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Characterization of Venusian atmospheric dynamics using Venus Express images and ground-based observations

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Characterization of Venusian atmospheric dynamics using Venus Express images and ground-based observations

A thesis submitted in partial fulfillment of the requirement
for the degree of Bachelor of Science with Honors in
Physics from the College of William and Mary in Virginia,

by

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Accepted for Honors

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Contents

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Abstract

The equatorial atmosphere of Venus rotates 60 times faster than the solid planet, a poorly understood phenomenon known as superrotation. Kelvin-like waves have been hypothesized to maintain the superrotation against dissipation, and the planet-scale "Y-feature", a transient cloud feature, is likely their visible manifestation. In order to detect these waves, the spatial and temporal evolution of Venus' atmosphere as a whole must be better characterized on long time scales. Using data from the Venus Monitoring Camera on board Venus Express, we have found yearly average zonal wind profiles by using Correlation Image Velocimetry. In order to better characterize the measurement uncertainty and separate it from real variation compared to using the standard deviation, we have developed a method of uncertainty calculation using correlation fields. We observed a consistent trend of increasing zonal wind velocity, about $20 \ \mathrm{ms}^{-1}$ over eight years of observation, in the area that the Y-feature is present, which may be caused by Kelvin-like waves accelerating the mean flow. This variation is comparable to the standard deviation and uncertainty, and thus cannot be definitively confirmed. Our new method of uncertainty calculation gave comparable uncertainty to the standard deviation and future work will be needed for improvement in the uncertainty calculation.

Chapter 1

Background

1.1   The Venusian atmosphere

The atmosphere of Venus is the thickest and most dynamic among the terrestrial planets and exhibits unusual behavior. Venus rotates very slowly – once every 243 days, comparable to its orbital period of 225 days. In contrast to the solid planet, the equatorial atmosphere circles the planet in just four days, 60 times the planet's rate of rotation. In comparison, the highest wind speeds on Earth are only around 20% of the Earth's rotational speed. Per kilogram, the atmosphere has more angular momentum than the solid planet. This phenomenon, termed "superrotation", is poorly understood. There must be a forcing mechanism that maintains the superrotation against dissipation by friction, and this mechanism has yet to be definitively determined. Determining the cause of Venus' superrotation is one of the outstanding problems in planetary science.[1]

Based on numerical modeling, it seems that the atmospheres of most slowly rotating planets and moons will superrotate. A common mechanism for slow rotational rates is tidal locking, which occurs when tidal forces from a star or planet force a smaller body to have equal rotational and orbital periods. The Earth's moon is tidally locked, as is Saturn's moon Titan, which is the only moon in the solar system

with a significant atmosphere. Measurements by Cassini suggest that Titan does indeed exhibit superrotation. Many of the currently known Earth-sized exoplanets, including all seven known planets of the TRAPPIST-1 system, are tidally locked due to their proximity to their parent star. A superrotating atmosphere could potentially equalize temperatures across these planets enough so that they have conditions suitable for life.

The slow rotation of Venus leads to far different patterns of atmospheric circulation than any other planet. On Earth, atmospheric circulation on large scales is geostrophic, meaning that the flow of air is dominated by Coriolis force. This type of flow dominates in hurricanes and in the circulation of Earths oceans. Jupiter and Saturn, which have roughly twice the rotation rate of Earth, are more extreme examples of geostrophic regimes, as evidenced by the massive cyclones that dot their cloud bands.

Kelvin and Rossby waves are common types of waves found in geostrophic regimes. Kelvin waves balance the Coriolis force against a boundary, like a coastline. Earth's equator, where the Coriolis force changes sign, is also a barrier, and Kelvin waves can travel along it as a waveguide. Rossby waves balance the Coriolis force and a pressure gradient. Large-scale meanderings of the Earth's polar jet streams are examples of terrestrial Rossby waves.

Venus' slow rotation gives rise to a negligible Coriolis force, thus the circulation is said to be cyclostrophic, balancing the centrifugal force and a pressure gradient. On Earth, cyclostrophic regimes are only encountered in localized, fast circulation, like tornadoes, or at the equator. However, the entire Venusian atmosphere is in this regime. Rossby and Kelvin waves cannot form in cyclostrophic regimes. This makes the planet an interesting laboratory to study many atmospheric phenomena (such as superrotation) that have no counterpart on Earth or the other planets.

1.2 History of Venus observations

Before the advent of modern astronomy and space exploration, the atmospheric and surface conditions of Venus were almost entirely unknown. Visual observers since Galileo had seen nothing but a bright, cream-colored disk entirely devoid of any cloud features. In this vacuum of knowledge, leading hypotheses included that Venus was covered in a planet-wide, carbon-rich swamp teeming with life or a dusty desert like the Sahara. However, microwave observations in the late 1950s revealed that the surface temperature was over 600 °C – hot enough to melt lead.[2]

Although featureless in visible light, near-ultraviolet observations starting in 1911 revealed cloud features made visible by an unknown ultraviolet absorber. The first systematic efforts by Dollfus, Boyer and Camichel to study the motion of ultraviolet cloud features began in the late 1940s.[3] Although early attempts to determine the rotation speed of the atmosphere through spectroscopic means gave ambiguous results, periodic variations in ultraviolet albedo were observed that corresponded to a four-day atmospheric rotation period.[4]

More detailed imaging showed that the albedo variation was due to a planet-scale dark patch in the clouds, which Boyer and Camichel called the "Y-feature" as it resembled a sideways letter Y. The two forks of the Y extended to about 45 north and south in latitude. However, in-situ imaging by spacecraft would be needed to study the Y-feature in more detail than just in gross morphologies.

Venus was a popular target for early space exploration by both the United States and Soviet Union. Data from the Soviet Venera and U.S. Mariner series of probes confirmed the superrotation of the atmosphere in the late-1960s and 1970s. Mariner 10's flyby in 1975 revealed the Y-feature as having subtle albedo variations and a more complex morphology than was visible from Earth. The Pioneer Venus Orbiter, in orbit
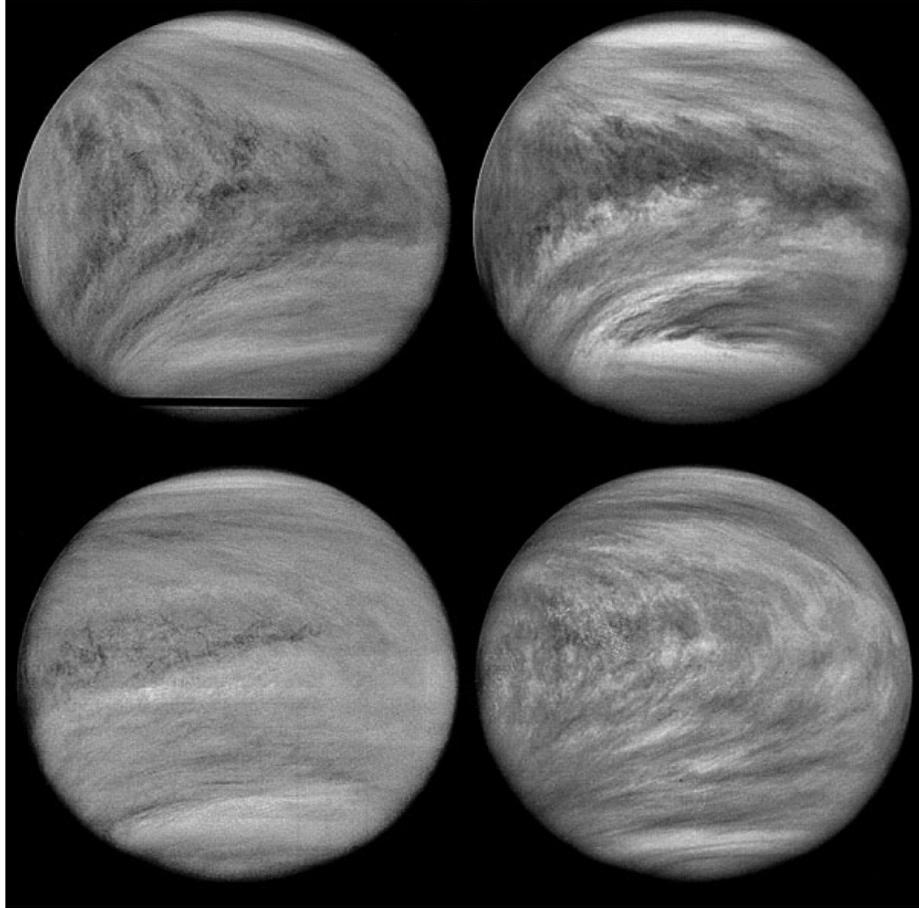
Figure 1.1: This ultraviolet OCPP image from the Pioneer Venus Orbiter shows the full four-day rotation of the superrotating atmosphere and Y-feature. (NASA)

from 1979 to 1989, allowed for the first long-term studies of Venusian atmospheric dynamics with its Orbiter Cloud Photo Polarimeter (OCPP).

Pioneer Venus images showed that the Y-feature is an atmospheric wave. The spacecraft observed alternating dark and light areas in the feature, which were suggestive of wave motion. The dark areas correspond to upwelling of lower atmospheric layers rich in the ultraviolet absorber and the light areas to downwelling. This wave propagates prograde and has a period between 0.7 and 0.1 days less than the bulk superrotating equatorial atmosphere.[5]

Pioneer Venus also observed that the Y-feature has striking temporal variation and goes through cycles of dissipation and reformation. The feature begins the cycle as a series of alternating light and dark U-shaped patches circling the planet. Since the atmosphere at higher latitudes has a higher angular velocity than at the equator, the U-shapes are distorted into Y-shapes after about 10 days. The high-latitude arms of the Y wind faster around the planet than the equatorial portion, producing symmetrical spirals in the northern and southern hemispheres. Eventually the feature winds up around the planet so much that it dissipates and after some time reforms. This lifespan is approximately 30 days.[6] There was considerable long-term variation in the feature, which could appear as a U, V, Y, or Ψ. The long-term evolution of the Y-feature is not well understood due to intermittent coverage by Pioneer Venus, and it appears to have completely disappeared for a year in 1982.[5] Even the nature of its short-term evolution is uncertain as it does appears that the Y-feature does not necessarily immediately reform after dissipating.

The Galileo probe observed Venus during its flyby in 1989, but it was not until 2006 that continuous ultraviolet imaging was available from an orbiter. The European Space Agency's Venus Express (VEX) probe was specifically designed to observe the atmospheric dynamics of Venus and was in orbit around the planet from 2006 to 2015. The on board Venus Monitoring Camera (VMC) had an ultraviolet filter (centered on 365 nm) specifically to study the motion of the cloud tops and was the primary source of data for this thesis (see Section 2.2 for a discussion of this data).

At the time of writing, the Japanese Space Agency's Akatsuki spacecraft (also known as the Venus Climate Orbiter) is orbiting Venus and like Venus Express will focus on atmospheric dynamics. In orbit since late 2015, Akatsuki will provide data of the same or better quality than Venus Express. See Table 1.1 for more information on spacecraft missions.

Spacecraft	Year(s)	Mission	Instrument(s)	Agency
Mariner 10	1974	Flyby	Television Photography	NASA
Pioneer Venus Orbiter	1979-1989	Orbiter	OCPP	NASA
Galileo	1990	Flyby	SSI	NASA
Venus Express	2006-2015	Orbiter	VMC	ESA
Akatsuki	2015-present	Orbiter	UVI, LIR, IR1, IR2	JAXA

Table 1.1: Spacecraft that have encountered Venus and captured images useful for analysis of atmospheric dynamics. The instruments listed are those that have returned this data. While the ultraviolet UVI camera on Akatsuki will be used for study of the Y-feature, the other three infrared cameras may also be of use.

Recent infrared observations by the Subaru Telescope have shown patterns closely resembling the Y-feature at 8.66 μm and 11.34 μm.[7] This would indicate that the Y-feature is also visible as inhomogeneities in cloud top altitude and temperature, which would not be thought *a priori* to be associated with the upwelling of the ultraviolet absorber that is characteristic of the Y-feature. However these images have not been directly compared with ultraviolet images taken at the same time and the time resolution of the observations was not sufficient to confirm its four-day periodicity. Akatsuki observed a large stationary gravity wave at similar wavelengths in December 2015.[8] It had a similar shape to the Y-feature and was a transient feature likely generated by the interactions between the atmosphere and the terrain, but seemingly completely unrelated to the Y-feature. It is possible that the Subaru observations spotted a similar gravity wave and not an infrared manifestation of the Y-feature.

1.3   The mechanism of the Y-feature

Many analyses of the Y-feature attribute it to a Kelvin wave at the equator and Rossby waves at mid-latitudes. However, as discussed in Section 1.1, these wave types are impossible in the cyclostrophic regime of Venus' atmosphere, although waves

with Kelvin-like characteristics are possible. These solutions were arrived at due to simplifying assumptions such as neglecting horizontal wind shear and meridional circulation. In addition, there only appears to be a single equatorial Kelvin-like mode present in the Y-feature based on analysis of Venus Express data.[9]

Peralta, et al. presented a compelling analysis of the Y-feature in their 2015 paper. Previous studies of cyclostrophic regimes relied on numerical simulations that did not allow for easy interpretation of the results and could not reproduce the evolution of the Y-feature. Peralta, et al. analytically derived wave solutions that resemble Kelvin waves with the centrifugal force replacing the Coriolis force. When plotted and projected onto a sphere, the resulting waves correspond extremely well to Pioneer Venus images taken over the 30-day lifespan of the Y-feature and show subtle details never before captured in a model of the feature.

Chapter 2

Cloud-tracking

2.1 Thesis objective

The goal of this thesis was to make yearly profiles of zonal winds on Venus to better characterize the temporal variation of Venusian atmospheric dynamics. The end goal of this line of research will be to search for Kelvin-like waves as described by Peralta, et al. and contribute to the understanding of superrotation and the Y-feature. A good understanding of the long-term variations in the background zonal wind and the uncertainty of measurement will allow for these waves to be extracted from short-term data.

2.2 Venus Express data

During its nine years in orbit, Venus Express captured over 100,000 images in ultraviolet (345-385 nm) through nearly 3,000 orbits with the Venus Monitoring Camera (VMC). We have access to this entire set of images, which have been processed and mapped into a rectilinear projection by the Akatusuki mission team (see Figure 2.1). Venus Express had a polar orbit, which allowed it to map temperatures across the entire planet. However this orbit was not ideal for images of the Y-feature as most images only cover the southern hemisphere and do not show the entire feature.

Thus photos from ground-based telescopes are helpful to confirm the presence of the Y-feature as it is a transient phenomenon.

2.3 Correlation Image Velocimetry

To determine the zonal wind profiles of Venus, we used two-dimensional Correlation Image Velocimetry (CIV), a type of automated cloud-tracking. The basic programs were written in IDL by graduate students John Blalock and Ryan McCabe at Hampton University. The advantage of this particular implementation of CIV is that it is entirely automated – most previous wind tracking methods have used manual or both manual and automated pair selection and cloud-tracking. Our data pipeline is also streamlined, which allows for years of data to be easily run, with the only limiting factor being computing power.

The first step of CIV is finding image pairs. The program searches for a two images that have similar coverage and an acceptable time separation (between 90 minutes and 6 hours). The Sobel edge-detection algorithm is used to minimize imaging and processing artifacts. Image pairs that return fewer than 1,000 wind vectors are excluded and discontinuities in the vector field are removed with a low-pass filter.

Given a suitable image pair, the program will attempt to find the position of the same cloud features in both images and calculate the resulting wind vector. The program focuses on one small subwindow of the image at a time, shifting it east, west, north, and south to find the part of the subsequent image that most closely correlates to the features within it (see Figure 2.2). The amount that the program moves the sub-window for this search is constrained by bootstrapping to the zonal profile found by Khatuntsev and Patsaeva, et al. using manual wind tracking of Venus Express images.[10] This way vectors that are inordinately far off the expected profile as a result of spurious correlation with a different, but similar-looking feature
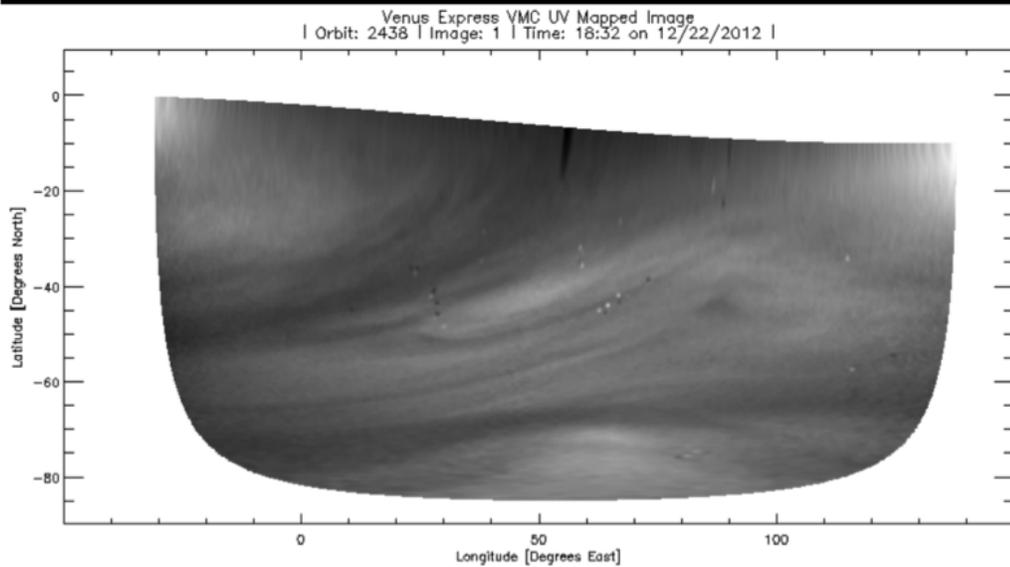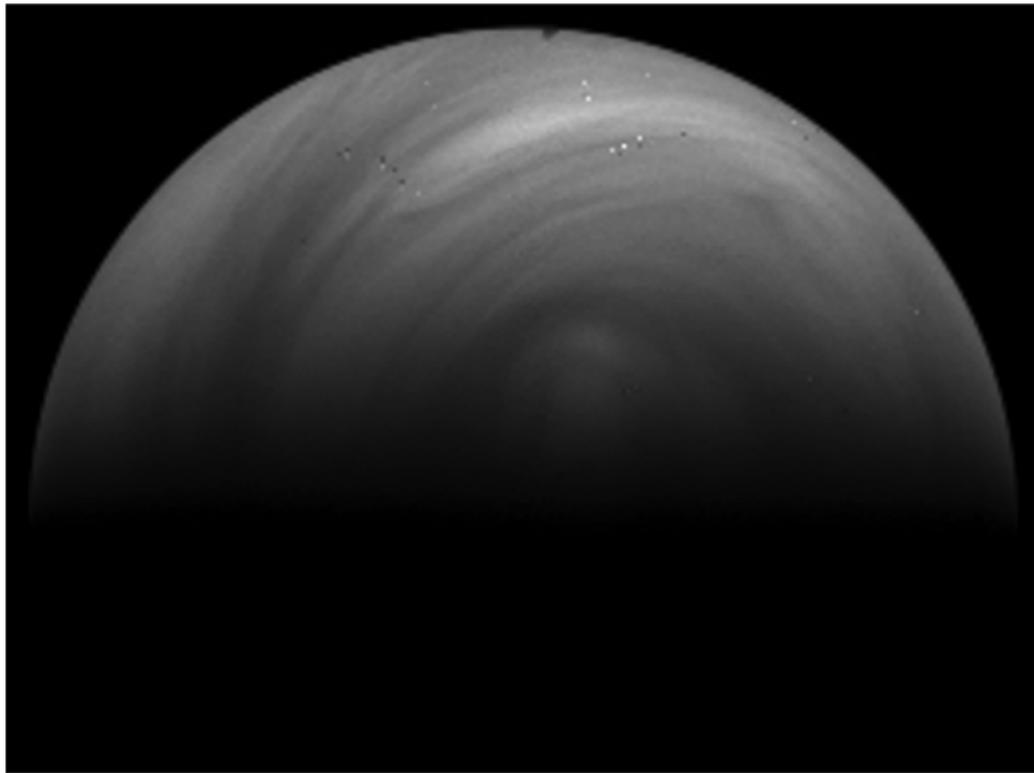
Figure 2.1: A representative ultraviolet image from Venus Express. The top image is a raw image from the VMC, and the bottom plot is the same image, but converted to a rectilinear projection. Several image artifacts are visible as white pixels and black streaks. (ESA/Ryan McCabe)
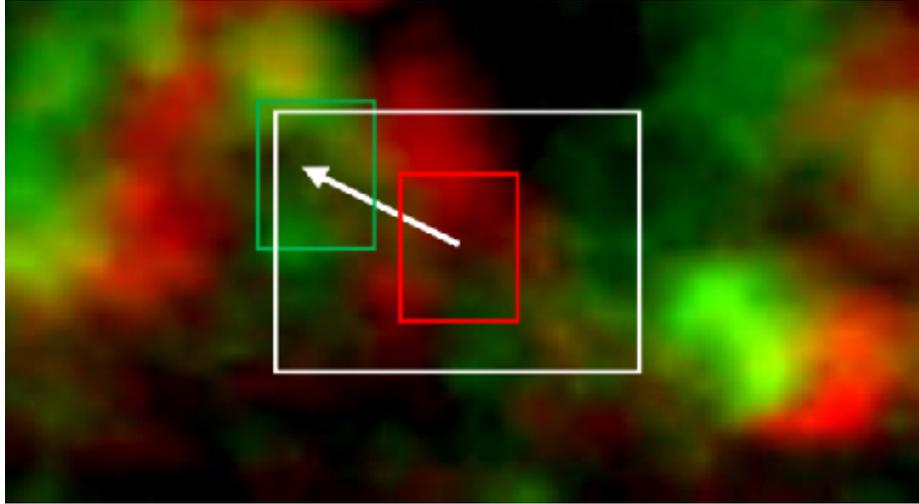
Figure 2.2: This image illustrates a hypothetical CIV measurement. The first image (red) is being correlated with the second (green). The green subwindow box is moved around the white search box until it reaches a maximum correlation value with the red subwindow box. Once the value for maximum correlation is found, the wind vector (the white arrow) can be drawn. (John Blalock)

are not calculated. Once the program finds the peak correlation, it can calculate a wind vector. This process is repeated across the entire image to build up the vector field.

Winds can then be broken into their components along latitude and longitude to create zonal and meridional wind plots, respectively, of the entire planet. A measure of uncertainty is calculated by taking the standard deviation of all wind vectors along a certain latitude or longitude, which is simple to compute and interpret, but does not distinguish between uncertainty in measurement and real spatial variation over a certain latitude. The standard deviation method of uncertainty calculation is commonly used in previous studies using wind-tracking.

2.4 Improved cloud-tracking and uncertainty calculation

A new CIV method, developed by John Blalock, seeks to separate uncertainties and real spatial variation. When the program searches for the peak correlation it builds up a correlation field, a contour map of correlation value vs. position. Normally these correlation fields are discarded as soon as the program is finished with them, but if they are saved and analyzed, they can yield a more accurate wind vector and uncertainty.

While a standard CIV program draws wind vectors based solely on the single highest correlation value – the "peak" – this new method takes the contours of the correlation field into account to extract more information about the correlation. The values for correlation run between -1.0 and 1.0, with 1.0 being perfect correlation. A threshold is set for correlation, 0.9 for example, and an ellipse is fitted to all areas above the threshold. Multiple areas above the threshold are possible in a single correlation field, but typically there is only one. This more naturally generalizes the single pixel peak to a peak area and the size of the ellipse indicates the uncertainty in measurement (see Figure 2.3).

The wind vector can be calculated two ways from the ellipse: the "center of mass" of the ellipse (the geometric center) or the "center of gravity", a weighted average taking into account the correlation values inside the ellipse (or the peak value can be used and the ellipse would only serve to measure uncertainty). Uncertainty is measured by calculating the zonal and meridional distance between the furthest extent of the ellipse in those directions and the wind vector. Asymmetries in the north-south or east-west distances can give information about measurement bias or real variation that would otherwise be swept under the rug with the standard deviation uncertainty
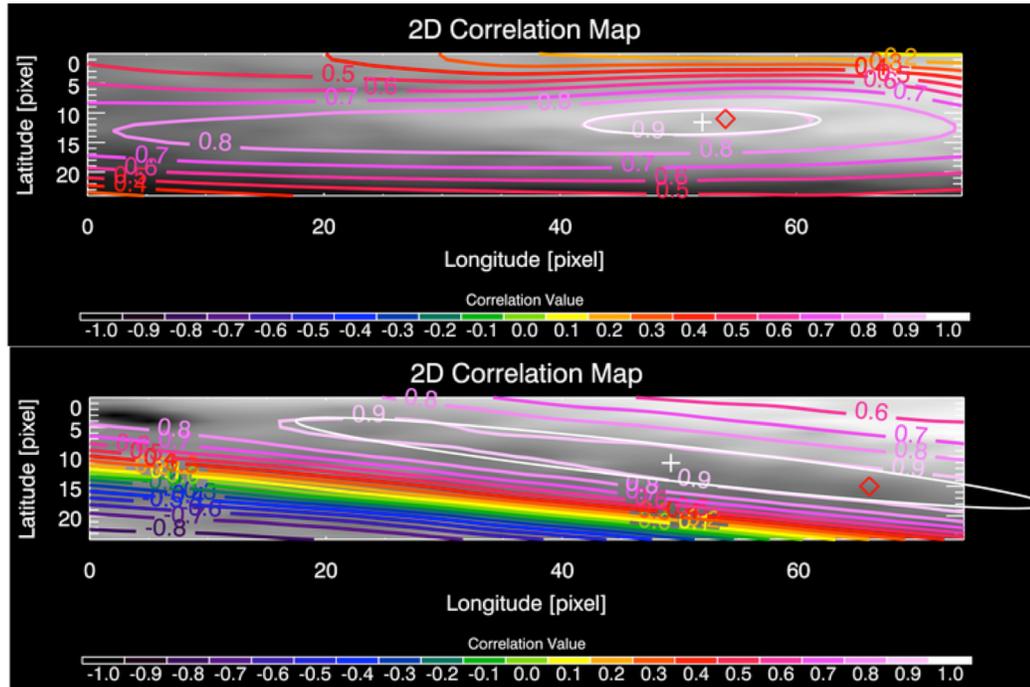
Figure 2.3: Two representative correlation fields. The correlation contours are overlaid over the (black and white) Venus Express image. A white ellipse has been fitted over the areas above the threshold correlation value (0.9 here). The red diamond is the peak correlation and the cross is the center of mass of the ellipse. Both plots, especially the bottom one, show the large zonal uncertainties typical of the streaky Venusian atmosphere.

calculation. If there are periodic features, like with waves, there can be multiple regions of high correlation, which show up as anomalous variation.

To detect wave-like behavior, the residual velocities can be analyzed after the mean wind field is subtracted. If the uncertainties calculated by the cloud-tracking program are larger than these residual velocities, either the limit of the image analysis has been reached or there are no significant waves.

The program using the new cloud-tracking technique has been used successfully to analyze data from the Cassini spacecraft orbiting Saturn. We have adapted this code to work with Venus Express data.

Chapter 3

Observations with ground-based telescopes

3.1 Complement to spacecraft images

Ground-based images are very useful to compare with images from Venus Express due to the spacecraft's incomplete coverage of the planet. Earth-based telescopes can always image pole-to-pole in latitude so that the presence of the Y-feature can be more confidently confirmed than with Venus Express images alone. Over 300 ultraviolet, visible, and infrared images taken by amateur astronomers taken during the Venus Express mission are available from ESA's Venus ground-based image Active Archive (VAA).[11]

The main limitations of ground-based imaging are the atmosphere and the geometry of the orbits of Venus and Earth. Atmospheric scintillation caused by high-altitude turbulence limits the resolution of Earth-based telescopes to about 0.4 arcseconds under exceptional conditions. Adaptive optics can reduce this resolution limit significantly but are only available on large telescopes and rarely used for planetary imaging. However, through lucky imaging – taking many photos and selecting the ones least affected by scintillation – and stacking – combining multiple images into a smooth image that can be highly sharpened – ground-based observations can yield

images sharp enough for analysis of large-scale atmospheric dynamics.

Due to Venus' orbit being interior to Earth's, the planet is at maximum 45 degrees above the horizon and often lower. Thus observations can only be carried out for a few hours around dusk or dawn before the airmass becomes too high for useful data (around airmass 6). In addition, Venus is only fully illuminated when it is at its smallest angular size and close to the sun in the sky, so all observations must be made with only a portion of the disk illuminated. However, mid-infrared images do not suffer this problem as they rely on thermal emissions from the planet itself instead of reflected sunlight.

In addition to using previously obtained images, we took images of Venus using the Astrophysical Research Consortium (ARC) 3.5-meter Telescope at the Apache Point Observatory (APO) in Sunspot, New Mexico through a collaboration with Dr. Candace Gray - from New Mexico State University - and Dr. Kevin McGouldrick - from the University of Colorado Boulder.[12]

Our images were taken using ARCTIC (Astrophysical Research Consortium Telescope Imaging Camera), a CCD camera capable of imaging from 300 nm to 1,000 nm.[13] We also intended to use NICFPS (Near Infrared Camera and Fabry-Perot Spectrometer) for observations between 900 nm and and 2,150 nm.[14] Using a broad range of wavelengths allows several atmospheric layers to be studied (see Table 3.1).

3.2 Apache Point Observatory

The observing window was chosen to so that simultaneous observations could be done with Akatsuki. This will provide better understanding of how the Y-feature appears in different wavelengths and help with future analysis of Akatsuki data. The range of wavelengths and simultaneous observation could allow for the measurement of vertical wind shear, which could also be used to detect equatorial Kelvin-like waves.

Wavelength	Atmospheric Layer
350 nm	65 km (cloud tops)
900-1000 nm	60 km (top deck)
1,100 nm	0 km (surface)
1,270 nm	15-30 km
1,310 nm	30-50 km
1,740 nm	10-30 km
2,200 nm	~ 65 km (cloud top heights)
2,320 nm	25-40 km

Table 3.1: While near-ultraviolet wavelengths allow the study of the cloud tops due to the presence of the ultraviolet abosrber, a range of infrared wavelengths show different cloud layers for the observation of deeper atmospheric phenomena.

In addition, observing from two different phase angles will provide constraints on the unknown ultraviolet absorber.

3.3 December 2017 APO observing run

During five nights – 19-23 December 2017 – we collected images of Venus to determine if the Y-feature was present. Two nights were cloudy, which we used to take calibration images. This first observing run would also be used as a trial run as planetary imaging is not often done on APO's 3.5-meter Telescope.

The large aperture of the telescope proved to be somewhat of an obstacle. Because Venus is so bright, it would saturate the CCD on the minimum exposure time. Shorter exposure times on the CCD may have been possible, but the physical shutter limited it to 0.1 seconds. For the first night we had to duct-tape a neutral density filter on the front of ARCTIC.

In order to calibrate our images of Venus, which is illuminated by the sun – a G2V star – we collected images of bright G2V and A0V standard stars (i.e. stars with low variability) at the same time and airmass as our Venus images. Even with a 3.5-meter aperture, the neutral density filter made it difficult to collect enough light

on magnitude 4 stars.

Dark frames, dome flats, and bias flats were all taken to properly calibrate the light images we collected. The neutral density filters lengthened some dome flat exposures to over ten minutes, which is undesirable but unavoidable.

We used SDSS (Sloan Digital Sky Survey) filters: u' (300-400 nm), g' (400-550 nm), and z' (820-1200 nm). u' and z' were intended to be the primary filters for imaging Venus, while g' was only used for standard star calibration. After the first night, we determined the ideal exposure times and fitted neutral density filters of varying strength to individual filters which improved exposure times for calibration. Very low contrast cloud features may have been present in u' images, but z' showed a featureless disk, thus we exclusively used u' for all nights after the first. We decided to focus on ultraviolet images with ARTIC and did not use NCFIPS. See Section 4.2 for a discussion of the results of these observations.

Chapter 4

Results

4.1 Zonal profiles

Using the CIV method discussed in Section 2, we calculated the yearly zonal profiles for the full run of Venus Express data from 2006 to 2014. Only the first 50 images pairs for each orbit were used to reduce computing time (see Section 5.1). We also calculated meridional profiles, but zonal profiles are more relevant to the study of the Y-feature. Although in some years there were vectors found in the northern hemisphere, the data essentially only profiles the southern hemisphere where the vast majority of Venus Express images were captured.

As a result of Venus Express primarily imaging the southern hemisphere, there are very few wind vectors above about 10 degrees latitude, with the majority being found between -80 and 0 degrees (see Figure 4.1) Thus our zonal profiles should only be considered suitable between these latitudes.

In this region, we found a similar zonal profile to Khatuntsev et al. (see Figure 4.2). Our new method of uncertainty calculation overestimated the uncertainty relative to the standard deviation. Averaging the data from all seven years of data, the calculated uncertainty ranged from approximately 20 to 50 ms^{-1} while the standard deviation ranged from approximately 10 to 35 ms^{-1} (see Figure 4.3). As seen in Figure 4.2

the uncertainty envelope is larger than that of the standard deviation. The standard deviation envelope is comparable to that found by Khatuntsev et al. Uncertainty was lower than the standard deviation in the northern hemisphere, but this is likely due to there being several orders of magnitude fewer vectors in that hemisphere.

We also found yearly variations in the zonal winds between -45° and the equator (see Figure 4.4). Interestingly, this is exactly the zone in which the Y-feature is present. Equatorial Kelvin-like waves can accelerate and decelerate the mean flow, which may explain the variation in the profiles. A clear trend of increasing zonal velocity in this zone was observed over the eight-year data set. At maximum, this increase is approximately 20 ms^{-1}. Variation on a 100-day time-scale was seen by Kouyama et al. with similar uncertainties.[9]

Although the profiles suggest yearly variation, the variation is smaller or comparable to the uncertainty and the standard deviation. Thus the variation cannot be confirmed with certainty, although the trend of consistently increasing zonal velocity is highly suggestive that the variation is real. Further work is needed to determine long time-scale background profiles for a future search for Kelvin-like waves.

4.2 Ground-based observations

The images captured with APO's 3.5-meter Telescope are still in need of processing, but show very subtle cloud features that could be tracked. Figure 4.5 shows representative images taken at APO. The observing run was a valuable experience for future observations which may yield sharper images capable of being analyzed.
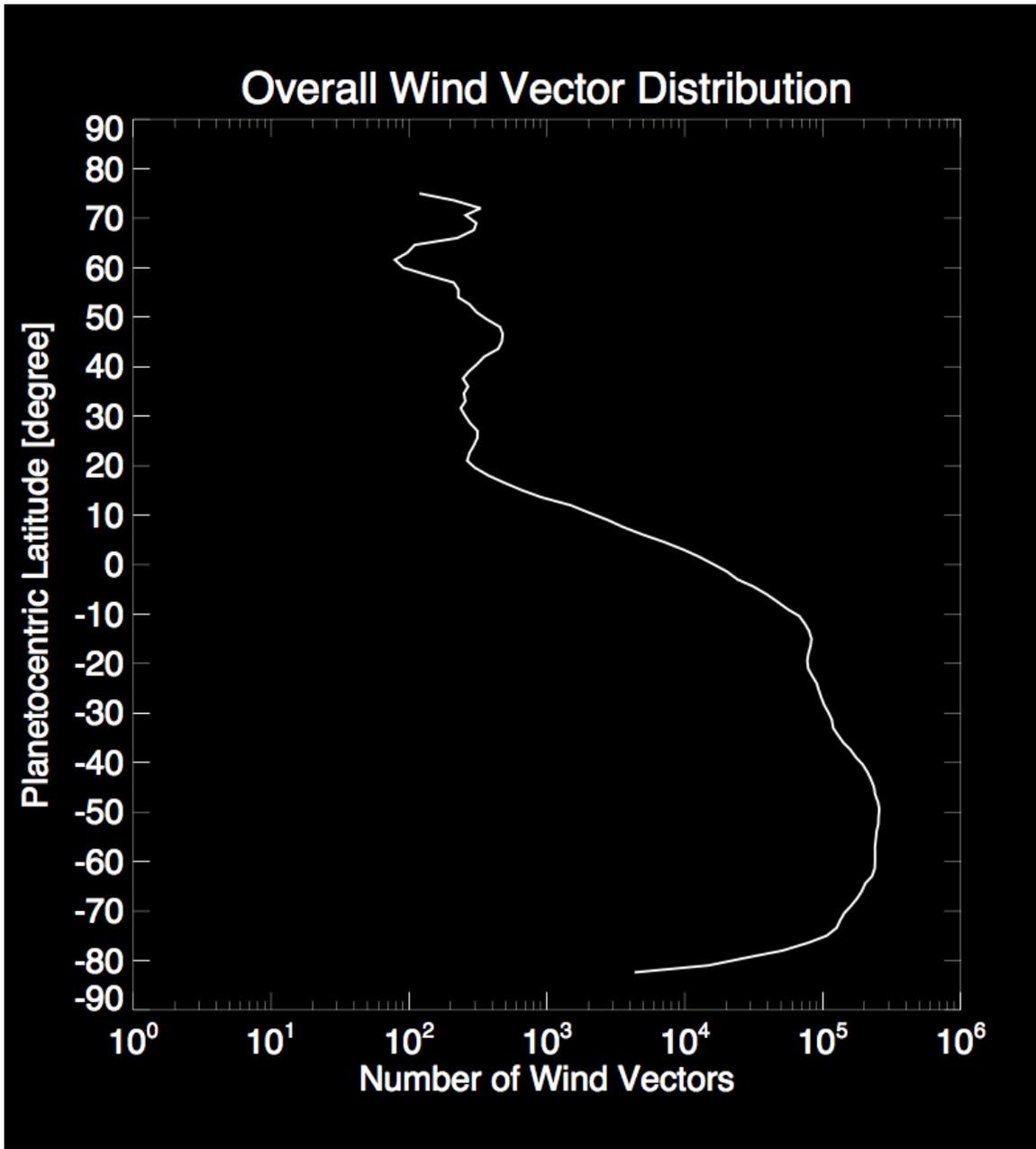
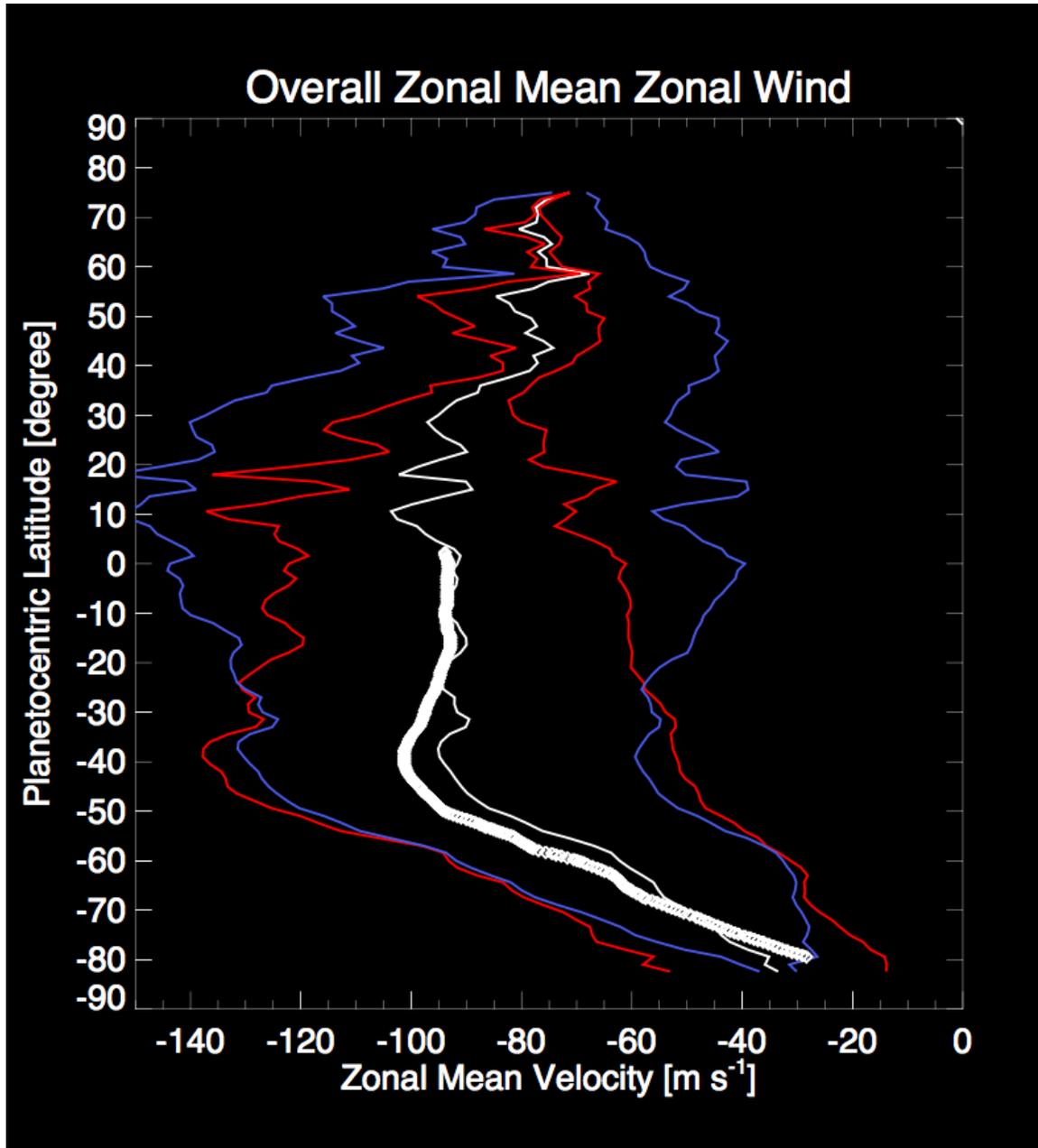Figure 4.1: Distribution of wind vectors vs. latitude.

Figure 4.2: **White diamonds**: Khatuntsev et al. profile, **white line**: wind measurement, **blue line**: standard deviation, **red line**: uncertainty. Only the bottom half of this plot is relevant as only the southern hemisphere (0 to -90 degrees) has enough wind vectors for sufficient measurements.
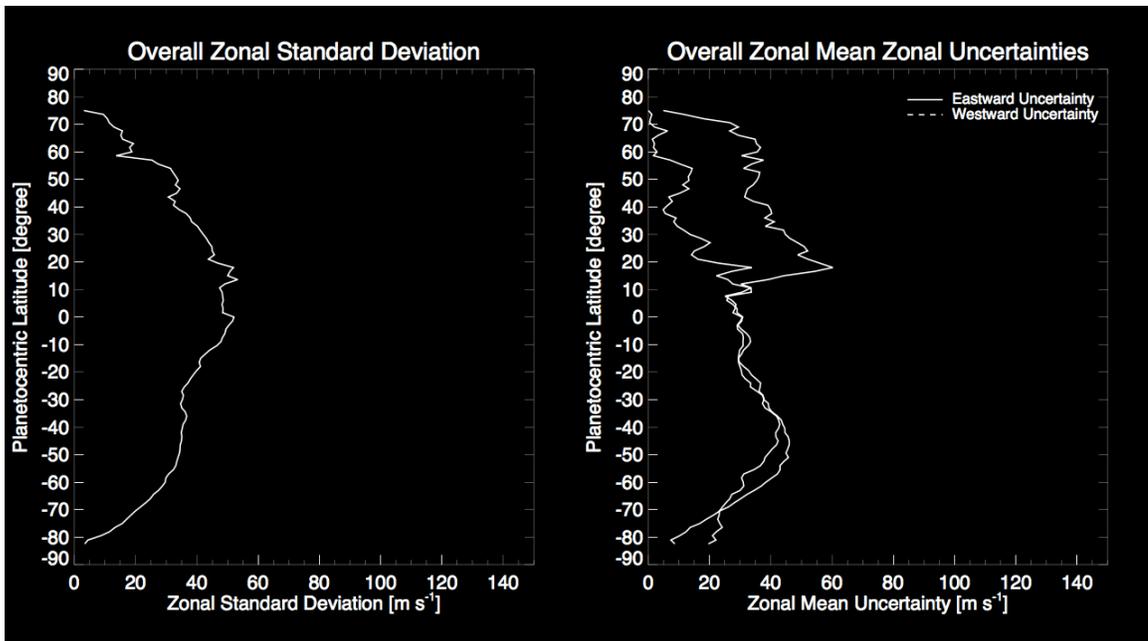
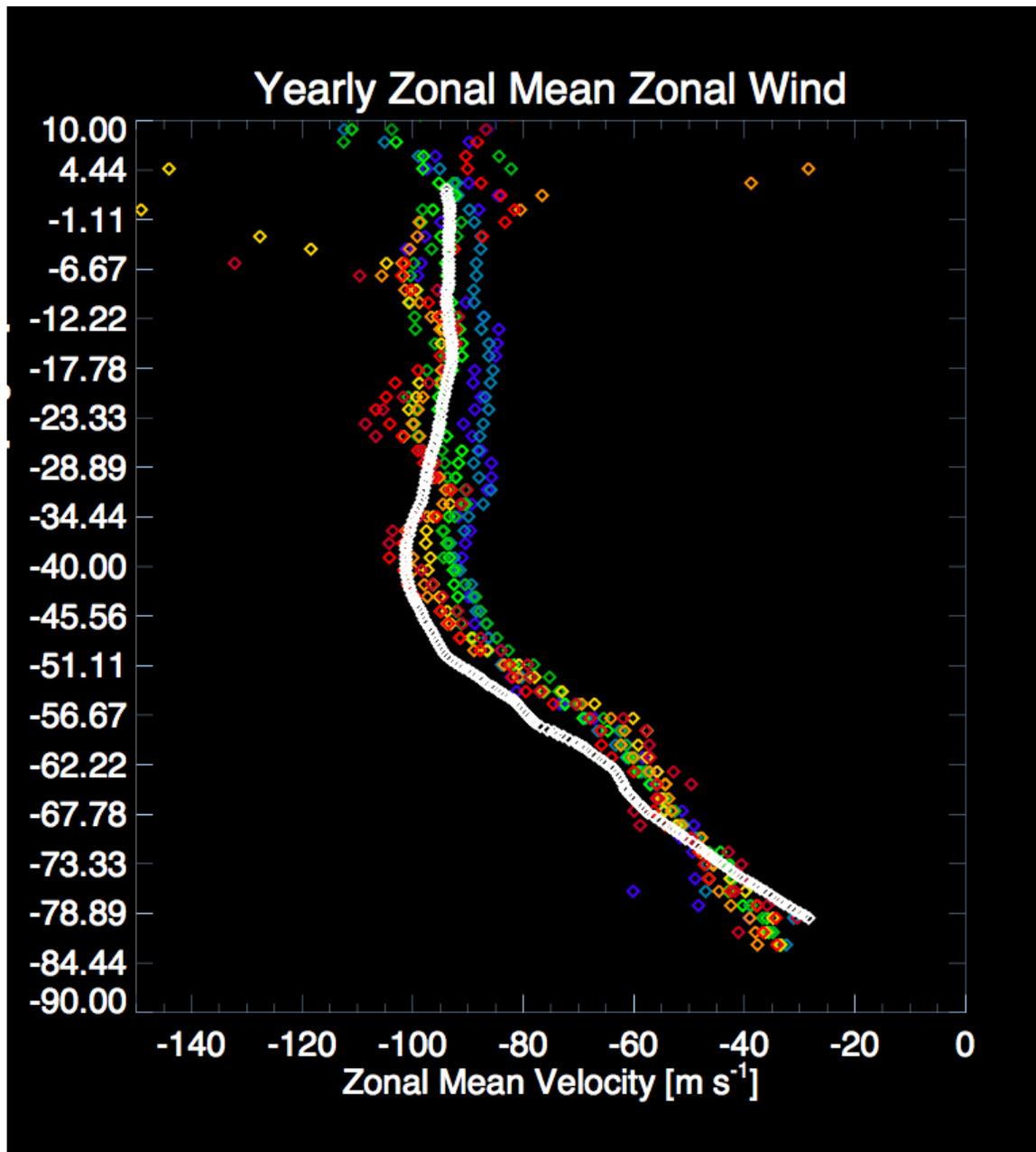Figure 4.3: Comparison of the zonal standard deviation and uncertainty.

Figure 4.4: The different yearly profiles are shown with diamonds colored with a red to blue spectrum, with bluer colors representing earlier years and redder colors representing later years. The white diamonds are the Khatuntsev et al. profile. Note the variation between -45° and 0° and the general trend of increasing velocity over the years.

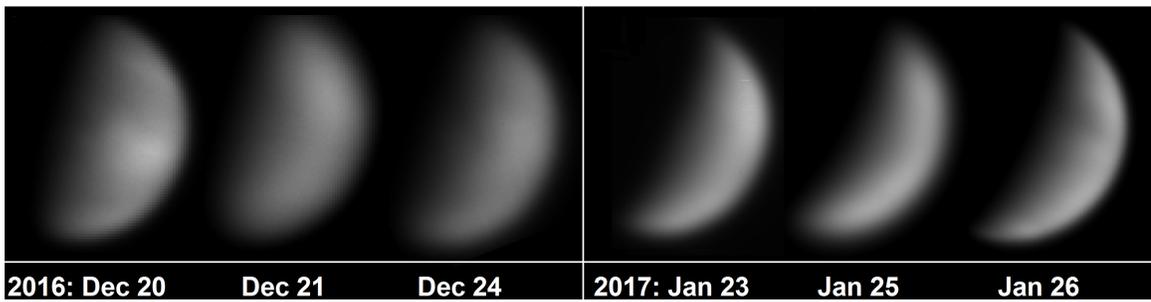**2016: Dec 20 Dec 21 Dec 24 2017: Jan 23 Jan 25 Jan 26**

Figure 4.5: These six images are representative of the hundredes of images taken with the u' filter on ARTIC with APO's 3.5-m Telescope. Note the significant change in the percent of the disk illuminated in just one month. Some light and dark bands can just be made out. (Ryan McCabe)

Chapter 5

Future Work

5.1   Reducing Uncertainty

There are several possible ways to reduce the uncertainty. Preliminary tests with large subwindow sizes have showed promising correlation fields with well-defined contours. We used 25x25 and 37x37 pixel subwindows our analysis, but we have experimented with 61x61, 81x81, and 101x101 subwindows. Larger subwindows may reduce uncertainty because they track large-scale motion. Most small-scale motion is present in streaky clouds, which have correspondingly streaky correlation fields and large uncertainties along the direction of the streaks. Loosely speaking, large-scale motion consists of movement of the streaks themselves, which produce better correlation fields. Additionally, the wind fields could be smoothed to reduce noise in the data.

Our data processing was significantly limited by computing power. To run a correlation of all orbits with small subwindows (25x25 or 37x37), a single CPU would take approximately 60 years. Using only the first 50 image pairs from a given orbit and running the correlations on 50 CPUs, it took one week to run. Large subwindows exacerbate this limitation. While increasing the size of subwindows decreases how many make up a given image, each correlation pair of subwindows takes longer to

run. For example a 101x101 subwindow takes approximately ten times as long as a 25x25 subwindow. A supercomputer is required to run the full data set on reasonable time scales. The computation time constraint also prevented any study of temporal variations on short time scales, which is necessary for detecting waves.

The Venus Express images themselves could potentially be more carefully selected and possibly reprocessed. Many images taken by Venus Express are unusable due to poor coverage of the planet and have been removed. Artifacts like black streaks and white spots (likely hot pixels) are present in some images, which may be a result of incomplete or incorrect processing. More subtle streaks in image brightness are also visible in some images, possibly due to the projection process as the streaking is often most prominent near the poles. Some particularly artifacted images have been automatically removed, but others may have made their way into the data pipeline. Reprocessing from the raw images could potentially remove some artifacts and lead to better correlation fields and hence decrease uncertainty overall.

If uncertainty in zonal wind measurements is reduced significantly over the standard deviation, the search for the Y-feature's Kelvin-like waves that may drive superrotation can begin. When a background wind profile can be confidently extracted from the data, the residual motion on short time scales (on the order of hours and days) can be analyzed for periodicities that would indicate waves. The uncertainties calculated during the analysis of the background wind fields compared with the velocity amplitudes of any detected waves would indicate if Venus Express' data is sufficient to detect these waves.

5.2 Future data

Akatsuki data should become available in the summer of 2017 in the same format as that from Venus Express. Despite its eccentric orbit, Akatsuki will be better suited

to our purposes because its orbit is close to equatorial and thus will show the entire Y-feature, or at least full latitudinal coverage where we would expect to find it.

Our ground-based observations have not yet resulted in any images sharp enough to be projected and analyzed for wind measurements. However, suitable images may be made after stacking and further processing. Improved observational techniques will also increase image quality. An important aspect of ground-based observations is the phase of Venus as seen from Earth, which we had not expected to be as important as it turned out to be. Our second run of observations at Apache Point in January 2017 resulted in less desirable images than our December 2016 run because less of Venus was illuminated. Thus the phase of Venus will have to be carefully considered when planning future observations.

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