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Probing the lower and middle cloud decks of Venus : correlation studies of Pioneer Venus OCPP images and ground-based near-infrared images

Selwyn Mung Tuc Yee
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**PROBING THE LOWER AND MIDDLE CLOUD DECKS OF VENUS:
CORRELATION STUDIES OF PIONEER VENUS OCPP IMAGES
AND GROUND-BASED NEAR-INFRARED IMAGES**

A Thesis

Presented to

The Faculty of the Department of Physics

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Selwyn Mung Tuc Yee

May, 1995

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A handwritten signature in cursive script, appearing to read "Patrick Hamill", written over a horizontal line.

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ABSTRACT

PROBING THE LOWER AND MIDDLE CLOUD DECKS OF VENUS: CORRELATION STUDIES OF PIONEER VENUS OCPP IMAGES AND GROUND-BASED NEAR-INFRARED IMAGES

by Selwyn M. T. Yee

Earth-based images of the Venus night-side in 1.0 to 2.3 μm near-infrared (NIR) atmospheric spectral windows show westward-moving contrast features in the lower cloud deck. Unfortunately, relatively few images have been recorded since 1983, during inferior conjunctions every 1.6 years. The Orbiting Cloud Photopolarimeter (OCPP) on the Pioneer Venus Orbiter imaged reflected sunlight at four wavelengths, including 0.365 and 0.935 μm . In this study, we tracked OCPP features and created mosaics of OCPP and NIR images from June 1988 to derive zonal rotation periods of 5 to 6.5 days for 0.935 μm OCPP features, and 5 to 6.8 days for 1.74 μm NIR features. Feature correlations between a 0.935 μm OCPP and an NIR image yielded a $5.59^{+0.27}_{-0.25}$ day zonal rotation period. Similar rotation periods and correlations for 0.935 and 1.74 μm features indicate a common atmospheric source. OCPP images were recorded from 1978 to 1992, representing a large atmospheric database.

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Contents

1	Infrared Studies of the Lower Atmosphere	1
1.1	Introduction	1
1.1.1	Near Infrared (NIR) Observations	3
1.1.2	Orbiting Cloud Photopolarimeter (OCP) Observations	6
1.2	Objectives	8
2	Background	11
2.1	The Lower Atmosphere of Venus	11
2.1.1	1.74 and 2.3 μm NIR Images and the Lower to Middle Cloud Deck	13
2.1.2	OCP 0.935 μm Images: Another Probe into the Middle and Lower Cloud Decks?	16
2.1.3	OCP 0.365 μm Images and the Upper Cloud Deck	17
2.2	The OCP Data Set from June 20 to 30, 1988	18
2.3	The NIR Data Set from June 24 to 28, 1988	19
3	Analytical Techniques	20
3.1	Data Reduction	20
3.1.1	Reduction of NIR Data	20

3.1.2	Reduction of OCPP Data	24
3.2	Analysis of Data	34
3.2.1	Tracking of Atmospheric Features	34
3.2.2	Mosaics	39
3.2.3	Correlation between Images at Different Wavelengths	40
4	Results and Conclusions	41
4.1	Comparison of Rotation Periods and Velocities of Hand-Tracked June 1988 OCPP 0.935 μm Features with Other Data Sets	41
4.1.1	Comparison of Zonal Velocities for 0.935 μm OCPP with 2.3 μm NIR Features	42
4.1.2	Comparison of Zonal Velocities for 0.935 μm OCPP with 1.74 and 2.3 μm Galileo NIR Features	42
4.1.3	Comparison of Rotation Periods for 0.935 μm OCPP with 1.74 μm NIR Features	42
4.1.4	Results of a Study of 0.418 and 0.986 μm Galileo Features . . .	51
4.2	Plots of Rotation Periods and Velocities of Hand-Tracked 0.365 μm OCPP Features	54
4.3	Mosaics of 0.365 and 0.935 μm OCPP, and 1.74 μm NIR Data	54
4.4	Correlation of a 0.935 μm OCPP Image with a 1.74 μm NIR Image .	68
4.5	Conclusions	71
	References	76
	A Image Times	78
	B Data from Hand Tracking OCPP 0.935 and 0.365 μm Features	80
B.1	Hand-Tracked OCPP 0.935 μm Atmospheric Features	80

B.2	Hand-Tracked OCPP 0.365 μm Atmospheric Features	84
C	Program Listings	87
C.1	center.c	87
C.2	map.c	93
C.3	correlbig.pro	104

List of Tables

2.1	Particle sizes for the upper, middle, and lower cloud regions (Esposito <i>et al.</i> , 1983).	12
2.2	Classification of 2.3 μm NIR Features from January and February 1990 (Crisp <i>et al.</i> , 1991b).	15
4.1	Rotation periods derived from 1.74 μm NIR features during June 24-27, 1988 (Crisp <i>et al.</i> , 1989).	51
4.2	The first four columns contain longitude and latitude coordinates for each pair of correlated points in ocpp07 and nir26. Any longitude for nir26 greater than 360° was not wrapped around to 0° for easier comparison with ocpp07. The next two columns contain the angular displacement between each pair of correlated points; Δ lon is the longitudinal and Δ lat is the latitudinal displacement. The next two columns contain the zonal (longitudinal) and meridional (latitudinal) rotation periods. The last column shows meridional (latitudinal) velocities. The positive velocities indicate a northward flow.	70
4.3	Zonal rotation periods derived from hand tracking, mosaic, and correlation analyses as a function of wavelength.	74

A.1 NIR Image times from June 1988. The time difference listed for an image is the difference between it and the previous image.	78
A.2 OCPP image times from June 1988. The map number denotes the number of images made by the OCPP instrument. The first pixel of each image was recorded at the start time, but each image took approximately four hours to complete. The time difference listed for an image is the difference between it and the previous image. Note: Since there was no time listing for polarimetry map 3749, the time for ocpp09.fits was estimated. ocpp09.fits is the third measurement on 23/06/88. Other days with three measurements were looked at, and the average time difference between the second and third measurements was taken, which came out to be 19220 seconds or 5:20:20.	79

List of Figures

1.1	Inferior conjunction of Venus.	5
1.2	Orbit of Pioneer Venus and the scanning geometry of the OCPP instrument. The figure was taken from Russell, <i>et al.</i> , 1977.	7
2.1	Zonal velocities derived from tracking 2.3 μm NIR features from January and February 1990 (Crisp <i>et al.</i> , 1991b). The 1 σ error bars in the original plot were not reproduced here. Note that the data points seem to split into two separate curves corresponding to the 7.4 and 5.5 day rotation periods discovered in the features.	15
2.2	Synthetically-generated spectra of thermal emission from the night-side atmosphere of Venus, taking into account absorption by CO_2 and H_2O and using an atmospheric thermal profile from A. Seiff (Lecacheux <i>et al.</i> , 1993). Different lines represent emission at various altitudes in the atmosphere.	17
3.1	Method for finding the geometric center of Venus.	22

3.2	Observing situation: The zenith is the line extending out normal to Venus's surface at the observed point . Pioneer-Venus observes that point from an angle θ_r from the zenith . This is the observer zenith angle . The sun makes an angle θ_i with the zenith . This is the solar zenith angle	25
3.3	Plot of $\log(I\mu)$ vs. $\log(\mu\mu_o)$ for all data points in image ocpp07, taken on 6/23/88 at 5:05 UT. Note the deviation of data from the least squares fit line for large values of $\log(\mu\mu_o)$	28
3.4	Same as Figure 3.3, but data was excluded for $\log(\mu\mu_o) < -2.5$. Note the better match of the least squares fit line to the data for large values of $\log(\mu\mu_o)$	29
3.5	The Gourad shading method linearly varies the intensities between data points. The numbers are intensity values. The gray pixels represent actual data points. The white pixels represent interpolated data values.	33
4.1	Scans of intensity vs. longitude at -15° latitude for $0.935 \mu\text{m}$ images ocpp01 (top), and ocpp02 (bottom). The images were recorded on June 20, 1988 and were separated by 4.04 hours. Common features can readily be seen in ocpp01 and ocpp02. In ocpp01, the trough at 117° , peak at 132° , trough at 146° , and peak at 152° correspond in ocpp02 to the trough at 115° , peak at 118° , trough at 134° , and peak at 139° . The best fit for matching the set of troughs and peaks is obtained by shifting the scan of ocpp01 relative to that of ocpp02 by 13.5°	43

4.2	Rotation periods vs. latitude derived from <i>good</i> tracking results in the 0.935 μm OCPP images. Least squares fit line: $Y = -(0.000671 \pm 0.0129)X + 6.351 \pm 0.228$	44
4.3	Results of averaging rotation periods vs. latitude of Figure 4.2 into 10° bins. Error bars indicate standard deviation about the mean values. .	44
4.4	Zonal velocities vs. latitude derived from <i>good</i> tracking results in the 0.935 μm OCPP images. For a legend of symbols, see Figure 4.2. . .	45
4.5	Results of averaging velocities vs. latitude of Figure 4.4 into 10° bins. Error bars indicate standard deviation about the mean values.	45
4.6	Rotation periods vs. latitude derived from <i>all</i> tracking results in the 0.935 μm OCPP images. Least squares fit line: $Y = (0.0149 \pm 0.00878)X + 6.192 \pm 0.173$	46
4.7	Results of averaging rotation periods vs. latitude of Figure 4.6 into 10° latitude bins. Error bars indicate standard deviation about the mean values.	46
4.8	Zonal velocities vs. latitude derived from <i>all</i> tracking results in the 0.935 μm OCPP images. For a legend of symbols, see Figure 4.6. . .	47
4.9	Results of averaging velocities vs. latitude of Figure 4.8 into 10° latitude bins. Error bars indicate standard deviation about the mean values.	47
4.10	Comparison of binned zonal velocities vs. latitude derived from <i>good</i> tracking results in the 0.935 μm OCPP images (see Figure 4.5) with zonal velocities vs. latitude derived from 2.3 μm NIR images (Crisp <i>et al.</i> , 1991b).	48

4.11	Comparison of binned zonal velocities vs. latitude derived from <i>all</i> tracking results in the 0.935 μm OCPP images with zonal velocities vs. latitude derived from 2.3 μm NIR images (Crisp <i>et al.</i> , 1991b). . .	48
4.12	Same as Figure 4.10, with a solid body rotation curve of 6.36 days superimposed. 6.36 days is the mean rotation period from the <i>good</i> tracking results.	49
4.13	Comparison of zonal velocities vs. latitude derived from <i>good</i> tracking results in the 0.935 μm OCPP images of June 1988 with the 1.74 and 2.30 μm Galileo NIR images of February 1990 (Carlson <i>et al.</i> , 1991). Error bars represent 1 σ dispersion for the binned Galileo data. . . .	49
4.14	Comparison of zonal velocities vs. latitude derived from all the binned tracking results in the 0.935 μm OCPP images of June 1988 with the 1.74 and 2.30 μm Galileo NIR images of February 1990 (Carlson <i>et al.</i> , 1991). Error bars represent 1 σ dispersion for the binned Galileo data.	50
4.15	Same as Figure 4.13, with a solid body rotation curve of 6.36 days superimposed. 6.36 days is the mean rotation from the <i>good</i> tracking results.	50
4.16	Plot of rotation periods vs. latitude derived from Earth-based NIR observations. See Table 4.1.	52
4.17	Comparison of binned zonal rotation periods vs. latitude derived from <i>good</i> tracking results of the June 1988 0.935 μm OCPP features with June 1988 1.74 μm NIR rotation periods vs. latitude from Figure 4.16.	52
4.18	Comparison of binned zonal rotation periods vs. latitude derived from <i>all</i> tracking results of the June 1988 0.935 μm OCPP features with June 1988 1.74 μm NIR rotation periods vs. latitude from Figure 4.16.	53

4.19	Rotation periods vs. latitude derived from good tracking results in the 0.365 μm OCPP images. Least squares fit line: $Y = (0.00406 \pm 0.0136)X + 4.748 \pm 0.219$	55
4.20	Zonal velocities vs. latitude derived from good tracking results in the 0.365 μm OCPP images.	55
4.21	Rotation periods vs. latitude derived from <i>all</i> tracking results in the 0.365 μm OCPP images. Least squares fit line: $Y = (0.0271 \pm 0.00983)X + 4.760 \pm 0.172$	56
4.22	Zonal velocities vs. latitude derived from <i>all</i> tracking results in the 0.365 μm OCPP images.	56
4.23	OCPP Mosaic: 0.365 μm , 4.0 day zonal rotation period.	58
4.24	OCPP Mosaic: 0.365 μm , 4.5 day zonal rotation period.	59
4.25	OCPP Mosaic: 0.365 μm , 5.0 day zonal rotation period.	60
4.26	OCPP Mosaic: 0.935 μm , 5.5 day zonal rotation period.	61
4.27	OCPP Mosaic: 0.935 μm , 6.0 day zonal rotation period.	62
4.28	OCPP Mosaic: 0.935 μm , 6.5 day zonal rotation period.	63
4.29	NIR Mosaic: 1.74 μm , 5.0 day zonal rotation period.	64
4.30	NIR Mosaic: 1.74 μm , 5.5 day zonal rotation period.	65
4.31	NIR Mosaic: 1.74 μm , 6.0 day zonal rotation period.	66
4.32	NIR Mosaic: 1.74 μm , 6.5 day zonal rotation period.	67
4.33	Image ocpp07 with common features marked by “+”.	72
4.34	Image nir26 with common features marked by “+”.	73

Chapter 1

Infrared Studies of the Lower Atmosphere

1.1 Introduction

Venus and Earth are sometimes called sister planets. They have similar diameters, masses, and hence, similar densities. Although Venus is closer to the Sun, its clouds are more reflective, and therefore the two planets absorb nearly the same amount of solar energy. There are, however, striking differences between Venus and Earth. While the average temperature at the surface of the Earth is 290 K, the temperature at the surface of Venus can reach 750 K. The atmospheric pressure at the surface of Venus is approximately 90 times that on Earth. Also, the orbits, composition of the atmospheres, and the atmospheric dynamics of Venus and Earth are very different.

Venus and Earth rotate in opposite directions, but revolve around the sun in the same direction. Venus undergoes retrograde rotation and Earth undergoes prograde rotation relative to their revolution around the sun. The rotation period for Venus is much slower than for Earth, making a year on Venus shorter than its day. Venus

completes a retrograde rotation once every 243 days, and revolves around the Sun in 225 days. Also, the rotation axis for Venus is nearly perpendicular to its orbital plane, while Earth's axis is inclined 23.5° , causing seasons as it revolves around the Sun.

The atmosphere of Venus contains 96% CO_2 , nearly 4% N_2 , and trace amounts of other compounds such as H_2O , H_2SO_4 (the constituent in the clouds), and argon (Shu, 1982). On Earth, water is abundant. This fact, combined with water's large heat capacity, makes it the key agent in convection of the Earth's atmosphere. The lack of water in the atmosphere on Venus and its high surface temperatures suggests an energy transport system fundamentally different from Earth's. Indeed, the atmosphere of Venus "superrotates" 50 to 60 times faster than the solid planet.

One important manifestation of the energy transport system in the Venusian atmosphere is the runaway greenhouse effect. Although the clouds on Venus scatter most incident sunlight, about 2% gets through. The shorter wavelength components of the sunlight penetrate to the lower atmosphere and surface, since the thick CO_2 atmosphere is relatively transparent to these wavelengths. However, when the light is absorbed and the energy reradiated, it does so mainly in the infrared. Much of this radiation from the surface becomes absorbed by atmospheric gases below the cloud deck such as CO_2 and H_2O (Kamp *et al.* 1988). Any radiation propagating upward becomes scattered once or many times by the thick cloud layer. This radiation is much more likely to get scattered back down and reabsorbed by the atmospheric gases than it is to propagate up through the clouds and escape. Thus, much of the radiation received by the atmosphere beneath the cloud deck is trapped. Of course, some radiation must leak out, balancing the amount retained. Otherwise the planet would become infinitely hot. In the lowest part of the atmosphere, an equilibrium temperature of about 750 K is measured.

If the atmosphere of Venus is opaque in much of the infrared, which wavelengths can be used to study it? The clouds scatter sunlight back out of the atmosphere, making it nearly opaque to visible wavelengths too. These clouds may have optical depths¹ approaching 40 in the visible. However, distinct features immersed in the atmosphere have been seen in the ultraviolet and at a few near infrared² wavelengths corresponding to narrow spectral windows between gaseous absorption bands.

1.1.1 Near Infrared (NIR) Observations

In June 1983, David Allen and John Crawford discovered bright and dark features on the night-side of Venus at NIR wavelengths (Allen *et al.* 1984). There are two remarkable things about this discovery.

First, there is little thermal emission from the upper atmosphere at these wavelengths. The temperature of the high clouds on the night-side of Venus has been measured at 230 to 240 K. Blackbody radiation for this temperature peaks near 12 μm . It is now believed that Allen was observing radiation coming up through regions in the middle and/or lower cloud layers that exist between 48 to 65 kilometers above the surface. This radiation comes from the hot atmospheric gases beneath the clouds. Variations in the optical thicknesses of the clouds attenuated the radiation by different amounts, creating the bright and dark features (Ragent, 1994).

Second, the atmospheres of Earth and especially Venus are opaque in much of the infrared spectrum due to absorption mainly by CO_2 and H_2O . By taking spectra during their observations, Allen and Crawford discovered that the observed radiation was coming primarily through two narrow spectral bands or “windows” in the Venusian

¹Let τ = optical depth, I_0 = intensity of radiation incident upon the atmosphere, and I = intensity of radiation transmitted through the atmosphere. Then $I = I_0 e^{-\tau}$.

²NIR stands for Near Infrared, in this case, the spectral region from about 1 to 3 μm .

atmosphere at 1.74 and 2.3 μm . This meant the NIR wavelengths surrounding these spectral windows were strongly absorbed, because absorption lines primarily from CO_2 and H_2O had broadened and overlapped, forming nearly continuous absorption regions. Absorption lines broaden as pressure and temperature of the atmosphere increases. The CO_2 absorption bands were saturated, meaning that nearly all the energy at these wavelengths was being absorbed by the atmosphere. How deep the features were located in the atmosphere could not be determined by the already saturated CO_2 bands. The effective altitude of the source of NIR radiation was finally estimated by using the amount of absorption in the double absorption feature of CO between 2.3 and 2.4 μm . The results of measuring the feature velocities and of considering particle-radiation interaction indicated that the features were somewhere in the lower regions of the cloud deck.

NIR radiation believed to be coming from deep in the atmosphere has been observed in spectral windows recently discovered at 1.0, 1.09, 1.18, 1.27, and 1.30 μm (Crisp *et al.* 1991a). Recently, Earth-based observations at 1.0 μm showed good correlation with topographic data obtained by the Magellan Orbiter (Lecacheux *et al.*, 1993; Meadows 1994). Lecacheux *et al.* concluded that the features observed at 1.0 μm are generated by thermal radiation from surface topography spatially modulated by passing through cloud opacity features. Using images from longer wavelength windows, the features common to both the 1.0 μm and longer wavelengths were subtracted out from the 1.0 μm images, leaving just the thermal radiation from surface topography. The features in the resulting images compare well with topographic maps from Magellan radar data and follow the solid rotation of the planet. Thus, radiation in the shortest wavelength windows has been shown to originate from the surface of Venus.

Obviously, measurements of NIR radiation can provide invaluable information on

Figure 1.1: Inferior conjunction of Venus.

the middle and lower atmosphere. Unfortunately, relatively little data exists since Earth-based NIR observations have only been done since 1983. Because the NIR night-side radiation is relatively weak compared to that seen from reflected sunlight, optimal imaging of this radiation can only be done for short periods near inferior conjunction³, which happens once every 584 days (1.60 years) (Abell, 1969). At inferior conjunction, Earth-based observers can see almost the entire night-side of Venus. However, the orbit of Venus is inclined 3.39° to the plane of the ecliptic⁴, so that a thin sunlit crescent is seen even at inferior conjunction.

³Inferior conjunction is defined as the moment when Venus is directly between the Sun and Earth relative to the plane of the ecliptic. See Figure 1.1.

⁴The plane of the ecliptic is the plane defined by the Earth revolving around the Sun.

1.1.2 Orbiting Cloud Photopolarimeter (OCP) Observations

The NIR data showed the utility of measurements made in the Venusian atmospheric spectral windows. However, experimental difficulties and the relatively short observation periods have prevented the collection of a long, frequently sampled data set of the type usually required for studying atmospheric motion and waves.

But images from the Pioneer Venus Orbiting Cloud Photopolarimeter (OCP) instrument may provide such a data set. The OCP was an instrument on the Pioneer Venus Orbiter, which orbited the planet from 1978 to 1992. When conditions were favorable⁵ one or more images of reflected solar radiation were taken per day at four different wavelengths by the OCP operating in polarimetry mode. One of these wavelengths was 0.935 μm , which is close to the 1.0 μm window mentioned in the previous section. Given that radiation from surface features have been observed to penetrate the entire atmosphere in the spectral window at 1.0 μm (Lecacheux *et al.*, 1993), one may infer that observations of reflected solar radiation at 0.935 μm may be, at least in part, coming from interactions occurring very deep in the atmosphere. If night-side NIR and reflected sunlight OCP images show similar features, then the much more abundant OCP data could greatly aid the study of the lower and middle atmosphere of Venus. The purpose of this study is to investigate the utility of the OCP imagery for providing information about the middle and lower atmosphere of Venus.

The Pioneer Venus OCP instrument took images at 0.265, 0.365, 0.550, 0.935

⁵OCP images were taken only during periods of favorable solar illumination ($\theta_i < 90^\circ$), and orbiter orientation ($\theta_r < 90^\circ$, see Figure 3.2). Also, the Deep Space Network of radio telescopes had to be available for receiving data.

Figure 1.2: Orbit of Pioneer Venus and the scanning geometry of the OCPP instrument. The figure was taken from Russell, *et al.*, 1977.

μm of sunlight reflected from the Venusian clouds and haze (aerosol) particles. It operated both as a photometer and a polarimeter, hence the name Orbiting Cloud Photopolarimeter. In the photometry mode, it measured only light intensity at $0.365 \mu\text{m}$. In the polarimetry mode, it measured (with reduced spatial resolution) the intensity and linear polarization of light at all four wavelengths using a Wollaston prism system. Measurement of the polarization of sunlight scattered by clouds provides information on cloud particle shape, size distribution, and refractive index (Russell *et al.* 1977).

The OCPP had a single detector which recorded one pixel at a time. The orbital motion and spin of the Pioneer Venus Orbiter provided scanning motion, allowing the OCPP instrument to construct a data array point by point over the course of approximately four hours. The spacecraft's orbital period was 24 hours. It was in a very elliptical, nearly polar orbit inclined 15° east of north (see Figure 1.2). The orbital

motion created the near latitudinal scanning motion for the OCPP. Pioneer Venus spun azimuthally at 5 r.p.m., creating the near longitudinal scanning motion. In the polarimetry mode of operation, each data array was 120x72 data points. However, because of the highly elliptical orbit and the constant angular velocity of the azimuthal scanning, the longitude and latitude positions of the data points were closer together when the spacecraft was nearer to Venus, and farther apart when the spacecraft was farther from Venus. Also, since the angular field of view of the OCPP camera is constant, the spatial resolution of each data point varied because of the distance between the spacecraft and Venus.

1.2 Objectives

The principal objective of this study is to investigate the imagery obtained by the OCPP at a wavelength of $0.935\ \mu\text{m}$ in order to establish the utility of these data for studying the Venus atmosphere. In order to accomplish this objective, three major analyses were attempted in this study.

First, the motion of individual features in a time series of 0.935 and $0.365\ \mu\text{m}$ OCPP images were tracked to calculate their zonal (east-west) velocities and rotation periods as a function of latitude. If each concentric layer of atmosphere moved zonally like a rigid body, feature velocities would have a cosine distribution with latitude, and rotation period would remain constant with latitude.

The second type of analysis was to create and investigate mosaics of images at each wavelength. Assuming the Venus atmosphere is rotating only in longitude ⁶, temporally adjacent images can be overlaid, but offset by a certain number of degrees

⁶This has been shown to be a very good approximation in NIR and $0.935\ \mu\text{m}$ wavelengths. See Crisp *et al.*, 1991b; Carlson *et al.*, 1991.

longitude. This longitude offset and the separation time between images determines a rotation rate. By varying the longitude offset, different rotation periods can be simulated. Several mosaics are made with different rotation periods. The mosaic which shows the best continuity of many of the features from one image to another will indicate the dominant rotation period for those features.

The last type of analysis was to attempt to correlate the $0.935\ \mu\text{m}$ OCPP images with $0.365\ \mu\text{m}$ OCPP and the $0.935\ \mu\text{m}$ OCPP images with $1.74\ \mu\text{m}$ NIR images. This was done by searching for similar shaped features at the different wavelengths. Such correlations will help determine the atmospheric region where the $0.935\ \mu\text{m}$ features reside. Correlations of the $0.935\ \mu\text{m}$ OCPP images with $0.365\ \mu\text{m}$ OCPP features indicate that the $0.935\ \mu\text{m}$ features are related to structures in the upper portions of the cloud deck, whereas correlations of the $0.935\ \mu\text{m}$ OCPP images with the $1.74\ \mu\text{m}$ NIR features indicate a relation to the middle and lower cloud decks. Stronger correlations are expected in the latter case. NIR-OCPP correlations were not expected to be good, since contrast in the OCPP images was believed to be due to variations in reflected sunlight, whereas the contrast in the NIR images was due to variations in thermal emission transmitted through the atmosphere of Venus.

In chapter 2, "Background", we present some of the findings of the atmospheric research done at OCPP and NIR wavelengths, and details about the OCPP and NIR data acquisition and data sets. Chapter 3, "Analysis Techniques", contains documentation for the data processing, and a description of how the feature tracking, mosaic and correlation studies were done. Chapter 4, "Results and Conclusions", first describes the results of the analyses, including plots of zonal velocity and rotation period vs. latitude, correlation findings, and mosaics of the data sets. The chapter ends with a table of rotation periods derived from the different analyses, and we propose that our results prove that the $0.935\ \mu\text{m}$ OCPP images do reveal some of the

same atmospheric features as the NIR images.

Chapter 2

Background

With continuing analysis of the 14 years of Pioneer Venus data, images from Galileo's flyby, and NIR images being made during each inferior conjunction, understanding of the Venus atmosphere grows each year. This chapter sets the context for this project by summarizing what is known about the lower atmosphere of Venus and describing how the OCPP and NIR data were recorded.

2.1 The Lower Atmosphere of Venus

The lower atmosphere of Venus extends from the surface to the tropopause, near the upper part of the cloud deck. The major cloud deck occupies altitudes between about 48 to 65 km.

Studies of OCPP linear polarization measurements have shown that the upper clouds (at least at low and mid-latitudes) are comprised mainly of H_2SO_4 droplets with a mean radius of $1\text{ }\mu\text{m}$ (Kawabata *et al.*, 1980). Mixed in with the cloud deck and extending above it is a system of submicron haze particles. Results from the study made by Kawabata *et al.* (1980, 1982) show these haze particles to have

an effective radius of $0.23 \pm 0.04 \mu\text{m}$. Earth-based observations, flybys, and descent probe measurements indicate that the haze occupies altitudes between 10 to 90 km, and enshrouds the entire planet (Ragent *et al.*, 1985).

The cloud deck itself can be divided into three sections: upper, middle, and lower cloud decks. Each cloud deck is composed of H_2SO_4 droplets with a multimodal¹ size distribution. See Table 2.1.

Table 2.1: Particle sizes for the upper, middle, and lower cloud regions (Esposito *et al.*, 1983).

Region	Altitude (km)	Mean Diameter (μm)
Upper Cloud	56.5 to 70	Bimodal; 0.4 & 2.0
Middle Cloud	50.5 to 56.5	Trimodal; 0.3, 2.5, & 7.0
Lower Cloud	47.5 to 50.5	Trimodal; 0.4, 2.0, & 8.0

One of the most striking discoveries about Venus is the rapid rotation of the atmosphere relative to the solid planet. Observational studies from Earth and orbiting spacecraft (such as Mariner 10 and Pioneer Venus) have been done at ultraviolet, visible, infrared, and radio wavelengths. At the cloud tops, atmospheric features such as the horizontal Y-shaped ultraviolet feature rotate zonally (east-west) with periods of 4 to 5 days (Rossow *et al.*, 1980). NIR features rotate with zonal periods between 5.5 and 7.4 days. Meridional (north-south) flow of NIR features is typically an order of magnitude slower, and is at the threshold of accuracy for Earth-based observations (Crisp *et al.*, 1991b). These features have been determined to lie in the middle to lower cloud decks (see the next section). Thus the atmosphere rotates 50 to 60 times faster than the planet itself. This phenomenon is called the “superrotation” of the

¹A multimodal size distribution means that there is more than one dominant size for the cloud particles.

Venus atmosphere, and encompasses altitudes up to 100 km (Rossow *et al.*, 1990). In addition to mass transport, there is evidence for wave motion² in the atmosphere.

2.1.1 1.74 and 2.3 μm NIR Images and the Lower to Middle Cloud Deck

Atmospheric features seen in 1.74 and 2.3 μm NIR images of the night-side of Venus are believed to be created as “thermal radiation from hot gases at altitudes below 35 km in the Venus atmosphere leaks through partial clearings in the higher, cooler sulfuric acid clouds (45 to 70 km)” (Crisp *et al.*, 1989). Crisp gives the following reasons for this assertion:

First, spectra of bright NIR features show an energy distribution strongly peaked in the 1.74 and 2.3 μm CO_2 and H_2O atmospheric windows. Radiative transfer models predict that an energy source emitting radiation at these wavelengths can be observed if it originates at altitudes as low as 35 km (Kamp *et al.*, 1988). Below that, absorption by CO_2 and H_2O lines become so dominant that the 1.74 and 2.3 μm atmospheric windows disappear.

Also, brightness temperatures of 1.74 μm features were found by calibrating the features against standard stars. Dark features were as low as 430 K, while the bright features had temperatures up to 480 K. The Pioneer Venus entry probe found similar temperatures at 30 to 35 km altitude, which agree with the altitude given by Kamp’s radiative transfer model. This also agrees with the previously mentioned results of considering absorption in atmospheric CO . However, probe measurements show

²In this case, wave motion is the propagation of an oscillating “disturbance” in the atmosphere. This may be compared to ocean waves in deep water, where there is no interaction with the ocean floor; a molecule of water oscillates up and down, but experiences no net horizontal motion.

temperature variations at these altitudes at widely separated probe locations that are only one-tenth of the observed range of brightness temperatures. This led Crisp et al. (1989) to conclude that “NIR feature contrasts are produced by horizontal variations in atmospheric transmission at altitudes above the emitting region instead of temperature variations in the emitting layer.” According to Kamp’s model (Kamp et al., 1988), a 10% to 20% variation in the optical depth of the cloud layer produces the observed feature contrasts.

Furthermore, the brightness and contrast of features “decreased with increasing distance from the sub-Earth point³.” This is expected for an emitting region located below a scattering or absorbing region, since atmospheric path lengths increase going away from the sub-Earth point. The passage of radiation through a spatially varying opacity structure in the clouds is thus the probable cause of the observed features.

Finally, for a mean feature rotation period of 6 days (70 m/s at the equator), entry probes from Pioneer Venus and other spacecraft and balloons (such as the Soviet Vega probes) measured similar wind speeds in situ at altitudes between 50 to 55 km. This constrains the region of spatially-varying opacity to the middle cloud layer.

More recent studies have attempted to classify NIR features, and showed that not all features rotate with a nearly uniform period of 6 days. In January and February 1990, a large number of observatories across the world took NIR images of the Venus nightside to compare with images acquired from Galileo’s encounter with Venus. The ground-based measurements were made before, during, and after the Galileo encounter. Coverage around the world was so good that some NIR features could be tracked for periods up to 46 days. From these images, 2.3 μm NIR

³The **sub-Earth point** can be defined as follows. Imagine a line drawn through the centers of the Earth and a planet (in this case, Venus). The intersection of this line with the surface of the planet nearest the Earth is the **sub-Earth point**.

features were divided into three major groups (Crisp *et al.*, 1991b). See Table 2.2 and Figure 2.1.

Table 2.2: Classification of 2.3 μm NIR Features from January and February 1990 (Crisp *et al.*, 1991b).

Latitude Range	Features
$< \pm 40^\circ$	Bright and dark markings with many spatial scales
$\pm 40^\circ$ to 60°	Bright, nearly zonal bands
$\pm 60^\circ$ to 75°	Dark and featureless, indicating greater optical depth

Figure 2.1: Zonal velocities derived from tracking 2.3 μm NIR features from January and February 1990 (Crisp *et al.*, 1991b). The 1σ error bars in the original plot were not reproduced here. Note that the data points seem to split into two separate curves corresponding to the 7.4 and 5.5 day rotation periods discovered in the features.

Among the low latitude ($< \pm 40^\circ$) features was a long, dark cloud which extended nearly 180° in longitude. This feature, other large features (> 2000 km) at $< \pm 60^\circ$, and features within the bright midlatitude ($\pm 40^\circ$ to 60°) bands rotated east-west with

a period of about 5.5 ± 0.15 days (80 ± 3 m/s). The smaller scale features (400 to 2000 km) at low latitudes had rotation rates of 7.4 ± 1 days (60 ± 7 m/s).

The large scale features rotate at a rate distinctly faster than the small scale features, causing Crisp *et al.* (1991b) to believe that they originate at different altitudes, and are thus caused by different processes.

2.1.2 OCPP 0.935 μm Images: Another Probe into the Middle and Lower Cloud Decks?

Little is known about the contrast features seen in the 0.935 μm OCPP images. Until recently, this data has been largely ignored because of its low contrast ($< 1\%$). Synthetically-generated spectra of the Venus night-side (Carlson *et al.*, 1991; Lecacheux *et al.*, 1993) show that 0.935 μm falls in a region of low atmospheric transmission (see Figure 2.2). The model used to generate these spectra took into account atmospheric absorption by H_2O and CO_2 , and used an atmospheric thermal profile from A. Seiff. Note how low the radiance at 0.935 μm is compared to the 1.0 μm atmospheric window.

It is believed that the 0.935 μm OCPP images show probing of layers of the atmosphere which at least partially overlap those layers seen in the NIR images. Images taken at the nearby wavelength of 0.986 μm during the 1990 Galileo flyby of Venus show features which move with a rotation period of $5.69^{+0.21}_{-0.23}$ days at the equator (Belton *et al.*, 1991), well within the range of Earth-based NIR measurements. Also, images at the 1.0 μm atmospheric window show a mixture of features caused by the same phenomena which create 1.74 and 2.3 μm features and by thermal emission from surface topography (Lecacheux *et al.*, 1993).

Certainly, these studies of nearby wavelengths prove that there is a strong possi-

Figure 2.2: Synthetically-generated spectra of thermal emission from the night-side atmosphere of Venus, taking into account absorption by CO_2 and H_2O and using an atmospheric thermal profile from A. Seiff (Lecacheux *et al.*, 1993). Different lines represent emission at various altitudes in the atmosphere.

bility that $0.935 \mu\text{m}$ images are indeed probing some of the same layers of atmosphere as the 1.74 and $2.3 \mu\text{m}$ images. In our study, we hope to add evidence which supports this conclusion.

2.1.3 OCPP $0.365 \mu\text{m}$ Images and the Upper Cloud Deck

The existence of near ultraviolet features in the Venus atmosphere has been known for many decades. Ground-based observations have been made since at least 1927,

but were limited by low spatial and temporal resolution (Rossow *et al.*, 1980). High spatial and temporal resolution images were taken by Mariner 10 for 8 days in 1974. Then came the Pioneer Venus OCPP instrument, taking images from 1978 to 1992 at four different wavelengths, including $0.365\ \mu\text{m}$.

Analyses of most of these data (Rossow *et al.*, 1990) show that the cloud tops have an overall zonal retrograde rotation period of 4 to 5 days, with slight “jets” (increases in wind velocity) at middle to high latitudes. Unlike the lower atmosphere and clouds, the cloud tops have significant meridional (north-south) winds which flow poleward in each hemisphere. Averaging OCPP observations for five years from 1979 to 1985, Rossow et al. tabulated meridional wind speeds increasing in magnitude toward the poles, roughly reaching $\pm 10\ \text{m/s}$ at $\pm 40^\circ$ latitude. The meridional flow is consistent with a Hadley circulation⁴.

Wave motion plays an important role in cloud top circulation. Several wave modes have been identified. The commonly seen Y-shaped feature is believed to be the result of wave motion.

2.2 The OCPP Data Set from June 20 to 30, 1988

The set of images used in this study is a series of 27 taken in the polarimetry mode of the OCPP instrument on consecutive days from June 20 to 30, 1988. Images from both the 0.365 and $0.935\ \mu\text{m}$ channels were used. This particular set of images was chosen by Dr. Boris Ragent of the NASA Ames Research Center and Dr. Larry

⁴Hadley circulation is caused by the differences between absorbed solar radiation and emitted infrared radiation as a function of latitude. Near the equator, the amount of absorbed solar radiation is greater than the amount of emitted infrared radiation. The reverse occurs near the poles. As a result, there is a net poleward transport of heat (Schubert, 1983; pg. 729). Warm atmospheric material rises due to solar heating, flows poleward, releases some of its heat to the atmosphere, sinks at the poles, and then returns to the equator.

D. Travis of the NASA Goddard Space Flight Center for two major reasons.

First of all, it was one of the longest series of images which had small time separations in the OCPP data set. Two to three images were taken every day except for June 21, 1988. This made the image set ideal for studying the time evolution of atmospheric features.

Second, the time period of the OCPP data set coincided with inferior conjunction of Venus. Consequently, many NIR observations were made during this time, including the set from June 24 to 28, 1988 which was chosen for comparison with the OCPP data set. For a table of image times, see Table A.2 in Appendix A.

2.3 The NIR Data Set from June 24 to 28, 1988

The set of NIR images used in this study was a series of 5 images taken on consecutive days from June 24 to 28, 1988, after inferior conjunction. Venus was then a morning object, and the seeing⁵ each morning was still excellent from the night before, ranging from 0.3 to 0.5 arc second (Crisp *et al.*, 1989). For a table of image times, see Table A.1 in Appendix A.

The observations were made by Dr. Ragent and Dr. William M. Sinton (formerly of the University of Hawaii Institute for Astronomy) from Mauna Kea using the University of Hawaii 2.2 m telescope. The telescope was equipped with a camera using a 128x128 element HgCdTe detector array, and a 1% passband filter centered at 1.74 μm (Crisp *et al.*, 1989). Processing was done by William Sinton and Paul Kalas at the University of Hawaii Institute for Astronomy.

⁵Seeing is defined as the minimum resolvable angle in the sky, limited by turbulence in the atmosphere. Mauna Kea frequently has excellent seeing, < 1 arcsecond.

Chapter 3

Analytical Techniques

3.1 Data Reduction

To conduct feature velocity and correlation analyses, the data must first be reduced to image files appropriate for computer analysis.

3.1.1 Reduction of NIR Data

Earth-based images of a planet are projections of a sphere onto a plane. This is the case for the NIR images. As atmospheric features move across the disk of a planet, their apparent sizes and shapes change due to the projected spherical geometry. Foreshortening near the limbs and at high latitudes significantly distorts these features.

This distortion is reduced by performing a cylindrical mapping of the data. This technique maps the surface of a sphere onto a cylinder. The cylinder can then be unfolded into a rectangular grid of linearly varying longitude and latitude. Therefore, a disk image of Venus can be mapped to a longitude-latitude grid by first converting it to a sphere. Mapping results are used up to about $\pm 60^\circ$ in latitude and longitude

from the sub-Earth point. Beyond this range, the effective spatial resolution is too poor to allow features to be accurately reconstructed.

These are the steps used to convert the raw NIR data to cylindrical maps. Explanation is provided in the following subsections.

1. Convert FITS¹ files to images of the disk of Venus.
2. Calculate the geometric center of the image of Venus.
3. Calculate the average radius (in pixels) of the disk of Venus.
4. Locate and mark the sub-Earth point corresponding to the center of the image on the disk.
5. Convert the image of Venus's disk to a cylindrical map of longitude and latitude, using the sub-Earth point to set the longitude and latitude on the map.

Conversion of FITS Files to Images (step 1)

The raw data was stored in binary files in FITS format, which has an ASCII text header with information such as date of observation, time, duration, the telescope used, sky coordinates, etc. These FITS files were converted to ASCII text files with an intensity for each pixel. The text files were then converted into images. Processing was done using a set of programs contained in IRAF (Image Reduction and Analysis Facility). IRAF is a software package for image and data analysis. IRAF functions can be used interactively or called from an IRAF program. See Tody, D., "The IRAF Data Reduction and Analysis System", in the IRAF manuals. Manuals are available from

¹FITS is a standardized computer file format to store astronomical images. It contains an ASCII header followed by binary data records. See Wells, *et al.*, *Astron. Astrophys. Supp. Ser.* **44**, 363 (1981).

National Optical Astronomical Observatories, P.O. Box 26732, Tucson, AZ 85726, and by anonymous ftp to iraf.noao.edu (140.252.1.1).

Calculation of Geometric Center and Average Radius (steps 2 and 3)

Finding the geometric center and average radius of each image is essential to the cylindrical mapping process. In the ideal case, finding the geometric center of a planet is simple. The edge of the disk is traced by the change in intensity from sky to planet, and all the edge pixel positions are averaged to find the center. But Venus is an inferior planet, which means it has a bright crescent. This crescent is extremely bright at NIR wavelengths, bright enough to saturate pixels on the CCD detector. As a result, the crescent appears to bulge out with a different curvature from the rest of the planet in the image.

Figure 3.1: Method for finding the geometric center of Venus.

To solve this problem, we have written a C program called `center` in which the user marks the x-pixel coordinate which separates the crescent from the non-

crescent side of Venus. The program then finds the edges of the disk on the non-crescent side and draws chords between edge pixels. It draws two chords at a time separated by about 90° on the disk (see Figure 3.1). Line equations of the form $y = mx + b$ are then calculated from these chords. Perpendicular lines bisecting the chords, and which point in toward the center, are then calculated. The intersection of these perpendiculars is an approximation to the geometric center. This procedure is repeated for many pairs of chords, then the x and y approximate center positions are averaged to calculate the final x and y center positions (**step 2**). The distances from all the edge pixels to the center are then averaged to find the average radius (**step 3**). See Appendix C for the program listing of `center`.

Marking the Sub-Earth Point and Cylindrical Mapping (steps 4 and 5)

To cylindrically map a disk image onto a linear grid of longitude and latitude, we must align the image so that the Venusian rotation axis is aligned in the y-direction on the grid. In general, the North-South direction on Venus lies at an angle relative to columns or rows on the CCD chip during observation. The angle is called the North Pole Position Angle, and it varies with time for several reasons. First, Earth's rotation axis is inclined 23.5° relative to Celestial North², while the Venusian rotation axis is inclined only 2° . Furthermore, the relative positions of the two planets in their orbits and the 3.39° inclination of the Venusian orbital plane relative to Earth's orbital plane also affect the magnitude of the North Pole Position Angle. A simple rotation of the image by the opposite of this angle corrects the alignment.

The following two equations express relations between longitude and latitude on

²Celestial North is defined to lie on the perpendicular to the Earth's orbital plane (Celestial Plane). Using the right-hand rule, Celestial North lies in the direction of the thumb as the fingers of the right hand curl in the direction of Earth's orbital motion.

the cylindrical map and pixel positions on Venus's disk:

$$x_{disk} = r_o \cos \theta_{lat} \sin \theta_{lon} + x_{center} \quad (3.1)$$

$$y_{disk} = r_o \sin \theta_{lat} + y_{center} \quad (3.2)$$

On the image of Venus's disk, x_{disk} is the x-pixel position on Venus's disk, y_{disk} is the y-pixel position, r_o is the average radius of the disk in pixels, and x_{center} and y_{center} are the pixel coordinates of the geometric center of the disk. On the cylindrical map, θ_{lon} and θ_{lat} are the longitude and latitude on Venus.

Venus and Earth are constantly in motion, so longitude and latitude at the geometric center of Venus change with time. The geometric center marks the sub-Earth point, since this is defined as the point on Venus where the line drawn between the centers of Earth and Venus intersects. The coordinates of the geometric center of Venus, which are the sub-Earth longitude and latitude for a particular observing time, are listed in ephemerides such as the *Astronomical Almanac*. The cylindrical mapping and calibration of the geometric center to the sub-Earth point was implemented in a C program called `map`. See Appendix C for a program listing.

3.1.2 Reduction of OCPP Data

The Pioneer Venus Orbiter was oriented 15° east of north with respect to the planet's rotation axis (see Figure 1.2). During periods of favorable viewing and solar illumination, the OCPP operating in its polarimetry mode, recorded images of reflected sunlight at four wavelengths including 0.365 and 0.935 μm . The nearly polar orbit meant the latitudinal distortion of the observed features was small. The nearly longitudinal scan motion along almost constant latitude lines provided some geometrical distortion, but was kept low by limiting the longitude range to 80° to 100° in

the images used for this study. Thus the images taken by the OCPP instrument were very much like longitude-latitude maps, that is, like cylindrical projections of the NIR images. However, for each pixel of each image, the OCPP experimental team provided a listing of intensity and polarization obtained for all four wavelengths, the true planetary longitude, true planetary latitude, time of observation, observer zenith angle, and solar zenith angle. The intensity, longitude, and latitude data provided the necessary information for a true longitude-latitude map. The OCPP took approximately four hours to complete the scans for each image. Figure 3.2 defines the observer and solar zenith angles.

Figure 3.2: Observing situation: The **zenith** is the line extending out normal to Venus's surface at the **observed point**. Pioneer-Venus observes that point from an angle θ_r from the **zenith**. This is the **observer zenith angle**. The sun makes an angle θ_i with the **zenith**. This is the **solar zenith angle**.

These are the steps to convert raw OCPP data to usable images. Explanation is provided in the following subsections.

1. Convert FITS files to images. Similar to step 1 for the NIR data.

2. Intensity processing - correct intensities for the solar and observer zenith angles.
 - (a) Minnaert technique
 - (b) Multiple scattering technique
3. Longitude correction
4. Image smoothing

Intensity Processing (step 2)

Raw OCPP images look quite bland and featureless. The observed atmospheric features have contrasts less than 1% at $0.935 \mu\text{m}$, and less than about 10% at $0.365 \mu\text{m}$. The low contrasts are due to the relatively small variations in the reflected light caused by the spatial variations in the structure of the clouds and atmosphere, that is, the observed “features.” Even if the structure of the cloud layers and atmosphere did not vary with planetary location, the intensity of reflected sunlight would still be strongly dependent on the solar and observer zenith angles, θ_i and θ_r (see Figure 3.2). So the observed intensity, $I_{\text{raw image}}$ may be considered to be composed of the sum of the varying component $I_{\text{atm}}(\theta_{\text{lon}}, \theta_{\text{lat}})$, where θ_{lon} and θ_{lat} are longitude and latitude respectively, and $I_{\text{scat}}(\theta_i, \theta_r)$. Or

$$I_{\text{raw image}} = I_{\text{atm}}(\theta_{\text{lon}}, \theta_{\text{lat}}) + I_{\text{scat}}(\theta_i, \theta_r) \quad (3.3)$$

In general, the magnitude of $I_{\text{atm}}(\theta_{\text{lon}}, \theta_{\text{lat}})$ is small compared to $I_{\text{scat}}(\theta_i, \theta_r)$, so that the feature contrasts in the raw images are small. Contrasts in the 0.365 and $0.935 \mu\text{m}$ can be improved by processing. Ideally, processing would accurately subtract $I_{\text{scat}}(\theta_i, \theta_r)$ from the raw image. In reality, however, $I_{\text{scat}}(\theta_i, \theta_r)$ is not an easily quantifiable function. The way the atmosphere scatters and absorbs sunlight also depends

on the detailed parameters describing the clouds and atmosphere, parameters not always well known. Two approaches to intensity processing, the Minnaert and Multiple Scattering techniques were tested. How these techniques attempt to subtract out $I_{scat}(\theta_i, \theta_r)$ is very different.

Intensity Processing: The Minnaert Technique

The Minnaert technique was originally developed for intensity processing of lunar images. The derivation of this technique was partly empirical and assumed a rough, rocky, diffusely reflecting surface. For the angular distribution of scattered light at moderate angles, a rocky surface is a fair approximation to the behavior of the multiple scattering from the particles in the Venus atmosphere. Let I be the scattered intensity, $\mu_o = \cos \theta_i$, $\mu = \cos \theta_r$, $k \approx 1$, a_o is a constant. Then (Ragent 1993),

$$I = a_o \mu_o^k \mu^{k-1}. \quad (3.4)$$

Multiplying both sides by μ ,

$$I\mu = a_o (\mu\mu_o)^k. \quad (3.5)$$

Taking the log of both sides,

$$\log(I\mu) = k \log(\mu\mu_o) + \log a_o. \quad (3.6)$$

Equation 3.6 is now in the form of a straight line $y = mx + b$, where $y = \log(I\mu)$, $m = k$, $x = \log(\mu\mu_o)$, and $b = \log a_o$. The experimental data are then placed on a plot of $\log(I\mu)$ vs. $\log(\mu\mu_o)$. Applying a least-squares fit to the experimental data for an image yields the values for the slope k and the y-intercept $\log a_o$. Physically, k can

Figure 3.3: Plot of $\log(I\mu)$ vs. $\log(\mu\mu_0)$ for all data points in image ocpp07, taken on 6/23/88 at 5:05 UT. Note the deviation of data from the least squares fit line for large values of $\log(\mu\mu_0)$.

be considered to be the limb-darkening coefficient (Limaye, 1984), since it determines how quickly the intensity drops for increasing solar zenith angle (more negative values of $\log(\mu\mu_0)$). If the Minnaert equation does describe the intensity vs. observer and solar zenith angles, the data points should fall on or near the least-squares fit line. This is exactly what happens for $\log(\mu\mu_0) > -2.5$. For $\log(\mu\mu_0) < -2.5$, the data noticeably deviates from a straight line (see Figure 3.3). Better results are obtained when these data are excluded from the least-squares fit (see Figure 3.4). After the least-squares fit line is calculated, the line is subtracted from the data, leaving the scatter around the line. This is the way $I_{scat}(\theta_i, \theta_r)$ is subtracted from the raw images using the Minnaert technique. Minnaert processing enhances the contrast of the atmospheric features effectively for a cone of angles extending about 60° from the center of the image.

Figure 3.4: Same as Figure 3.3, but data was excluded for $\log(\mu\mu_o) < -2.5$. Note the better match of the least squares fit line to the data for large values of $\log(\mu\mu_o)$.

Intensity Processing: The Multiple Scattering Technique

The second intensity processing method, the multiple scattering technique, was developed by Dr. Larry Travis of the NASA Goddard Institute for Space Studies, and implemented for use with OCPP data in a FORTRAN program called *pmnorm*.

The multiple scattering technique calculates “the amount of scattered light, including multiple scattering, from a uniformly stratified atmosphere with no horizontal inhomogeneities, using a model of cloud structure and atmosphere obtained from ‘standard’ cloud and atmosphere descriptions” (Ragent 1993). In other words, given each pixel’s linear polarization, solar and observation zenith angles, the program calculates the theoretical intensity of scattered radiation $I_{scat}(\theta_i, \theta_r)$ based on a model of the Venus atmosphere. This model was based on accepted values of atmospheric quantities, and assumed each layer of clouds and atmosphere was homogeneous. The calculated $I_{scat}(\theta_i, \theta_r)$ is then subtracted from $I_{raw\ image}$ to obtain the

desired $I_{atm}(\theta_i, \theta_r)$. Images processed with this technique appear to show the same atmospheric features, but with improved contrast relative to the Minnaert technique. The effective angular range around the center of the image over which the multiple scattering technique works also appears to be wider—about 80° . Therefore, the multiple scattering processing was chosen for the correlation studies.

Longitude Correction (step 3)

OCPP images are taken one pixel at a time over the course of four hours. Since the rotation period of the atmospheric features seen at NIR and OCPP $0.935 \mu\text{m}$ wavelengths is about 5.5 days at the equator, the planet's atmosphere undergoes noticeable rotation in the elapsed time between the first and last pixel. Therefore, in order to prepare an image where all wavelengths were effectively measured at the same time, a longitude correction must be applied to each pixel. A crude, but satisfactory solution is to use the rotation period to calculate an angular velocity, ω . If the time of the i -th pixel is t_i , the time of the first pixel is t_o , then the longitude correction Δlon_i for the i -th pixel is expressed by:

$$\Delta lon_i = \omega(t_i - t_o) \quad (3.7)$$

Image Smoothing (step 4)

Because of the longitude corrections and the spin scan imaging of Pioneer Venus, each “image” now consists of irregularly-spaced data points, which sparsely fill a longitude-latitude map. This makes the maps difficult to correlate with NIR maps containing regularly-spaced data. Therefore, the maps needed to be smoothed into images of regularly spaced data points, and many methods were tested before we decided that Gourad shading, as described below, was the best. Using this method,

the data points were interpolated to a grid of 0.25° per pixel.

A number of surface fitting routines are available which can interpolate between irregularly-spaced data points to create a smooth image. We tried using several of them:

Image Smoothing: Gaussian

First, a Gaussian smoothing routine written by David Crisp (private communication, 1993) was used. His program calculates the intensity at each pixel of the longitude-latitude grid, blank or not, by centering a two-dimensional Gaussian weighting-function of a user specified half-width-half-max value on it. In the two-dimensional case the half-width-half-max becomes the radius at which the Gaussian is half its maximum value. The program calculates the Gaussian-weighted sum of all the data points on the grid and assigns it to the intensity of the pixel where the Gaussian was centered. It then goes on to the next pixel in the grid and repeats the procedure.

The Gaussian smoothing tended to produce some smearing, creating streaks where there were closely spaced data points. The automated tracking program (see the following section “Tracking of Atmospheric Features”) recognized these streaks as nearly stationary atmospheric features, strongly influencing the program’s output and yielding ambiguous results.

Image Smoothing: Krig Method

The second method tried was “kriging.” Kriging is a method for interpolating between irregularly spaced data points, and is implemented as the function `krig2d` in the IDL Userlib package. IDL (Interactive Data Language) is a data and image processing software package developed by Research Systems, Inc. The function `krig2d`

lays a set of data points onto a grid of pixels, and creates another grid which contains the intensity variance of each pixel. The intensity variance of a pixel depends on the distance between it and the nearest data points. The program then minimizes the intensity variance array to get the best fit for regions where there is no data. Unfortunately, krig2d needs to solve $N+2$ simultaneous equations for N data points, which causes the calculation time to go as N^3 . The average OCPP array contains more than 2000 data points. The krig2d function effectively only worked for small numbers of data points or when interpolated to a small image, like 100x50 pixels. An attempt was made to use all 2000+ data points and interpolate them to a 361x181 image, but the function ran for over 3 hours, then reported it was out of memory. All runs were performed on a SPARC station LX with 48 megabytes of RAM.

Image Smoothing: Trigrd

The third method tested was the `trigrd` function, which is also from the IDL Routines package. It uses the `triangulate` function to create triangles between the data points using the Delaunay triangulation method. Then the `trigrd` function fits a surface to these triangles. This technique produced an image in about 10-15 seconds.

The images looked reasonable toward the center of the set of data points. However, there were bright edges and spikes on the left and especially right edge limits of the data points on the longitude-latitude maps. Apparently the `trigrd` function has trouble interpolating between regions where there is no data and where there is data. The bright edges and spikes had much more contrast than the atmospheric features in the data. This also corrupted the outputs from the wind tracking program (see the following section "Tracking of Atmospheric Features").

Figure 3.5: The Gourad shading method linearly varies the intensities between data points. The numbers are intensity values. The gray pixels represent actual data points. The white pixels represent interpolated data values.

Image Smoothing: Gourad

The Gourad shading routine from the Silicon Graphics IRIS image processing package proved to be the most satisfactory of the methods tested. It has successfully been used to smooth OCPP images in the past (Ragent, 1994: personal communication).

Gourad shading smoothly varies color (intensity in our case) between data points. It does this by first creating polygons between nearby data points. Then it linearly interpolates the color or intensity of the pixels on each vertex of a given polygon. Once the vertices are done, the interior is interpolated by row or column using the pixels on the vertices as reference points (see Figure 3.5).

The Gourad method yielded very clean images. The edges were not as bright as in the trigrad method. Using this method produced images whose edges are bright

only because of the multiple scattering intensity processing done before the Gourad shading. There were no artificial spikes as in the trigrid method. Instead, the left and right edges ended in shark-tooth-like projections which marked the extent of the data points. As previously stated, the data points were interpolated onto a grid of 0.25° per pixel.

3.2 Analysis of Data

As explained in the “Objectives” section in chapter 1, there are three types of analyses in this study. These analyses are:

1. Tracking the motion of atmospheric features in 0.935 and $0.365 \mu\text{m}$ OCPP images to calculate their zonal (east-west) velocities and rotation periods as a function of latitude.
2. Creating mosaics of the images in each wavelength.
3. Correlating the $0.935 \mu\text{m}$ OCPP images with $0.365 \mu\text{m}$ OCPP and $1.74 \mu\text{m}$ NIR images.

3.2.1 Tracking of Atmospheric Features

We have tracked the motion of features in a time series of 0.935 and $0.365 \mu\text{m}$ OCPP images to calculate their zonal (east-west) velocities and rotation periods as a function of latitude. If each concentric atmospheric layer moves zonally like a rigid body, feature velocities should have a cosine distribution with latitude, and the rotation period should remain constant with latitude.

Tracking atmospheric features is straightforward in theory, but tedious and often difficult in practice. The structure of features can change significantly in the average

four hour time span between OCPP images. These changes may be caused by a large number of dynamic processes including shear, convection, wave motion, or circulation. In the case of the $0.935\ \mu\text{m}$ images, it is also possible that more than one layer of atmospheric features is interacting with the incoming radiation. If the layers are moving at different speeds, the lower features would be appearing and disappearing between gaps in higher altitude features. To the observer, it would appear as if there were one layer of features undergoing rapid, large scale changes in shape and size.

Two approaches were tested: automated and manual tracking. Because of reasons which will be discussed, the automated tracking proved too unpredictable to use on $0.935\ \mu\text{m}$ images.

Automated Tracking Using the winds Program

The correlation program `winds` was written by Dr. David Crisp of the Jet Propulsion Laboratory. The program takes two cylindrically mapped images and partitions the first one (image 1) into boxes of user-specified longitude and latitude widths. It calculates the mean intensity and variance of the intensity in each box to determine whether there are features present. If there is no variance about the mean, then all the pixels in the box have the same intensity, indicating the box is featureless. The `winds` program ignores these boxes. Using the time difference between images and a specified cloud rotation rate, for example, of 5.5 days at the equator, the program approximates where the images 1 and 2 should overlap, and positions them accordingly. For each box in image 1, the program offsets the image 2 from its initial position, and finds the root mean square (rms) difference between the values of corresponding boxes in the overlapping images in this box. This is done for a user-specified range of longitude and latitude offsets, to find the minimum rms difference. The offset at minimum rms is used to calculate the feature velocity. The process is then repeated

for all other boxes in image 1.

There were several reasons why it was decided not to use the `winds` program to analyze the 0.935 μm data. First of all, for a given latitude, `winds` reports one velocity, which is the average of velocities measured at many longitudes weighted by their uncertainties. Visual observation and attempts at hand tracking of the data showed that in many instances in correlating constant latitude scans of two images there were only isolated features which could be unambiguously tracked. The velocity measurements reported in this study were based on these fewer, more reliable correlations.

Also, the program had trouble with image artifacts. The Gaussian and trigrid smoothing created image artifacts which remained in nearly the same position on all the images. The `winds` program interpreted these artifacts as slowly moving features, an interpretation that corrupted the velocity calculations.

But most importantly, the output of the `winds` program is influenced by the initial estimate for the zonal rotation period. This estimated rotation period is a required parameter. Tests of the program have shown that the resulting table of zonal velocity vs. latitude is biased toward the estimated rotation period (i.e., an estimated longer initial period gives slower velocities and an estimated shorter initial period gives faster velocities).

Hand Tracking Using a Cross-Correlation Program

Primarily because of the biasing of velocities due to estimated rotation period, we decided not to use the `winds` tracking program. Instead, an interactive IDL program, `correlbig` was developed which allowed both computer and hand tracking of latitude scans. See Appendix C for the program listing of `correlbig`. The user specifies the two images and the row(s) (latitudes) of the images to correlate. The program then

displays the intensity scans of both images for the specified row(s). It was found that averaging over 4° of latitude using scans that averaged the intensities at each longitude gave good results, smoothing out row to row variations in intensity due to the Gourad shading process. The user selects the desired longitude range from each scan using the mouse and cursor on the IDL image display. This way, unwanted features (such as bright image artifacts on the left and right edges of the scan) can be excluded. After the longitude range in each image is selected, the program does a cross correlation on the specified subsections of each image, and generates a plot of correlation coefficient vs. longitude displacement.

The program also generates plots of the scan (intensity vs. longitude) which were used to visually correlate and track features by overlapping the hardcopies on a light table. The hardcopy plots were displaced in longitude until features from the first plot showed optimal overlap with features from the second (see Figure 4.1).

Several difficulties were encountered in attempting to track features in the $0.935\ \mu\text{m}$ data. First, the $0.935\ \mu\text{m}$ data has low contrast, making only small dips and peaks in intensity. It is often hard to distinguish real features from intensity variations due to image processing and smoothing.

Not only was contrast low for the whole data set, but contrast in successive images was different. Typically, there were three OCPP images per day; one around 5:00 UT, one around 10:00 UT, and one between 13:00 and 15:00 UT. Typically, the contrast decreases from the earliest to the latest image each day. Therefore, definite peaks and dips in the intensity of a feature in an early image may have degraded into mere changes in slope in a subsequent image.

Sometimes, a pair of plots could be offset so that a certain group of features common to both plots could be aligned, only if other common features remain misaligned. This may be because there were features moving with different velocities at the same

latitude, or because of artifacts introduced in the Gourad shading process. This is a more subtle problem to detect.

Some of the same problems were present in tracking the 0.365 μm data, but not to the same degree. Due to the lack of high contrast features in the 0.935 μm data, fewer correlations could be tracked by eye as definitely as in the higher contrast 0.365 μm data. The optimal longitude offset found manually frequently disagreed with the offset at the peak of the computer-generated correlation coefficient plot. For example, for offsets of 10° found by manual tracking, the correlation coefficient plot may differ by 2° , sometimes as much as 5° . In all cases, the offset given by the computer plot was merely used as a rough guide, and the manual (hand) tracking results were recorded as the true offsets.

Once these offsets were determined, the zonal rotation period T_{rot} (in days per rotation) was determined from:

$$T_{rot} = \frac{\Delta t}{\Delta\theta_{lon}} \frac{1 \text{ day}}{24 \text{ hr}} \frac{360^\circ}{\text{rotation}}, \quad (3.8)$$

where Δt is the time difference in hours between images, and $\Delta\theta_{lon}$ is the longitude offset in degrees. The zonal wind velocity u (in meters/s) is given by:

$$u = \frac{r\Delta\theta_{lon} \cos \theta_{lat}}{\Delta t} \frac{\pi}{180^\circ} \frac{1 \text{ hr}}{3600\text{s}}, \quad (3.9)$$

where r is the radius of Venus which is taken to be 6.1×10^6 meters, and θ_{lat} is the latitude at which the zonal velocity is measured.

3.2.2 Mosaics

The second type of analysis is to create mosaics of images taken during successive observations in each wavelength. Assuming the Venus atmosphere is rotating only in longitude (which appears to be a good approximation in NIR and $0.935\ \mu\text{m}$ wavelengths), successive images can be overlaid, but offset by the number of degrees longitude that corresponds to the motion of the features during the time between images. This longitude offset and the separation time between images determines a rotation rate. By varying the longitude offset, different rotation periods can be simulated. For example, the longitude offset may be obtained from the feature correlations described in the previous section. Mosaics may also be made with other rotation periods. The mosaic that shows the best connection of features between images will indicate the dominant rotation rate. However, for the NIR data, different rotation periods even at the same latitude have been found to give better connections for different features (see chapter 2). This means a mosaic made using a fixed rotation period may never give a perfect match, since it only represents one rotation period. In preliminary mosaics, similar effects have been found in both OCPP wavelength images.

Still, mosaics provide an excellent visual check on the rotation periods calculated from feature tracking. Since only a few atmospheric features were tracked by hand, much can be learned from studying mosaics of whole images which cannot be learned from plots of rotation period vs. latitude. Features of a certain size, shape, darkness, or at certain latitudes may have a certain rotation period. This could be seen by examining mosaics made using different rotation periods.

3.2.3 Correlation between Images at Different Wavelengths

The last type of analysis was to correlate the 0.935 μm OCPP images with 0.365 μm OCPP and 1.74 μm NIR images. This was done by searching for similar shaped features at the different wavelengths. Such correlations would help determine the atmospheric region where the 0.935 μm features reside. Correlations with 0.365 μm OCPP features indicate that the 0.935 μm features are related to structures in the upper cloud deck, whereas correlations with the 1.74 μm NIR features indicate a relation to the middle and lower cloud decks. Stronger correlations are expected in the latter case. Finding correlations is difficult, since the sources of radiation for the OCPP and NIR images are different. Contrast in the OCPP images was caused by spatial fluctuations in the reflected sunlight, whereas the contrast in the NIR images was caused by spatial fluctuations in transmitted thermal emission from the night-side of Venus. Indeed, clouds or atmospheric features may reflect sunlight from above and absorb thermal emission from below, causing an anti-correlation between some OCPP and NIR features.

A correlation study of Galileo data at wavelengths similar to those in the OCPP data (0.418 and 0.986 μm) was recently done (M. J. S. Belton *et al.*, 1991). A summary is presented in chapter 4, and compared to this study's correlation results.

Chapter 4

Results and Conclusions

4.1 Comparison of Rotation Periods and Velocities of Hand-Tracked June 1988 OCPP 0.935 μm Features with Other Data Sets

The features tracked were chosen because their motions were easy to follow through consecutive images. When a feature is identified as trackable, an intensity scan at its latitude is taken in the two consecutive images which contain the feature. These scans form plots of intensity vs. longitude. In the following plots, tracking results are classified as *good* or *all*. A *good* feature shows the same characteristic shape in the plots of both images, and thus is easy to track. Some features noticeably change shape between images, and more subjectivity must be applied to tracking. These features plus the *good* ones comprise *all* features. Figure 4.1 shows an example of tracking *good* features.

Figures 4.2 to 4.9 show plots of derived zonal rotation periods and velocities from *good* and *all* features from the OCPP 0.935 μm images. Figures 4.3, 4.5, 4.7, and 4.9

show the results of averaging these data into 10° latitude bins. Error bars represent the standard deviation about the mean value in each bin.

4.1.1 Comparison of Zonal Velocities for $0.935\ \mu\text{m}$ OCPP with $2.3\ \mu\text{m}$ NIR Features

Figures 4.10 to 4.12 compare zonal velocities for the June 1988 OCPP $0.935\ \mu\text{m}$ features obtained from this study with the January and February 1990 $2.3\ \mu\text{m}$ NIR features (Crisp *et al.*, 1991b). On Figure 4.12, the mean OCPP rotation period of 6.36 ± 1.36 days is superimposed on the data for comparison.

4.1.2 Comparison of Zonal Velocities for $0.935\ \mu\text{m}$ OCPP with 1.74 and $2.3\ \mu\text{m}$ Galileo NIR Features

Figures 4.13 to 4.15 compare zonal velocities for the June 1988 OCPP $0.935\ \mu\text{m}$ features obtained from this study with the February 1990 1.74 and $2.30\ \mu\text{m}$ NIR features imaged by the NIMS (Near Infrared Mapping Spectrometer) experiment in the Galileo Mission Orbiter when it flew by Venus (Carlson *et al.*, 1991). In Figure 4.15, the mean OCPP rotation period of 6.36 days is superimposed on the data for comparison.

4.1.3 Comparison of Rotation Periods for $0.935\ \mu\text{m}$ OCPP with $1.74\ \mu\text{m}$ NIR Features

Table 4.1 shows rotation periods of features in NIR images taken during the same time period as the June 1988 OCPP images (Crisp *et al.*, 1989). Tracking of the NIR features was done in 3° latitude bins, then these results were averaged over 15° bins to

Figure 4.1: Scans of intensity vs. longitude at -15° latitude for $0.935 \mu\text{m}$ images ocpp01 (top), and ocpp02 (bottom). The images were recorded on June 20, 1988 and were separated by 4.04 hours. Common features can readily be seen in ocpp01 and ocpp02. In ocpp01, the trough at 117° , peak at 132° , trough at 146° , and peak at 152° correspond in ocpp02 to the trough at 115° , peak at 118° , trough at 134° , and peak at 139° . The best fit for matching the set of troughs and peaks is obtained by shifting the scan of ocpp01 relative to that of ocpp02 by 13.5° .

Figure 4.2: Rotation periods vs. latitude derived from *good* tracking results in the $0.935\ \mu\text{m}$ OCPP images. Least squares fit line: $Y = -(0.000671 \pm 0.0129)X + 6.351 \pm 0.228$.

Figure 4.3: Results of averaging rotation periods vs. latitude of Figure 4.2 into 10° bins. Error bars indicate standard deviation about the mean values.

Figure 4.4: Zonal velocities vs. latitude derived from *good* tracking results in the $0.935\ \mu\text{m}$ OCPP images. For a legend of symbols, see Figure 4.2.

Figure 4.5: Results of averaging velocities vs. latitude of Figure 4.4 into 10° bins. Error bars indicate standard deviation about the mean values.

Figure 4.6: Rotation periods vs. latitude derived from *all* tracking results in the 0.935 μm OCPP images. Least squares fit line: $Y = (0.0149 \pm 0.00878)X + 6.192 \pm 0.173$.

Figure 4.7: Results of averaging rotation periods vs. latitude of Figure 4.6 into 10° latitude bins. Error bars indicate standard deviation about the mean values.

Figure 4.8: Zonal velocities vs. latitude derived from *all* tracking results in the 0.935 μm OCPP images. For a legend of symbols, see Figure 4.6.

Figure 4.9: Results of averaging velocities vs. latitude of Figure 4.8 into 10° latitude bins. Error bars indicate standard deviation about the mean values.

Figure 4.10: Comparison of binned zonal velocities vs. latitude derived from *good* tracking results in the $0.935\ \mu\text{m}$ OCPP images (see Figure 4.5) with zonal velocities vs. latitude derived from $2.3\ \mu\text{m}$ NIR images (Crisp *et al.*, 1991b).

Figure 4.11: Comparison of binned zonal velocities vs. latitude derived from *all* tracking results in the $0.935\ \mu\text{m}$ OCPP images with zonal velocities vs. latitude derived from $2.3\ \mu\text{m}$ NIR images (Crisp *et al.*, 1991b).

Figure 4.12: Same as Figure 4.10, with a solid body rotation curve of 6.36 days superimposed. 6.36 days is the mean rotation period from the *good* tracking results.

Figure 4.13: Comparison of zonal velocities vs. latitude derived from *good* tracking results in the $0.935 \mu\text{m}$ OCPP images of June 1988 with the 1.74 and $2.30 \mu\text{m}$ Galileo NIR images of February 1990 (Carlson *et al.*, 1991). Error bars represent 1σ dispersion for the binned Galileo data.

Figure 4.14: Comparison of zonal velocities vs. latitude derived from all the binned tracking results in the $0.935 \mu\text{m}$ OCPP images of June 1988 with the 1.74 and $2.30 \mu\text{m}$ Galileo NIR images of February 1990 (Carlson *et al.*, 1991). Error bars represent 1σ dispersion for the binned Galileo data.

Figure 4.15: Same as Figure 4.13, with a solid body rotation curve of 6.36 days superimposed. 6.36 days is the mean rotation from the *good* tracking results.

Table 4.1: Rotation periods derived from 1.74 μm NIR features during June 24-27, 1988 (Crisp *et al.*, 1989).

Latitude	Rotation Period (days)		
	June 24	June 26	June 27
-45° to -30°	6.4 ± 1.3	6.3 ± 2.0	5.8 ± 2.0
-30° to -15°	5.3 ± 0.5	6.5 ± 0.8	6.5 ± 2.0
-15° to 0°	5.8 ± 0.5	6.5 ± 1.0	5.0 ± 1.0
0° to 15°	6.0 ± 0.3	6.5 ± 0.3	6.0 ± 1.0
15° to 30°	6.8 ± 0.3	6.5 ± 1.0	6.0 ± 1.0
30° to 45°	6.8 ± 1.5	6.3 ± 1.0	6.0 ± 1.0

give the final rotation periods. The numbers in the table represent mean $\pm$ standard deviation.

Figure 4.16 plots the data from Table 4.1. Figures 4.17 and 4.18 compare the binned rotation period vs. latitude measurements from the 0.935 μm OCPP images to the NIR rotation periods.

4.1.4 Results of a Study of 0.418 and 0.986 μm Galileo Features

A study of Galileo Mission SAS data at wavelengths (0.418 μm (violet) and 0.986 μm (NIR)) similar to those in the OCPP data has recently been published (Belton *et al.*, 1991). Features at the two wavelengths are very different in appearance. Images at 0.418 μm show bands stretching diagonally up from east to west from the equator to middle and high latitudes like the Y-shaped features seen at shorter ultraviolet wavelengths. Images at 0.986 μm show banding which is more parallel to the equator, but still slightly diagonal in the same direction as the 0.418 μm images. Belton *et al.* calculated zonal velocities for both wavelengths, made mosaics of cylindrically-

Figure 4.16: Plot of rotation periods vs. latitude derived from Earth-based NIR observations. See Table 4.1.

Figure 4.17: Comparison of binned zonal rotation periods vs. latitude derived from *good* tracking results of the June 1988 $0.935 \mu\text{m}$ OCPP features with June 1988 $1.74 \mu\text{m}$ NIR rotation periods vs. latitude from Figure 4.16.

Figure 4.18: Comparison of binned zonal rotation periods vs. latitude derived from *all* tracking results of the June 1988 0.935 μm OCPP features with June 1988 1.74 μm NIR rotation periods vs. latitude from Figure 4.16.

projected 0.418 μm images, and performed a cross-correlation between images of 0.418 and 0.986 μm , to search for similarities or differences in the features.

Plots of zonal velocity vs. latitude showed a relatively flat 0.986 μm curve, ranging from approximately 65 to 78 m/s between -50° to 50° latitude. The velocity measured at the equator was 78 ± 3 m/s ($5.69^{+0.21}_{-0.23}$ day rotation period).

Zonal velocities derived from the 0.418 μm data ranged from approximately 92 to 109 m/s between -50° to 50° latitude. The best rotation period for the mosaic of 0.418 μm images was 4.4 days.

The cross-correlation studies showed strong anticorrelations between the two wavelengths at high, or polar latitudes. They proposed that the anticorrelations are a result of an increase in cloud density at the 60 to 65 km altitude region. This increase in cloud density would increase 0.986 μm reflectivity while decreasing 0.418

μm reflectivity.

4.2 Plots of Rotation Periods and Velocities of Hand-Tracked 0.365 μm OCPP Features

As in the previous section, the features tracked were chosen because their motions were easy to follow through consecutive images. When a feature was identified as trackable, an intensity scan at its latitude was taken in the two consecutive images which contained the feature. These scans form plots of intensity vs. longitude. In the following plots, tracking results are classified as *good* or *all*. A *good* feature shows the same characteristic shape in the plots of both images, and thus is easy to track. Some features noticeably change shape between images, and more subjectivity must be applied to tracking. These features plus the *good* ones comprise *all* features. Figure 4.1 shows an example of tracking good features. Figures 4.19 to 4.22 show plots of derived zonal rotation periods and velocities from *good* and *all* features from the OCPP 0.365 μm images.

4.3 Mosaics of 0.365 and 0.935 μm OCPP, and 1.74 μm NIR Data

Mosaics at all three wavelengths were taken from data obtained during the same period in June 1988, so the features from these wavelengths can be directly compared. However, it should be remembered that the features in the OCPP and NIR images were created by different phenomena. Contrast in the OCPP images was caused by spatial fluctuations in the reflected sunlight, whereas the contrast in the NIR images

Figure 4.19: Rotation periods vs. latitude derived from good tracking results in the $0.365 \mu\text{m}$ OCPP images. Least squares fit line: $Y = (0.00406 \pm 0.0136)X + 4.748 \pm 0.219$.

Figure 4.20: Zonal velocities vs. latitude derived from good tracking results in the $0.365 \mu\text{m}$ OCPP images.

Figure 4.21: Rotation periods vs. latitude derived from *all* tracking results in the 0.365 μm OCPP images. Least squares fit line: $Y = (0.0271 \pm 0.00983)X + 4.760 \pm 0.172$.

Figure 4.22: Zonal velocities vs. latitude derived from *all* tracking results in the 0.365 μm OCPP images.

was caused by spatial fluctuations in transmitted thermal emission from the night-side of Venus. Therefore, any common features seen in the OCPP data will not simultaneously be seen in the NIR data, but should be seen at a time approximately half a rotation period earlier or later.

Figures 4.23 to 4.25 show mosaics of $0.365\ \mu\text{m}$ OCPP data recorded on consecutive days from June 23, 24, 25, 26, 27, and 28, 1988. The longitudinal displacement between images depicted rotation periods of 4.0, 4.5, and 5.0 days. The 4.5 day period seems to provide the best connection of features between images. This is in good agreement with the 4.75 ± 0.59 day rotation period found by hand tracking.

Figures 4.26 to 4.28 show mosaics of $0.935\ \mu\text{m}$ OCPP data recorded on consecutive days from June 23, 24, 25, 26, 27, and 28, 1988. The longitudinal displacement between images depicted rotation periods of 5.5, 6.0, and 6.5 days. A period between 6.0 and 6.5 days seems to provide the best overall connection of features between images. This does not mean that all features match well at these rotation periods. The light-colored horizontal streak at -60° connects well between June 23 and 24 (1st and 2nd images from the left) for a rotation period of 5.5 or 6.0 days. On the other hand, the light-colored diagonal streak at -45° connects best between June 25 and 26 (3rd and 4th images from the left) for a rotation period of 5.0 days. The best overall period between 6.0 and 6.5 days is in good agreement with the rotation periods of 6.36 ± 1.36 days found by hand tracking and somewhat slower than the $5.59^{+0.27}_{-0.25}$ days found by correlation of an OCPP and NIR image (see the next section).

Figures 4.29 to 4.32 show mosaics of $1.74\ \mu\text{m}$ NIR data recorded on consecutive days from June 24, 25, 26, 27, and 28, 1988. The longitudinal displacement between images depicted rotation periods of 5.0, 5.5, 6.0, and 6.5 days. All these periods provide acceptable inter-image connection of most features, with slightly better connectivity in the 5.0 and 5.5 day periods. For example, the connection of features

between June 25 and 26 (2nd and 3rd images from the left), between latitudes of $\pm 15^\circ$ looks better at 5.0 to 5.5 days than 6.0 and 6.5 days. The same applies for the light and dark streaks between June 26 and 27 (3rd and 4th images), between 15° and 45° latitude. However, the connection of light and dark streaks between June 25 and 26 (2nd and 3rd images from the left), between latitudes of -40° to -60° look better at 6.5 days than 5.0 days. As in the case of the $0.935 \mu\text{m}$ OCPP images, not all the features match up better at the best overall rotation period. The best overall period between 5.0 and 5.5 days is consistent with many of the measured periods in Table 4.1, and is in good agreement with the period of $5.59^{+0.27}_{-0.25}$ days found by correlation of an OCPP and NIR image (see the next section).

4.4 Correlation of a $0.935 \mu\text{m}$ OCPP Image with a $1.74 \mu\text{m}$ NIR Image

When studying the OCPP $0.935 \mu\text{m}$ and NIR $1.74 \mu\text{m}$ images from June 1988, we noticed that one of the OCPP images (ocpp07) strongly resembled one of the NIR images (nir26). Assuming we were seeing the same features in both images, zonal rotation periods were calculated using the change in planetary longitude for each feature as it moved from image to image, and time difference between the two images.

The results should be used with some caution, since correlated points (which are points marked on each image representing what is believed to be the same feature) show significant meridional (latitudinal) motion. Latitudinal displacements for correlated points ranged from 4.0° to 16.0° , which translate to northward meridional velocities of 1.4 m/s to 5.7 m/s (see Table 4.2). The maximum velocity of 5.7 m/s

in our data occurred for the pair of correlated points at latitudes of -50.5° in ocpp07 and -34.5° in nir26. Recalling that typical meridional velocities for the upper cloud deck are poleward, and reach about ± 10 m/s at $\pm 40^\circ$ latitude (see Section 2.1.3), it is tempting to conclude that we *may* be seeing motion in the middle or upper cloud decks being superimposed on the motions of the lower cloud deck. However, in our data the meridional motion trend in the southern hemisphere is opposite to what is usually observed; the northward meridional velocity increases for more southerly features. Northward flow in the southern hemisphere has previously been observed, but generally decreases and changes to a southward flow as you travel south. Schubert reported this type of flow for time and longitudinally averaged velocities from Mariner 10 and Pioneer Venus ultraviolet features. He said (Schubert, 1983; pg. 732), “Very small northward velocities (1 or 2 m/s) appear to persist into the southern hemisphere, but south of $\sim 25^\circ\text{S}$ the mean meridional flow is also poleward, consistent with a cloud-level Hadley cell in the southern hemisphere.” Certainly, more work needs to be done to resolve the apparent inconsistencies.

The time of observation for ocpp07 was June 23, 1988 at 5:05 UT; the time for nir26 was June 26, 1988 at 16:38 UT. If the same atmospheric features were appearing at both wavelengths, then common features in the images could be identified and a rotation period could be calculated by using the differences in planetary longitude and observation time. The longitude-latitude map images ocpp07 and nir26 provide the longitudes of the features at the times of observation. Figure 4.33 shows ocpp07 and Figure 4.34 shows nir26. Correlated points are marked in each figure by “+” signs.

The NIR images were received from earlier analyses at the University of Hawaii both in the form of original co-added images and cylindrical maps. Checking the sub-Earth longitude from the *The Astronomical Almanac*, we determined that the

Table 4.2: The first four columns contain longitude and latitude coordinates for each pair of correlated points in ocpp07 and nir26. Any longitude for nir26 greater than 360° was not wrapped around to 0° for easier comparison with ocpp07. The next two columns contain the angular displacement between each pair of correlated points; Δ lon is the longitudinal and Δ lat is the latitudinal displacement. The next two columns contain the zonal (longitudinal) and meridional (latitudinal) rotation periods. The last column shows meridional (latitudinal) velocities. The positive velocities indicate a northward flow.

Planetary Longitude		Planetary Latitude		Angular Displacement		Rotation Period (days)		Meridional Velocity (m/s)
ocpp07	nir26	ocpp07	nir26	Δ lon	Δ lat	zonal	meridional	
132.5°	366.0°	8.0°	20.5°	233.5°	12.5°	5.37	100	4.4
138.5°	372.0°	6.5°	18.5°	233.5°	12.0°	5.37	104	4.3
136.0°	368.5°	1.0°	12.0°	232.5°	11.0°	5.39	114	3.9
155.0°	384.5°	-9.0°	-5.0°	229.5°	4.0°	5.46	313	1.4
160.0°	390.5°	-13.0°	-8.5°	230.5°	5.0°	5.44	251	1.8
164.5°	374.0°	-44.0°	-29.5°	209.5°	14.5°	5.98	86.4	5.1
171.5°	384.5°	-44.0°	-30.0°	213.0°	14.0°	5.88	89.5	5.0
167.5°	380.5°	-50.5°	-34.5°	213.0°	16.0°	5.88	78.3	5.7

longitudes shown on the cylindrical map image nir26 were offset by an unknown amount. The geometric center of the disk of Venus should map to the sub-Earth longitude in the cylindrically-mapped image. On the images provided to us it did not, so we performed our own cylindrical mapping of the co-added image of the disk of Venus. We ran the program `center` to obtain the geometric center of Venus. On the 200x200 coadded image, the center was found with a standard deviation of 2.28 pixels in x and 0.82 pixels in y. Then the program `map` was used to perform the cylindrical mapping to an accurate longitude-latitude map (see Appendix C for a listing of `center` and `map`). The geometric center was set to the sub-Earth longitude and latitude coordinates to calibrate the map.

Then we created an IDL program to display ocpp07 and nir26 and record longitude

positions of features marked with a cursor. There were eight points which were easily identifiable in both images. These eight points were marked in each image, giving eight measurements of the longitude shift between images (see Table 4.2). The mean longitude shift $\pm$ (standard deviation) was $224.38^\circ \pm 10.53^\circ$.

The OCPP image was taken at June 23, 1988, 05:05:10 UT, and the NIR image was taken at June 26, 1988, 16:38 UT. The time difference between images is 3.48 days. Thus, the rotation period of features between the two images is:

$$T_{rot} = \left(\frac{3.48 \text{ days}}{224.38^\circ \pm 10.53^\circ} \right) \left(\frac{360^\circ}{\text{rotation}} \right) = 5.59_{-0.25}^{+0.27} \text{ days per rotation} \quad (4.1)$$

This period is in fair agreement with the best-fit rotation periods of 5.0 to 5.5 days previously obtained for the $1.74\mu\text{m}$ mosaics, and somewhat faster than the best-fit rotation periods of 6.0 to 6.5 days previously obtained for the $0.935\mu\text{m}$ mosaics. However, as mentioned in the second paragraph of this section, there are some apparent questions about the analysis used to obtain this average zonal rotation period of $5.59_{-0.25}^{+0.27}$ days, and the data in Table 4.2.

4.5 Conclusions

There is strong evidence supporting the hypothesis that the reflected sunlight $0.935\mu\text{m}$ OCPP images probe features at some of the same altitude regions in the atmosphere of Venus as those that are sampled by the night-side 1.74 and $2.3\mu\text{m}$ NIR images. Similar zonal rotation periods are found with the different types of analyses in this study (see Table 4.3) and, importantly, if the results from the previous section are valid, then similar features were seen in a $0.935\mu\text{m}$ OCPP and a $1.74\mu\text{m}$ NIR

image.

Table 4.3: Zonal rotation periods derived from hand tracking, mosaic, and correlation analyses as a function of wavelength.

Wavelength	Hand Tracking	Mosaics	Correlation
0.365 μm	4 to 6 days, mean of 4.75 ± 0.59	4.5 to 5 days	–
0.935 μm	4.5 to 8 days, mean of 6.36 ± 1.36	6.0 to 6.5 days	–
1.74 μm	5.0 to 6.8 days	5 to 5.5 days	–
0.935 and 1.74 μm	–	–	$5.59^{+0.27}_{-0.25}$ days

The zonal rotation periods for 0.935 and 1.74 μm features are similar. For the OCPP 0.935 μm images, the values obtained from hand tracking results and mosaics both show a mean rotation period of 6.36 ± 1.36 days. The night-side 1.74 μm mosaics look best with a 5.0 to 5.5 day zonal rotation period, but mosaics up to 6.5 days still give a fair connection of most features. This near-equivalence suggests that the same regions of the atmosphere are being imaged.

The apparent correlation of features in the OCPP 0.935 μm image from June 23 and the night-side 1.74 μm image from June 26 strengthens the evidence. One would expect the rotation period derived from the average magnitude of feature motion between these two images to be similar to the mean periods for the 0.935 and 1.74 μm images. In fact, the average rotation period was determined to be $5.59^{+0.27}_{-0.25}$ days, which is within the range of rotation periods determined for NIR feature motions (see Table 4.1). In turn, the range of NIR periods also encompasses the mean zonal rotation period of 6.36 ± 1.36 days found from hand tracking OCPP 0.935 μm data. (see Table 4.3).

Similar zonal rotation periods and contrast features at 0.935 μm and 1.74 μm imply that the OCPP and NIR data are providing images of the same or overlapping layers of the atmosphere. Thus, we have found that the 14-year time series of OCPP

images will provide a great wealth of data to be added to the the NIR images already used to study the clouds and dynamics of the lower atmosphere of Venus, and have begun the exploitation of this data for such studies.

Indeed, previously published NIR results (such as those to which the OCPP 0.935 μm data were compared) as well as the NIR data from June 1988 show large low-latitude cloud structures, small features apparently produced by convective activity, and higher-latitude streaks over large latitudinal regions. Assuming that the features obtained are characteristic of the cloud structures entrenched in the atmospheric flows, we now have a much more comprehensive experimental base for testing models of atmospheric dynamics involving driving mechanisms, mass motions, instabilities, and wave motions.

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Appendix A

Image Times

Table A.1: NIR Image times from June 1988. The time difference listed for an image is the difference between it and the previous image.

NIR Image Times from June 1988			
Image	Date	Start Time(UT)	Time Diff.(Hr)
nir24	24/06/88	16:28	–
nir25	25/06/88	16:19	23.85
nir26	26/06/88	16:38	24.15
nir27	27/06/88	16:42	24.07
nir28	28/06/88	16:26	23.73

Table A.2: OCPP image times from June 1988. The map number denotes the number of images made by the OCPP instrument. The first pixel of each image was recorded at the start time, but each image took approximately four hours to complete. The time difference listed for an image is the difference between it and the previous image. Note: Since there was no time listing for polarimetry map 3749, the time for ocpp09.fits was estimated. ocpp09.fits is the third measurement on 23/06/88. Other days with three measurements were looked at, and the average time difference between the second and third measurements was taken, which came out to be 19220 seconds or 5:20:20.

OCPP Image Times from June 1988				
Image	Map no.	Date	Start Time(UT)	Time Diff.(Hr)
ocpp01	3740	20/06/88	05:48:20	—
ocpp02	3741	20/06/88	09:50:50	4.04
ocpp03	3742	20/06/88	15:07:10	5.27
ocpp04	3744	21/06/88	15:16:10	24.15
ocpp05	3745	22/06/88	06:31:00	15.25
ocpp06	3746	22/06/88	10:40:40	4.16
ocpp07	3747	23/06/88	05:05:10	18.41
ocpp08	3748	23/06/88	08:22:00	3.28
ocpp09	3749	23/06/88	13:42:00	5.34
ocpp10	3750	24/06/88	05:41:30	15.99
ocpp11	3751	24/06/88	09:33:30	3.87
ocpp12	3752	24/06/88	14:46:30	5.22
ocpp13	3753	25/06/88	05:40:00	14.89
ocpp14	3754	25/06/88	09:32:00	3.87
ocpp15	3755	25/06/88	14:41:20	5.16
ocpp16	3756	26/06/88	05:38:40	14.96
ocpp17	3757	26/06/88	09:27:10	3.81
ocpp18	3758	26/06/88	14:36:40	5.16
ocpp19	3759	27/06/88	06:02:50	15.44
ocpp20	3760	27/06/88	10:47:40	4.75
ocpp21	3761	28/06/88	05:31:30	19.73
ocpp22	3762	28/06/88	09:20:00	3.81
ocpp23	3763	28/06/88	14:29:30	5.16
ocpp24	3764	29/06/88	14:35:20	24.10
ocpp25	3765	30/06/88	05:28:00	15.88
ocpp26	3766	30/06/88	09:13:10	3.75
ocpp27	3767	30/06/88	15:17:30	6.07

Appendix B

Data from Hand Tracking OCPP

0.935 and 0.365 μm Features

An “X” in the “Good” column signifies that there is good correlation between the cross-sections of the image pair.

B.1 Hand-Tracked OCPP 0.935 μm Atmospheric Features

ocpp01 and ocpp02, $\Delta t = 4.04$ hr			
Lat.	Lon. Shift	Rotation Perd. (days)	Good
-15°	13.5°	4.49	X
0°	10°	6.06	X

ocpp05 and ocpp06, $\Delta t = 4.16$ hr

Lat.	Lon. Shift	Rotation Perd. (days)	Good
-17°	10°	6.24	X
-13°	9°	6.93	

ocpp07 and ocpp08, $\Delta t = 3.28$ hr

Lat.	Lon. Shift	Rotation Perd. (days)	Good
-45°	10°	4.92	X
-42°	10°	4.92	
-29°	9°	5.47	X
-16°	8°	6.15	X
-5°	7.5°	6.56	X
5°	7.5°	6.56	
10°	11.25°	4.37	

ocpp10 and ocpp11, $\Delta t = 3.87$ hr

Lat.	Lon. Shift	Rotation Perd. (days)	Good
-38°	13°	4.47	
-25°	12.25°	4.74	
-6°	15°	3.87	
-2°	10.25°	5.66	
5°	8.5°	6.83	X

ocpp11 and ocpp12, $\Delta t = 5.21$ hr

Lat.	Lon. Shift	Rotation Perd. (days)	Good
-22°	13.5°	5.79	X
5°	12°	6.51	X

ocpp13 and ocpp14, $\Delta t = 3.87$ hr

Lat.	Lon. Shift	Rotation Perd. (days)	Good
-31°	8°	7.26	X
-19°	7.25°	8.01	X
-13°	5°	11.61	X
-7°	8.75°	6.63	X
10°	8°	7.26	X

ocpp16 and ocpp17, $\Delta t = 3.81$ hr

Lat.	Lon. Shift	Rotation Perd. (days)	Good
-5°	10.75°	5.32	X
0°	11.5°	4.97	X
15°	11.75°	4.86	X
20°	9.75°	5.86	X

ocpp19 and ocpp20, $\Delta t = 4.75$ hr

Lat.	Lon. Shift	Rotation Perd. (days)	Good
-28°	17°	4.19	X
-19°	14.25°	5.00	
-15°	9.75°	7.31	
-8°	11.75°	6.06	
10°	11.25°	6.33	

ocpp21 and ocpp22, $\Delta t = 3.81$ hr

Lat.	Lon. Shift	Rotation Perd. (days)	Good
-32°	13°	4.40	X
0°	8°	7.14	
7°	11.25°	5.08	

ocpp22 and ocpp23, $\Delta t = 5.15$ hr

Lat.	Lon. Shift	Rotation Perd. (days)	Good
-30°	11.5°	6.72	X
2°	12°	6.44	
15°	12.5°	6.18	

ocpp25 and ocpp26, $\Delta t = 3.75$ hr

Lat.	Lon. Shift	Rotation Perd. (days)	Good
-28°	9°	6.25	X
-16°	9°	6.25	X
-6°	9°	6.25	X

B.2 Hand-Tracked OCPP 0.365 μm Atmospheric Features

In the “comments” column, many references are made to the “dark Y feature.” This refers to the dark cloud streaks resembling a sideways “Y” which often appears in ultraviolet images.

ocpp01 and ocpp02, $\Delta t = 4.04$ hr

Lat.	Lon. Shift	Rotation Perd. (days)	Comments	Good
-25°	13.5°	4.49	dark Y feature	X
-10°	14°	4.33	dark Y feature	X
-3°	14°	4.33	dark Y feature	X
3°	13°	4.66	dark Y feature	X
20°	13°	4.66	dark Y feature	X
25°	17°	3.56	top edge of dark Y	

ocpp10 and ocpp11, $\Delta t = 3.87$ hr

Lat.	Lon. Shift	Rotation Perd. (days)	Comments	Good
-25°	12°	4.84	bottom edge of dark Y	X
-20°	11.5°	5.04	dark Y feature	X
-10°	9.75°	5.95	dark Y feature	
7°	10.75°	5.40	dark Y feature	
15°	13.25°	4.38	top edge of dark Y	X
20°	13.75°	4.22	top edge of dark Y	X

ocpp14 and ocpp15, $\Delta t = 5.16$ hr

Lat.	Lon. Shift	Rotation Perd. (days)	Comments	Good
-7°	17.5°	4.42		X
-2°	17.75°	4.36		X
2°	18.5°	4.18		X
7°	18.5°	4.18		X
12°	18.5°	4.18		X
20°	12.75°	6.07		X
25°	15.75°	4.91		X
30°	13.75°	5.63		X

ocpp21 and ocpp22, $\Delta t = 3.81$ hr

Lat.	Lon. Shift	Rotation Perd. (days)	Comments	Good
-26°	14.25°	4.01		
-16°	11°	5.20		X
-8°	13°	4.40		X
-3°	13.5°	4.23		
10°	13.75°	4.15		
18°	15.25°	3.75		

Appendix C

Program Listings

C.1 center.c

The ANSI C program center.c finds the center and radius of a planetary image by using a series of chords to estimate the radius of curvature.

```
/* center - a program which finds the center and radius of a planetary or */
/* solar image from its iraf text file. Compile with:          */
/*                               */
/* gcc center.c -o center -lm or cc center.c -o center -lm  */
/*                               */
/* Written by Selwyn Yee                               */
/*                               */
#include <stdio.h>
#include <stdlib.h>
#define MAXLEN 256
#define HEADER 70
#define FAIL 1
#define THRESH 0.1

main()
{
    FILE *fp;
    char filename[50];
    int xmin, xmax;
    double ylimb[MAXLEN+1][2]; /* y-coords of Venus' limb; 2 pts for each x */
    double pixel[MAXLEN+1][MAXLEN+1];
    void get_data(double pixel[][MAXLEN+1], FILE *);
    int find_arc(int, double ylimb[][2], double pixel[][MAXLEN+1]);
    void find_center(double ylimb[][2], int, int);
```

```

printf("File to be read: ");
while (*gets(filename) == NULL)
    printf("Please enter the file name again: ");
if ((fp = fopen(filename, "r")) == NULL) {
    fprintf(stderr, "Error: can't open %s.\n", filename);
    exit(FAIL);
}
printf("Enter the starting x-value: ");
scanf("%d", &xmin);
printf("Starting x-value = %d\n\n", xmin);
get_data(pixel, fp);
xmax = find_arc(xmin, ylimb, pixel);
find_center(ylimb, xmin, xmax);
if (fclose(fp) == EOF)
    printf("Error in closing %s\n", filename);
return 0;
}

/* get_data - skips the header of the iraf text file and reads the data into */
/* the array pixel[][]. */
void get_data(double pixel[][MAXLEN+1], FILE *fp)
{
    int i, j = 0;
    char line[81];

    /* Skip over the header. */
    for (i = 1; i <= HEADER; i++) {
        while ((line[j++] = fgetc(fp)) != '\n')
            ;
        line[j] = '\0';
        j = 0;
    }

    for (j = 1; j <= MAXLEN; j++) {
        for (i = 1; i <= MAXLEN; i++) {
            fscanf(fp, "%lf", &pixel[i][j]);
        }
    }
}

/* find_arc - given a threshold intensity THRESH, this function traces the */
/* outline of Venus' disk from xmin to xmax. It finds the limb by: */
/* */

```

```

/* (1) For each x value, it scans the column looking for the transition */
/* from sky to Venus and Venus to sky. */
/* */
/* (2) It detects a transition from sky to Venus when the intensity from a */
/* pixel is greater than THRESH AND the previous pixel is less than or */
/* equal to THRESH AND the average of the last 10 pixels is less than or */
/* equal to THRESH. The opposite scheme is used for the transition */
/* from Venus to sky. */

int find_arc(int xmin, double ylimb[][2], double pixel[][MAXLEN+1])
{
    FILE *ap;
    int xcoord, ycoord, i, xmax = 0;
    double last[10] = {0, 0, 0, 0, 0, 0, 0, 0, 0, 0};
    double ave;

    /* Open a file to write the points of the arc into. Plotting these points */
    /* is a good check on the accuracy of find_arc(). */

    if ((ap = fopen("arc", "w")) == NULL)
        fprintf(stderr, "Error: can't open arc.\n");

    /* Find the arc defining the non-crescent part of Venus. */
    for (xcoord = xmin; xcoord <= MAXLEN; xcoord++) {
        for (ycoord = 1; ycoord <= MAXLEN; ycoord++) {
            if (pixel[xcoord][ycoord] > THRESH && ycoord >= 2
                && last[(ycoord-2) % 10] <= THRESH) {
                ave = 0;
                for (i = 0; i <= 9; i++)
                    ave += last[i];
                ave /= 10.0; /* average of last 10 pixels */
                if (ave < THRESH) { /* Made transition from sky to Venus */
                    ylimb[xcoord][1] = ycoord - 0.5;
                    fprintf(ap, "%3d %3d\n", xcoord, ycoord);
                    xmax = (xcoord > xmax) ? xcoord : xmax;
                }
            }
            else if (pixel[xcoord][ycoord] <= THRESH && ycoord >= 2
                && last[(ycoord-2) % 10] > THRESH) {
                ave = 0;
                for (i = 0; i <= 9; i++)
                    ave += last[i];
                ave /= 10.0; /* average of last 10 pixels */
            }
        }
    }
}

```

```

        if (ave >= THRESH) { /* Made transition from Venus to sky */
            ylimb[xcoord][2] = ycoord - 0.5;
            fprintf(ap, "%3d %3d\n", xcoord, ycoord);
            xmax = (xcoord > xmax) ? xcoord : xmax;
        }
    }
}
/* Update array last[] */
    last[(ycoord-1) % 10] = pixel[xcoord][ycoord];
}
}
if (fclose(ap) == EOF)
    printf("Error in closing file ärc:\n");
return xmax;
}

/* find_center() : */
/* */
/* (1) Takes the array of points ylimb[] (which defines the non-crescent */
/* limb of Venus) and creates chords between point 1 to point n/4, and */
/* point n/2 to point 3n/4. It keeps incrementing by one pixel until */
/* it draws chords between points n/4 to n/2, and 3n/4 to n. It does */
/* this by calculating line equations(with slope & y-intercept) between */
/* the 2 points representing each chord. */
/* */
/* (2) Calculates the perpendicular line of each chord from its midpoint. */
/* */
/* (3) The intersection of each perpendicular line and its neighbor is */
/* calculated, and the center of Venus is set to the average of these */
/* intersections. */

void find_center(double ylimb[][2], int xmin, int xmax)
{
    int halfx, i;
    int chord1x1, chord1y1, chord1x2, chord1y2;
    int chord2x1, chord2y1, chord2x2, chord2y2;
    double m1, m2, m1perp, m2perp, b1, b2, b1perp, b2perp;
    double xcenter = 0, ycenter = 0;
    double get_slope(double, double, double, double);
    double get_intrcpt(double, double, double);
    double midpt(double, double);
    double midx, midy;
    double xcen[MAXLEN+1]; /* x-values of the calculated radii. */
    double ycen[MAXLEN+1]; /* y-values of the calculated radii. */

```

```

void get_intrsct(double, double, double, double, double *, double *);
double std_dev(double value[], double, int, int);
double get_radius(double, double, double ylimb[][2], int, int);

halfx = xmin + (xmax - xmin) / 2; /* midpoint between xmin and xmax */
for (i = xmin; i <= halfx; i++) {
    chord1x1 = i;
    chord1y1 = ylimb[(int)chord1x1][1];
    chord1x2 = halfx - xmin + i;
    chord1y2 = ylimb[(int)chord1x2][1];
    chord2x1 = xmax - i + xmin;
    chord2y1 = ylimb[(int)chord2x1][2];
    if (chord2x1 == xmax) /* At xmax, could be only 1 pt for limb */
        chord2y1 = ylimb[(int)chord2x1][1];
    chord2x2 = halfx - i + xmin;
    chord2y2 = ylimb[(int)chord2x2][2];
    m1 = get_slope(chord1x1, chord1y1,
        chord1x2, chord1y2);
    b1 = get_intrcpt(m1, chord1x1, chord1y1);
    m2 = get_slope(chord2x1, chord2y1,
        chord2x2, chord2y2);
    b2 = get_intrcpt(m2, chord2x1, chord2y1);
    m1perp = -1 / m1; /* Slope of the perpendicular line. */
    midx = midpt(chord1x1, chord1x2);
    midy = midpt(chord1y1, chord1y2);
    b1perp = get_intrcpt(m1perp, midx, midy);
    m2perp = -1 / m2; /* Slope of the perpendicular line. */
    midx = midpt(chord2x1, chord2x2);
    midy = midpt(chord2y1, chord2y2);
    b2perp = get_intrcpt(m2perp, midx, midy);
    get_intrsct(m1perp, m2perp, b1perp, b2perp, &xcen[i], &ycen[i]);
    xcenter += xcen[i]; ycenter += ycen[i];
}
xcenter /= (double)(halfx - xmin + 1);
ycenter /= (double)(halfx - xmin + 1);
printf("Center at (%g, %g)\n\n", xcenter, ycenter);
printf("Standard deviation in x = %g\n", std_dev(xcen, xcenter, xmin, halfx));
printf("Standard deviation in y = %g\n", std_dev(ycen, ycenter, xmin, halfx));
printf("\nRadius = %g\n", get_radius(xcenter, ycenter, ylimb, xmin, xmax));
}

/* get_slope - calculates the slope of a chord or line. */

```



```

double get_slope(double point1x, double point1y, double point2x, double point2y)
{
    return (point2y - point1y) / (point2x - point1x);
}

/* get_intrcpt - calculates the y-intercept of a chord or line. */

double get_intrcpt(double m, double pointx, double pointy)
{
    return pointy - m * pointx;
}

/* midpt(point1, point2) - calculates the point in the middle of point1 and */
/* point2, regardless of which one is bigger. */

double midpt(double point1, double point2)
{
    double min, max;

    min = (point1 < point2) ? point1 : point2;
    max = (point1 > point2) ? point1 : point2;
    return min + (max - min)/2.0;
}

/* get_intrsct - calculates the intersection point of two line equations. */

void get_intrsct(double m1, double m2, double b1, double b2, double *x, double *y)
{
    *x = (b2 - b1) / (m1 - m2);
    *y = m1 * (*x) + b1;
}

/* std_dev - calculates standard deviation of a set of values about the mean. */
#include <math.h>

double std_dev(double value[], double mean, int start, int end)
{
    int i;
    double variance = 0;

    for (i = start; i <= end; i++)
        variance += (value[i] - mean) * (value[i] - mean);
    variance /= (double)(end - start + 1);
    return sqrt(variance);
}

```

```

/* get_radius - uses the points on the limb and the center point to find the */
/* average radius value. */

double get_radius(double xcenter, double ycenter, double ylimb[][2],
    int xmin, int xmax)
{
    double x, radius = 0;
    double xsquared, ysquared;
    int i, j;

    for ( i = xmin; i <= xmax; i++) {
        x = i;
        for ( j = 1; j <= 2; j++) {
            if (i == xmax && j == 2) /* Might be only 1 limb pt for xmax */
                ;
            else {
                xsquared = (x - xcenter) * (x - xcenter);
                ysquared = (ylimb[i][j] - ycenter) * (ylimb[i][j] - ycenter);
                radius += sqrt(xsquared + ysquared);
            }
        }
    }
    radius /= (2.0 * (xmax - xmin) + 1.0); /* Only 1 pt for x = xmax */
    return radius;
}

```

C.2 map.c

The ANSI program map.c performs cylindrical mapping of an NIR disk image of Venus. The inputs to the program are:

1. Name of the text data file.
2. The x and y pixel coordinates of the geometric center of the disk, (found from the program center.c).
3. The radius of the disk (found from the program center.c).

4. The north position angle of Venus, as read from an ephemeris such as the *Astronomical Almanac*.
5. The sub-Earth latitude.
6. The sub-Earth longitude.
7. The limiting mapping angle `map_limit`. For an angle of `map_limit`, the mapping program will cylindrically map the disk of Venus from the sub-Earth longitude $\pm \text{map_limit}$, and from the sub-Earth latitude $\pm \text{map_limit}$.

The program `map.c` is composed of several functions, and is linked together by executing the following make-file on a UNIX environment running `gcc` (Gnu C-compiler). The functions are listed after the make-file.

```
map: mapmain.o get_data.o mapit.o round.o rotate.o spin.o interpolate.o
    gcc mapmain.o get_data.o mapit.o round.o rotate.o spin.o \
        interpolate.o -o map -lm
mapmain.o: mapmain.c
    gcc -c mapmain.c
get_data.o: get_data.c
    gcc -c get_data.c
mapit.o: mapit.c interpolate.o
    gcc -c mapit.c
round.o: round.c
    gcc -c round.c
rotate.o: rotate.c round.o spin.o interpolate.o
    gcc -c rotate.c
spin.o: spin.c
    gcc -c spin.c
interpolate.o: interpolate.c
    gcc -c interpolate.c

/* mapmain - the main function for "map" which maps the sphere of Venus */
/* (or any planetary image) onto a flat surface.          */

#include <stdio.h>
#include <stdlib.h>
```

```

#include <math.h>
#include "map.h"
#define FAIL 1

main()
{
    FILE *inp, *outp;
    char infile[50], outfile[50];
    double xcenter, ycenter, r0;
    double halfmap, map_limit;
    double data[VENUSLEN][VENUSLEN]; /* original image array */
    double data2[VENUSLEN][VENUSLEN]; /* rotated image array */
    double phi, theta, sublon;
    double subearth[2]; /* coords of center(sub-Earth) pt after rotation */
    void get_data(double data[][VENUSLEN], FILE *, FILE *);
    void mapit(double data[][VENUSLEN], double, double, double, double,
        double, double *, FILE *);
    void rotate(double data[][VENUSLEN], double data2[][VENUSLEN],
        double, double, double, double, double, double *);
    int i, j;
    printf("File containing original image: ");
    while (*gets(infile) == NULL)
        printf("Please enter the file name again: ");
    if ((inp = fopen(infile, "r")) == NULL) {
        fprintf(stderr, "Error: can't open %s.\n", infile);
        exit(FAIL);
    }
    printf("Enter center coordinates (x,y): ");
    scanf("%lf,%lf", &xcenter, &ycenter);
    printf("Enter radius: ");
    scanf("%lf", &r0);
    printf("Enter North-angle(angle north makes counterclockwise");
    printf(" from vertical): ");
    scanf("%lf", &phi);
    printf("Enter sub-Earth latitude: ");
    scanf("%lf", &theta);
    printf("Enter sub-Earth longitude: ");
    scanf("%lf", &sublon);
    printf("Enter limiting mapping angle(in degrees): ");
    scanf("%lf", &map_limit);
    printf("Enter filename for the mapped image: ");
    gets(outfile);

```

```

while (*gets(outfile) == NULL)
    printf("Please enter the file name again: ");
if ((outp = fopen(outfile, "w")) == NULL) {
    fprintf(stderr, "Error: can't open %s.\n", outfile);
    exit(FAIL);
}
get_data(data, inp, outp);
if (theta == 0 && phi == 0) {
    subearth[0] = xcenter;
    subearth[1] = ycenter;
    mapit(data, r0, xcenter, ycenter, map_limit, sublon, subearth, outp);
}
else {
    rotate(data, data2, theta, phi, xcenter, ycenter, r0, subearth);
    mapit(data2, r0, xcenter, ycenter, map_limit, sublon, subearth, outp);
}
if (fclose(inp) == EOF)
    printf("Error in closing %s\n", infile);
if (fclose(outp) == EOF)
    printf("Error in closing %s\n", outfile);
printf("\nThe data was output to the file %s.\n", outfile);
printf("\nTables of latitude & long. were output to \"lat\" & \"lon\".\n");
return 0;
}

#include <stdio.h>
#include "map.h"
#define HEADER 70

/* get_data - copies the header of the iraf text input file to the output */
/* file and changes the image dimensions(NAXIS1 and NAXIS2) of the output */
/* file to be of value MAPLEN. Then reads data from "infile". */

void get_data(double data [[VENUSLEN], FILE *inp, FILE *outp)
{
    int i, j = 0;
    char buf;
    /* Step through the header, copying and editing. */
    for (i = 1; i <= HEADER; i++) {
        /* Lines 3 and 4 are where the image dimensions are written. */
        if (i == 3 — i == 4) {
            for (j = 1; j <= 27; j++) {
                fputc(fgetc(inp), outp);
            }
        }
    }
}

```

```

    }
    for (j = 1; j <= 3; j++) { /* Skip dimensions in "infile" */
        fgetc(inp);
    }
/* Write image dimension (x or y). */
    if (i == 3)
        fprintf(outp, "%d", XMAPLEN);
    else
        fprintf(outp, "%d", YMAPLEN);
    }
    while ((buf = fgetc(inp)) != '\n') {
        fputc(buf, outp);
    }
    fputc('\n', outp);
}

/* Read data from "infile". IRAF text files are written with the left */
/* subscript varying fastest. */
    for (j = 0; j < VENUSLEN; j++) {
        for (i = 0; i < VENUSLEN; i++)
            fscanf(inp, "%lf", &data[i][j]);
    }
}

/* rotate - takes the array data[][] and rotates it by the angles theta and */
/* phi. The objective is to undo the rotations on Venus from the North- */
/* angle and sub-Earth latitude so that north is parallel to the y-axis */
/* (straight up in the image) and Venus' latitude lines run parallel to the */
/* y-z plane. */
/* */
/* The image is in the x-y plane, with z being the depth of the sphere */
/* of Venus. Theta and phi are the angles defined in a spherical coordinate */
/* system; with theta being the angle from the z-axis and phi being the */
/* angle defined counterclockwise from the x-axis as you look down on the */
/* x-y (image) plane. */
/* */
/* NORTH-ANGLE */
/* From this description it becomes clear that the North-angle, which I */
/* define as the angle that Venusian north makes counterclockwise from the */
/* y-axis as you look down on the x-y (image) plane. */
/* axis) is a rotation in phi. This can be undone by rotating by */
/* -(North-angle). */
/* */

```

```

/* SUB-EARTH LATITUDE */
/* The sub_Earth point of Venus is defined as follows: Imagine a line */
/* drawn between the centers of Earth and Venus. That line's intersection */
/* with Venus is the sub-Earth point, which is given in latitude and long- */
/* itude. Therefore the sub-Earth latitude sits right on the apparent */
/* equator of Venus. Since latitude and theta are defined in the same */
/* directions, you must do a rotation of +theta to move the real equator up */
/* to that point. */
/* */
/* METHOD OF ROTATION */
/* Thinking of the sphere of Venus with latitude and longitude lines, it */
/* makes no sense to unrotate by latitude(theta) before unrotating by the */
/* North-angle(phi). Therefore, to do both rotations in the proper order, */
/* the phi rotation matrix must be multiplied on the left by the theta rota- */
/* tion matrix, so that the image gets rotated first by phi, then by theta. */
/* The resulting matrix is written into spin[]. */

#include <stdio.h>
#include <math.h>
#include "map.h"
#define DEG_TO_RAD 0.017453293 /* Conversion from degrees to radians */
#define IN 0

void rotate(double data[][VENUSLEN], double data2[][VENUSLEN], double theta,
           double phi, double xcenter, double ycenter, double r0, double *sub)
{
    double rot_mat[3][3];
    int xcoord, ycoord;
    double xdisk, ydisk, xmap, ymap, r0square, rsquare, z;
    long npix = 1;
    int spin(double rot_mat[][3], double, double, double, double *, double *);
    int round(double);
    double interpolate(double data[][VENUSLEN], double, double);

    /* Convert phi and theta from degrees to radians. */
    theta = -theta; /* Want to unrotate by angle theta */
    phi *= DEG_TO_RAD;
    theta *= DEG_TO_RAD;
    /* Define and calculate the rotation matrix */
    rot_mat[0][0] = cos(phi);
    rot_mat[0][1] = -sin(phi);
    rot_mat[0][2] = 0.0;
    rot_mat[1][0] = cos(theta) * sin(phi);

```

```

rot_mat[1][1] = cos(theta) * cos(phi);
rot_mat[1][2] = sin(theta);
rot_mat[2][0] = -sin(theta) * sin(phi);
rot_mat[2][1] = -sin(theta) * cos(phi);
rot_mat[2][2] = cos(theta);

/* For each pixel in the corrected image(data2[][]), initialize it to zero */
/* and if it falls on Venus, rotate to its corresponding position in the */
/* original image (data[][]). Get the interpolated intensity of this spot. */
/* Else if the pixel does not fall on Venus, leave the intensity at zero. */

r0square = r0 * r0;
for (xcoord = 0; xcoord < VENUSLEN; xcoord++) {
    xdisk = (double)xcoord - xcenter; /* x coord relative to center */
    for (ycoord = 0; ycoord < VENUSLEN; ycoord++) {
        data2[xcoord][ycoord] = 0.0;
        ydisk = (double)ycoord - ycenter; /* y coord relative to center */
        rsquare = xdisk*xdisk + ydisk*ydisk;
        if (rsquare <= r0square) {
            z = sqrt(r0square - rsquare);
            if (spin(rot_mat, xdisk, ydisk, z, &xmap, &ymap) == IN) {
/* convert back to x and y pixel coordinates */
                xmap += xcenter;
                ymap += ycenter;
                data2[xcoord][ycoord] = interpolate(data, xmap, ymap);
            }
        }
    }
}

/* Do the inverse rotation on the center point and return that value to */
/* mapit(). The inverse rotation is done since we are going in the opposite */
/* direction: from original to corrected image. */

/* Redefine and calculate the rotation matrix */
rot_mat[0][0] = cos(phi);
rot_mat[0][1] = sin(phi);
rot_mat[0][2] = 0.0;
rot_mat[1][0] = -cos(theta) * sin(phi);
rot_mat[1][1] = cos(theta) * cos(phi);
rot_mat[1][2] = -sin(theta);
rot_mat[2][0] = -sin(theta) * sin(phi);
rot_mat[2][1] = sin(theta) * cos(phi);

```



```

    rot_mat[2][2] = cos(theta);
    spin(rot_mat, 0, 0, r0, &xmap, &ymap);
    sub[0] = xmap + xcenter;
    sub[1] = ymap + ycenter;
    printf("\nrotate: subearth at (%g, %g)\n", sub[0], sub[1]);
}

/* spin - takes the rotation matrix rot_mat[][] and the x, y, and z coords */
/* of a pixel and calculates the mapped x, y, and z coords. */

int spin(double rot_mat[][3], double x, double y, double z,
        double *xmap, double *ymap)
{
    double zmap, point[3];
    int j;

    *xmap = *ymap = zmap = 0.0;
    point[0] = x;
    point[1] = y;
    point[2] = z;
    for (j = 0; j <= 2; j++) {
        *xmap += rot_mat[0][j] * point[j];
        *ymap += rot_mat[1][j] * point[j];
        zmap += rot_mat[2][j] * point[j];
    }
    if (zmap < 0)
        return 1;
    else
        return 0;
}

#include <stdio.h>
#include <math.h>
#include "map.h"

/* interpolate - calculates the overlap of a pixel from data2[][] onto */
/* data[], and takes an average of the intensities of the overlapped */
/* pixels weighted by the areas of overlap. This weighted average is */
/* assigned to the pixel in data2[][]. */
/*
/* Assume each pixel coordinate refers to the upper right corner of the */
/* pixel(i.e. the first pixel in an array is (1,1) and the upper right */
/* corner has coords (1,1) and the lower left corner is (0,0)). */

```

```

double interpolate(double data[][VENUSLEN], double xmap, double ymap)
{
    double xlo, xhi, ylo, yhi;
    double a00, a01, a10, a11;
    double i00, i01, i10, i11;
    xlo = floor(xmap);
    xhi = ceil(xmap);
    ylo = floor(ymap);
    yhi = ceil(ymap);
    /* Calculate areas of overlap of the lower left, upper left, lower right, and*/
    /* upper right pixels respectively in data[][] with the pixel in data2[][]. */
    a00 = (xlo - xmap + 1.0) * (ylo - ymap + 1.0);
    a01 = (xlo - xmap + 1.0) * (ymap - ylo);
    a10 = (xmap - xlo) * (ylo - ymap + 1.0);
    a11 = (xmap - xlo) * (ymap - ylo);
    /* Look up the corresponding intensities in data[][]. */
    i00 = data[(int)xlo][(int)ylo];
    i01 = data[(int)xlo][(int)yhi];
    i10 = data[(int)xhi][(int)ylo];
    i11 = data[(int)xhi][(int)yhi];
    return a00*i00 + a01*i01 + a10*i10 + a11*i11;
}

#include <math.h>
/* round - if fractional part of f >= 0.5, f gets set to next highest */
/* integer. If < 0.5, f is set to the next lower integer. */

int round(double f)
{
    double f_int;
    f_int = floor(f);
    return (f - f_int >= 0.5) ? (int)ceil(f) : (int)f_int;
}

#include <stdio.h>
#include <math.h>
#include "map.h"
#define DEG_TO_RAD 0.017453293 /* Conversion from degrees to radians */

/* mapit() maps columns(x-values) only from an angular range of -ANG_LIMIT
*/
/* to +ANG_LIMIT. It multiplies each of these x-coordinates from data[][] */
/* by 1/cosine(theta), then puts it into lonmap[][]. */

```

```

void mapit(double data[][VENUSLEN], double r0, double xcenter, double ycenter,
double map_limit, double sublon, double *subearth, FILE *outp)
{
    int xmap, ymap, i, latpix, lonpix;
    double dx, dy;
    double data3[XMAPLEN][YMAPLEN];
    double lon[XMAPLEN], lat[YMAPLEN];
    double xdisk, ydisk, slat, slon;
    int xhalf, yhalf;
    int x_lim0, y_lim0, x_lim1, y_lim1;
    FILE *f_lat, *f_lon;
    long pixcnt = 1;
    double interpolate(double data[][VENUSLEN], double, double);
    int get_pix(double *, double);

    if ((f_lat = fopen("lat", "w")) == NULL)
        fprintf(stderr, "Error: can't open \"lat\".\n");
    if ((f_lon = fopen("lon", "w")) == NULL)
        fprintf(stderr, "Error: can't open \"lon\".\n");
    /* Initialize data3[][] to -1. This is to indicate these pixels have not */
    /* yet been assigned values. */
    for (ymap = 0; ymap < YMAPLEN; ymap++) {
        for (xmap = 0; xmap < XMAPLEN; xmap++) {
            data3[xmap][ymap] = -1.;
        }
    }
    /* Calculate dx & dy; the number of degrees per pixel in the map. */
    dx = 360. / (XMAPLEN - 1);
    dy = 180. / (YMAPLEN - 1);
    xhalf = (XMAPLEN - 1)/2; /* The center x coord for mapped image */
    yhalf = (YMAPLEN - 1)/2; /* The center y coord for mapped image */

    /* Calculate tables of latitude and longitude as a function of the mapped */
    /* pixel positions. Finally, write the tables into files called "lat" and */
    /* "lon". */
    for (xmap = 0; xmap < XMAPLEN; xmap++) {
        lon[xmap] = xmap * dx;
        slon = lon[xmap] + sublon;
        if (slon >= 360.0)
            slon -= 360.0;
        else if (slon < 0.0)
            slon += 360.0;
    }
}

```

```

        fprintf(f_lon, "%7.3f\n", slon);
        lon[xmap] *= DEG_TO_RAD;
    }
    for (ymap = 0; ymap < YMAPLEN; ymap++) {
        lat[ymap] = (ymap - yhalf) * dy;
        fprintf(f_lat, "%7.3f\n", lat[ymap]);
        lat[ymap] *= DEG_TO_RAD;
    }
    /* Lower and upper pixel limits which define the angular limit map_limit */
    x_lim0 = (int)(map_limit/dx);
    x_lim1 = (int)((360. - map_limit)/dx);
    y_lim0 = yhalf - (int)(map_limit/dy);
    y_lim1 = yhalf + (int)(map_limit/dy);
    printf("dx=%4.2f dy=%4.2f map_lim=%4.1f\n", dx, dy, map_limit);
    printf("minlon=%7.2f minlat=%7.2f", lon[0], lat[0]);
    printf("maxlon=%7.2f maxlat=%7.2f\n", lon[XMAPLEN-1], lat[YMAPLEN-1]);
    printf("x_lim0=%d x_lim1=%d ", x_lim0, x_lim1);
    printf("y_lim0=%d y_lim1=%d\n", y_lim0, y_lim1);

    /* Coordinates are assigned to each pixel using the latitude and longitude */
    /* tables, and the corresponding pixel in the disk image of Venus (data[]) */
    /* is mapped to it. */

    for (ymap = y_lim0; ymap <= y_lim1; ymap++) {
        ydisk = r0 * sin(lat[ymap]) + ycenter;
        for (xmap = 0; xmap <= x_lim0; xmap++) {
            xdisk = cos(lat[ymap]) * r0 * sin(lon[xmap]) + xcenter;
            data3[xmap][ymap] = interpolate(data, xdisk, ydisk);
        }
        for (xmap = x_lim1; xmap < XMAPLEN; xmap++) {
            xdisk = cos(lat[ymap]) * r0 * sin(lon[xmap]) + xcenter;
            data3[xmap][ymap] = interpolate(data, xdisk, ydisk);
        }
    }
    /* Write data3[][] to the output file. */
    for (ymap = 0; ymap < YMAPLEN; ymap++) {
        for (xmap = 0; xmap < XMAPLEN; xmap++) {
            fprintf(outp, "%14.7G", data3[xmap][ymap]);
            if (pixcnt++ % 5 == 0)
                fputc('\n', outp);
        }
    }
}

```

C.3 correlbig.pro

The IDL program correlbig.pro allows both hand tracking and cross-correlations on features in consecutive OCPP images. The user specifies a latitude where a feature resides, and then uses the mouse to select the longitude range to scan. The program then generates intensity scans at the specified latitude and longitude ranges which can be tracked by eye and cross-correlated by a mathematical cross-correlation function.

```
; lon_axis creates a vector to giving the correct longitude values on a row
; plot of images 1 & 2 for a given value of dpix (deg/pix).          ; dpix is the
resolution of the images.
function lon_axis,lon1,lon2,dpix

    return,(findgen((lon2-lon1)/dpix))*dpix + lon1
end

; CORRELBIG AVERAGES +/- 2 DEGREES AROUND ROW1

pro correlbig,image1,image2,img1str,img2str,row1

; cross-correlate the rows in images 1 and 2
;
; image1 & image2 are the images to correlate
; img1str & img2str are the strings containing the image names
; nrow1 & nrow2 are the rows in the images to correlate

xdim = 684
ydim = 724

lonlim1 = 80 ; longitude of first pixel in x-direction
lonlim2 = 250 ; longitude of last pixel in x-direction

degshift = 2 ; number of degrees to shift below and above starting row.

nrow1 = float(0.) ; cast nrow1 as floating point

; row1 is row for 361x181 image. Convert.

nrow1 = (row1-degshift+1)/181.*ydim - 1.
```

```

nrow1 = round(nrow1)
nrow2 = float(0.)      ; cast nrow1 as floating point

; row2 is row for 361x181 image. Convert.

nrow2 = (row1+degshift+1)/181.*ydim - 1.
nrow2 = round(nrow2)

dpix = 0.25      ; set the degrees per pixel

mag = 0.5      ; set image magnification factor
sxdim = mag*xdim
sydim = mag*ydim ; scaled x & y dimensions

; display images 1 & 2 with nrow1 marked

wtile = 'row ' + strtrim(string(nrow1),2) + ' marked'
window,1,title=wtile,xsize=sxdim,ysize=2*sydim,xpos=280,ypos=295
tvslc,congrid(image1,sxdim,sydim,/interp),0,sydim

; draw a line in nrow1 of image1

tvbox,[sxdim,1],sxdim/2,sydim+mag*nrow1
tvslc,congrid(image2,sxdim,sydim,/interp),0,0

; draw a line in nrow1 of image2

tvbox,[sxdim,1],sxdim/2,mag*nrow1
window,0      ; send the rest of the plots to window 0

;plot all the data on the same graph, so user can decide on lon limits

plon1 = 80
plon2 = 250
plonlim1 = plon1 - lonlim1
plonlim2 = plon2 - lonlim1

plot,lon_axis(plon1,plon2,dpix),image1(plonlim1/dpix:plonlim2/dpix,nrow1),$
  /xstyle,xtitle='longitude',yrange=[60,200],/ystyle,$
  title='image 1 for specified rows'
oplot,lon_axis(plon1,plon2,dpix),image1(plonlim1/dpix:plonlim2/dpix,nrow2)

print,'Use mouse to mark lower lon limit: '
cursor,lon1a,lat,/down
lon1a = round(lon1a)
plon1a = (lon1a-lonlim1)/dpix ; convert lon to actual column in image

```

```

oplot,[lon1a,lon1a],[0,50000]

print,'lower lon limit = ',lon1a,'. Mark upper lon limit: '
cursor,lon1b,lat,/down
lon1b = round(lon1b) ; convert lon1 and lon2 to int
plon1b = (lon1b-lonlim1)/dpix ; convert lon to actual column in image
oplot,[lon1b,lon1b],[0,50000]

print,'upper lon limit = ',lon1b,'.'
plot,image1(*,nrow1),xrange=[plon1a,plon1b],/xstyle,xtitle='longitude',$
    title='Image 1 for rows 1 and 2'
oplot,image1(*,nrow2)

plot,lon_axis(plon1,plon2,dpix),image2(plonlim1/dpix:plonlim2/dpix,nrow1),$
    /xstyle,xtitle='longitude',yrange=[60,200],/ystyle,$
    title='image 2 for specified rows'
oplot,lon_axis(plon1,plon2,dpix),image2(plonlim1/dpix:plonlim2/dpix,nrow2)

print,'Use mouse to mark lower lon limit: '
cursor,lon2a,lat,/down
lon2a = round(lon2a)
plon2a = (lon2a-lonlim1)/dpix ; convert lon to actual column in image
oplot,[lon2a,lon2a],[0,50000]
print,'lower lon limit = ',lon2a,'. Mark upper lon limit: '

cursor,lon2b,lat,/down
lon2b = round(lon2b) ; convert lon1 and lon2 to int
plon2b = (lon2b-lonlim1)/dpix ; convert lon to actual column in image
oplot,[lon2b,lon2b],[0,50000]
print,'upper lon limit = ',lon2b,'.'

; redisplay images 1 & 2 with nrow1 and lon limits marked

wtitle = 'row ' + strtrim(string(nrow1),2) + ' marked'
window,1,title=wtitle,xsize=sxdim,ysize=2*sydim,xpos=280,ypos=295
tvsc1,congrid(image1,sxdim,sydim,/interp),0,sydim
tvbox,[sxdim,1],sxdim/2,sydim+mag*nrow1 ; mark nrow1 of image1
tvbox,[1,20],mag*plon1a,sydim+mag*nrow1 ; mark plon1a in image1
tvbox,[1,20],mag*plon1b,sydim+mag*nrow1 ; mark plon1b in image1
tvsc1,congrid(image2,sxdim,sydim,/interp),0,0
tvbox,[sxdim,1],sxdim/2,mag*nrow1 ; mark nrow1 of image2
tvbox,[1,20],mag*plon2a,mag*nrow1 ; mark plon2a in image2
tvbox,[1,20],mag*plon2b,mag*nrow1 ; mark plon2b in image2
window,0 ; send the rest of the plots to window 0

```

```

; calculate average of nrow1 and nrow2 for image1 and image2

img1avg = ftarr(xdim)
img2avg = ftarr(xdim)

for i=nrow1,nrow2 do begin
    img1avg(plon1a:plon1b) = img1avg(plon1a:plon1b) + image1(plon1a:plon1b,i)
    img2avg(plon2a:plon2b) = img2avg(plon2a:plon2b) + image2(plon2a:plon2b,i)
endfor

img1avg = img1avg/float(nrow2-nrow1+1)
img2avg = img2avg/float(nrow2-nrow1+1)

!p.multi = [0,1,2]    ; stack two plots vertically on the same window

plot,lon_axis(lon1a,lon1b,dpix),img1avg(plon1a:plon1b),/xstyle,$
    xtitle='longitude',yrange=[min(image1(plon1a:plon1b,nrow1)),$
    max(image1(plon1a:plon1b,nrow1))],title='Image 1 for specified rows'

plot,lon_axis(lon2a,lon2b,dpix),img2avg(plon2a:plon2b),/xstyle,$
    xtitle='longitude',yrange=[min(image2(plon2a:plon2b,nrow1)),$
    max(image2(plon2a:plon2b,nrow1))],title='Image 2 for specified rows'

!p.multi = 0          ; reset plotting to one per window

answer = "
read,answer,prompt='Ok to do correlation (y/n)?'
if answer eq 'y' then begin
    lonlen1 = fix(plon1b - plon1a + 1)    ; convert lonlen to int
    lonlen2 = fix(plon2b - plon2a + 1)    ; convert lonlen to int
    maxlen = lonlen1 > lonlen2            ; maxlen = the longer lonlen

;::::::::::::::::::::::::::::::::::::::::::
;                                     ;
;  DO THE CROSS-CORRELATION  ;
;                                     ;
;::::::::::::::::::::::::::::::::::::::::::

correl = correl_ocpp(image1(plon1a:plon1b,nrow1:nrow2),$
    image2(plon2a:plon2b,nrow1:nrow2),xshift=maxlen/2,yshift=0,$
    xoffset_b=plon2a-plon1a)

shift = (findgen(maxlen) - maxlen/2)*dpix
ctitle = 'Correlation of Rows ' + $
    strtrim(string(nrow1),2) + '-' + strtrim(string(nrow2),2) + $

```



```

    ' of ' + img1str + ' & ' + img2str + ' (Gourad)'
plot,shift,correl,xtitle='displacement (degrees longitude)',$
  ytitle='correlation coefficient',symsize=.5,psym=7,title=ctitle,$
  yrange=[min(correl),max(correl)],/xstyle,xminor=10

read,answer,prompt='Print data and correlation plots? (y/n): '
if answer eq 'y' then begin
  set_plot,'ps' ; output the following plots in postscript format
  !fancy=2

; print plot of correlation coefficient vs. longitude offset

  device,filename='correl.ps',/landscape
  plot,shift,correl,xtitle='displacement (degrees longitude)',$
    ytitle='correlation coefficient',symsize=.5,psym=7,title=ctitle,$
  yrange=[min(correl),max(correl)],/xstyle,xminor=10
  corrstr = '(Center at Row ' + strtrim(string(row1),2) + $
    ' in 361x181' + ' data, averaged over ' + $
    strtrim(string(2*degshift),2) + ' degrees)'
  xyouts,.5,1,corrstr,/normal,align=.5
  device,/close
  spawn,'lpr -h -Pssa1 correl.ps' ~ ; send plot to printer on ssal
  print,'Printing correlation'

; print overlapped scans of image1 and image2

  device,filename='data.ps',/landscape
  dtitle = img1str + ' and ' + img2str + ' for Rows ' + $
    strtrim(string(nrow1),2) + ' and ' + strtrim(string(nrow2),2)
  plot,lon_axis(plon1,plon2,dpix),title=dtitle,$
    image1(plonlim1/dpix:plonlim2/dpix,nrow1),/xstyle,xtitle='longitude'
  oplot,lon_axis(plon1,plon2,dpix),image1(plonlim1/dpix:plonlim2/dpix,nrow2)
  oplot,lon_axis(plon1,plon2,dpix),image2(plonlim1/dpix:plonlim2/dpix,nrow1)
  oplot,lon_axis(plon1,plon2,dpix),image2(plonlim1/dpix:plonlim2/dpix,nrow2)
  oplot,[lon1a,lon1a],[0,50000]
  oplot,[lon1b,lon1b],[0,50000]
  oplot,[lon2a,lon2a],[0,50000]
  oplot,[lon2b,lon2b],[0,50000]
  xyouts,.5,1,corrstr,/normal,align=.5
  device,/close
  spawn,'lpr -h -Pssa1 data.ps' ; send plot to printer on ssal
  print,'Printing data from images 1 and 2'

; Print data with same lon and intensity limits.

```

```

lonmin = lon1a < lon2a
lonmax = lon1b > lon2b
intmin = min(img1avg(plon1a:plon1b)) < $
    min(img2avg(plon2a:plon2b))
intmax = max(img1avg(plon1a:plon1b)) > $
    max(img2avg(plon2a:plon2b))

; print scan of image1

device,filename='data.ps',/landscape
dtitle = img1str + ' (Gourad Shading), Average of Rows ' + $
    strtrim(string(nrow1),2) + ' and ' + strtrim(string(nrow2),2)
plot,lon_axis(lon1a,lon1b,dpix),img1avg(plon1a:plon1b),$
    xrange=[lonmin,lonmax],/xstyle,xtitle='longitude',ytitle='intensity',$
    title=dtitle,symsize=.5,psym=7,yrange=[intmin,intmax],/ystyle
xyouts,.5,1,corrstr,/normal,align=.5

device,/close
spawn,'lpr -h -Pssa1 data.ps' ; send plot to printer on ssal
print,'Printing data from image1'

; print scan of image2

device,filename='data.ps',/landscape
dtitle = img2str + ' (Gourad Shading), Average of Rows ' + $
    strtrim(string(nrow1),2) + ' and ' + strtrim(string(nrow2),2)
plot,lon_axis(lon2a,lon2b,dpix),img2avg(plon2a:plon2b),$
    xrange=[lonmin,lonmax],/xstyle,xtitle='longitude',ytitle='intensity',$
    title=dtitle,symsize=.5,psym=7,yrange=[intmin,intmax],/ystyle
xyouts,.5,1,corrstr,/normal,align=.5

device,/close
spawn,'lpr -h -Pssa1 data.ps' ; send plot to printer on ssal
print,'Printing data from image2'

set_plot,'X' ; reset the plot output to the X environment
endif
endif
stop
end

```