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Center #: R6544-0A0  
Contract#: NAG 2-515  
Prime #:  
Subprojects ?: N  
Main project #:  
Project unit: EE  
Project director(s): STEFFES P G  
Cost share #:  
Center shr #:  
Mod #:  
Rev #: 0  
OCA file #:  
Work type : RES  
Document : GRANT  
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Total to date:
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Sponsor amount: 34,828.00  
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Does subcontracting plan apply ?: N  
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OCA contact: Ina R. Lashley  
Sponsor/division names: NASA
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Sponsor/division codes: 105
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Title: PIONEER VENUS RADIO OCCULATION (ORO) DATA REDUCTION: PROFILES OF 13CM ABSSORB

PROJECT ADMINISTRATION DATA

OCA contact: Ina R. Lashley 894-4820  
Sponsor technical contact  
L E LASHER  
(415)694-6456  
PIONEER OPERATIONS OFFICE, MS/244-14  
NASA-AMES RESEARCH CENTER  
MOFFETT FIELD CA 94035  

Security class (U,C,S,TS): U  
Defense priority rating : N/A  
Equipment title vests with: Sponsor
NONE PROPOSED.

Administrative comments -
THIS GRANT IS ADMINISTERED UNDER "NASA PROVISIONS FOR RESEARCH GRANTS & COOPERATIVE AGREEMENTS" (FORM 1463A) AND "SPECIAL CONDITIONS" ATTACHED.
GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 09/25/90

Project No. E-21-F17_________ Center No. R6544-0A0_________
Project Director STEFFES P G_________ School/Lab ELEC ENGR_______
Sponsor NASA/AMES RESEARCH CTR, CA______________________________
Contract/Grant No. NAG 2-515______________ Contract Entity GTRC
Prime Contract No. ____________________________________________

Title PIONEER VENUS RADIO OCCULATION (ORO) DATA REDUCTION: PROFILES OF 13CM ABS

Effective Completion Date 900930 (Performance) 900930 (Reports)

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NOTE: Final Patent Questionnaire sent to PDPI.
REPORT

TO THE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

- AMES RESEARCH CENTER -

SEMIANNUAL STATUS REPORT

(INCLUDES QUARTERLY PROGRESS REPORT #2)

for

GRANT NAG 2-515

PIONEER-VENUS RADIO

OCCULTATION (ORO) DATA REDUCTION:

PROFILES OF 13 CM ABSORPTIVITY

Paul G. Steffes, Principal Investigator

July 1, 1988 through December 31, 1988

Submitted by

Professor Paul G. Steffes
School of Electrical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0250
(404) 894-3128
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I. INTRODUCTION

Recent studies of the radio emission spectrum of Venus (Steffes, 1986 and 1987, and Steffes et al., 1987) have suggested that significant variations (both spatial and temporal) in the abundances of sulfur-bearing gases may be occurring below the Venus cloud layers. One technique for monitoring the abundance of sulfur-bearing gases (especially gaseous H$_2$SO$_4$) at and below the main Venus cloud layer (altitudes below 50 km) is to measure the 13 cm wavelength opacity using Pioneer-Venus Orbiter Radio Occultation Studies (PV-ORO).

In this study, we are working to characterize possible variations in the abundance and distribution of subcloud H$_2$SO$_4$ vapor in the Venus atmosphere by using a number of 13 cm radio occultation measurements made over a range of latitudes from polar to equatorial, obtained in late 1986 and early 1987 (Radio Occultation Season #10). Using the DSN receiver data tapes recorded during these occultations, we are developing 13 cm absorptivity profiles, from which we will infer gaseous H$_2$SO$_4$ abundance profiles. By comparing each abundance profile with those obtained at different latitudes and with those obtained from Pioneer-Venus Radio Occultation studies made in late 1978 and early 1979, we hope to characterize both temporal and spatial variations in subcloud H$_2$SO$_4$ abundance. Subsequent data interpretation studies and correlative studies with radio emission data will also be conducted.

II. SUMMARY OF ACTIVITIES

In the first quarter of this period (July 1, 1988 through September 30, 1988), the Principal Investigator, Professor Steffes, and Graduate Research Assistant, Jon M. Jenkins, made two trips to the Jet Propulsion Laboratory
(JPL) to reduce P-V radio occultation data, and attended the Pioneer Venus Science Steering Group (SSG) meeting at Ames Research Center. The first trip to A. J. Kliore's group at JPL focused on "resurrecting" software written prior to 1979 for the inversion of ORO data, in order to obtain 13 cm absorptivity profiles. This posed a challenge since the software was designed to run on a different computer system than is currently used. For example, the file containing the S-band antenna pattern parameters was stored on magnetic tape in an ASCII format which was incompatible with the current PRIMOS (t.m.) operating system. We were able to upgrade and convert the software and data files so that preliminary absorptivity profiles were developed for orbits 2787 (entry) and 2801 (entry). During that week, Mr. Bob Jackson (of Ames Research Center) was able to provide antenna pointing information for both of these orbits (this is essential information for reduction of amplitude data).

After returning to Georgia Tech, a modem and PC-PLOT IV+, a terminal emulation package, were purchased. This enabled us to establish a long-distance remote link to RODAN (Radio Occultation Data Analysis Network) at JPL. Minor modifications to the inversion software were made using the remote link. In addition, eight additional orbits were targeted for reduction based on the depth to which the radio signal probed and the latitude of the occultation. Mr. Luke Mullen (of JPL) provided this valuable information. A complete list of the orbits to be analyzed, including the latitude, solar zenith angle, and lowest altitude of the periapsis point of the probing radio beam, is included in Table I. We contacted Mr. David Lozier (at Ames Research Center) and requested pointing information for these orbits to use during the second trip to JPL. Happily, this information was available at the beginning of the second trip to JPL.
Mr. Jon Jenkins visited JPL for a second time from August 29 to September 12, 1988. Professor Paul Steffes joined Mr. Jenkins at JPL on September 7. During these two weeks, the Prime computer, which supports RODAN, experienced hard disk problems and was not operational for four full working days and portions of others. In spite of this problem, the power and frequency profiles for four new orbits were loaded from magnetic tape and processed. Examination of the corrected power profiles revealed that the antenna pointing correction was not being computed correctly. Further analysis of the program revealed a long-existing "bug" in the software. This was corrected and the antenna pointing corrections now appear to be properly computed.

To understand the importance of the antenna pointing issue, it must be remembered that the direction of the beam of the High Gain Antenna (HGA) aboard the Pioneer-Venus Orbiter is only adjusted once per orbit, so that it will be pointed directly toward earth at the periapsis of each orbit. Since during radio occultations, the trajectory of the ray path back to earth can vary by as much as ±3.5° from the geometric "straight line" direction back to earth, significant signal reductions will occur. The reductions are not due to atmospheric effects, but are due to the gain dependence of the orbiter antenna on incident angle. During the Pioneer-Venus primary mission, the antenna slew commands were sent to the orbiter so that its antenna beam would always track the "expected" ray path back to earth. Thus, little, if any, correction was needed for power variations due to S-band antenna mispointing. However, since such tracking is no longer employed, a correction to the received signal amplitude, such as shown in Figure 1 for the Orbit 2792 entry occultation, is required.
In Figure 2a, we show such a corrected received power profile from the entry occultation during Orbit 2801. Figure 2b shows the signal reduction due to refractive defocusing in the planet's atmosphere obtained during the same orbit. This defocusing is computed from ray trajectory information which is inferred from the doppler (frequency) data collected at the DSN receiving station. It is plotted as a function of ray periapsis altitude, rather than as a function of time, so as to show the increasing defocusing that occurs deep in the highly refractive atmosphere. When the refractive defocusing is subtracted from the corrected power profile, the difference is the "excess attenuation" which is due to actual absorption by atmospheric constituents (Figure 2c). By using an inverse Abel integral transform, it is possible to obtain the profile of absorptivity (in units of decibels per kilometer) shown in Figure 2d. (Note that these figures are different from similar ones presented in Quarterly Progress Report #1 for Grant NAG 2-515, since they were derived using the revised antenna pointing correction algorithm.)

Also during the second trip to JPL, studies were made of the quality of the 13 cm data taken during occultations. In general, it was found that data taken during ingress or entry occultations (e.g. orbit 2801N) were far superior to data taken during egress of exit occultations (e.g. orbit 2801X). This is due to the fact that, during entry occultations, the spacecraft transmitted frequency is locked to a reference transmitted by the DSN uplink station, and is, therefore, extremely stable. (This is critical for the proper determination of the refractive defocusing.) During the exit occultation, the signal being transmitted from the spacecraft is initially referenced to the spacecraft's internal oscillator, which, in addition to being inherently less stable, is modulated by the variations in the power
supply voltage which result from a failed section of the solar cell array used to power the spacecraft. As a result, a large majority of occultations used in this study will be entry (suffix "N") occultations, rather than exit (suffix "X") occultations.

During the SSG meeting, which followed the second trip to JPL, we had several fruitful discussions with Mr. Jim Phillips concerning the antenna pointing issue. A presentation describing our project was also given. We also had the opportunity to discuss the uncertainties associated with data derived from radio occultations with Dr. G. L. Tyler of Stanford University.

In the second quarter of Grant NAG 2-515 (October 1, 1988 through December 31, 1988), work has focused on the reduction of 13 cm absorptivity data from additional orbits. During the month of October, the JPL-RODAN (Radio Occultation Data Analysis Network) System was shut down for hardware upgrades. However, work continued on devising better techniques for accurately characterizing the error bars for the derived absorptivity profiles.

In early November, Professor Steffes and Graduate Research Assistant Jon Jenkins travelled to Austin, Texas to present a paper at the 20th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society (AAS/DPS). The paper presented the first results for Venus microwave opacity obtained since Pioneer-Venus Orbit #358 in November 1979 (Jenkins and Steffes, 1988: Abstract attached as Appendix 1). Since early November, we have reduced data from an additional five orbits (see Table I) probing equatorial and mid-latitude regions. The resulting absorptivity profiles are shown in Figures 3 through 7.

While reducing the data from these orbits, additional problems with the existing data reduction software have been discovered. Many of the problems
relate to the generation of "round-off" errors in the various calculations performed, and have been corrected. While we are encouraged by the quality of the recently-derived 13 cm absorptivity profiles, it has become clear that their usefulness in characterizing potential spatial or temporal variations in subcloud H₂SO₄ abundance is dependent on our ability to accurately characterize the uncertainty in the derived profiles. Reductions of early (1978-79) Pioneer-Venus radio occultation data in order to obtain absorptivity profiles (Cimino, 1982) used relatively crude techniques for estimating uncertainties, which may have drastically underestimated the uncertainties at some altitudes. A key future activity for this project will be development of a theoretically sound procedure for characterizing uncertainties in the derived absorptivity profiles.

III. INTERPRETATION OF RESULTS

To show the usefulness of the 13 cm opacity data for inferring the nature of the gaseous H₂SO₄ abundance, we compare in Figure 8 the measured absorptivity profile from orbit 2801N with that absorptivity which would result from a saturation abundance of gaseous H₂SO₄ (from Steffes, 1985) in the 43 to 55 km altitude range. It can be seen that for altitudes in the 49 to 51 km altitude range (the nominal altitude range of the Venus lower cloud – see Ragent and Blamont, 1980), absorptivity values close to those caused by a saturation abundance of gaseous H₂SO₄ are seen. At lower altitudes, most values for absorptivity are below those caused by a saturation abundance. It should be noted that error bars for this preliminary absorptivity data have not yet been computed.
Figure 9 shows the full extent to which application of our laboratory results can be carried. The abundance of gaseous $\text{H}_2\text{SO}_4$ (derived from the absorptivity profile in Figure 2d by using laboratory results from Steffes, 1985) is plotted as a function of altitude, along with a plot of the saturation abundance of gaseous $\text{H}_2\text{SO}_4$, for comparison. As our work in the Pioneer—Venus Guest Investigator Program yields more absorptivity profiles for a wide range of locations in the Venus atmosphere, we hope to be able to well characterize the abundance, structure, and spatial variations of gaseous $\text{H}_2\text{SO}_4$ in the Venus atmosphere. We also hope to make comparative studies with earlier radio occultation measurements in order to detect possible temporal variations in $\text{H}_2\text{SO}_4$ abundance and structure.

At the November 1988, AAS/DPS (Division for Planetary Sciences of the American Astronomical Society) Meeting, two independent groups brought to our attention observations made of diurnal variations in the Venus millimeter-wave emission spectrum. Results reported by both the Cal.—Tech. group (Pierce et al., 1988) and by the U.C.—Berkeley group (de Pater, personal communication) showed a higher brightness temperature on the night side of the planet at wavelengths near 2.6 mm. While some atmospheric opacity near 2.6 mm is due to high altitude carbon monoxide (CO), both groups reported the variation at wavelengths well separated from the $J = 0 \rightarrow 1$ CO transition. Since the highest level of significant millimeter-wave opacity at these wavelengths appears to occur in the 45-55 km altitude range, it is possible that either diurnal variations in the main cloud bulk density or diurnal variations in the abundance of gaseous $\text{H}_2\text{SO}_4$ are responsible for the observed emission variations. (Note that no measurements, either remote or in-situ, have suggested diurnal variations in atmospheric or surface temperatures.)
Since the 13 cm opacity is mainly due to the abundance of gaseous $\text{H}_2\text{SO}_4$ with little relation to cloud bulk density (see Steffes, 1985)s, we hope to be able to search for diurnal variations in the 13 cm opacity measured from Pioneer-Venus radio occultation studies. If no variations are detected, then the 2.6 mm variations will be attributable to the clouds. If such 13 cm variations are detected, we will attempt to correlate them with the variations in 2.6 mm emission. Further study of the 2.6 mm absorption from gaseous $\text{H}_2\text{SO}_4$ may be required, and possible laboratory measurements will be considered as part of a separate project we are conducting under the Planetary Atmospheres Program (Grant NAGW-533).

IV. PROPOSED ACTIVITY FOR THE NEXT QUARTER

In the third quarter of this project, we plan to continue reducing data for the remaining targeted orbits (correcting the existing software as necessary) and derive abundance profiles for sulfuric acid vapor from the results. We will also begin development of software to simulate P-V radio occultation experiments. This software will allow us to study the effects of noise on the measurements and improve the data reduction method. Eventually, this will lead to an effective procedure for determining the uncertainties in the derived absorptivity profiles.
V. REFERENCES


VI. KEY FIGURES
TABLE I
RADIO OCCULTATIONS (BY ORBIT NUMBER)
TO BE ANALYZED FOR 13 CM
ABSORPTIVITY PROFILES

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* N suffix indicates entry occultation, X suffix indicates exit occultation.
** Orbits from which 13 cm absorptivity profiles have been obtained as of 12/9/88.
Figure 1: Antenna gain correction (dB) due to change of ray path for Orbit 2792 entry occultation.

#PTS 398

POWER CORRECTION (dB)

TIME

85000 85020 85040 85060 85080 85100 85120
Figure 2: Radio occultation data for orbit 2801N (entry) -- August 6, 1986.

a) Received power level (dB) normalized to free space conditions as a function of ray periapsis radius. Signal level was corrected for variations in spacecraft antenna gain.

b) Refractive defocussing (dB) due to atmospheric refraction.

c) Excess attenuation due to atmospheric absorption versus ray periapsis radius (km).

d) Profile of atmospheric absorptivity (dB/km)
Figure 3: Profile of atmospheric absorptivity (dB/km) for Orbit 2792N (July 28, 1986).
Figure 4: Profile of atmospheric absorptivity (dB/km) for Orbit 2798N (August 3, 1986).
Figure 5: Profile of atmospheric absorptivity (dB/km) for Orbit 2814N (August 19, 1986).
Figure 6: Profile of atmospheric absorptivity (dB/km) for Orbit 2815N (August 20, 1986).
Figure 7: Inferred profile of atmospheric absorptivity (dB/km) for Orbit 2787N (July 23, 1986). The obvious problem with this profile (negative absorptivity), was caused, we believe, by antenna pointing errors at either the spacecraft or the DSN receiving site.
Figure 8: Comparison of absorptivities measured with radio occultation technique (circular points -- from Pioneer-Venus Orbit 2801-entry occultation) with absorptivity which would result from saturation abundance of $\text{H}_2\text{SO}_4$ (from Steffes, 1985). The absorption coefficient scale is logarithmic (exponents of 10). All measurements were made at the 13-cm wavelength (2.293 GHz).

Absorption Coefficient Inferred from Radio Occultation Data of Orbit 2801N

Altitude (km) (above 6052 km)

Absorption Coefficient (dB/km)

- inferred from orbit 2801N
- due to a saturation vapor abundance of sulfuric acid
Figure 9: Abundances of gaseous H$_2$SO$_4$ inferred from Pioneer-Venus 13-cm absorptivity profiles (circular points) compared with the saturation abundance profile of gaseous H$_2$SO$_4$ (from Steffes, 1985). The mixing ratio scale is logarithmic (exponents of 10).

Sulfuric Acid (H$_2$SO$_4$) Vapor Abundance

Altitude (km) (above 6052 km)

Mixing Ratio
VII. APPENDIX
Preliminary Results for 13-cm Absorptivity Observed during Pioneer-Venus Radio Occultation Season #10 (1986-87)

J.M. Jenkins, P.G. Steffes (Georgia Institute of Technology)

Studies of recent measurements of the 1.35 to 3.6 cm emission from Venus have suggested that long term temporal and/or spatial variations in the abundance of gaseous H$_2$SO$_4$ may occur immediately below the main cloud layer (48 km and below). One important tool for evaluating these effects is the reduction of the microwave data from the 1986-87 Pioneer-Venus radio occultation experiments. This data was taken over a wide range of latitudes and could be critical for determining whether temporal variations or spatial variations in gaseous H$_2$SO$_4$ abundance could be occurring.

We have begun processing 13 cm radio occultation data from Pioneer Venus Season #10 to obtain absorptivity profiles for the 1986-1987 epoch. Data from selected orbits spanning latitudes from polar to mid latitude have been selected, corrected and inverted to obtain absorption profiles as a function of altitude. Abundance profiles of gaseous H$_2$SO$_4$ can be inferred from the absorption profiles. Careful selection and processing of radio occultation data from Season #10 may provide insight into the possible variations of gaseous H$_2$SO$_4$ below the main cloud layer in Venus' atmosphere.

*This work was supported in part by NASA Grant NAG2-515. This material is based on work supported under a National Science Foundation Graduate Fellowship.
REPORT
TO THE
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
- AMES RESEARCH CENTER -

SEMIANNUAL STATUS REPORT #3
(Includes Quarterly Progress Report #6)

for
GRANT NAG 2-515

PIONEER-VENUS RADIO
OCCULTATION (ORO) DATA REDUCTION:
PROFILES OF 13 CM ABSORPTIVITY

Paul G. Steffes, Principal Investigator

July 1, 1989 through December 31, 1989

Submitted by

Professor Paul G. Steffes
School of Electrical Engineering
Georgia Institute of Technology
Atlanta, Georgia  30332-0250
(404) 894-3128
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I. INTRODUCTION

Recent studies of the radio emission spectrum of Venus (Steffes, 1986 and Steffes et al., 1990) have suggested that significant variations (both spatial and temporal) in the abundances of sulfur-bearing gases may be occurring below the Venus cloud layers. One technique for monitoring the abundance of sulfur-bearing gases (especially gaseous H$_2$SO$_4$) at and below the main Venus cloud layer (altitudes below 50 km) is to measure the 13 cm wavelength opacity using Pioneer-Venus Radio Occultation Studies (PV-ORO) (Steffes, 1985).

In this study, we have been working to characterize possible variations in the abundance and distribution of subcloud H$_2$SO$_4$ vapor in the Venus atmosphere by using a number of 13 cm radio occultation measurements made over a range of latitudes from polar to equatorial, obtained in late 1986 and early 1987 (Radio Occultation Season #10). Using the DSN receiver data tapes recorded during these occultations, we have developed 13 cm absorptivity profiles, from which we will infer gaseous H$_2$SO$_4$ abundance profiles. By comparing each abundance profile with those obtained at different latitudes and with those obtained from Pioneer-Venus Radio Occultation studies made in late 1978 and early 1979, we hope to characterize both temporal and spatial variations in subcloud H$_2$SO$_4$ abundance. Subsequent data interpretation studies and correlative studies with radio emission data are also being conducted.

II. SUMMARY OF ACTIVITIES

In the first half of this second year of Grant NAG 2-515 (July 1, 1989 through December 31, 1989) we have continued the work of reducing 13 cm radio occultation data to obtain 13 cm absorptivity profiles. A summary of our
activity is given in Table I. An example of an absorptivity profile recently obtained is shown in Figure 1. This activity has been conducted using the JPL-Radio Occultation Data Analysis Network (JPL-RODAN), which we access remotely from Georgia Tech. Also, from late June through early August 1989, Graduate Student Jon M. Jenkins visited JPL in order to process a new group of orbits as well as to work on error analysis of the data processing software, which is discussed in Section III. As shown in Table II, we have currently completed reduction of data from 16 occultations and are in the process of reducing data from an additional 5 orbits.

To this date, all data has been processed with our "new" software. This refers to several changes made to the original software used for computing absorptivity profiles in 1980. As described in previous reports, a revision was made which accurately corrects for variations in antenna gain during the radio occultation.

While reducing data, it was also found that the apparent signal levels received during some occultations actually increased as the spacecraft entered occultation rather than decreased, as would be expected. The only physical explanation for such an effect would be a significant mis-direction of the spacecraft antenna or operational problems at the DSN receiving site. Reviewing the work of Cimino (1982) showed that when such profiles appeared, they were simply characterized as being due to "operational problems." In fact, 50 percent of the radio occultations obtained in the 1978-80 period were so characterized. Additional tests which we have made of the original software used during that period, however, have shown that this effect was due neither to spacecraft antenna mis-direction nor to operational problems at the DSN receiving site. In fact, a "bug" in the portion of the software which
adjusts the signal levels so as to allow the proper determination of the 13 cm absorptivity profile was found. (This portion of the software could be considered an "Automatic Gain Control," or AGC.) Correction of this problem has drastically increased our resource of usable orbits. An example of the effect of this correction was presented in Quarterly Progress Report #5, which we submitted in September 1989, and was presented at the September 1989 Pioneer-Venus Science Steering Group (PV-SSG) meeting at UCLA.

Figure 2 shows averages of the 13 cm absorptivity profiles we have obtained for 5 different latitudinal areas, based on the 16 profiles currently available. When the polar latitude profiles are compared with other occultation-derived profiles obtained at lower latitudes, it appears as if the majority of absorptivity measured for the polar occultations lies at lower altitudes than for the equatorial or mid-latitude occultations. (A similar effect had been observed with the 1979 data.) Since the 13 cm opacity is largely due to gaseous H$_2$SO$_4$ (Steffes, 1985), this suggests a variation in the altitude of the cloud base (i.e. the altitude below which the absorption occurs). Moreover, when these absorption profiles (and the values for peak absorptivities below the clouds, shown in Table II) are compared with those obtained during the initial Pioneer-Venus radio occultations (1978-79) (Cimino, 1982), it appears as if the average 13 cm opacity has dropped, implying a reduced abundance of gaseous H$_2$SO$_4$. While this is suggestive of both spatial and long-term temporal variation in the subcloud abundance of gaseous H$_2$SO$_4$, it cannot be considered proof of such until the uncertainties in the derived absorptivity profiles are properly characterized.

In Figure 3, we show the absorptivity profile inferred for Orbit 2801N, along with the absorptivity which would be predicted to occur from a
saturation abundance of gaseous $\text{H}_2\text{SO}_4$, using results from a new laboratory measurement by Fahn and Steffes (1989). The same results were used in Figure 4 to infer the abundance of gaseous $\text{H}_2\text{SO}_4$ from the absorptivity profile given in Figure 3. In the future, we hope to develop $\text{H}_2\text{SO}_4(\text{g})$ abundance profiles for all 21 orbits, with error bars.

All of these results were presented at the 21st Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society (AAS-DPS) in Providence, Rhode Island, on October 31, 1989 (Jenkins and Steffes, 1989).

III. PROPAGATION OF ERRORS

Statistical errors are inherent in any set of experimental observations. The significance of small scale structure in experimental data is dependent on the magnitude of the statistical errors. Thus, knowledge of the variance of the noise fluctuations riding on the true data values is necessary to evaluate the validity of theoretical predictions or to compare independent sets of observations. In the case of indirect observations, where the desired quantity, $y$, is obtained by transforming the observed quantity, $x$, it is not possible to measure the noise power directly. If $y$ is related to $x$ by a linear transform $T$, then the covariance matrix of $y$ is given by

$$C_y = TC_x T^T$$

where

$$C_x = E[(x-x)(x-x)^T]$$

(Here, $x$ is the true value, and $\hat{x}$ is the measured value.)
If the errors are small, and the transform $T$ is nonlinear, then $C_y$ can be estimated by expanding $T$ in a Taylor series:

$$y = T_0 + T_1x + T_2x^2 + \ldots$$

and using the formula

$$C_y = T_1C_xT_1^T$$

This is the result of neglecting all terms higher than first order, and is known as the standard propagation of errors.

In the case of radio occultation experiments, frequency, $f$, and power, $p$, are measured directly. The errors $\Delta f$ and $\Delta p$ can be estimated in a variety of ways. The approach used is to fit a line to the set of points $[f(t_{n-4}), \ldots, f(t_n), f(t_{n+1}), \ldots, f(t_{n+4})]$ for each point $t_n$, and use the mean square error as the estimate for $\Delta f$. The same method is used to estimate $\Delta p$. Since the noise process is very nearly white Gaussian noise, and is stationary over short intervals, this provides a simple and adequate initial method for estimating the errors $\Delta f$ and $\Delta p$. This step is performed in the program RPP, which removes bias and drift from the frequency residuals (see Figure 5).

The frequency $f$ is used to determine the ray path parameters, $\beta$ (bending angle) and $b$ (ray impact parameter), in the program DIP1. These parameters are transformed to find the index of refraction, $n$, in the program DIP2. In the program ABS, $\beta$ and $b$ are used to determine refractive defocusing, which is subtracted from the corrected attenuation profile to yield the excess attenuation $\tau$. Finally, $\tau$ is transformed via the inverse Abel transform to obtain the absorptivity profile, $a$. For each of these quantities, the associated transforms are linearized and used to estimate the errors by the method of standard propagation of errors.
By September, RPP, DIP1, and DIP2 had been modified to carry the propagation of errors up to the program ABS. At this writing, we have just completed modifications to ABS, allowing us to estimate the errors in the absorptivity profile, so that objective interpretations and comparisons of the various orbits can be made.

IV. CONCLUSION AND PLANS FOR FUTURE WORK

As stated in our previous reports, reduction of data from additional orbits (giving a total of 21) is necessary in order to better characterize the possible temporal and spatial variations. We are well on our way to achieving this goal. However, of equal importance will be the proper characterization of the uncertainties which accompany these profiles. Only by accurate determination of the uncertainties will the potential detection of both temporal and spatial variations in 13 cm opacity be reliably obtained. Finally, we have recently begun study of alternative methods for computing the inverse Abel transform, which is used in obtaining the absorptivity profiles. The method which is currently used may in fact be suboptimal, especially under the low signal-to-noise conditions characteristic of radio occultation experiments. Alternative methods for performing the inverse Abel transform are being investigated which may result in lower uncertainties in the derived absorptivity profiles.
V. REFERENCES


V. KEY FIGURES
TABLE I
PIONEER-VENUS RADIO OCCULTATION (ORO) DATA REDUCTION: PROFILES OF 13-CM ABSORPTIVITY

DECEMBER 1989 PROGRESS REPORT

1. TO DATE, 16 ORBITS HAVE BEEN PROCESSED FROM OCCULTATION SEASON 10 (LATE 1986). (SEE TABLE II.)

2. PROBLEMS WITH PREVIOUSLY EXISTING SOFTWARE HAVE BEEN DETECTED IN AREAS OF ANTENNA POINTING CORRECTION, SIGNAL GAIN NORMALIZATION, (ALSO KNOWN AS AGC ACTION), AND SIGNAL PATH DETERMINATION. CORRECTIONS HAVE BEEN DEVELOPED.

3. PROFILES OF ABSORPTIVITY HAVE BEEN DEVELOPED (2.29 GHz, or 13 cm) WHICH ARE RELATED TO THE ABUNDANCE OF GASEOUS \( \text{H}_2\text{SO}_4 \) IN THE ATMOSPHERE.

4. PROFILES GENERALLY SHOW A LOWER 13 cm ABSORPTIVITY THAN TYPICALLY MEASURED IN THE FIRST RADIO OCCULTATION SEASON (1979-1980), HOWEVER, PROPER CHARACTERIZATION OF UNCERTAINTIES (I.E. ERROR BARS) IS NECESSARY TO CONFIRM ANY LONG-TERM TEMPORAL VARIATION.

5. DATA DOES NOT SUGGEST ANY DIURNAL VARIATIONS TO MATCH THOSE OBSERVED BY EMISSION MEASUREMENTS AT 2.6 mm.

6. LATITUDINAL VARIATIONS ARE APPARENT, I.E. ABSORPTIVITY BEGINS AT LOWER ALTITUDES IN POLAR REGIONS.

7. ABUNDANCES OF GASEOUS \( \text{H}_2\text{SO}_4 \) IN THE 5-20 PPM RANGE ARE COMMON BELOW THE CLOUD LAYERS.

8. FUTURE WORK:
   COMPLETE REDUCTION OF ADDITIONAL 5 ORBITS.
   COMPLETE CHARACTERIZATION OF UNCERTAINTIES FOR ALL 21 ORBITS IN ORDER TO VERIFY POSSIBLE TEMPORAL OR SPATIAL VARIATIONS.
   INVESTIGATE ALTERNATIVE METHODS FOR COMPUTING THE INVERSE ABEL TRANSFORM SO AS TO REDUCE UNCERTAINTY IN DERIVED ABSORPTIVITY PROFILES.
**TABLE II. DATA PROCESSING STATUS**

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*Note that N suffix indicates entry occultation, and X suffix indicates exit occultation.

**Deepest altitude probed (relative to radius of 6052 km) before loss of signal.
Figure 1: Profile of atmospheric absorptivity (dB/km) for Orbit 2845N (September 19, 1986) at a frequency of 2.295 GHz.
Figure 2: Average 13 cm opacity measured by Pioneer-Venus Radio Occultation Experiments over the period from July through December 1986. Absorptivity profiles are for five different latitudinal areas:
1. EQUATORIAL: Latitudes from 10° to 25°N. 2. LOW: Lower-middle latitudes from 35° to 45°N. 3. MID: Central middle latitudes around 60°N. 4. HIGH: Higher-middle latitudes around 80°N. 5. POLAR: Latitudes above 85°N.
Figure 3: Profile of atmospheric absorptivity measured for Orbit 2801N (August 6, 1986) (solid line) contrasted with absorptivity expected from a saturation abundance of gaseous H$_2$SO$_4$ (dashed line) computed by Fahd and Steffes (1989).
Figure 4: Abundance profile for gaseous $\text{H}_2\text{SO}_4$ derived from the absorptivity profile from Orbit 2801N using the $\text{H}_2\text{SO}_4$ absorptivity expression of Fahd and Steffes (1989).
**Propagation of Errors**

- **RPP**
  - \( f, P \)
    - \( \Delta f, \Delta P \) estimated from residual frequency \( f \), and received power \( P \).

- **DIP 1**
  - \( \beta, b, P_c \)
    - \( C_\beta = <\Delta \beta, \Delta \beta> \), \( C_b \) and \( C_{\beta b} \) found by linearizing transforms \( \beta = T_\beta(f) \), and \( b = T_b(\beta) \) and applying standard propagation of errors.

- **DIP 2**
  - \( n \)
    - \( C_n = <\Delta n, \Delta n> \) found by a similar procedure.

- **ABS**
  - \( \alpha \)
    - \( C_\alpha = <\Delta \alpha, \Delta \alpha> \) found by a similar procedure.

**Figure 5:** Flow chart of the progression of calculations in the propagation of errors in the sequence of programs applied to process Pioneer-Venus radio occultation data.
REPORT

TO THE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

- AMES RESEARCH CENTER -

SEMIANNUAL STATUS REPORT #4

(INCLUDES QUARTERLY PROGRESS REPORT #8)

for

GRANT NAG 2-515

PIONEER-VENUS RADIO

OCCULTATION (ORO) DATA REDUCTION:

PROFILES OF 13 CM ABSORPTIVITY

Paul G. Steffes, Principal Investigator

January 1, 1990 through June 30, 1990

Submitted by

Professor Paul G. Steffes
School of Electrical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0250
(404) 894-3128
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I. INTRODUCTION

Recent studies of the radio emission spectrum of Venus (Steffes, 1986 and Steffes et al., 1990) have suggested that significant variations (both spatial and temporal) in the abundances of sulfur-bearing gases may be occurring below the Venus cloud layers. One technique for monitoring the abundance and distribution of these gases (especially $\text{H}_2\text{SO}_4$) at and below the main Venus cloud layer (altitudes below 50 km) is to measure the 13 cm wavelength opacity using Pioneer-Venus Radio Occultation Studies (PV-ORO) (Steffes, 1985).

In this study, we have been working to characterize possible variations in the abundance and distribution of subcloud $\text{H}_2\text{SO}_4$ vapor in the Venus atmosphere by using a number of 13 cm radio occultation measurements made over a range of latitudes from polar to equatorial, obtained in late 1986 and early 1987 (Radio Occultation Season #10). Using the DSN receiver data tapes recorded during these occultations, we have developed 13 cm absorptivity profiles, from which it is possible to infer gaseous $\text{H}_2\text{SO}_4$ abundance profiles. By comparing each abundance profile with those obtained at different latitudes and with those obtained from Pioneer-Venus Radio Occultation studies made in late 1978 and early 1979, we are able to characterize both temporal and spatial variations in subcloud sulfuric acid vapor concentration.
II. SUMMARY OF ACTIVITIES

In the second half of this second year of Grant NAG 2-515 (January 1, 1990 through June 30, 1990) we have continued the work of reducing 13 cm radio occultation data to obtain 13 cm absorptivity profiles. A summary of our activity is given in Table I. During this period of time all remaining software has been modified to apply the standard propagation of errors to each step in the processing of the data in order to derive error bars for the absorptivity profiles. A schematic diagram of this process, and the theoretical basis for the standard propagation of errors has been discussed in previous reports (Steffes, 1989 and 1990). This activity has been conducted using the JPL-Radio Occultation Data Analysis Network (JPL-RODAN), which is accessed remotely from Georgia Tech both by telephone modem and by INTERNET/ARPANET. We have worked with JPL to improve the function of its INTERNET interface. This has allowed us to off-load more of the data processing and data analysis to Georgia Tech machines. Graduate Student Jon M. Jenkins visited JPL from March 14 through March 20, 1990 in order to reprocess all existing data sets with the new error estimating software. In addition, two new data sets were acquired and processed: orbits 2921N and 2923N ("N" implies data from entry occultation). As shown in Table II, we have currently completed reduction of data from 19 occultations and hope to reduce data from an additional 3 orbits by September 30, the closing date for this grant.
In May 1990, we submitted a paper to the journal *Icarus* entitled, "Results for 13 cm Absorptivity and H$_2$SO$_4$ Abundance Profiles from the Season 10 (1986) Pioneer-Venus Radio Occultation Experiment" (Jenkins and Steffes, 1990). In this paper, we described our work in developing 13 cm absorptivity profiles and their accompanying error bars for the 19 orbits listed in Table II. (Note that the 13 cm abundance profiles are directly related to the abundances of gaseous H$_2$SO$_4$, as discussed below.) We also discussed the fact that only a few profiles, located mainly at equatorial latitudes, had statistically significant 13 cm opacity (See, for example, Figure 1, the absorptivity profile for orbit 2787N; latitude: 11.26°.) Most of the other profiles could only place upper limits on the 13 cm absorptivity at the locations probed, because the opacity was so small. (See, for example, Figure 2, the absorptivity profile for orbit 2819N; latitude: 65.86°.)

In Jenkins and Steffes (1990), we also present averages of the 13 cm absorptivity profiles we obtained for 5 different latitudinal areas (See Figure 3). When the occultation profiles for the different areas are compared, it appears as if the level of significant absorptivity for polar occultations lies at lower altitudes than for the equatorial or mid-latitude occultations. (A similar effect had been observed with the 1979 data.) Since the 13 cm opacity is principally due to gaseous H$_2$SO$_4$ (Steffes, 1985), this suggests a variation in the altitude of the cloud base (i.e. the altitude below which the absorption occurs. However, this can only be considered valid if accurate error bars can be inferred for the
averaged profiles. In Figures 4 through 8, we show the 5 profiles and error bars developed for each (using standard propagation of errors) confirming the significance of this effect. Moreover, when these absorption profiles (and the values for peak absorptivities below the clouds, as shown in Table II) are compared with those obtained during the initial Pioneer-Venus radio occultations (1978-79) (Cimino, 1982), it appears as if the average 13 cm opacity has dropped, implying a reduced abundance of sulfuric acid vapor. While this is suggestive of long-term temporal variation in the subcloud abundance of gaseous H₂SO₄, it cannot be considered proof until the uncertainties in the earlier absorptivity profiles are properly characterized.

In Figure 9, we show the abundance of sulfuric acid vapor (with error bars) as a function of radius, inferred from the derived absorptivity profile using results from a recent laboratory measurement by Fahd and Steffes (1990). By September, we hope to develop gaseous H₂SO₄ abundance profiles for all 22 orbits with error bars.

III. CONCLUSION AND PLANS FOR FUTURE WORK

As stated in previous reports, reduction of data from additional orbits (giving a total of 22) is necessary in order to better characterize the possible temporal and spatial variations in the abundance and distribution of sulfuric acid vapor in the atmosphere of Venus. This goal has almost been achieved (19 of 22 orbits have been processed.) Now that error estimates have been
placed on the absorptivity profiles, it is possible to evaluate the existence of statistically significant temporal and spatial variations in the 13 cm opacity. In addition, we can now carry the propagation of errors through the algorithms which generate gaseous $\text{H}_2\text{SO}_4$ abundance profiles and which average selected profiles together to generate the representative profile of each latitudinal region.

Of equal, if not more importance, will be the empirical evaluation of alternative methods for computing the inverse Abel transform. It is clear that the final step of transforming the excess attenuation into absorptivity via the inverse Abel transform introduces the greatest statistical errors into the measurements. This is due to the fact that the inverse Abel transform corresponds to half order differentiation (Bracewell, 1977). Thus, it may be possible to reduce the magnitude of the estimated errors and retain small-scale structure by employing an alternative method for evaluating this recalcitrant transform. In order to accomplish this task, software is being developed to simulate the occultation experiment. Given a model atmosphere and spacecraft trajectory, the software will generate time series for the received power and frequency. Noise will be added to these quantities and the results fed to the data inversion software. By inserting the various methods for computing the inverse Abel transform into the inversion software, their performances can be objectively compared in order to select the method which is most stable and accurate under low signal-to-noise conditions. This simulation software will not only
allow us to determine the method which best handles noise, but will also allow us to locate and evaluate some sources of systematic errors within the data inversion software (i.e. the effect of truncating the last data point prior to inverting the excess attenuation).
IV. REFERENCES


V. KEY FIGURES
1. TO DATE, 19 ORBITS HAVE BEEN PROCESSED FROM OCCULTATION SEASON 10 (LATE 1986), INCLUDING ERROR BARS (SEE TABLE II).

2. PROBLEMS IN PREVIOUSLY EXISTING SOFTWARE HAVE BEEN DETECTED IN AREAS OF ANTENNA POINTING CORRECTION, SIGNAL GAIN NORMALIZATION (ALSO KNOWN AS AGC ACTION), AND SIGNAL PATH DETERMINATION. CORRECTIONS HAVE BEEN DEVELOPED.

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6. LATITUDINAL VARIATIONS ARE APPARENT, I.E. ABSORPTIVITY BEGINS AT LOWER ALTITUDES IN POLAR REGIONS.

7. ABUNDANCES OF GASEOUS H$_2$SO$_4$ IN THE 5–20 PPM RANGE ARE COMMON BELOW THE CLOUD LAYERS.

8. FUTURE WORK:

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   INVESTIGATE ALTERNATIVE METHODS FOR COMPUTING THE INVERSE ABEL TRANSFORM SO AS TO REDUCE UNCERTAINTY IN DERIVED ABSORPTIVITY PROFILES.

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**TABLE I**

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**June 1990 Progress Report**

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* Note that an N suffix indicates an entry occultation, and an X suffix indicates an exit occultation.

** Deepest altitude probed (relative to a radius of 6052 km) before loss of signal.
Figure 1: Absorptivity profile (13 cm) for orbit 2787N showing substantial statistically significant opacity below the 49 km altitude (6101 km radius).
Figure 2: Absorptivity profile (13 cm) for orbit 2819N showing little statistically significant opacity. The latitude of this profile is 65.86°.
Figure 3: Average 13 cm opacity profiles measured by Pioneer-Venus Radio Occultation Experiments from July through December 1986. Absorptivity profiles are for five different latitudinal areas:
1. Equatorial: latitudes from 10° to 25°N. 2. Mid latitudes from 35° to 45°N. 3. 60s: latitudes centered at 60°N. 4. 70s: latitudes centered at 70°N. 5. Polar: latitudes above 85°N.
Figure 4: Average absorptivity for equatorial orbits (latitudes from 10° to 25°N) with error bars (13 cm).
Figure 5: Average absorptivity for mid-latitude orbits (latitudes from 35° to 45°N) with error bars (13 cm).
Figure 6: Average 13 cm absorptivity for orbits centered around 60°N latitude, with error bars.
Figure 7: Average 13 cm absorptivity for orbits centered around 70°N latitude, with error bars.
Figure 8: Profiles of 13 cm absorptivity obtained at polar latitudes (dotted lines, 4 orbits) and average of the four profiles (solid line, with error bars). All profiles are for latitudes above 85°N.
Figure 9: Profile of $\text{H}_2\text{SO}_4$ abundance inferred from the 13 cm opacity measured with the Pioneer Venus Orbiter Radio Occultation experiment. Error bars reflect uncertainty in the inferred 13 cm absorptivity. Dotted line is saturated abundance of gaseous $\text{H}_2\text{SO}_4$, from Fahd and Steffes (1990). The latitude was $40.81^\circ$N and the Solar Zenith Angle was $137.6^\circ$ (nightside).
RENEWAL PROPOSAL
AND ANNUAL REPORT
TO THE
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
- AMES RESEARCH CENTER -

for
GRANT NAG 2-515
(Pioneer Venus Guest Investigation)

PIONEER-VENUS RADIO
OCCULTATION (ORO) DATA REDUCTION:
PROFILES OF 13 CM ABSORPTIVITY

Current Grant Performance Period: July 1, 1988 through June 30, 1989
Proposed Renewal Period: July 1, 1989 through June 30, 1990
Requested Funding Level: $17,414 (FY 89 Funds) + $17,414 (FY 90 Funds)

Submitted by
Professor Paul G. Steffes
School of Electrical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0250
(404) 894-3128
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I. INTRODUCTION/ABSTRACT

Recent studies of the radio emission spectrum of Venus (Steffes, 1986 and 1987, and Steffes et al., 1989) have suggested that significant variations (both spatial and temporal) in the abundances of sulfur-bearing gases may be occurring below the Venus cloud layers. One technique for monitoring the abundance of sulfur-bearing gases (especially gaseous $\text{H}_2\text{SO}_4$) at and below the main Venus cloud layer (altitudes below 50 km) is to measure the 13 cm wavelength opacity using Pioneer-Venus Orbiter Radio Occultation Studies (PV-ORO).

In this study, we are working to characterize possible variations in the abundance and distribution of subcloud $\text{H}_2\text{SO}_4$ vapor in the Venus atmosphere by using a number of 13 cm radio occultation measurements made over a range of latitudes from polar to equatorial, obtained in late 1986 and early 1987 (Radio Occultation Season #10). Using the DSN receiver data tapes recorded during these occultations, we are developing 13 cm absorptivity profiles, from which we will infer gaseous $\text{H}_2\text{SO}_4$ abundance profiles. By comparing each abundance profile with those obtained at different latitudes and with those obtained from Pioneer-Venus Radio Occultation studies made in late 1978 and early 1979, we hope to characterize both temporal and spatial variations in subcloud $\text{H}_2\text{SO}_4$ abundance. Subsequent data interpretation studies and correlative studies with radio emission data will also be conducted.

II. SUMMARY OF ACTIVITIES DURING FIRST YEAR OF GRANT NAG 2-515

In the first year of Grant NAG 2-515 (July 1, 1988 through June 30, 1989), the Principal Investigator, Professor Steffes, and Graduate Research Assistant, Jon M. Jenkins, have made several trips to the Jet Propulsion
Laboratory (JPL) to reduce P-V radio occultation data, and to Ames Research Center to attend the Pioneer Venus Science Steering Group (SSG) meetings. The first trip to A. J. Kliore's group at JPL focused on "resurrecting" software written prior to 1979 for the inversion of ORO data, in order to obtain 13 cm absorptivity profiles. This posed a challenge since the software was designed to run on a different computer system than is currently used. For example, the file containing the S-band antenna pattern parameters was stored on magnetic tape in an ASCII format which was incompatible with the current PRIMOS (t.m.) operating system. We were able to upgrade and convert the software and data files so that preliminary absorptivity profiles were developed for orbits 2787 (entry) and 2801 (entry). During that week we established contact with Mr. Bob Jackson (of Ames Research Center) who was able to provide antenna pointing information for both of these orbits (this is essential information for reduction of amplitude data).

After returning to Georgia Tech, a modem and PC-PLOT IV+, a terminal emulation package, were purchased. This enabled us to establish a long-distance remote link to RODAN (Radio Occultation Data Analysis Network) at JPL. Additional modifications to the inversion software were made using the remote link. In addition, ten additional orbits were targeted for reduction based on the depth to which the radio signal probed and the latitude of the occultation. Mr. Luke Mullen (of JPL) provided this valuable information. A complete list of the orbits being analyzed, including the latitude, solar zenith angle, and lowest altitude of the periapsis point of the probing radio beam, is included in Table I. We contacted Mr. David Lozier (at Ames Research Center) and requested pointing information for these orbits to use during the second trip to JPL. Happily, this information was available at the beginning of the second trip to JPL.
During the second trip to JPL, examination of the corrected power profiles revealed that the antenna pointing correction was not being computed correctly. Further analysis of the program revealed a long-existing "bug" in the software. This was corrected and the antenna pointing corrections now appear to be properly computed.

To understand the importance of the antenna pointing issue, it must be remembered that the direction of the beam of the High Gain Antenna (HGA) aboard the Pioneer-Venus Orbiter is only adjusted once per orbit, so that it will be pointed directly toward earth at the periapsis of each orbit. Since during radio occultations, the trajectory of the ray path back to earth can vary by as much as ±3.5° from the geometric "straight line" direction back to earth, significant signal reductions will occur. The reductions are not due to atmospheric effects, but are due to the gain dependence of the orbiter antenna on incident angle. During the Pioneer-Venus primary mission, the antenna slew commands were sent to the orbiter so that its antenna beam would always track the "expected" ray path back to earth. Thus, little, if any, correction was needed for power variations due to S-band antenna mispointing. However, since such tracking is no longer employed, a correction to the received signal amplitude, such as shown in Figure 1 for the Orbit 2792 entry occultation, is required.

In Figure 2a, we show such a corrected received power profile from the entry occultation during Orbit 2801. Figure 2b shows the signal reduction due to refractive defocusing in the planet's atmosphere obtained during the same orbit. This defocusing is computed from ray trajectory information which is inferred from the doppler (frequency) data collected at the DSN receiving station. It is plotted as a function of ray periapsis altitude, rather than
as a function of time, so as to show the increasing defocusing that occurs deep in the highly refractive atmosphere. When the refractive defocusing is subtracted from the corrected power profile, the difference is the "excess attenuation" which is due to actual absorption by atmospheric constituents (Figure 2c). By using an inverse Abel integral transform, it is possible to obtain the profile of absorptivity (in units of decibels per kilometer) shown in Figure 2d.

Studies have also been made of the quality of the 13 cm data taken during occultations. In general, it was found that data taken during ingress or entry occultations (e.g. orbit 2801N) were far superior to data taken during egress of exit occultations (e.g. orbit 2801X). This is due to the fact that, during entry occultations, the spacecraft transmitted frequency is locked to a reference transmitted by the DSN uplink station, and is, therefore, extremely stable. (This is critical for the proper determination of the refractive defocusing.) During the exit occultation, the signal being transmitted from the spacecraft is initially referenced to the spacecraft's internal oscillator, which, in addition to being inherently less stable, is modulated by the variations in the power supply voltage which result from a failed section of the solar cell array used to power the spacecraft. As a result, a large majority of occultations used in this study will be entry (suffix "N") occultations, rather than exit (suffix "X") occultations.

During the Fall 1988 SSG meeting, which followed the second trip to JPL, we had several fruitful discussions with Mr. Jim Phillips concerning the antenna pointing issue. A presentation describing our project was also given. We also had the opportunity to discuss the uncertainties associated with data derived from radio occultations with Dr. G. L. Tyler of Stanford University.
Our current work has focused on the reduction of 13 cm absorptivity data from additional orbits. We have also worked on devising better techniques for accurately characterizing the error bars for the derived absorptivity profiles. In early November, Professor Steffes and Graduate Research Assistant Jon Jenkins travelled to Austin, Texas to present a paper at the 20th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society (AAS/DPS). The paper presented the first results for Venus microwave opacity obtained since Pioneer-Venus Orbit #358 in November 1979 (Jenkins and Steffes, 1988). Since November, we have reduced data from an additional six orbits (see Table I). The resulting absorptivity profiles are shown in Figures 3 through 9.

While reducing the data from these orbits, additional problems with the existing data reduction software have been discovered. Some of the problems relate to the generation of "round-off" errors in the various calculations performed, and have been corrected. While we are encouraged by the quality of the recently-derived 13 cm absorptivity profiles, it has become clear that their usefulness in characterizing potential spatial or temporal variations in subcloud H₂SO₄ abundance is dependent on our ability to accurately characterize the uncertainty in the derived profiles. Reductions of early (1978-79) Pioneer-Venus radio occultation data in order to obtain absorptivity profiles (Cimino, 1982) used relatively crude techniques for estimating uncertainties, which may have drastically underestimated the uncertainties at some altitudes. A key future activity for this project will be development of an theoretically sound procedure for characterizing uncertainties in the derived absorptivity profiles.
III. PROPOSED ACTIVITY FOR THE NEXT GRANT YEAR

To show the usefulness of the 13 cm opacity data for inferring the nature of the gaseous H$_2$SO$_4$ abundance, we compare in Figure 10 the measured absorptivity profile from orbit 2801N with that absorptivity which would result from a saturation abundance of gaseous H$_2$SO$_4$ (from Steffes, 1985) in the 43 to 55 km altitude range. It can be seen that for altitudes in the 49 to 51 km altitude range (the nominal altitude range of the Venus lower cloud - see Ragent and Blamont, 1980), absorptivity values close to those caused by a saturation abundance of gaseous H$_2$SO$_4$ are seen. At lower altitudes, the values for absorptivity are below those caused by a saturation abundance, as expected. Figure 11 shows the full extent to which application of our laboratory results can be carried. The abundance of gaseous H$_2$SO$_4$ (derived from the absorptivity profile in Figure 2d by using laboratory results from Steffes, 1985) is plotted as a function of altitude, along with a plot of the saturation abundance of gaseous H$_2$SO$_4$, for comparison. As our work in the Pioneer-Venus Guest Investigator Program yields more absorptivity profiles for a wide range of locations in the Venus atmosphere, we hope to be able to well characterize the abundance, structure, and spatial variations of gaseous H$_2$SO$_4$ in the Venus atmosphere. We also hope to make comparative studies with earlier radio occultation measurements in order to detect possible temporal variations in H$_2$SO$_4$ abundance and structure. In fact, initial inspection of the 13-cm absorptivity profiles shown in Figures 3 through 9, which were obtained during Radio Occultation Season #10 (July 1986 through October 1986), shows absorptivity profiles which appear somewhat less than those derived by Cimino (1982) from measurements made during the first two Radio Occultation seasons (December 1978 through November 1979). While this may be suggestive
of a long-term temporal reduction in subcloud $\text{H}_2\text{SO}_4$ abundance, it cannot be considered proof of such until the uncertainties in the derived profiles are properly characterized. Two general approaches will be used in characterizing the uncertainties.

The first approach will involve developing a computer-based model of the radio occultation propagation problem in which relations between postulated absorptivity and refractivity profiles for the Venus atmosphere, and the resulting amplitude and doppler frequency profiles which would be measured by the radio occultation experiment will be investigated. Since these relations are highly nonlinear, the effects of discontinuities in the absorptivity and refractivity profiles will be studied carefully.

The second approach involves repeating the steps required to infer the absorptivity profiles from the amplitude and frequency data, as described in Section II. However, for each step in the inversion process, covariance matrices are developed which relate the statistical uncertainties to those in the previous step, as per Lipa and Tyler (1979). Since some steps in the inversion process are nonlinear, the resulting percentage errors in the inferred 13-cm absorptivity profiles will drastically vary depending on the position (altitude) of the data point and the relation of its value to those of previous data points. The ultimate goal will be to trace statistical errors from the observed amplitude and frequency data to the inferred absorptivity profile.

At the November 1988 AAS/DPS (Division for Planetary Sciences of the American Astronomical Society) Meeting, two independent groups brought to our attention observations made of diurnal variations in the Venus millimeter-wave emission spectrum. Results reported by both the Cal.-Tech. group
(Pierce et al., 1988) and by the U.C.-Berkeley group (de Pater, personal communication) showed a higher brightness temperature on the night side of the planet at wavelengths near 2.6 mm. While some atmospheric opacity near 2.6 mm is due to high altitude carbon monoxide (CO), both groups reported the variation at wavelengths well separated from the J = 0 + 1 CO transition. Since the highest level of significant millimeter-wave opacity at these wavelengths appears to occur in the 45-55 km altitude range, it is possible that either diurnal variations in the main cloud bulk density or diurnal variations in the abundance of gaseous H$_2$SO$_4$ are responsible for the observed emission variations. (Note that no measurements, either remote or in-situ, have suggested diurnal variations in atmospheric or surface temperatures.) Since the 13 cm opacity is mainly due to the abundance of gaseous H$_2$SO$_4$ with little relation to cloud bulk density (see Steffes, 1985), we hope to be able to search for diurnal variations in the 13 cm opacity measured from Pioneer-Venus radio occultation studies. If no variations are detected, then the 2.6 mm variations will be attributable to the clouds. If such 13 cm variations are detected, we will attempt to correlate them with the variations in 2.6 mm emission. Further study of the 2.6 mm absorption from gaseous H$_2$SO$_4$ may be required, and possible laboratory measurements will be considered as part of a separate project we are conducting under the Planetary Atmospheres Program (Grant NAGW-533).

IV. FACILITIES

The School of Electrical Engineering of the Georgia Institute of Technology has extensive physical facilities devoted to a wide variety of research and development problems. The large faculty and staff conduct
teaching, research, and applied research in almost every area of electrical engineering including microwave and millimeter-wave propagation. In addition to the School itself, the facilities of the Georgia Tech Research Institute (GTRI), a world-renown organization in the area of microwave/millimeter-wave propagation and systems, are also available. Finally, the facilities of the Atmospheric Sciences Program of the School of Geophysical Sciences at Georgia Tech are also available in this area. Overall, the ability to perform the proposed research at the Georgia Institute of Technology is excellent.

For support of any 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 Computing Services. Since 1955 this centralized service facility has operated a variety of computer systems. In 1983, a Control Data Corporation CYBER 180/855 was installed; in 1984, a second of these systems began operation. These two systems share disk storage and use the NOS operating system. Early in 1985, an IBM 4381 system was installed running MVS and VM. The hardware configuration, a broad variety of programming languages, applications programs, and library subroutines, all combine to provide an impressive amount of computer power to both time-sharing, remote batch, and on-site batch users. Time-sharing terminals, CALCOMP and Versatec plotters, and an optical scanner offer additional versatility. Other computers available within the School of Electrical Engineering include a Data General Eclipse/S-250 and three Digital Equipment Corporation VAX systems, in addition to numerous personal computers.

While all of the required processing and analysis of the "raw data" obtained from the DSN receiving stations could be conducted at Georgia Tech, we have found that initial reduction of the amplitude and doppler data
obtained from the DSN receiving stations is most efficiently completed by out
working at JPL using the RODAN (Radio Occultation Data Analysis Network)
system. This is due to the availability of a large number of existing soft-
ware utilities and ephemerides. Over the past year we have found that travel
to JPL is necessary to accomplish certain labor-intensive tasks, including
error characterization. However, our ability to remotely access the RODAN
system from Georgia Tech has significantly increased our ability to analyze
data without traveling to JPL. After initial reduction, further analysis and
interpretive studies of the data are conducted at the School of Electrical
Engineering at Georgia Tech.

V. PROPOSED PROCEDURE AND LEVEL OF EFFORT

The proposed program will continue an ambitious effort to characterize
possible spatial or temporal variations in the abundance of gaseous H₂SO₄ in
the Venus atmosphere by deriving 13-cm absorptivity profiles from Pioneer-
Venus Orbiter Radio Occultation (PV-ORO) measurements, obtained during Pioneer
Venus Radio Occultation Season #10 (late 1986). As described above, this
effort will include data reduction efforts conducted both at Georgia Tech and
JPL, which will then be followed by analysis of the data uncertainties and
interpretive study.

The proposed level of effort in the next year of Grant NAG 2-515 (July 1,
1989 through June 30, 1990) involves one professor (P. G. Steffes, Associate
Professor of Electrical Engineering) at 12% time, and one graduate student
(Jon M. Jenkins) at 50% time. (Note: We are only requesting support for
20% time for Mr. Jenkins with the remainder coming from an NSF graduate
fellowship.) Support for two trips to JPL (for Mr. Jenkins, to work on data
reduction) and two trips to the Pioneer-Venus Science Steering Group (PV-SSG) meetings are also being requested. As requested, two budgets are being submitted (see Section VII): the first for the six month period from July 1, 1989 through December 31, 1989 (to be funded from Federal FY 89 funds), and the second for the six month period from January 1, 1990 through June 30, 1990 (to be supported by Federal FY 90 funds). Equal levels of support are requested for each six month period. As mentioned, subsequent correlation studies with results from ground-based radio astronomical observations of the Venus emission would be conducted at Georgia Tech under Grant NAGW-533 from the Planetary Atmospheres Program.
VI. REFERENCES


VII. PROJECTED BUDGET
(FY 89 Funds)

For the period of July 1, 1989 through December 31, 1989

Estimated Cost Breakdown

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<td>B. 1 Graduate Student</td>
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<td>A. Travel to JPL (1 trip, 3 wks duration for 1 graduate student)</td>
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<tr>
<td>B. Travel to semiannual Pioneer Venus Science Steering Group Meeting (NASA-Ames): (1 trip, 4 days duration for P.I.)</td>
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SUBTOTAL - ESTIMATE OF DIRECT COSTS $10,884

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<th>V. OVERHEAD (Indirect Expense)**</th>
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TOTAL ESTIMATED COST: $17,414

*The salary and wage rates are based on current FY 89 salaries for the Georgia Institute of Technology. An increase of 10% is estimated for the performance in Georgia Tech FY 90. The Georgia Tech Fiscal Year is July 1 through June 30.

**Rates are effective for the period July 1, 1988 through June 30, 1989 and are subject to adjustment thereafter upon DCAA audit and ONR negotiations.
VII. PROJECTED BUDGET (Page 2 of 2)
(FY 90 Funds)

For the period of January 1, 1990 through June 30, 1990

Estimated Cost Breakdown

I. DIRECT SALARIES AND WAGES*:

A. Principal Investigator
   P. G. Steffes
   12% time, 6 months
   $ 4,002

B. 1 Graduate Student
   20% time, 6 months
   $ 2,592

II. FRINGE BENEFITS**:

   25.5% of Direct Salaries & Wages
   (less students)
   $ 1,020

III. TRAVEL

   A. Travel to JPL (1 trip, 3 wks
      duration for 1 graduate student)
   $ 2,200

   B. Travel to semiannual Pioneer Venus
      Science Steering Group Meeting
      (NASA-Ames): (1 trip, 4 days duration
      for P.I.)
   $ 900

IV. MATERIALS, SUPPLIES, AND SERVICES

   A. Copying Costs and Mailing of Reports
      and Journal Papers
   $ 170

   SUBTOTAL - ESTIMATE OF DIRECT COSTS
   $10,884

V. OVERHEAD (Indirect Expense)**:

   60% of Modified Total Direct Cost Base
   $ 6,530

   TOTAL ESTIMATED COST:
   $17,414

*The salary and wage rates are based on current FY 89 salaries for the
Georgia Institute of Technology. An increase of 10% is estimated for the
performance in Georgia Tech FY 90. The Georgia Tech Fiscal Year is July 1
through June 30.

**Rates are effective for the period July 1, 1988 through June 30, 1989 and
are subject to adjustment thereafter upon DCAA audit and ONR negotiations.
VIII. COGNIZANT PERSONNEL

For scientific or technical matters relating to the contract:

Paul G. Steffes  
School of Electrical Engineering  
Georgia Institute of Technology  
Atlanta, Georgia 30332-0250  
Telephone: (404) 894-3128

For contractual and business matters:

Georgia Tech Research Institution  
Centennial Research Building  
Georgia Institute of Technology  
Atlanta, Georgia 30332-0250  
Telephone: (404) 894-4814
IX. KEY FIGURES
### TABLE I

**RADIO OCCULTATIONS (BY ORBIT NUMBER)**
**TO BE ANALYZED FOR 13 CM**
**ABSORPTIVITY PROFILES**

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<thead>
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* N suffix indicates entry occultation, X suffix indicates exit occultation.
** Orbits from which 13 cm absorptivity profiles have been obtained as of 2/15/89.
*** Orbits currently being reduced (as of 2/15/89).
Figure 1: Antenna gain correction (dB) due to change of ray path for Orbit 2792 entry occultation.
Figure 2: Radio occultation data for orbit 2801N (entry) -- August 6, 1986.

a) Received power level (dB) normalized to free space conditions as a function of ray periapsis radius. Signal level was corrected for variations in spacecraft antenna gain.

b) Refractive defocussing (dB) due to atmospheric refraction.

c) Excess attenuation due to atmospheric absorption versus ray periapsis radius (km).

d) Profile of atmospheric absorptivity (dB/km)
Figure 3: Profile of atmospheric absorptivity (dB/km) for Orbit 2792N (July 28, 1986) at a frequency of 2.294 GHz.
Figure 4: Profile of atmospheric absorptivity (dB/km) for Orbit 2798N (August 3, 1986) at 2.294 GHz.
Figure 5: Profile of atmospheric absorptivity at 2.294 GHz for Orbit 2801N (August 6, 1986), over the radius range from 6090 km to 6150 km (altitude range of 38 km to 98 km, relative to a mean planetary radius of 6052 km).
Figure 6: Expanded view of profile of atmospheric absorptivity at 2.294 GHz for Orbit 2801N (August 6, 1986), over the radius range from 6092 km to 6100 km. (This corresponds to an altitude range of 40 to 48 km, relative to a mean planetary radius of 6052 km.)
Figure 7: Profile of atmospheric absorptivity (dB/km) at 2.294 GHz for Orbit 2814N (August 19, 1986).
Figure 8: Profile of atmospheric absorptivity (dB/km) at 2.294 GHz for Orbit 2815N (August 20, 1986).
Figure 9: Inferred profile of atmospheric absorptivity (dB/km) for Orbit 2787N (July 23, 1986). The obvious problem with this profile (negative absorptivity), was caused, we believe, by antenna pointing errors at either the spacecraft or the DSN receiving site.
Figure 10: Comparison of absorptivities measured with radio occultation technique (circular points -- from Pioneer-Venus Orbit 2801-entry occultation) with absorptivity which would result from saturation abundance of H₂SO₄ (from Steffes, 1985). The absorption coefficient scale is logarithmic (exponents of 10). All measurements were made at the 13-cm wavelength (2.293 GHz).

Absorption Coefficient Inferred from Radio Occultation Data of Orbit 2801N

- Inferred from orbit 2801N
- due to a saturation vapor abundance of sulfuric acid
Figure 11: Abundances of gaseous H$_2$SO$_4$ inferred from Pioneer-Venus 13-cm absorptivity profiles (circular points) compared with the saturation abundance profile of gaseous H$_2$SO$_4$ (from Steffes, 1985). The mixing ratio scale is logarithmic (exponents of 10).

Sulfuric Acid (H$_2$SO$_4$) Vapor Abundance

- Inferred from orbit 2801N
- Saturation vapor abundance

Altitude (km) (above 6052 km)
BIOGRAPHICAL SKETCH

STEFFES, PAUL G. - Associate Professor of Electrical Engineering
Georgia Institute of Technology

EDUCATION

S.B., S.M., Massachusetts Institute of Technology 1977
Electrical Engineering
Ph.D., Stanford University, Electrical Engineering 1982

EMPLOYMENT HISTORY

Georgia Institute of Technology, School of Electrical Engineering, Assistant Professor 1982-Present

Duties include both research and teaching.

Research Activities: Principal Investigator--NASA Planetary Atmospheres Program, "Laboratory Evaluation and Application of Microwave Absorption Properties under Simulated Conditions for Planetary Atmospheres." This research includes study of the interaction between a number of atmospheric constituents and electromagnetic waves, along with applications of these studies to spacecraft measurements of the microwave absorption in atmospheres of Venus and the outer planets (1984-1989). Principal Investigator--NASA Pioneer Venus Guest Investigator Program, "Pioneer Venus Radio Occultation (ORO) Data Reduction: Profiles of 13 cm Absorptivity." This research infers 13 cm wavelength absorptivity profiles using the Pioneer Venus Orbiter, and then uses such profiles to characterize abundance profiles for gaseous H₂SO₄ in the Venus atmosphere. Principal Investigator--National Science Foundation Grant, "Remote Sensing of Clouds Bearing Acid Rain." This research studied and designed a microwave/millimeter-wave system for remotely sensing the pH of acidic clouds. Principal Investigator--GTE Spacenet Program: "Satellite Interference Locating System (SILS)." The program involves location of interfering signals on the surface of the earth (geodesy) without disrupting regular satellite operations (1986-1989). Principal Investigator--Emory University-Georgia Tech Biomedical Technology Research Center, "Research in Development of a Non-Invasive Blood Glucose Monitoring Technique." This research involves the use of active infrared systems to determine glucose levels in the human eye and bloodstream. Co-director--Ku Band Satellite Earth Station System. Responsible for development of a Ku-band uplink/downlink system for use in inter-university networks. Co-investigator--"Radar Warning Receiver Evaluations" with Georgia Tech Research Institute (GTRI).

Teaching Effort: Resource Professor for Satellite Communications Systems (graduate course) and Electromagnetics III (undergraduate required course covering waves, waveguides, and antennas). Have also taught...

PAST ACADEMIC RESEARCH

Stanford University Electronics Lab
Graduate Research Assistant, Center for Radar Astronomy
Supervisor: Prof. Von R. Eshleman
1979-1982

Research was concentrated in the area of microwave radio occultation experiments from Voyager and Mariner spacecraft, with specific interest in microwave absorption in planetary atmospheres. Work included computer-based theoretical development of microwave absorption coefficients for planetary atmospheres, to facilitate the use of radio occultation-derived microwave absorption profiles in determining constituent densities. Additional work included the development of a fully instrumented experimental facility for use in measuring the microwave properties of planetary atmospheres under simulated planetary conditions. The research resulted in a Ph.D. dissertation entitled "Abundances of Cloud-Related Gases in the Venus Atmosphere as Inferred from Observed Radio Opacity."

Massachusetts Institute of Technology
Graduate Research Assistant, Research Laboratory of Electronics (Radio Astronomy and Remote Sensing Group)
Supervisor: Prof. David H. Staelin
1976-1977

Responsible for development, operation, and data analysis for an 8-channel, 118 GHz radiometer system flown aboard the NASA Flying Laboratory (CV-990) as an engineering model for a meteorological sensing satellite. Duties included hardware development of millimeter-wave, microwave, analog, and A to D segments of the system, in addition to airborne operation and reduction of data. The research resulted in a Master's thesis entitled "Atmospheric Absorption at 118 GHz" detailing the first airborne measurement of high altitude atmospheric absorption in the 2.5 millimeter wavelength range, due to atmospheric oxygen.

INDUSTRIAL EXPERIENCE

Watkins-Johnson Company, San Jose, California
Member of the Technical Staff of the Sensor Development Section of the Recon Division
1977-1982

Responsibilities included customer proposals and system design and development, particularly in the area of millimeter-wave systems. Responsibility for millimeter-wave systems development included government sponsored study and development of ELINT (Electronic Intelligence) and radar warning receiving systems to frequencies as high as 110 GHz, as well as internal company-sponsored development projects including a 60 GHz communications system, and millimeter-wave downconverters.
AWARDS AND PROFESSIONAL AFFILIATIONS


PUBLICATIONS


DISTRIBUTED REPORTS


REPORT
TO THE
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
- AMES RESEARCH CENTER -
FINAL TECHNICAL REPORT
(INCLUDES QUARTERLY REPORT #9)

for
GRANT NAG 2-515

PIONEER-VENUS RADIO OCCULTATION (ORO) DATA REDUCTION:
PROFILES OF 13 CM ABSORPTIVITY

Paul G. Steffes, Principal Investigator

July 1, 1988 through September 30, 1990

Submitted by

Professor Paul G. Steffes
School of Electrical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0250
(404) 894-3128
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I. Introduction

Recent studies of the radio emission spectrum of Venus [Steffes, 1986 and Steffes et al., 1990] have suggested that variations (both temporal and spatial) in the abundances of sulfur-bearing gases may be occurring below the Venus cloud layers. One technique for monitoring the abundances of sulfur-bearing gases (especially gaseous $\text{H}_2\text{SO}_4$) is to measure the 13 cm wavelength opacity using Pioneer-Venus Orbiter Radio Occultation studies (PVORO) [Steffes, 1985].

In order to characterize possible variations in the abundance and distribution of subcloud sulfuric acid vapor, we have processed 13 cm radio occultation signals from 23 orbits that occurred in late 1986 and 1987 (Radio Occultation Season #10) and 7 orbits that occurred in 1979 (Radio Occultation Season #1). During Season #10, the atmosphere was probed to altitudes as low as 39.4 km (above a mean radius of 6051.92 km) at latitudes in the northern hemisphere from 11 to 89°N. During the orbits from Season #1, the atmosphere was probed to altitudes as low as 36.7 km. The data were inverted to produce 13 cm absorptivity profiles. Finally, pressure and temperature profiles obtained with the Pioneer-Venus night probe and the northern probe [Seiff et al., 1980] were used along with the absorptivity profiles to infer upper limits for vertical profiles of the abundance of gaseous $\text{H}_2\text{SO}_4$. In addition to inverting the data, error bars have been placed on the absorptivity profiles and $\text{H}_2\text{SO}_4$ abundance profiles using the standard propagation of errors [Brandt, 1963]. These error bars were developed by
considering the effects of statistical errors only. The profiles show a distinct pattern with regard to latitude which is consistent with latitude variations observed in data obtained during occultation seasons #1 and #2 (late 1978 and early 1979) [Cimino, 1982]. However, when compared with the earlier data, the recent occultation studies suggest that the amount of sulfuric acid vapor occurring at and below the main cloud layer may have decreased during the time interval between early 1979 and late 1986.

II. Processing of Radio Occultation Data

Radio occultation studies using the Pioneer-Venus Orbiter allow us greater flexibility in studying the vertical structure of the neutral atmosphere of Venus than either in-situ probes or radio astronomical observations. The atmosphere can be probed at a wide range of latitudes due to the geometry of the spacecraft’s orbit and its changing orientation with respect to Earth throughout an occultation season. In addition, the longevity of the orbiter has made it possible to conduct long term studies of the microwave properties of the atmosphere of Venus with greater vertical resolution than radio astronomical observations.

Complete descriptions of the theoretical bases for this technique are given in Fjeldbo and Eshleman (1965), Fjeldbo et al. (1971) and Eshleman (1973). For the Pioneer-Venus application, consider the geometry illustrated by Figure 1. In this experiment, the spacecraft modulation is switched off and a continuous wave (CW) signal is transmitted during the occultation event.
successful experiment, the radiated carrier signal must have a stable amplitude and frequency. To ensure that the frequency is stable, a reference signal is uplinked to the spacecraft from the Earth station. The spacecraft locks its oscillator to this signal and downlinks a noninteger harmonic of the received frequency. The power output of the spacecraft is stabilized internally. The occultation experiment begins when the path of the signal transmitted by the spacecraft tangentially grazes the edge of the atmosphere of Venus. As the spacecraft's trajectory carries it toward the limb of the planet, the path of the signal slices deeper into the atmosphere, traversing a longer pathlength through the limb. Refraction in the atmosphere causes the signal to bend around the limb of the planet. This increases the Doppler shift since a larger component of the velocity of the spacecraft is now parallel to the ray path back to Earth. It is important to note that this also affects the uplinked reference signal from Earth. Hence the Doppler shift of the signal received at Earth includes the shift incurred by the uplink to the spacecraft as well as by the downlink.

The power of the received signal is attenuated by two atmospheric effects and by mispointing of the spacecraft antenna. The curvature of the atmosphere and the changing refractive index profile cause spreading of the transmitted beam, an effect known as refractive defocusing. Secondly, absorption and scattering in the atmosphere extract energy from the signal, causing an additional drop in received power. In addition, as the ray is bent by
refraction in the atmosphere, it is also bent away from the main axis of the spacecraft antenna, causing a drop in power due to the smaller off-axis gain of the antenna. As the experiment progresses, the Doppler shift increases and the amplitude drops until the spacecraft can no longer maintain lock with the uplinked frequency reference.

For Figure 1, we assume that for each instant in time, the illustrated distances \( R_e, D \) and \( y \) (and hence, \( R_{es}, R_s \) and the angle \( \gamma \)) are known from interpolations of spacecraft tracking data, from Earth and planetary ephemerides and from the knowledge of the tracking station position relative to the center of the Earth. Thus the other quantities follow as:

\[
\begin{align*}
\alpha &= D \sin(\delta - \beta) + y \cos(\delta - \beta) \\
\delta &= (\delta - \beta) + \sin^{-1}(a/R_e) \\
R_1 &= (R_e^2 - a^2)^{1/2} \\
R_2 &= (R_s^2 - a^2)^{1/2}
\end{align*}
\]

[\textit{Eshleman et al.}, 1980].

The impact parameter \( a \) and the bending angle \( \delta \) can be used to calculate the vertical profile of refractivity if we assume a perfectly stratified atmosphere with no horizontal variations other than planetary curvature in the region probed by the beam [\textit{Fjeldbo et al.}, 1971]:

\[
\ln(n(r)) = \frac{1}{\pi} \int_{a(r)}^{\infty} \frac{\delta(a) \, da}{\sqrt{a^2 - a^2(r)}}
\]
The lowest depth, \( r \), probed for each ray is related to the ray impact parameter by \( a = n \cdot r \). Thus, the natural log of the index of refraction \( n \) is the inverse Abel transform of the integral of the bending angle \( \delta \). Once \( n(r) \) is determined it is possible to obtain pressure and temperature profiles, assuming hydrostatic equilibrium and that the major constituents are well known and well mixed [Lipa and Tyler, 1979].

In order to invert the amplitude data to obtain absorptivity profiles it is necessary to first remove the effects of refractive defocusing and mispointing of the spacecraft antenna. The refractive defocusing can be computed using geometric optics and is then subtracted from the signal attenuation profile. Let \( I \) be the received signal intensity normalized by the free space intensity at the spacecraft receiver input. Then the reduction in intensity due to refractive defocusing, \( I^{-1} \), is given by

\[
I^{-1} = \left( \frac{V}{R_{es} \sin \beta} \right) \left( \frac{\cos(\delta-\beta)}{R_{es}} \right) dy
\]

where the first bracketed term represents the focusing effect of the curved limb normal to the plane of the figure and the second term is the refractive defocusing in the plane of the figure [Eshleman et al., 1980]. For an Earth-Venus distance much larger than the spacecraft-Venus distance, equation (3) reduces to

\[
I^{-1} = \frac{V}{a(1-R_2 \frac{\partial \beta}{\partial a})}
\]

(4)
To understand the importance of the antenna pointing issue, it must be noted that, as currently operated, the direction of the beam of the High Gain Antenna (HGA) aboard the Pioneer-Venus Orbiter is only adjusted once per orbit so that it is pointed directly to Earth at the periapsis of each orbit. Since the ray path back to Earth can be bent by as much as $3.5^\circ$ from the true direction to Earth, significant signal reductions occur. These reductions are not due to atmospheric effects, but are due to the gain dependence of the orbiter antenna on incidence angle. During the Pioneer-Venus primary mission, slew commands were sent to the orbiter so that the antenna beam would continually track the virtual image of the Earth. Thus, little if any correction was needed for power variation due to S-band antenna mispointing. However, since such tracking was not used during Season #10, it is necessary to trace the ray path for each data point and determine the gain of the orbiter antenna at the ray's angle of departure.

After correcting the amplitude data for the effects of refractive defocusing and for antenna mispointing, we are left with the excess attenuation profile $\tau$. This residual attenuation is the result of integrating the absorption coefficient $\alpha$ over the downlink ray path for each sample point. (This assumes that scattering is negligible compared to absorption at the transmitted frequency.) This can be written as an integral over radius using Bouger's rule [Lipa and Tyler, 1979]:

\[ \tau = \int a \, dr \]
\[ \tau(r_0) = 2 \int_{r_0}^{\infty} \frac{\alpha(x) \, dx}{\sqrt{1 - \left( \frac{a(r_0)}{rn(x)} \right)^2}} \]  \hfill (5)

where \( \tau \) is in dB and \( \alpha \) is expressed in dB/km. This expression can be rewritten in the form of an Abel transform by making the approximation \( da \approx n \cdot dr \):

\[ \tau(r_0) = 2 \int_{r_0}^{\infty} \frac{\alpha(r(a)) \cdot \alpha da}{n(r(a)) \sqrt{\alpha^2 - a(r_0)^2}} \]  \hfill (6)

The form of the Inverse Abel Transform that has been applied to the data is the following:

\[ a(r_0) = - \frac{n(r_0)}{2 \pi a(r_0)} \cdot \frac{d}{da} \left[ 2 \int_{a(r_0)}^{\infty} \frac{\tau(a) \, da}{\sqrt{\alpha^2 - a(r_0)^2}} \right] \]  \hfill (7)

Thus, the absorption coefficient can be recovered as a function of height by applying an inverse Abel transform to the excess attenuation \( \tau \) and multiplying the result by the refractivity profile.

Although this is a fairly complete description of the mathematical procedure for reducing radio occultation data, a complete analysis requires characterization of experimental uncertainties. Since the derived quantities \( \alpha \) and \( n \) cannot be observed directly, neither can the uncertainties associated with each of them. The next section describes our method for placing error bars on the absorptivity profiles.
III. Error Analysis

Statistical errors are inherent in any set of experimental observations. The significance of small scale structure in experimental data is dependent on the magnitude of these statistical errors. Thus, knowledge of the variance of the noise fluctuations riding on the true data is necessary to evaluate the validity of theoretical predictions or to compare independent sets of observations. In the case of indirect observations, where the desired vector quantity, $y$, is obtained by transforming the observed vector of quantities, $x$, it is not possible to measure the noise power directly. If $y$ is related to $x$ by a linear transform $T_{yx}$, then the covariance matrix of $y$ is given by

$$C_y = T_{yx} C_x T_{yx}^T$$  \hspace{1cm} (8)

where

$$C_x = \langle (x-\bar{x}) \cdot (x-\bar{x})^T \rangle$$  \hspace{1cm} (9)

[Brandt, 1963]. Here, $x$ is the vector of true values, and $\bar{x}$ is the measured, or average value and $\langle \cdot \rangle$ is the expectation operator. If the errors are small and the transform $T_{yx}$ is nonlinear, then $C_y$ can be estimated by expanding $T_{yx}$ in a Taylor series

$$y = t_0 + T_1 (x-\bar{x}) + T_2 (x-\bar{x})^2 + ...$$  \hspace{1cm} (10)

where
Now the estimate for the \( C_y \) is given by
\[
C_y = T_1' C_x T_1^T
\] (12)

This is the result of neglecting all terms higher than first order and is known as the standard propagation of errors [Brandt, 1963].

To see how this method may be applied to a multistep procedure such as the reduction of radio occultation data, consider the vector quantity \( z = T_2 y \). Now, \( C_z \) is given by
\[
C_z = T_2' C_y T_2^T
\]
\[
= T_2 (T_1 C_x T_1^T) T_2^T
\]
\[
= (T_2 T_1) C_x (T_2 T_1)^T
\]
\[
= T_3 C_x T_3^T
\] (13)

where \( T_3 = T_2 T_1 \). This forms the basis for placing error bars on the absorptivity profiles discussed in Section IV. Note that this procedure can be carried out with fewer numerical computations if the sequence of transformation matrices are multiplied in the appropriate order before the covariance matrix for the desired quantity is determined. For example, if \( k \) transformations are used which can be represented as \( n \times n \) matrices, then forming the
covariance matrix at each step \((C_i = T_i \cdot C_{i-1} \cdot T_i^T)\) requires \(2n^2\) multiplies for a total of \(2kn^2\) operations. By contrast, forming the product \(T_f = T_k \cdot T_{k-1} \cdots T_2 \cdot T_1\) requires \(kn^2\) multiplies and forming the covariance matrix \(C = T_f \cdot C_i \cdot T_f^T\) requires an additional \(2n^2\) multiplies, resulting in only \((k+2)n^2\) total operations.

Figure 2 illustrates the propagation of errors through the various steps of inverting the frequency and amplitude data to obtain the absorptivity profile. In the figure, each transformation of variables is represented by a labeled box. The random variables which flow from each box are related to the random quantities that flow into that box by that transform. For example, the ray path parameters are determined from the frequency data and trajectory information. Thus, \(\Delta a\) and \(\Delta \delta\) are dependent on the uncertainties in the frequency data, \(\Delta f\). In the first step, errors are estimated for power and frequency. Lipa and Tyler (1979) developed a model for estimating these errors based on their method for estimating the amplitude and frequency of the sampled signal received from the spacecraft. In the case of this study, the available data consisted only of the excess Doppler shift (Hz) and relative power (dB) as time series. Because the original sampled signal is needed to estimate the errors in frequency and power by Lipa and Tyler's method, an alternative method has been developed.

The approach used is to fit a line to the set of points \(\{f(t_{n-4}), f(t_{n-3}), \ldots, f(t_{n-1}), f(t_n), f(t_{n+1}), \ldots, f(t_{n+3}), f(t_{n+4})\}\) for each point \(t_n\) in time, and use the mean square error as the estimate for \(\Delta f_n\), the variance for the frequency at point \(n\). The same procedure
is used to estimate the variance at each point of the power profile. Since the noise process is very nearly white Gaussian noise and is stationary over short intervals [Lipa and Tyler, 1979], this provides a simple method for estimating the errors $\Delta f$ and $\Delta p$. We are assuming (as did Lipa and Tyler) that the random processes $\Delta f$ and $\Delta p$ are independent and uncorrelated so that $<p_m f_n> = 0$ for all $m$ and $n$, and $<p_m p_n> = <f_m f_n> = 0$ for $m \neq n$. Thus the covariance matrices $C_f$ and $C_p$ are diagonal and the covariance matrix $C_{fp}$ is identically zero.

The next step involves determining the uncertainties in the ray path parameters, which are derived from the frequency data and the spacecraft trajectory. The equations used to determine these parameters are linearized and the standard propagation of errors used so that

\[
\begin{align*}
C_\delta &= T_{bf} C_f T_{bf}^T \\
C_a &= T_{af} C_f T_{af}^T \\
C_{\delta a} &= T_{bf} C_f T_{af}^T = C_a \delta
\end{align*}
\]  

(14)

Since $C_f$ is diagonal, $C_f$, $C_{\delta a}$ and $C_a$ are also diagonal at this point of the processing. This assumes that the uncertainties in the trajectory data are negligible compared to the uncertainties arising from the noise on the received signal.

Before the index of refraction is calculated, all profiles, such as $a$, $\delta$, and $p$ are "averaged and decimated" by partitioning the points of each profile into bins based on ray asymptote height.
The size of the bins is specified by the user and, in most cases in this study, is 0.5 km. The points in each bin are replaced by a single point which is the average value of all the points in that bin. This is a useful technique since the derivative $\frac{d\delta}{da}$ increases as the occultation progresses, causing the points to become denser in altitude with respect to time. The result is a set of vectors which have been decreased from a typical length of over 400 to less than 100 points. An additional benefit is that the variance of each new point is roughly a factor of $1/n$ times the variances of the $n$ points in that bin. Also, the points at the bottom of each profile, which are more noisy than upper points, have experienced more averaging, and hence, greater reduction in noise, due to the fact that the lower bins tend to have more points in them.

Because of this significant reduction in the lengths of all the vectors used in the remaining data reduction, it is convenient to trace the errors as they propagate through the data processing by considering the transformations of the vectors $\delta$, $a$ and $p$. Thus, all references to the covariance matrices associated with these vectors, $C_\delta$, $C_a$, or $C_p$, or the uncertainties $\Delta\delta$, $\Delta a$ or $\Delta p$ are with regard to this stage of the processing.

The uncertainties associated with the index of refraction is determined as per Lipa and Tyler (1979). The exponential function imbedded in equation (2) is approximated by linearizing about zero, the integral is approximated by a summation using the trapezoidal rule and the result is linearized with respect to the variables $\delta$.
and so that

$$\Delta n = T_{n\delta} \Delta \delta + T_{na} \Delta a$$  \hspace{1cm} (15)$$

where $T_{n\delta}$ is the linear transform relating $\delta$ to $n$ (to the first order), and $T_{na}$ is the transform relating $a$ to $n$.

From the fact $a = n \cdot r$, it follows that

$$\Delta r = T_{ra} \Delta a + T_{rn} \Delta n$$

$$= (T_{ra} + T_{rn} T_{na}) \Delta a + T_{rn} T_{n\delta} \Delta \delta$$  \hspace{1cm} (16)$$

where $T_{ra}$ is a diagonal matrix with diagonal entries $(T_{ra})_{ii} = n_i^{-1}$ and $T_{rn}$ is a diagonal matrix with diagonal entries $(T_{rn})_{ii} = -a_i/n_i^2$.

After the calculation of the index of refraction, all vectors are averaged and decimated again, only this time with respect to the radius profile instead of the ray asymptote. Then, if desired, the data is smoothed by a 5 point running average. Let $T_{ave}$ denote the matrix representing the process of averaging and decimating the vectors, and $T_s$ denote the matrix representing the smoothing process.

Now the excess attenuation is determined by performing the antenna correction and removing the refractive defocusing. We have determined that the uncertainties in performing the antenna correction are small compared to the other sources of error (by 3 orders of magnitude) and have chosen to neglect them. We have

$$\Delta \tau = T_{sp} \Delta p + T_{ta} T_s T_{ave} \Delta a + T_{t\delta} T_s T_{ave} \Delta \delta$$  \hspace{1cm} (17)$$
where $T_{ra}$ and $T_{r6}$ are due to refractive defocusing.

The inverse Abel transform of the excess attenuation is computed in two steps. Examining equation (7) reveals that the integral corresponds to the forward Abel transform of $\tau$. The result of this transform is arbitrarily named $F$ and has the associated uncertainty

$$\Delta F = T_{Pr} \Delta \tau + T_{ra} \Delta a$$

$$= T_{Pr} T_{rp} \Delta p + T_{Pr} T_{r6} T_s T_{av0} \Delta \delta$$

$$+ (T_{Pr} T_{ra} T_s T_{av0} + T_{ra}) \Delta a$$

$$= T_{Pr} \Delta p + T_{ra} \Delta \delta + T_{ra} \Delta a$$

The derivative of $F$ is taken with respect to $a$ and scaled by the factor $-n/(2\pi a)$ to yield the absorptivity profile $a$. The uncertainty in $a$ is given by

$$\Delta a = T_{af} \Delta F + T_{aa} \Delta a + T_{an} \Delta n$$

$$= T_{af} (T_{rp} \Delta p + T_{r6} \Delta \delta + T_{ra} \Delta a)$$

$$+ T_{aa} \Delta a + T_{an} (T_{n6} \Delta \delta + T_{na} \Delta a)$$

$$= T_{af} T_{rp} \Delta p + (T_{af} T_{r6} + T_{an} T_{n6}) \Delta \delta$$

$$+ (T_{af} T_{ra} + T_{aa} + T_{an} T_{na}) \Delta a$$

$$= T_{af} \Delta p + T_{a6} \Delta \delta + T_{aa} \Delta a$$

Finally, it is possible to compute the covariance matrix of $a$:
\[
C_a = \langle \Delta a \cdot \Delta a^T \rangle \\
= T_a^p C_p T_a^p + T_a^\delta C_\delta T_a^\delta + T_a^\alpha C_a T_a^\alpha + T_a^\iota C_{\iota} T_a^\iota
\]

Since \( C_{\delta a} = C_{\alpha}^T \), we need only compute one of the final two terms in the sum above. The error bars displayed on the figures discussed in the next section are the square roots of the diagonal elements of the matrix \( C_a \).

IV. Discussion of Results

Table I lists the 23 data sets from Season #10 (July 23, 1986 through January 7, 1987) and the 7 data sets from Season #1 (December 28, 1978 through January 26, 1979) which have been reduced by the method described in section II. The latitude and solar zenith angles for the deepest point probed in each experiment are given, as well as the maximum absorptivity measured before loss of lock (in the case of the entry occultations). Most of the occultations were entries and are denoted by the suffix "N". Orbit 2787X is the only data set analyzed which resulted from an exit occultation. We found that the data sets from most exit occultation experiments had to be discarded due to the instability of the spacecraft's onboard oscillator. Although the frequency data from 2787X appears to be relatively stable (in that the data could be processed), the results for this experiment are not deemed to be as reliable as the data from the entry occultations.

Figures 3 through 5 show the absorptivity measured for entry occultation experiments conducted for orbits 2787, 2801 and 2928,
respectively. Figures 6 through 10 show averages of the 13 cm absorptivity profiles we have currently obtained for 5 different latitudinal areas, based on the 23 profiles currently available. Figure 6 is the result of averaging profiles 2787N and 2792N. Figure 7 is the result of combining 2798N and 2801N. The profile in Figure 8 is the result of averaging 2814N, 2815N, 2819N, 2859N, 2860N, 2862N and 2952N. Profiles 2844N, 2845N, 2850N, 2851N and 2853N were combined to produce Figure 9. Figure 10 is the result of averaging 2921N, 2923N, 2928N and 2930N. Profiles 2939N and 2955N were not included in the averaged profiles of Figures 9 and 8, respectively, due to the relatively high altitude at which loss of signal occurred in these experiments. Profile 2787N was not included due to the unknown systematic errors resulting from the unstable spacecraft frequency for exit occultations.

When the occultation profiles for the different areas are compared, it appears that the level of significant absorptivity for the various latitudinal regions decreases with increasing latitude. A similar effect had been observed with the 1979 data, although the difference between the levels for the polar occultations and the collar occultations (latitudes in the 70's) was severe. Since the 13 cm opacity is principally due to gaseous H₂SO₄ [Steffes, 1985], this suggests a variation in the altitude of the cloud base with latitude (i.e. the altitude below which the absorption occurs). Although, the error bars are quite large (there is no statistically significant absorptivity in many of the profiles), we view the trends in the latitudinal variations as being valid. This is
especially noticeable in Figure 11, where the average absorptivity profile for the equatorial zone is compared with that for polar latitudes.

Moreover, when these absorption profiles (and the values for peak absorptivities below the clouds, as shown in Table I) are compared with those obtained during the initial Pioneer-Venus radio occultations (1978-79) [Cimino, 1982], it appears that the average 13 cm opacity has dropped, implying a reduced abundance of sulfuric acid vapor. While this is suggestive of long-term temporal variation in the subcloud abundance of gaseous $\text{H}_2\text{SO}_4$, it cannot be considered proof until the uncertainties in the earlier absorptivity profiles are properly characterized. We have newly processed 7 orbits from Radio Occultation Season #1 (including error bars). An example of these profiles is shown in Figure 12 (Orbit 40N). The larger significant absorptivity is noteworthy, especially when compared with the average for the 70° latitude range obtained during Season #10 (Figure 9). An average of orbits from Season #1 at latitudes above 70°N (24N, 40N and 44N) is given in Figure 13, along with the averaged profile for 70° obtained for Season #10. This figure suggests graphically that the abundance of $\text{H}_2\text{SO}_4$ decreased from 1979 to 1986, although the error bars for both profiles do overlap somewhat.

Figure 14 through 36 display the abundance of sulfuric acid vapor as a function of radius inferred from the derived absorptivity profiles from all 23 orbits analyzed from Season #10 and the saturation vapor pressure using results from a recent
laboratory measurement by Fahd and Steffes (1990). For Figures 14 through 18, the pressure and temperature measurements from the Pioneer-Venus night probe were used to derive the abundance profiles. The pressure and temperature measurements from the Pioneer-Venus north probe were used for Figures 19 through 36 [Seiff, et al., 1980]. These figures show the extent to which interpretation of the amplitude data from occultation experiments can be carried, that is, to determine upper limits for the concentration of opaque constituents in planetary atmospheres.

V. Summary of Activities

In the 27 months of Grant NAG 2-515 (July 1, 1988 through September 30, 1990) we have worked on reducing 13 cm radio occultation data to obtain 13 cm absorptivity profiles and the resulting abundance profiles for gaseous H$_2$SO$_4$. A summary of our activities is given in Table II. During this period of time all previously existing software was corrected and modified to apply the standard propagation of errors to each step in the processing of the data to derive error bars for the absorptivity profiles and H$_2$SO$_4$ abundance profiles. This activity has been conducted using the JPL-Radio Occultation Data Analysis Network (JPL-RODAN), which was accessed remotely from Georgia Tech both by telephone modem and by INTERNET/ARPANET. We worked with JPL to improve the function of its INTERNET interface. This allowed us to off-load some data processing and data analysis to Georgia Tech machines. Graduate student Jon M. Jenkins and Professor Steffes visited JPL 5 times
during the course of the project to load the data sets from magnetic tape and process them with the new error estimating software. Also, we attended 5 Pioneer-Venus Science Steering Group (PV-SSG) meetings and have worked effectively with the Radio Science Team Leader (Dr. A. J. Kliore) to evaluate the data.

In May 1990, we submitted a paper to the journal *Icarus* entitled, "Results for 13 cm Absorptivity and \( \text{H}_2\text{SO}_4 \) Abundance Profiles from the Season 10 (1986) Pioneer-Venus Radio Occultation Experiment" [Jenkins and Steffes, 1990]. In this paper, we described our work in developing 13 cm absorptivity profiles and their accompanying error bars for the orbits listed in Table I. (Note that the 13 cm abundance profiles are directly related to the abundances of gaseous \( \text{H}_2\text{SO}_4 \), as discussed previously.)

V. Conclusions and Suggestions for Future Work

As noted, the error bars placed on the absorptivity profiles derived using the current method are quite large. This may be due in part to overestimating the uncertainties in the frequency and power profiles at the beginning of the process. However, we feel that it is better to overestimate the errors rather than to underestimate them. It is clear that the final step of transforming the excess attenuation into absorptivity via the inverse Abel transform introduces the greatest statistical errors into the measurements. This is due to the fact that the inverse Abel transform corresponds to half order differentiation
Thus, it may be possible to reduce the magnitude of the estimated errors and retain small-scale structure by employing an alternative method for evaluating this recalcitrant transform.

In order to accomplish this task, software is being developed to simulate the occultation experiment. Given a model atmosphere and spacecraft trajectory, the software will generate time series for the received power and frequency. Noise will be added to these quantities and the results fed to the data inversion software. By inserting various methods for computing the inverse Abel transform into the inversion software, their performances can be objectively compared to select the method which is most stable and accurate under low signal-to-noise conditions. This simulation software will not only allow us to determine the method which best handles noise, but will also allow us to locate and evaluate some sources of systematic errors within the data inversion software. Graduate Assistant Jon M. Jenkins will continue to pursue this in his dissertation research. His Ph.D. Thesis (expected 6/91) will include both the Venus atmospheric results described here and the new techniques for processing radio occultation data.

The Pioneer-Venus Orbiter Radio Occultation experiments represent a potentially powerful tool for examining the middle atmosphere of Venus. Our results suggest the presence of latitudinally-dependent variations in the abundance of sulfuric acid vapor and a global decrease in the overall abundance of H_2SO_4 below the main cloud layer. In the future, we hope to be able to
verify the statistical validity of these possibilities by modifying the techniques applied in the data inversion software and reprocessing additional data from earlier occultation seasons. Likewise, we hope that radio occultation opportunities using the more powerful Magellan spacecraft can be used to probe to deeper altitudes with higher accuracies than have been previously achieved.
VII. BIBLIOGRAPHY


<table>
<thead>
<tr>
<th>Orbit*</th>
<th>Latitude (°)</th>
<th>SZA (°)</th>
<th>Depth** (km)</th>
<th>Maximum Absorptivity Measured Before Loss of Signal (dB/km)</th>
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<tbody>
<tr>
<td>2787N</td>
<td>11.1</td>
<td>160.6</td>
<td>47.0</td>
<td>0.0095 ± 0.0035</td>
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<td>2787X</td>
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<td>137.7</td>
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* Note that an N suffix indicates an entry occultation, and an X suffix indicates an exit occultation.

** Deepest altitude probed (relative to a radius of 6051.92 km) before loss of signal.
TABLE II

PIONEER-VENUS RADIO OCCULTATION (ORO) DATA REDUCTION:
PROFILES OF 13-CM ABSORPTIVITY

FINAL REPORT

1. TO DATE, 23 ORBITS HAVE BEEN PROCESSED FROM OCCULTATION SEASON 10 (LATE 1986 AND EARLY 1987), INCLUDING ERROR BARS AND 7 ORBITS HAVE BEEN PROCESSED FROM OCCULTATION SEASON 1 (EARLY 1979).

2. PROBLEMS IN PREVIOUSLY EXISTING SOFTWARE HAVE BEEN DETECTED IN AREAS OF ANTENNA POINTING CORRECTION, SIGNAL GAIN NORMALIZATION (ALSO KNOWN AS AGC ACTION), AND SIGNAL PATH DETERMINATION. CORRECTIONS HAVE BEEN DEVELOPED.

3. PROFILES OF ABSORPTIVITY AND GASEOUS H₂SO₄ ABUNDANCE AND THE ACCOMPANYING ERROR BARS HAVE BEEN DEVELOPED (2.29 GHz OR 13 cm).

4. PROFILES GENERALLY SHOW A LOWER 13 cm ABSORPTIVITY THAN TYPICALLY MEASURED IN THE FIRST RADIO OCCULTATION SEASON (1979–1980), HOWEVER, PROPER CHARACTERIZATION OF UNCERTAINTIES (I.E. ERROR BARS) OF EARLIER PROFILES IS NECESSARY TO CONFIRM ANY LONG TERM TEMPORAL VARIATION.

5. DATA DOES NOT SUGGEST ANY DIURNAL VARIATIONS TO MATCH THOSE OBSERVED BY EMISSION MEASUREMENTS AT 2.6 mm.

6. LATITUDINAL VARIATIONS ARE APPARENT, I.E. ABSORPTIVITY BEGINS AT LOWER ALTITUDES IN POLAR REGIONS.

7. ABUNDANCES OF GASEOUS H₂SO₄ IN THE 5–20 PPM RANGE ARE COMMON BELOW THE CLOUD LAYERS.

8. FUTURE WORK:

   INVESTIGATE ALTERNATIVE METHODS FOR COMPUTING THE INVERSE ABEL TRANSFORM SO AS TO REDUCE UNCERTAINTY IN DERIVED ABSORPTIVITY PROFILES.

   RADIO OCCULTATION STUDIES WITH MORE POWERFUL MAGELLAN SPACECRAFT.
Figure 1: Occultation Geometry
Figure 2: Flow chart for propagation of errors.
Figure 3: Atmospheric absorptivity profile measured for Orbit 2787N which occurred on July 23, 1986 at 11.1°N.
Figure 4: Atmospheric absorptivity profile measured for Orbit 2801N which occurred on August 6, 1986 at 40.8°N.
Figure 5: Atmospheric absorptivity profile measured for Orbit 2928N which occurred on December 11, 1986 at 88.6°N.
Figure 6: Average 13 cm opacity profile obtained for the equatorial latitudes (11 to 25°N).
Figure 7: Average 13 cm opacity profile obtained for the mid latitudes (35 to 45°N).
Figure 8: Average 13 cm opacity profile obtained for latitudes between 59 and 68°N.
Figure 9: Average 13 cm opacity profile obtained for latitudes between 72 and 80°N.
Figure 10: Average 13 cm opacity profile obtained for the polar region (latitudes above 85°N).
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Figure 14: Gaseous $\text{H}_2\text{SO}_4$ abundance as a function of radius measured for orbit 2787X, which occurred on July 23, 1986 at -37.7°N (solid line) and the abundance expected from saturation vapor pressure (dotted line).
Figure 15: Sulfuric acid vapor abundance profile measured for orbit 2787N, which occurred on July 23, 1986 at 11.1°N (solid line) and the abundance expected from saturation vapor pressure (dotted line).
Figure 16: Gaseous $\text{H}_2\text{SO}_4$ abundance as a function of radius measured for orbit 2792N, which occurred on July 28, 1986 at 24.8°N (solid line) and the abundance expected from saturation vapor pressure (dotted line).
Figure 17: Sulfuric acid vapor abundance profile measured for orbit 2798N, which occurred on August 3, 1986 at 36.1°N (solid line) and the abundance expected from saturation vapor pressure (dotted line).
Figure 18: Gaseous H$_2$SO$_4$ abundance as a function of radius measured for orbit 2801N, which occurred on August 6, 1986 at 40.8°N (solid line) and the abundance expected from saturation vapor pressure (dotted line).
Figure 19: Sulfuric acid vapor abundance profile measured for orbit 2814N, which occurred on August 19, 1986 at 59.3°N (solid line) and the abundance expected from saturation vapor pressure (dotted line).
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Figure 21: Sulfuric acid vapor abundance profile measured for orbit 2819N, which occurred on August 24, 1986 at 65.6°N (solid line) and the abundance expected from saturation vapor pressure (dotted line).
Figure 22: Gaseous H$_2$SO$_4$ abundance as a function of radius measured for orbit 2844N, which occurred on September 18, 1986 at 79.6°N (solid line) and the abundance expected from saturation vapor pressure (dotted line).
Figure 23: Sulfuric acid vapor abundance profile measured for orbit 2845N, which occurred on September 19, 1986 at 79.3°N (solid line) and the abundance expected from saturation vapor pressure (dotted line).
Figure 24: Gaseous H$_2$SO$_4$ abundance as a function of radius measured for orbit 2850N, which occurred on September 24, 1986 at 75.6°N (solid line) and the abundance expected from saturation vapor pressure (dotted line).
Figure 25: Sulfuric acid vapor abundance profile measured for orbit 2851N, which occurred on September 25, 1986 at 74.4°N (solid line) and the abundance expected from saturation vapor pressure (dotted line).
Figure 26: Gaseous $\text{H}_2\text{SO}_4$ abundance as a function of radius measured for orbit 2853N, which occurred on September 27, 1986 at 72.6°N (solid line) and the abundance expected from saturation vapor pressure (dotted line).
Figure 27: Sulfuric acid vapor abundance profile measured for orbit 2859N, which occurred on October 3, 1986 at 67.3°N (solid line) and the abundance expected from saturation vapor pressure (dotted line).
Figure 28: Gaseous H$_2$SO$_4$ abundance as a function of radius measured for orbit 2860N, which occurred on October 4, 1986 at 66.7°N (solid line) and the abundance expected from saturation vapor pressure (dotted line).
Figure 29: Sulfuric acid vapor abundance profile measured for orbit 2862N, which occurred on October 6, 1986 at 65.9°N (solid line) and the abundance expected from saturation vapor pressure (dotted line).
Figure 30: Gaseous $\text{H}_2\text{SO}_4$ abundance as a function of radius measured for orbit 2921N, which occurred on December 4, 1986 at 87.2°N (solid line) and the abundance expected from saturation vapor pressure (dotted line).
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Figure 32: Gaseous H$_2$SO$_4$ abundance as a function of radius measured for orbit 2928N, which occurred on December 11, 1986 at 88.6°N (solid line) and the abundance expected from saturation vapor pressure (dotted line).
Figure 33: Sulfuric acid vapor abundance profile measured for orbit 2930N, which occurred on December 13, 1986 at 87.5°N (solid line) and the abundance expected from saturation vapor pressure (dotted line).
Figure 34: Sulfuric acid vapor abundance profile measured for orbit 2939N, which occurred on December 22, 1986 at 77.8°N (solid line) and the abundance expected from saturation vapor pressure (dotted line).
Figure 35: Gaseous $\text{H}_2\text{SO}_4$ abundance as a function of radius measured for orbit 2952N, which occurred on January 4, 1986 at 60.4°N (solid line) and the abundance expected from saturation vapor pressure (dotted line).
Figure 36: Sulfuric acid vapor abundance profile measured for orbit 2955N, which occurred on January 7, 1986 at 56.4°N (solid line) and the abundance expected from saturation vapor pressure (dotted line).