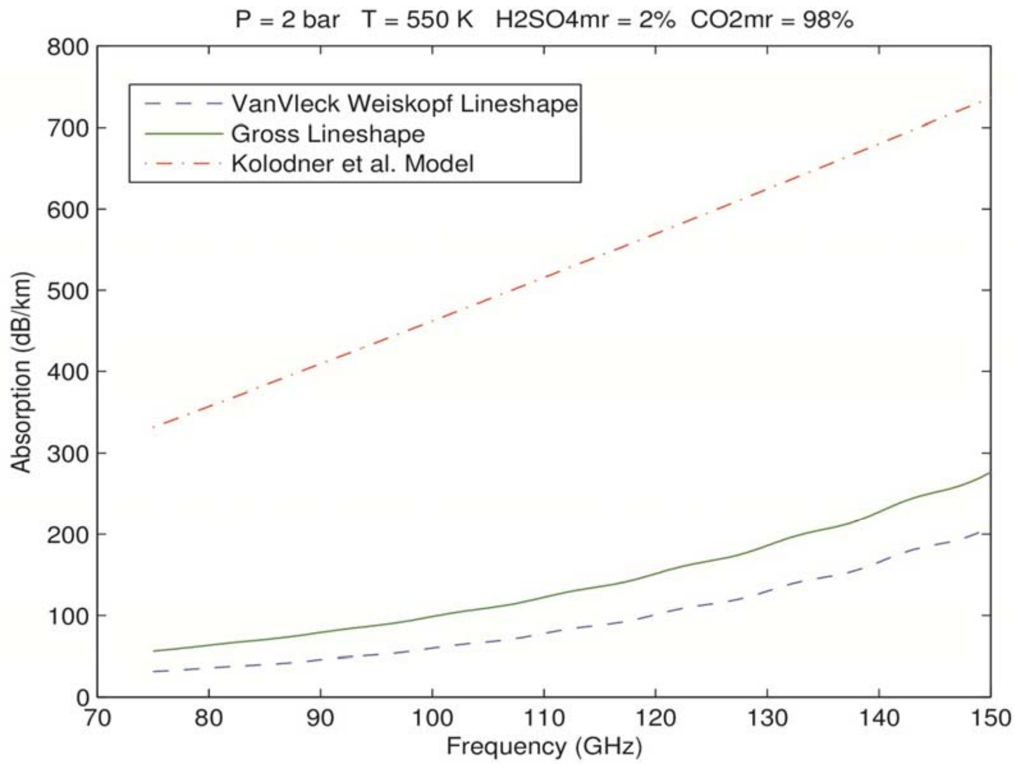

Figure 12: Comparison of different models for the 2-4 mm opacity of gaseous H_2SO_4 in a CO_2 atmosphere under simulated Venus conditions as will be used in our laboratory. Shown are models from Kolodner et al. (1998) and subsequent models developed using the latest line catalog (Cohen and Drouin, 2013) assuming either Gross or Van Vleck-Weisskopf lineshapes.

V. PROPOSED PROCEDURE AND LEVEL OF EFFORT

An aggressive program of microwave remote sensing studies and laboratory measurements of the millimeter-wave properties of gaseous sulfuric acid under simulated Venus conditions is proposed. The millimeter-wave experiments will enable us to retrieve constituent variations at and above the cloud base, known to be the source of variations in Venus millimeter-wavelength emissions reported by radio astronomical observers, and will also illuminate the ability of new ground-based millimeter-wave arrays (such as ALMA and CARMA) to provide planet-wide maps of atmospheric constituents comparable in sensitivity and resolution to those obtained with spacecraft instruments. Additional measurements in the 7.5-10 mm wavelength range will support proposed Ka-Band radio occultation studies of the Venus atmosphere to be included in a range of proposed Venus-targeting Discovery class missions.

Key activities involve:

YEAR 1: Complete modification of the existing 2-4 mm laboratory system to allow measurement of the 75-110 GHz (2.7-4mm) opacity from gaseous H_2SO_4 in a CO_2 atmosphere under simulated conditions for the Venus atmosphere. Complete measurements of the H_2SO_4/CO_2 mixture in the 0.3-2 Bar and 475-575K range.

YEAR 2: Modify system so as to conduct measurements in the 110-150 GHz (2-2.7 mm) range. Complete opacity measurements of gaseous H_2SO_4 in a CO_2 atmosphere under simulated conditions for the Venus atmosphere in the 0.3-2 Bar pressure range. Modify system so as to conduct measurements in the 30-40 GHz (7.5-10 mm) range.

YEAR 3: Complete measurements of the 7.5-10 mm opacity of H_2SO_4 in a CO_2 atmosphere under simulated conditions for the Venus atmosphere. Subsequently develop millimeter-wavelength opacity models for gaseous H_2SO_4 and apply results to our radiative transfer model. Retrieve abundance variations at the cloud base from existing millimeter-wave (2.6-3.0 mm) maps. Additionally, provide model for 7.5-10 mm opacity to Venus mission teams in preparation for Ka-Band radio occultations to be conducted in the next generation of Venus missions.

The level of effort for the scientific research for this three year grant (August 1, 2015 through July 31, 2018) will involve one professor (P.G. Steffes, Professor of Electrical and Computer Engineering) at 25% time (3.0/months/year), and one graduate student (Graduate Research Assistant Amadeo Bellotti) at 50% time. (Note that 50% is the maximum support level for Ph.D. students, with the remaining 50% considered as registered academic thesis research. Professor Steffes is authorized to commit up to 50% time (total) for research in space sciences and engineering.) Support is requested for laboratory supplies and gases, and for travel of the PI and the graduate student to attend and present results at the annual AAS/DPS Meetings.

In addition to the participation in the program by Professor Steffes and the paid graduate research assistant, contributions to the program from both graduate and undergraduate students working on special projects for academic credit have been substantial. Likewise, in the spirit of the NASA Graduate Student Researchers Program, and in conjunction with Georgia Space Grant Consortium, we continue to seek out talented underrepresented minority students and involve them in our program.

The amount of collaborative work we have conducted in both our Venus atmospheric studies and in our studies of the outer planets has demonstrated a need for a reference source of information regarding the microwave and millimeter-wave absorption properties of planetary atmospheres. At the suggestion of Dr. Reta Beebe (NMSU) who is responsible for the Planetary Atmospheres node of the Planetary Data System (PDS), we created a web page which allows direct access to references of laboratory results for the microwave and millimeter-wave absorptive and refractive properties of planetary atmospheric constituents, both from our group and from others in the world. The URL for this page is http://users.ece.gatech.edu/~psteffes/palpapers/ Additionally, all of our recent publications involving laboratory *results* have been published in the journal Icarus (publisher Elsevier), which now provides archival service of not only papers, but also of accompanying data files which can provide readers with easy access to the complete data sets from our laboratory measurement campaigns.

V. REFERENCES

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VI. FACILITIES

The specific laboratory measurements described in this proposal will be conducted at the Planetary Atmospheres Laboratory and the accompanying Remote Sensing Laboratory, which are located within the School of Electrical and Computer Engineering at Georgia Tech. Over the past 30 years, this laboratory has become a world leader in the laboratory measurement of the microwave and millimeter-wave properties of simulated planetary atmospheres. A description of the equipment being used for the proposed measurements is given in Section IV of this proposal. As described in Part IV of this proposal, significant upgrades to our millimeter-wave systems are now being completed. Most of these upgrades have been supported by internal Georgia Tech resources,

For support of the required data analysis and computing activities, a wide range of computing services for education, research, and administration is provided by the Georgia Tech Office of

Information Technology. Numerous personal computers and a new laboratory-laptop are also available to support this project.

VII. BIOSKETCH

Dr. Paul Steffes. Professor
Georgia Institute of Technology, School of Electrical and Computer Engineering

Role in Proposed Work – Principal Investigator

Experience Related To The Responsibilities For the Study of Planetary Atmospheres:
For 35 years, Professor Steffes has worked directly in conducting laboratory measurements to support microwave remote sensing of planetary atmospheres, and in the execution of spacecraft-based radio occultation measurements and earth and space-based radio astronomical measurements. Over the past 30 years, his laboratory has become a world leader in the laboratory measurement of the microwave and millimeter-wave properties of simulated planetary atmospheres. For over 35 years he has been an active member of the Division for Planetary Sciences of AAS. In 1996, he was awarded the IEEE Judith Resnik Award, "For contributions to an understanding of the Venus atmosphere through innovative microwave measurements," In January 2004, he was named a Fellow of the Institute of Electrical and Electronics Engineers (IEEE), "for contributions to the understanding of planetary atmospheres." He is currently a science team member for the Juno Mission, and is a Lifetime National Associate of the National Academies.

Relevant Publications:

--- J. M. Jenkins and P. G. Steffes, "Results for 13 cm Absorptivity and H2SO4 Abundance Profiles from the Season 10 (1986) Pioneer-Venus Orbiter Radio Occultation Experiment," Icarus, vol. 90, pp. 129-138, March 1991.
---D. R. DeBoer, and P.G. Steffes, "Laboratory Measurements of the Microwave Properties of H2S under Simulated Jovian Conditions with an Application to Neptune", Icarus, Vol. 109, pp. 352-366, June 1994.
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---P.N. Mohammed and P.G. Steffes, “Laboratory Measurements of the W-band (3.2 mm) Properties of Phosphine (PH_3) and Ammonia (NH_3) under Simulated Conditions for the Outer Planets.” Journal of Geophysical Research, vol 109, no. E07S13, pp 1-9, July 2004.
---T. R. Hanley 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, no. RS6010, pp.1-12, November-December 2007.
---T. R. Hanley, P.G. Steffes, and B.M. Karpowicz, “A New Model of the Hydrogen and Helium-Broadened Microwave Opacity of Ammonia Based on Extensive Laboratory Measurements,” Icarus, vol. 202, pp. 316-335, July 2009.
---K. Devaraj and P.G. Steffes “The Georgia Tech Millimeter Wavelength Measurement System and Some Applications to the Study of the Planetary Atmospheres” submitted to Radio Science, May 2010.
---K. Devaraj and P.G. Steffes, “The 2-4 Millimeter-Wave Opacity of Ammonia: Extensive Laboratory Measurements and a New Model,” submitted to Icarus, June 2010.

VIII. Current and Pending Support for Principal Investigator (Paul G. Steffes)

A. Current Support:

1. National Aeronautics and Space Administration - Grant NNG06GF34G,
“Laboratory Evaluation and Application of Microwave Absorption
Properties under Simulated Conditions for Planetary Atmospheres,”
$345,000 for the three year period (9/15/06 - 9/14/10, includes one-year NCE).
P.I. time commitment: 25% (3 person-months per CY).
(This proposal is for renewal/continuation of research conducted under this predecessor grant.)

2. Southwest Research Institute – Subcontract 699054X, from NASA Contract
NNM06AA75C, Juno-MWR (Microwave Radiometer) Team Member
$ 988,373 for the seven-year period (1/23/06 – 9/30/12). P.I. time commitment:
25% (3 person-months per CY).

B. Pending Support Other than this proposal:

None

Title: Laboratory Evaluation and Application of Microwave Absorption Properties under Simulated Conditions for Planetary Atmospheres

IX. BUDGET

The level of effort for the scientific research for this four year grant (August 1, 2015 through December 31, 2014) will involve one professor (P.G. Steffes, Professor and Associate Chair of Electrical and Computer Engineering) at 25% time (3.0/months/year), and one graduate student (Graduate Research Assistant) at 50% time. (Note that 50% is the maximum support level for Ph.D. students, with the remaining 50% considered as registered academic thesis research. Thus, the Ph.D. student supported on this project will work full-time on this project which includes dissertation research. Professor Steffes is authorized to commit up to 50% time (total) for research in space sciences and engineering.) Support is requested for laboratory supplies and gases, and for travel of the PI and the graduate student to attend and present results at the annual AAS/DPS Meetings.

Detailed Budget
(Annual Budgets beginning on
August 1 of each year listed)

		2015	2016	2017
1. Direct Labor*		$86,570	$86,570	$86,570
A. Principal Investigator (Paul G. Steffes) 25% time, calendar year (.25 person-years)	$ 52,323			
B. 1 Graduate Student (Ph.D. student) 50% time, calendar year (.5 person-years)	$ 24,700			
C. Fringe benefits (24.9% of direct salaries and wages, less students)**	$ 10,540			
2. Other Direct Costs:				
a. Supplies (Gas mixtures, microwave connectors, o-rings, pressure vessel components for lab experiments)		$ 3,000	$3,000	$3,000
b. Travel (For graduate student and principal investigator: Attend AAS/DPS Meetings --5 days, (Pasadena, CA) Airfare: $600 plus $220 /day for food and lodging)		$ 3,400	$3,400	$3,400
3. Facilities and Administrative Costs: Overhead (indirect expense), 50.5% of direct cost base **		$41,698	$41,698	$41,698
4. Other Applicable Costs: Tuition Remission ($11,448 per student per CY)**		$11,448	$11,448	$11,448

5. <u>Total Estimated Costs</u> <u>$135,716</u> <u>$135,716</u> <u>$135,716</u>

* The salary and wage rates are based on FY15 salaries for the Georgia Institute of Technology. The Georgia Tech Fiscal Year is July 1 through June 30.
**Rates are proposed for the period July 1, 2014 through June 30, 2015, and are subject to adjustment upon ONR negotiations..