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- Ames Research Center -

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**Reduction and Analysis of Seasons 15 and 16 (1991-1992)  
Pioneer Venus Radio Occultation Data and Correlative Studies with Observations  
of the Near Infra-Red Emission of Venus**

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April 1, 1992 through May 31, 1995



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(NASA-CR-199071) REDUCTION AND  
ANALYSIS OF SEASONS 15 AND 16 (1991  
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## Introduction

Radio occultation experiments and radio astronomical observations have suggested that significant variations (both spatial and temporal) in the abundances of sulfur-bearing gases are occurring below the Venus cloud layers (Steffes *et al.* 1990, Jenkins and Steffes 1991, Jenkins *et al.* 1994). In addition, Near Infra-Red images of the nightside of Venus revealed large-scale features which sustain their shape over multiple rotations (the rotation periods of the features are  $6.0 \pm 0.5$  days (Crisp *et al.* 1990a, b). Presumably, the contrast variations in the NIR images are caused by variations in the abundance of large particles in the cloud deck. If these particles are composed of liquid sulfuric acid, one would expect a strong anti-correlation between regions with a high abundance of sulfuric acid vapor, and regions with a large abundance of large particles (Crisp *et al.* 1989). One technique for monitoring the abundance and distribution of sulfuric acid vapor ( $\text{H}_2\text{SO}_4$ ) 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 (PVORO) (Jenkins and Steffes 1991).

In this study, we sought to characterize variations in the abundance and distribution of subcloud  $\text{H}_2\text{SO}_4(\text{g})$  in the Venus atmosphere by using a number of 13-cm radio occultation measurements conducted with the Pioneer Venus Orbiter near the inferior conjunction of 1991. A total of ten data sets were examined and analyzed, producing vertical profiles of temperature and pressure in the neutral atmosphere, and sulfuric acid vapor abundance below the main cloud layer. Two of the vertical profiles of the abundance of  $\text{H}_2\text{SO}_4(\text{g})$  were correlated with NIR images of the night side of Venus made during the same period of time by Boris Ragent (under a separate PVO Guest Investigator Grant). Initially, we had hoped that the combination of these two different types of data would make it possible to constrain or identify the composition of the large particles causing the features observed in the NIR images. However, the sparseness of the radio occultation data set, combined with the sparseness of the NIR data set (one image per day over an 8 day period) made it impossible to draw strong conclusions. Considered on their own, however, the parameters retrieved from the radio occultation experiments are valuable science products.

In addition to the work on data obtained from Pioneer Venus, supplements to this grant under the NASA Venus Data Analysis Program and from Magellan Operations funds have been received to design and partially process data from radio occultation experiments with the Magellan spacecraft that occurred in October, 1991, December, 1992, and in the summer of 1994. While these data do not fall in the narrow time period necessary for direct comparison and correlation with the NIR images, they do provide additional information on the distribution of  $\text{H}_2\text{SO}_4(\text{g})$  in different latitude regions than the Pioneer Venus data, and provide a means to extend temporal variation studies made with Pioneer Venus. In addition, the quality of these data sets far exceeds that of the 1991 PVORO data, due in part to more favorable experimental geometry, and the higher effective isotropic radiated power (EIRP) of the Magellan spacecraft. The progress on this project is detailed in this report as well.

The organization of this report is as follows. First, the results of the PVORO studies are presented, along with a discussion of the cross-correlation made with NIR imagery. Next, the primary results of three radio occultation experiments obtained with the Magellan spacecraft in October, 1991, are described. Important characteristics of the total Magellan radio occultation data set are given, along with a discussion of

anticipated results. This is followed by a summary of activities section, and finally by conclusions and suggestions for future work.

### Pioneer Venus Radio Occultation Studies

During the course of Grant NCC 2-753 (April 1, 1992 through March 31, 1992) ten PVORO data sets from season 15 (1991) were processed to obtain 13-cm absorptivity profiles, H<sub>2</sub>SO<sub>4</sub>(g) profiles, and temperature and pressure profiles in the neutral atmosphere. This was accomplished using standard techniques for reducing radio occultation data, as well as more novel methods for retrieving absorptivity profiles (Jenkins *et al.* 1994, Jenkins 1992). A selected number of these experiments were cross-correlated with NIR images obtained by Dr. Boris Ragent (under a separate agreement).

Table I gives a summary of various parameters of interest for these ten experiments, including date, solar zenith angle, planetocentric longitudes and latitudes probed, and range of solar zenith angles during each experiment. All altitudes are with respect to a mean radius of 6052 km. The tracks of the proximate point of each of these experiments during the time the radio signal probed the neutral atmosphere are given in

**Table I: Season 15 Data Summary**

Orbit Number	Day of Year	Date	Solar Zenith Angle (°)	Longitudes (°)	Latitudes (°)	Lowest Altitude Probed (km)
4637	229	08/17/91	98.4 97.6	225.1 223.3	16.4 9.1	40.0
4642	234	08/22/91	88.8 88.0	230.1 228.7	10.9 0.4	40.0
4649	241	08/29/91	75.0 76.0	231.2 230.9	3.5 -9.7	40.0
4661	253	09/10/91	53.5 57.1	252.3 253.0	-8.5° -16.0	43.7
4663	255	09/12/91	50.3 53.1	255.1 255.6	-9.6 -15.3	45.7
4668	260	09/17/91	42.5 46.6	262.7 263.1	-8.0 -17.9	43.9
4670	262	09/19/91	39.4 43.6	265.9 266.1	-7.1 -15.5	43.5
4691	283	10/10/91	22.6 11.5	-53.5 -57.3	15.5 2.4	40.0
4697	289	10/16/91	25.9 15.1	-40.0 -43.3	22.3 13.9	40.0
4699	291	10/18/91	27.6 18.3	-35.3 -38.5	24.3 18.6	40.0

Fig. 1. (The proximate point is the location of the deepest atmospheric volume through which the radio signal passes at each point in time during the observation.) As indicated in Fig. 1 and Table I, these experiments probed regions of the Venus atmosphere between 18°S and 25°N, and covered a 100° wide range of planetocentric longitudes. It is important to note that the atmosphere rotates much faster than the planet surface, so that the planetocentric longitudes given do not specify the longitudinal relationship between atmospheric regions probed by each experiment. Although the near broadside geometry of the spacecraft orbit serendipitously allowed us to probe the equatorial region where the NIR features were located, it also increased the systematic and statistical errors in the retrieved profiles. This is due to several factors: 1) It is difficult to measure the orbital parameters of a spacecraft while it's orbital plane is nearly broadside to the Earth-Venus direction (i.e. the angular momentum vector of the spacecraft is nearly parallel to the line-of-sight.) This increased the systematic errors in any retrieved profiles. 2) Under these conditions, the depth to which radio occultation experiments could probe was geometry-limited. The inversion of radio occultation data in the vicinity of the turnover point is not stable, which makes the retrieved profiles near this point unreliable. 3) The near-broadside geometry decreased the sensitivity of the experiments by reducing the dynamic range of the variation in frequency of the spacecraft signal during the experiments. This is a consequence of having a smaller component of the spacecraft velocity parallel to the line-of-sight, and consequently increased the statistical errors due to thermal noise compared to other experiment geometries. These effects were somewhat mitigated by the relatively short Earth-Venus distance which improved the signal to noise ratio (SNR).

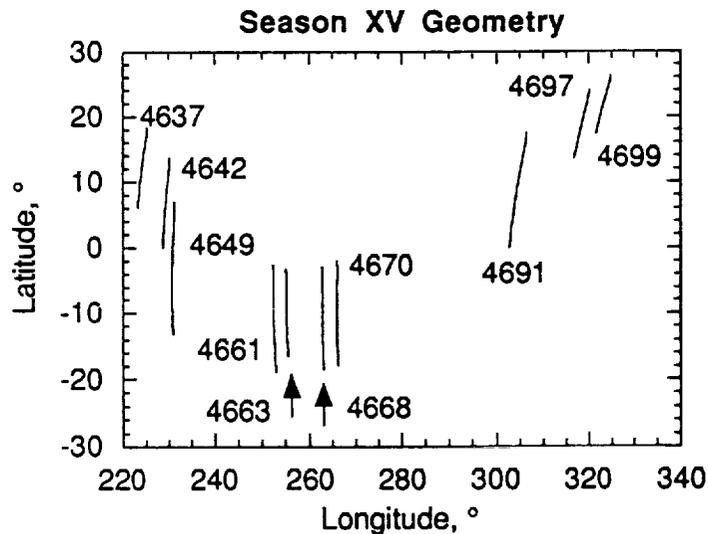


Figure 1: Tracks of the atmospheric regions probed during each of the ten PVORO radio occultation experiments analyzed in this study. Longitudes given are planetocentric. The longitudinal resolution during each experiment was  $\sim 10^\circ$ , so that each of these curves is the center of a  $10^\circ$  wide ribbon that represents the horizontal region probed during each experiment.

Figure 2 shows the ten temperature profiles retrieved from these experiments, along with uncertainties typical of each profile. The average temperature at each altitude

was computed and subtracted from each profile, with the residuals presented in Fig. 3. The profiles from orbit 4642 is noticeably colder than the others,  $\sim 20$  K colder between 40 and 60 km altitude, while the atmospheric region probed during orbit 4691 is  $\sim 10$  K warmer than the average. This is intriguing since the latitudes probed by these two experiments nearly coincided. While the variations between the various profiles are statistically significant, there does not appear to be a simple progressive trend in the orbit-to-orbit variations that would be indicative of a 4 or 6 day period. Thus, it does not seem possible to correlate the large dark NIR features with temperature variations. They are, however, indicative of dynamical phenomenon in the equatorial region of the Venus atmosphere.

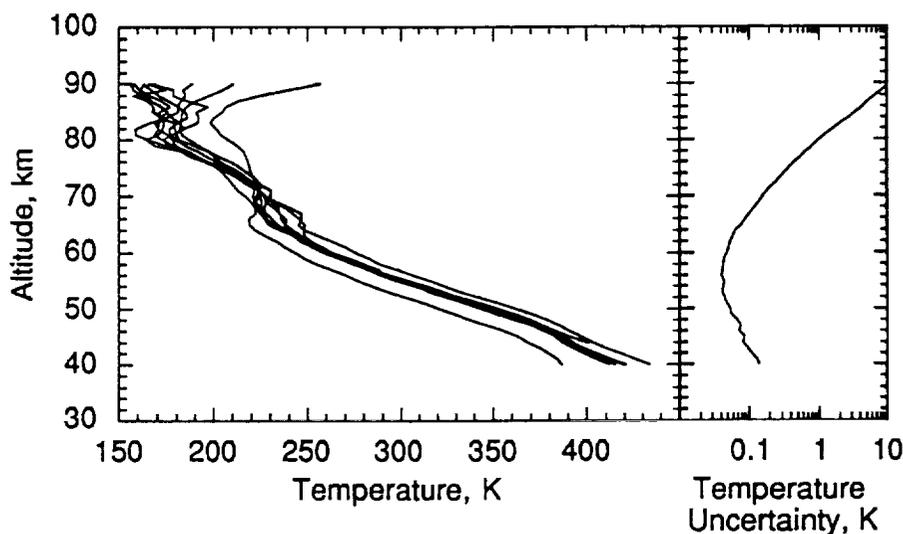


Figure 2: Temperature profiles retrieved from each of the ten PVORO experiments analyzed in this study. The profiles from orbits 4642 and 4691 are significantly cooler and warmer than the average, respectively, which is surprising since they both probed latitudes between  $2^{\circ}\text{N}$  and  $10^{\circ}\text{N}$ .  $1\text{-}\sigma$  temperature uncertainties typical of these profiles is shown in the right panel.

In order to isolate structures with wavelengths less than the scale height, we passed high-pass quadratic boxcar filters over each temperature profile with a 10-km height. (These filters are fully described in Hinson and Jenkins 1995, but correspond to fitting a quadratic polynomial to each data point within 5 km of each altitude and taking the output to be the difference between the original temperature and the value of the polynomial at that altitude.) The results are given in Fig. 3, demonstrating the existence of wave-like structures in the temperature profiles with amplitudes of 2 to 5 K. Interestingly, power spectra of these temperature residuals reveal peak energies located near 2.85 km wavelength. This can hardly be coincidental, and suggests that gravity waves are the source of these small-scale disturbances, since they are capable of producing signatures with these amplitudes at this vertical wavelength (Hinson and Jenkins 1995).

One of the major goals of this research was to derive vertical profiles of  $\text{H}_2\text{SO}_4(\text{g})$  abundance to correlate with NIR imagery. To that end, vertical absorptivity profiles for each of these experiments were retrieved using the methods of Jenkins

(1992), and were subsequently combined with the temperature/pressure profiles to obtain  $\text{H}_2\text{SO}_4(\text{g})$  profiles. Figures 5a and 5b display the results, along with the saturation vapor mixing ratio for comparison. The  $1-\sigma$  error bars for these profiles is approximately 7 ppm, and is nearly constant throughout the altitude range in each panel of the figures, although there are systematic errors at the top and bottom boundaries of the measurements which may exceed this value. Despite small-scale differences among the profiles, they all show peak  $\text{H}_2\text{SO}_4(\text{g})$  abundances of 30-55 ppm located near 46 km, and for those that extend below 45 km, a general decrease in  $\text{H}_2\text{SO}_4(\text{g})$  below this peak (for all but orbit 4649). This is consistent with the results of the PVORO experiment conducted on July 23, 1986 during orbit 2787 which measured 40 ppm  $\text{H}_2\text{SO}_4(\text{g})$  at an altitude of 47 km at  $11.1^\circ\text{N}$ . It appears, then, that there is no compelling evidence for large-scale longitudinal variations in  $\text{H}_2\text{SO}_4(\text{g})$  that might be related to the large cloud particles responsible for the large dark NIR features.

As stated earlier, our attempts to correlate the PVORO results with NIR images were hampered by the low number of occultation experiments conducted during the actual NIR observations and the sparseness of NIR images (one per day). This gave us only two points for comparison with the images. In addition, the task of placing the tracks of the occultation experiments on the NIR images was problematic because the rotation period of the atmosphere at these levels could not be unambiguously deduced from the images (B. Ragent, personal communication.) Thus, one profile (orbit 4670) most likely probed near the edge of the large dark NIR feature observed, and the profile from orbit 4668 probed a region not well characterized as either light or dark. Two profiles were obtained a few days prior to the NIR observations (4661 and 4663), but could not be drawn upon for correlation purposes due to the ambiguity in atmospheric rotation rates. In any case, as stated above, the derived sulfuric acid vapor profiles do not appear to be statistically much different from one another, so that the general conclusion we can draw is that the abundance of sulfuric acid vapor appears to be independent of the large particles responsible for the dark features observed in the NIR images.

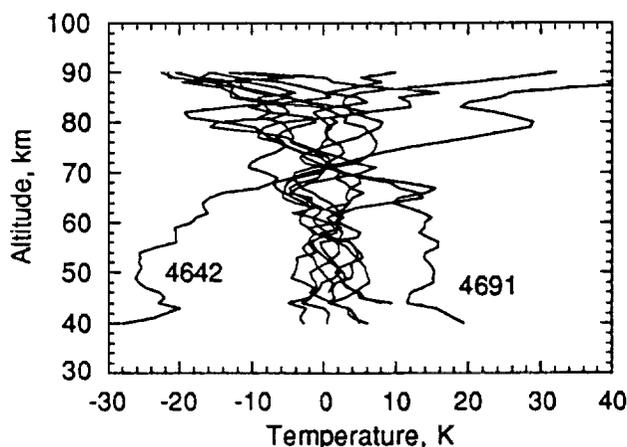


Figure 3: The results of subtracting the mean temperature profile from each of the ten profiles shown in Fig. 2.

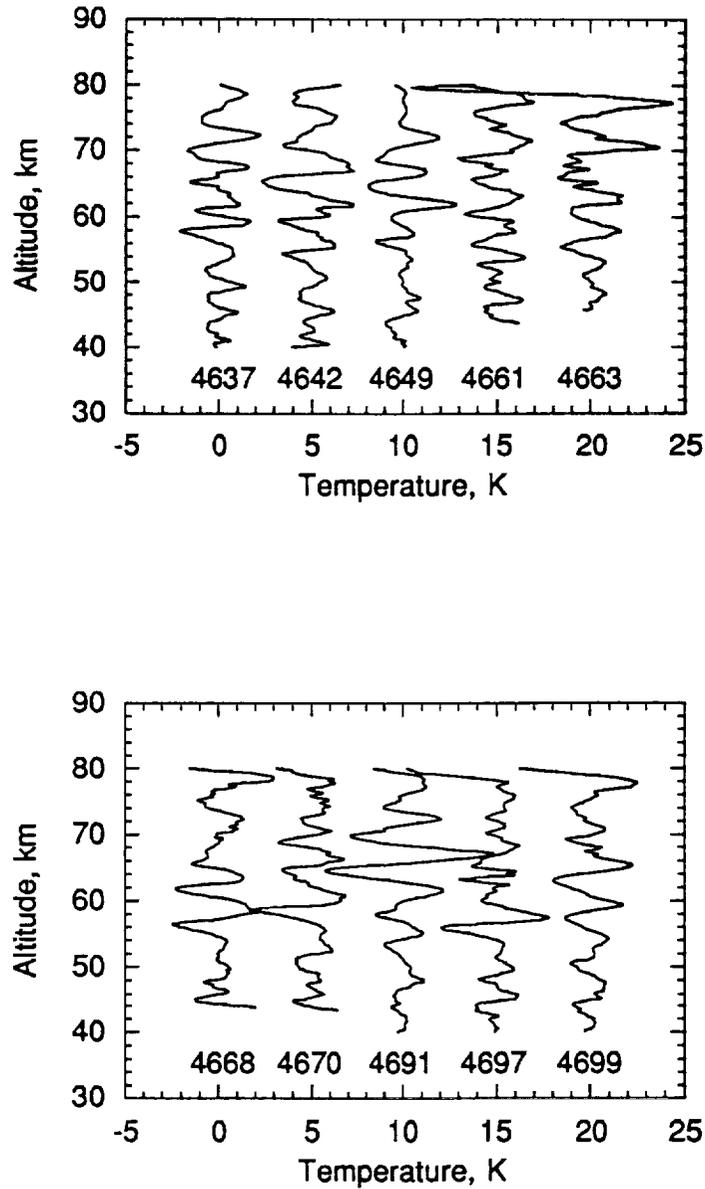


Figure 4. The results of high-pass filtering the temperature profiles in Fig. 2 with an effective cut-off frequency of  $0.125 \text{ km}^{-1}$ . The residuals in all cases show a strong concentration of energy near  $2.85 \text{ km}$  wavelength. The oscillations apparent in these profiles may be due to vertically-propagating gravity (buoyancy) waves.

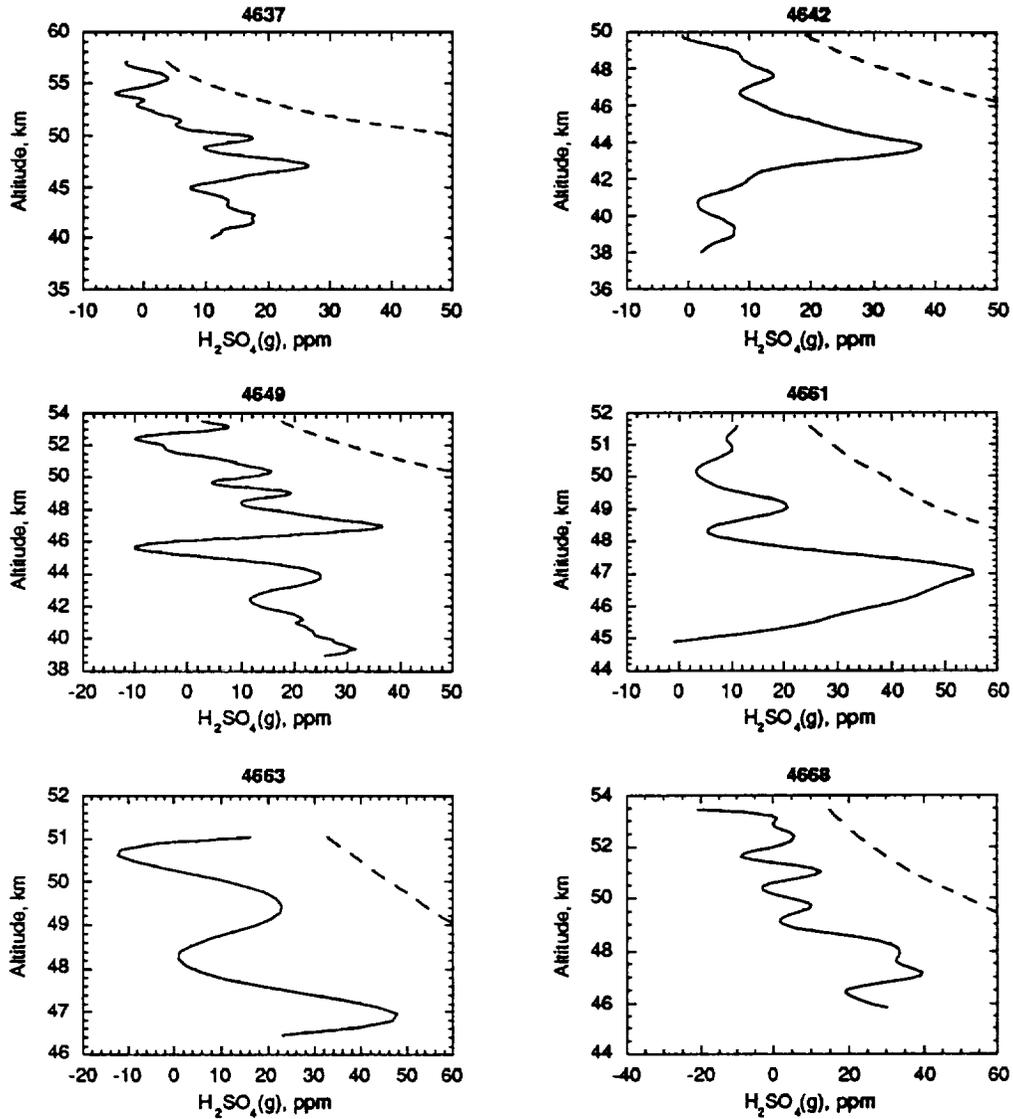


Figure 5a: Profiles of  $\text{H}_2\text{SO}_4(\text{g})$  abundance retrieved from experiments conducted in the summer of 1991 with the Pioneer Venus Orbiter. Despite small-scale differences, the gross features of the profiles are similar. The dotted line in each panel is the saturation vapor pressure of  $\text{H}_2\text{SO}_4(\text{g})$ . The other four profiles are shown in Fig. 5b.

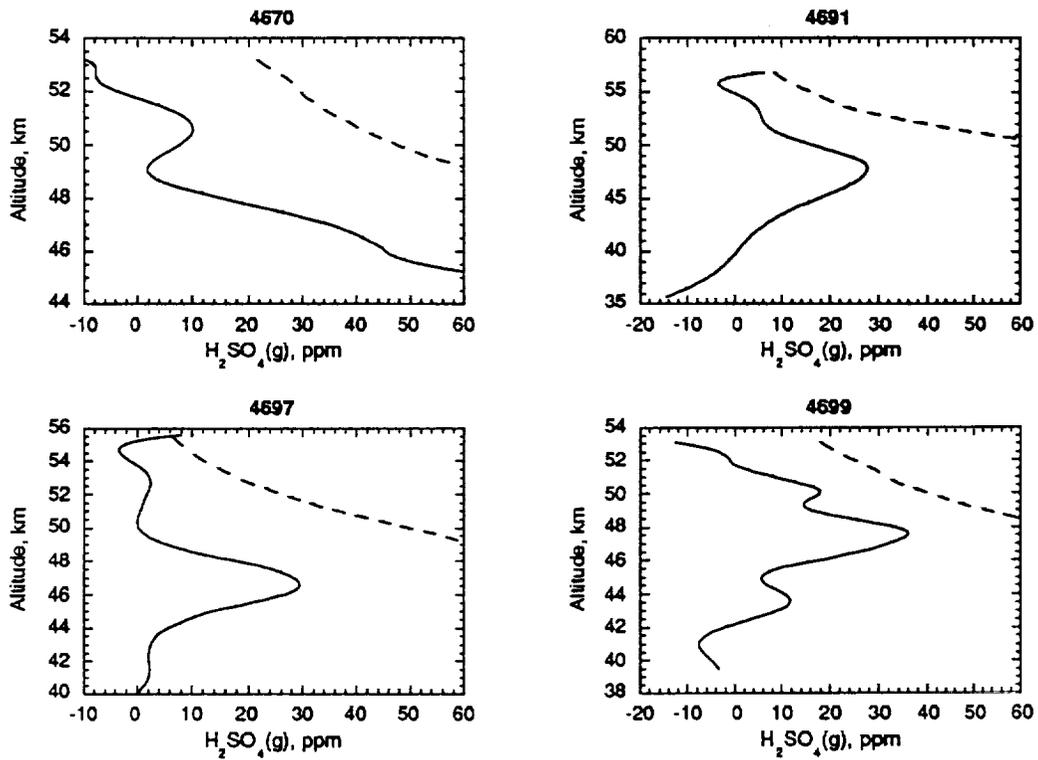


Figure 5b: Profiles of  $\text{H}_2\text{SO}_4(\text{g})$  abundance retrieved from experiments conducted in the summer of 1991 with the Pioneer Venus Orbiter. Despite small-scale differences, the gross features of the profiles are similar. The dotted line in each panel is the saturation vapor pressure of  $\text{H}_2\text{SO}_4(\text{g})$ . The other six profiles are shown in Fig. 5a.

## Magellan Radio Occultation Studies

During the course of NCC 2-753, Dr. Jenkins participated in the design, planning or analysis for 30 radio occultation experiments with the Magellan spacecraft: three on October 5, 1991, two on December 6, 1992, and four on December 20, 1992, and 21 during the summer of 1994. The data from the first three experiments has been processed to infer  $\text{H}_2\text{SO}_4(\text{g})$  abundance profiles, temperature and pressure profiles, and average electron density profiles. These results were reported in Steffes *et al.* (1994) and Jenkins *et al.* (1994). Pursuant to these basic results, Hinson and Jenkins (1995) studied small-scale wave structures in the temperature profiles and intensity scintillations observed during each experiment. They reported the discovery of a spectrum of gravity waves in the Venus atmosphere. Such phenomena is interesting because they may contribute to the superrotation of the Venus atmosphere. The following section summarizes the major results of these studies, but concentrates on the  $\text{H}_2\text{SO}_4(\text{g})$  profiles, as these were the major responsibility of J. Jenkins (D. Hinson operated under an independent grant under the Venus Data Analysis Program).

**Experiment Geometry.** Dual-wavelength (3.6 and 13 cm) radio occultation data were recorded (ingress only) on three successive orbits (numbers 3212-3214) of the Magellan spacecraft on 5-6 October 1991. Figure 6 shows the view from Earth of the experiment geometry. Due to the slow rotation rate of Venus' surface and the slow variation of the Sun-Earth-Venus geometry, each occultation occurred over the same topography and at the same local time and solar zenith angle. However, the atmosphere of Venus rotates about  $10^\circ$  in longitude during one spacecraft orbit (3.26 hr), and the longitudinal resolution of the measurements is also about  $10^\circ$ , so that the three data sets pertain to distinct regions of the atmosphere.

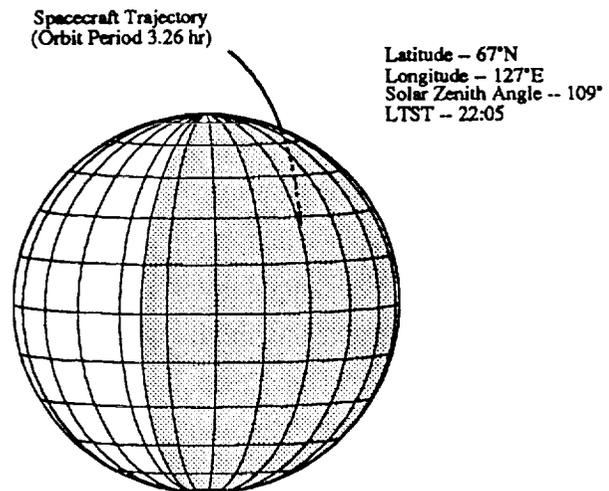


Figure 6: Experiment geometry.

**Atmospheric Structure and Circulation.** We completed the initial steps of data reduction for the 1991 experiments, yielding time histories of the frequency and intensity of the radio signals received from Magellan during each occultation. We then retrieved "atmospheric profiles" from the frequency measurements. Our data processing algorithms are based on established methods (Fjeldbo *et al.* 1971) but include important advances as well (Jenkins *et al.* 1994). Results include vertical profiles of number density, pressure, and temperature in the neutral atmosphere, and profiles of electron number density in the ionosphere. For example, Fig. 7 shows measurements of temperature vs. altitude from orbit 3213. The profile extends from about 33 to 98 km (0.03 to 6000 mbar). Statistically significant temperature oscillations are present throughout this altitude interval. Profiles from the other two orbits look similar on this scale.

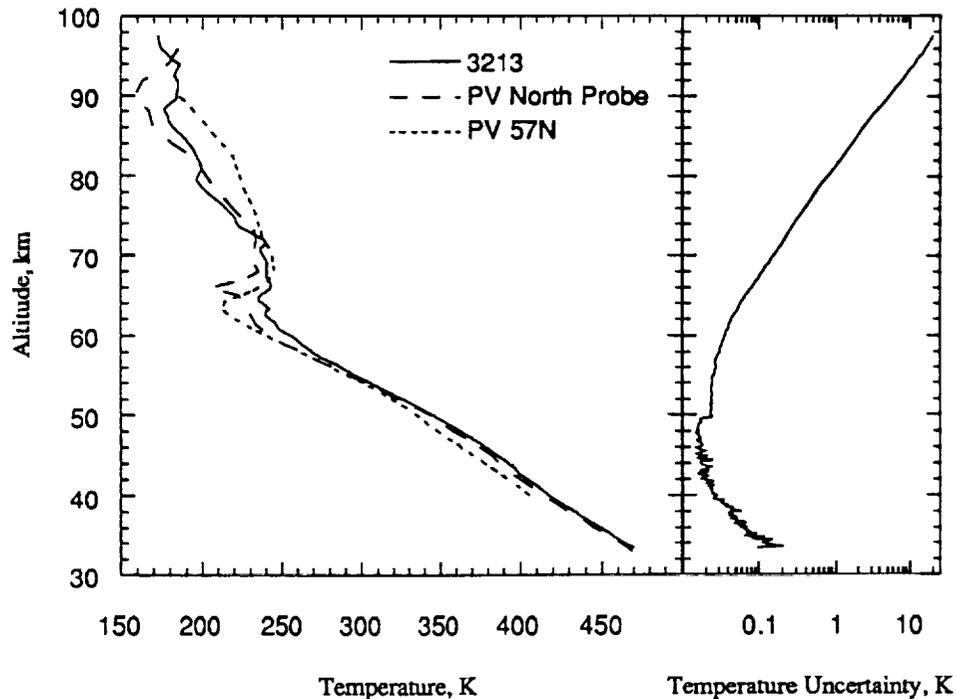


Figure 7. Temperature profile retrieved from second Magellan radio occultation (left panel, solid line) with associated uncertainty(right).

For comparison, Fig. 7 also shows results obtained from the Pioneer Venus North Probe at 60°N (Seiff *et al.* 1980) and from a Pioneer Venus radio occultation at 67°N (orbit 57N; Kliore and Patel 1982). These three temperature profiles are generally similar. It is interesting to note, however, that radio occultation measurements from 1978-81 revealed a "cold polar collar", which appears as a minimum in the meridional cross section of temperature centered near 60-65 km altitude (~100 mbar) and 65-70°N latitude. The reduction in temperature at this pressure level relative to the equator was as large as 40 K in the earlier measurements. Individual temperature profiles that sliced through the collar (such as the one from PV orbit 57N) exhibit a strong temperature inversion (up to 30 K) at about 66 km altitude overlying a deep temperature minimum (~210 K) near 63 km. This thermal feature is related to a mid-latitude jet in the zonal circulation (Newman *et al.* 1984). The absence of the cold collar in the Magellan profiles confirms the variability of this feature (Newman *et al.* 1984, Walterscheid *et al.* 1985), and suggests that the jet may have weakened or shifted in latitude during the last decade.

Profiles of electron number density were obtained from differential Doppler measurements on each orbit. Peak densities occur at altitudes between 140 and 145 km, consistent with Pioneer Venus observations (Brace *et al.* 1983). However, the magnitude of the peaks (2500, 3000, and 6000 cm<sup>-3</sup> on the three orbits) is much smaller than that observed at the same solar zenith angle and at nearly the same time in the solar cycle by PV radio occultations in 1979 (~10<sup>4</sup> cm<sup>-3</sup>). The Magellan profiles also exhibit statistically significant orbit-to-orbit variations, both in the height and magnitude of the peak density. The cause for this variability, and for the differences from earlier measurements, is unclear but provides motivation for acquiring additional data.

**Sulfuric Acid Vapor.** Intensity measurements on all three orbits exhibit excess attenuation due to absorption by sulfuric acid vapor. Figure 8 shows abundance profiles retrieved from data at 13-cm wavelength. (The error bars do not include the uncertainty in laboratory measurements of the absorptivity of sulfuric acid vapor.) All profiles appear to be supersaturated between 45 and 50 km, but this may be accounted for by uncertainties in the saturation abundance of  $\text{H}_2\text{SO}_4(\text{g})$ , and the mitigating presence of  $\text{SO}_2(\text{g})$ , which is not included in this analysis. The peak abundances lie between 18 and 24 ppm. The rapid decay of all three profiles below 38 km confirms that sulfuric acid vapor decomposes below this altitude (von Zahn *et al.* 1983). The abundance profiles for orbits 3213 and 3214 show a pronounced minimum at altitudes between 40 and 43 km and a strong secondary peak near 39 km, unlike the one from orbit 3212. This difference is statistically significant, which indicates the presence of zonal variations in the abundance of sulfuric acid vapor between 34 and 50 km. Some of these variations may be associated with atmospheric waves.

**Additional Magellan Radio Occultation Studies.** Of the 27 additional experiments conducted with Magellan after 1991, 16 of these resulted in successful data acquisition.

Two of the six experiments conducted in December of 1992 were successful. Four data sets were lost due to hardware failure at the Deep Space Network (DSN) station in

Goldstone, CA. In addition, six experiments conducted in June, 1994, were lost due to operator error at this same DSN station. However, a total of 15 experiments were successfully executed in the summer of 1994. These experiments should provide a wealth of information on the state and dynamics of the Venus atmosphere to altitudes as low as 33 km over a wide range of latitudes in both hemispheres. The short orbital period of the Magellan spacecraft also makes it possible to study short term variations in the atmosphere, and isolate long-term temporal variability from spatial variations. This could not be accomplished with the Pioneer Venus Orbiter, due to its 24 hour period. The principal results will include electron density in the ionosphere, temperature, pressure and density profiles of the neutral atmosphere, and sulfuric acid vapor profiles. In addition, as laboratory measurements refine our knowledge of the opacity of sulfuric

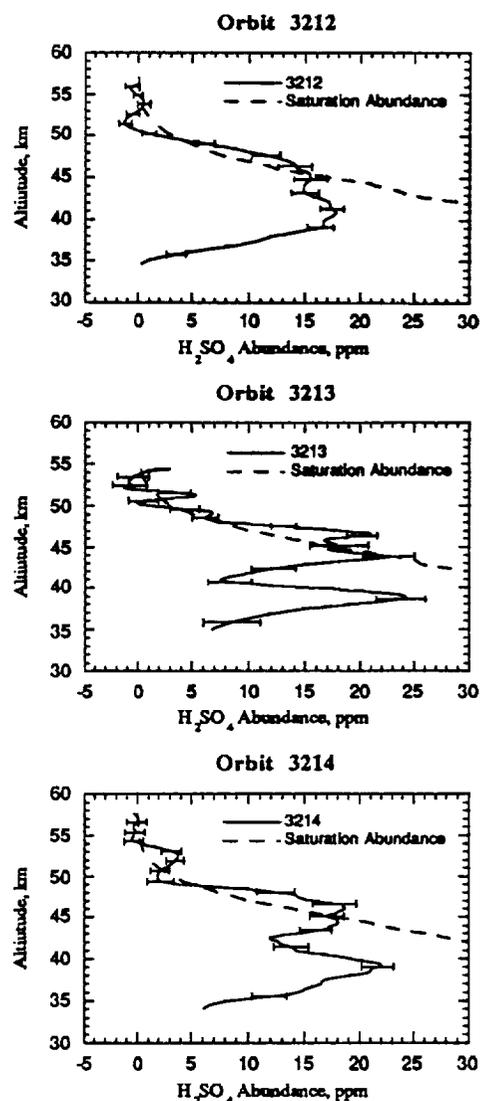


Figure 8: Sulfuric acid vapor abundance profiles from Magellan radio occultation measurements along with saturation abundance and associated uncertainties.

acid vapor and sulfur dioxide (SO<sub>2</sub>) at both 13 cm and 3.6 cm, it will be possible to develop profiles of SO<sub>2</sub> as well as H<sub>2</sub>SO<sub>4</sub>(g). Table II contains a summary of the experimental parameters relevant to each data set.

**Table II. Summary of Experimental Parameters for Magellan Radio Occultations**

Date	# Experiments	Latitude, °N	Longitude, °	Solar Zenith Angle, °
10/05/91	3	67	127	109
12/7/92	1	-88	0	94
6/24/94	1	81	138	85
6/24/94	1	-86	216	90
7/16/94	3	71	185	73
8/8/94	5	38	94	39
8/8/94	5	-52	92	54

### Summary of Activities

Over the course of NCC 2-753, Dr. Jenkins has attended several professional and project-related meetings, presented seminars, and written or co-written several journal articles. These activities are detailed below:

#### Conference Papers and Seminars:

Dr. Jenkins attended the International Colloquium on Venus held in Pasadena, CA on August 10-12, 1992, and presented a paper titled "Long-term Variations in Abundance and Distribution of Sulfuric Acid Vapor in the Venus Atmosphere Inferred from Pioneer Venus and Magellan Radio Occultation Studies".

Dr. Jenkins attended the 24th Annual Meeting of the DPS/AAS held in Munich, Germany, October 12-16, 1992, and presented a paper titled "Preliminary Correlation of Recent NIR Images of Venus with Pioneer Venus Orbiter Radio Occultation Studies" (Jenkins and Ragent, 1992), and co-authored a paper presented by Dr. Paul Steffes (Georgia Tech) titled "Preliminary Results from the October 1991 Magellan Radio Occultation Experiment" (Steffes *et al.*, 1992).

In addition, Dr. Jenkins gave a seminar titled "Optimal Algorithms for Processing Radio Occultation Data: The Venus Example" for a graduate seminar at Stanford University on May 27, 1992. On December 18, 1992, Dr. Paul G. Steffes and Dr. Jon Jenkins presented a seminar to the Magellan Project titled "Radio Occultation Studies at Venus".

Dr. Jenkins also presented a paper entitled "Venus: A Failed Earth?" at the NASA Conference on Circumstellar Habitable Zones held at NASA Ames Research Center in January, 1993.

Dr. Jenkins attended the 25th Annual Meeting of the DPS/AAS held in Boulder, Colorado, in October of 1993, and presented a paper titled "Atmospheric Profiles and Sulfuric Acid Vapor (H<sub>2</sub>SO<sub>4</sub>) Profiles from the October 1991 Magellan Orbiter Radio Occultation Experiments at Venus" (Jenkins *et al.* 1993). He co-authored a paper entitled "Magellan Radio Occultation Measurements of Atmospheric Waves on Venus" at that same meeting (Hinson and Jenkins 1993).

Dr. Jenkins attended the 26th Annual Meeting of the DPS/AAS held in Washington, DC in October of 199, and co-authored a paper titled "Magellan Radio Occultation Measurements of Atmospheric Waves on Venus" (Hinson and Jenkins 1993).

#### **Journal Articles:**

The 1991 Magellan radio occultation studies have resulted in three publications: Steffes *et al.* (1994), Jenkins *et al.* (1994), and Hinson and Jenkins (1995).

#### **Conclusions and Suggestions for Future Work**

The ten data sets analyzed from PVORO studies during Season 15 in 1991 have resulted in valuable data products. Although the intended goal of identifying or constraining the constituents in large cloud particles responsible for dark features in NIR imagery was not realized, the results suggest that there is not a relationship between the abundance of sulfuric acid vapor below the cloud deck and the presence of these particles. This does not mean that the particles are not composed in part or totally of sulfuric acid droplets, but it does suggest that whatever mechanism supports the existence of these particles is decoupled from the abundance of sulfuric acid vapor below the clouds. A manuscript describing the null conclusions regarding the cross-correlation between the PVORO data sets and the NIR images is in preparation, in collaboration with B. Ragert (San Jose State University). A manuscript describing the general results of the PVORO Season 15 studies of sulfuric acid vapor is also in preparation. The small-scale structures revealed in the temperature-pressure profiles are of great interest and warrant further study and modeling. A first step would be to apply the methods of Hinson and Jenkins (1995) to see if the presence of gravity waves is supported quantitatively as well as qualitatively. More sophisticated modeling techniques might be of value if this proves to be the case.

The data obtained with the Magellan spacecraft in 1992 and 1994 is presently being reduced and analyzed. The 1992 study is being supported under the remaining funds from the NASA Venus Data Analysis Program under NCC 2-867. The analysis of the 1994 data will be conducted under a joint NASA Planetary Atmospheres Program grant with D. Hinson (Stanford University).

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