

**Year 1 Report on NASA Award Number NNX09AE85G**

INVESTIGATION OF THE VENUS ATMOSPHERIC DYNAMICS  
FROM VMC AND VIRTIS INSTRUMENTS ON VENUS EXPRESS

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## 1. INTRODUCTION

This is the Year 1 Progress Report on NASA Grant NNX09AE85G (Venus Atmospheric Dynamics from VMC and VIRTIS Instruments on Venus Express). The Venus Monitoring Camera (VMC) continues to function well and is collecting images of Venus in all filters. The Visible InfraRed Imaging Spectrometer (VIRTIS) has suffered a cooler failure and is not currently acquiring mapping data in the near infrared.

Processed VMC images have been retrieved from the VMC Team. The flat-fielding of the images requires that the on-orbit flats be acquired using Venus cloud cover as the target when at close approach when the image contrast is negligible due to the very high spatial resolution. Processing of these “flats” takes a few days when the final processed Level 2 version (.01) is available. DLR also provides mapped products (Level 3) although these are not used in the data analysis done at University of Wisconsin.

## 2. PROGRESS MADE DURING YEAR 1

Progress was made on all areas of investigation proposed and is described below with some highlights.

### 2.1 HIGHLIGHTS

Two papers were published in refereed journals during this period. The first one described the work begun previously on the structures seen in the polar regions of Venus in ultraviolet and near infrared data.

- Limaye, S. S., J. P. Kossin, C. Rozoff, G. Piccioni, D. V. Titov, and W. J. Markiewicz, 2009, Vortex circulation on Venus: Dynamical similarities with terrestrial hurricanes, *Geophys. Res. Lett.*, 36, L04204, doi:10.1029/2008GL036093.

This paper on the dynamical instability in the polar region of Venus as determined by a model simulation based on the cloud tracking data was published in *Geophysical Research Letters* and the print issue highlighted the paper on the cover with a composite picture of the Venus vortex and Hurricane Frances (Figure 1).

*Figure 1. Geophysical Research Letters cover highlighting the paper on vortex circulation on Venus.*

The second paper describes the cloud motions using the visual tracking results from the VMC images (Moissl et al.). The tracking was done at University of Wisconsin by R. Moissl as part of his Ph.D. research. He also successfully completed the research and earned his degree from Branschweig University in Germany. I served as one of the mentors for him.



- Moissl, R., I. Khatuntsev, S. S. Limaye, D. V. Titov, N. I. Ignatiev, T. Roatsch, K.-D. Matz, R. Jaumann, M. Almeida, G. Portyankina, T. Behnke, S. F. Hviid, (2009), Venus cloud top winds from tracking UV features in Venus Monitoring Camera images, *J. Geophys. Res.*, 114, E00B31, doi:10.1029/2008JE003117.

## 2.2 VMC OBSERVING SEQUENCE PLANNING

VMC has been acquiring images on most orbits since the operational phase began in late May 2006. Coverage has been obtained at all four wavelengths. In the initial orbits the exposures were varied to arrive at optimum signal level and contrast in the data. Global scale images were obtained from apoapsis portion and small-scale images at much higher resolution ( $\sim 200$  m) were taken on some orbits near the periapsis passage, along with the some images of the planetary limb.

One aspect of when and how the VMC images are acquired during the Venus Express orbit that has had an adverse effect on the cloud tracking has been that bulk of the images are acquired in the post-apoapsis portion of the orbit. This results in the images with a pixel size  $> 35$  km/pixel which has an adverse effect on the cloud tracking in that the time required needs to be longer than one hour for sufficient accuracy in the zonal component (it is not adequate for meridional component at all). To ameliorate this, I suggested that VMC acquire a few images when the spacecraft is closer to the planet by using the pointing ability of the spacecraft to take multiple images at different pointing of the spacecraft when the planet is larger than the field-of-view of the VMC. Figure 2 illustrates the strategy that was recommended to the Venus Express Science Operations Center (VSOC) at the December 2008 VMC Team meeting in Katlenberg-Lindau. Orbits 1108-1110 were the first ones when this imaging strategy was adopted and the results of cloud tracking show that this strategy was very useful and productive. Sample results of the cloud tracking are shown in Figure 3 (below).

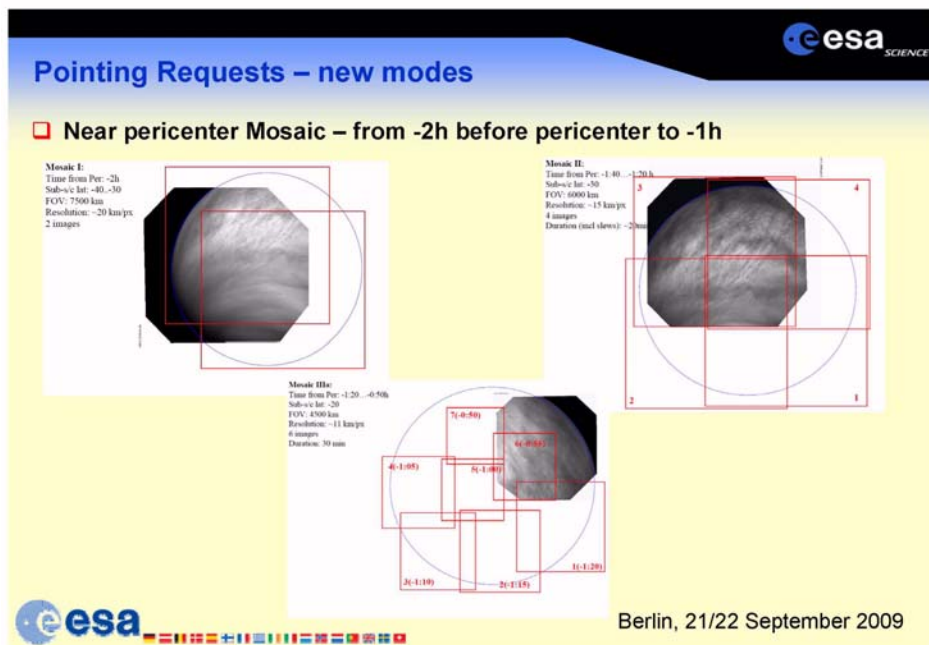


Figure 2. Three mosaics to be acquired by pointing the spacecraft when closer to the planet, later than the normal imaging mode. Such images were acquired in May 2009.

This mode has been recommended for implementation in future planning of observations to be acquired by VMC.

### 2.3 DIGITAL TRACKING OF IMAGES

Tracking of cloud features in processed VMC images from recent orbits is continuing with small updates to the tracking procedure. Figure 3 shows an example of the mosaic frames obtained at somewhat higher spatial resolution through controlled pointing of the Venus Express spacecraft about the nadir direction (nominal mode).

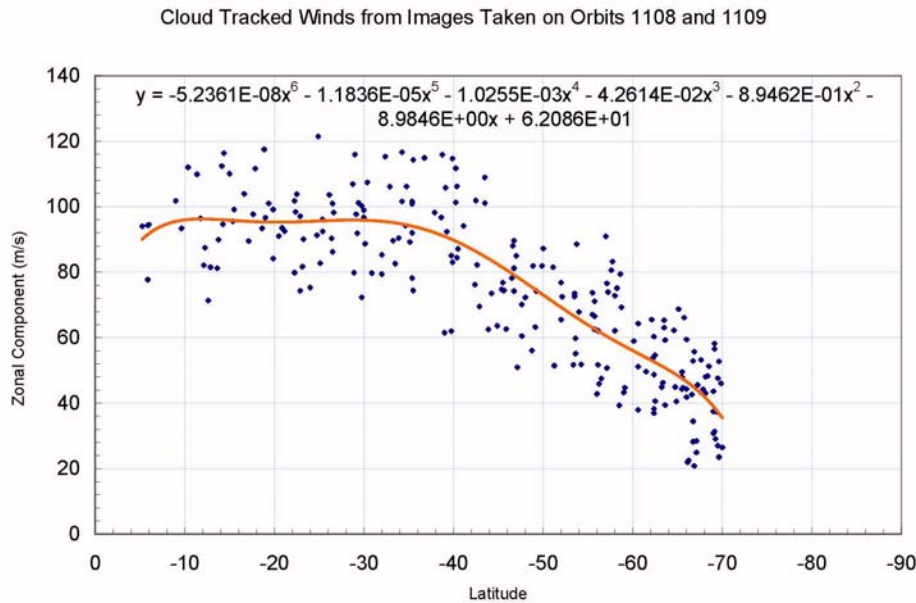


Figure 3. Zonal component of cloud motions obtained from image triplets with one hour spacing from the targeted mosaic sequence on orbits 1108 and 1109

### 2.4 GLOBAL STRUCTURE OF THE ATMOSPHERIC CIRCULATION

Since VMC images Venus in reflected sunlight, only the sun-lit hemisphere can be imaged. To provide some idea of a global view of the planet, the measured motions can be used to create a time-lapse composite view in a polar projection by rotating selected images through an angle determined by a representative rotation rate (~ 3.6 deg/hour) and the time interval between successive images. Figure 4 shows an example of such a space-time composite generated from images acquired over three consecutive orbits (orbits 443-446).



Figure 4. A draft image of a space-time composite view of the southern hemisphere of Venus generated by compositing selected VMC images from three successive orbits.

The images were remapped into a polar stereographic projection and the normalized using the Minnaert law to remove the effect of varying illumination and viewing geometry. The idea is to generate a composite by sliding over the images orbit by orbit to make a long animation using most of the VMC images acquired by the VMC to depict the temporal changes in the evolution of the vortex organization over a long time.

### 3. TEAM/SCIENTIFIC MEETINGS AND CONFERENCE PRESENTATIONS

I participated in several scientific conferences as well as VMC and Venus Express Team meetings either in person or by telephone and made presentations on my work. The table below lists the presentations made

Table 1. VMC/Venus Express Team Meetings and Conference presentations

<b>Date</b>	<b>Meeting</b>	<b>Topic/Presentation</b>	<b>Presenter/Authors</b>
March 23-27, 2009	40th Lunar and Planetary Science Conference, Woodlands, Texas	Vortex Circulation of Venus	S.S. Limaye
March 23-27, 2009	40th Lunar and Planetary Science Conference, Woodlands, Texas	A Venus Flagship Mission: Report of the Venus Science and Technology Definition Team	Bullock et al. and the Venus Science and Technology Definition Team
March 23-27, 2009	40th Lunar and Planetary Science Conference, Woodlands, Texas	In-Situ Exploration of Venus by Balloon -- Science Objectives and Mission Architecture	Baines, K. H., Atreya, S. K.; Crisp, D.; Hall, J. L.; Kerzhanovich, V. V.; Limaye, S. S.; Zahnle, K.
September 21-22, 2009	VMC Team Meeting, Berlin, Germany	Observation Planning, Data Analysis Status	By Telephone
14-18 September 2009	Europlanets Conference, Potsdam, Germany	Observations of Small-scale wave-like features in VMC images	R. Moissl, J. Borchert, W.J. Markiewicz, D.V. Titov, S. J. Limaye and the VMC Team
September 21-22, 2009	VMC Team Meeting	Venus Atmospheric Circulation: An update	S.S. Limaye
April 2009	European Geophysical Union Meeting, Vienna, Austria	Status of Venus Atmospheric Circulation from Venus Express – VMC Results	S.S. Limaye
October 14-18, 2009	41 <sup>st</sup> Annual Meeting of the Division for Planetary Sciences, Fajardo, Puerto Rico	Venus Atmosphere Observed by the Venus Monitoring Camera on Venus Express	Limaye, S.S., Markiewicz, W. J., Titov, D., Moissl, R., and the VMC Team
November 11-13, 2009	Venus Express SWT # 23	Participated by telephone	S.S. Limaye

## 4. EDUCATION AND PUBLIC OUTREACH EFFORTS

I participated in several activities for Venus Express and supported the Venus (see table below) Express/NASA URL for Education and Public Outreach Program (venus.wisc.edu) led by Ms. Rosalyn Pertzborn. The activities are listed below:

- 1) 7 Jul 2009, Astrobiology Learning Institute for Instructors (ALI'I), University of Hawaii, Honolulu, Hawaii USA  
Presented the Venus cloud tracking curriculum and a presentation on habitable worlds and conducted Venus Cloud tracking Curriculum training for teachers.  
Dr. Sanjay Limaye
  - 2) 9 May 2009, Madison Astronomical Society Monthly Meeting Lecture Solar System Exploration Update.
  - 3) 28 February 2009, Science City, Ahmedabad, Gujarat India  
Presented a "Exploration of Venus with Venus Express"
  - 4) 6 April 2009, Seminar at Massachusetts Institute of Technology Dept. of Atmospheric Science (Cambridge, MA USA)  
Venus Atmospheric Circulation
  - 5) 24 Feb 2009  
IYA 2009 Public Lecture followed by sky gazing, Nehru Planetarium, New Delhi, India  
Unveiling Venus  
Dr. Sanjay Limaye
  - 6) 5 Feb 2009, Visiting Scientist and Classroom Activity (in 6 classes), McKinley Middle School Honolulu, HI, USA
  - 7) Lecture / Venus Images Hands- On Cloud Tracking Activity  
Dr. Sanjay Limaye and Hsuan-Yun Pi
  - 8) 2 Feb 2009, Visiting Scientist and Classroom Activity (in 5 classes, grade 9-12), Kamehameha High School, Kea'au, Hawaii USA  
Hands-On Tracking Clouds on Venus and presentation on Venus Express Mission  
Dr. Sanjay Limaye and Hsuan-Yun Pi
  - 9) 30 Jan 2009, , Lihue, Hawaii USA:  
Astronomy and Astrobiology Workshop and IYA 2009 Activities and Lectures:  
Unveiling Venus  
Why Study the Planet Venus  
Tracking Clouds on Venus  
Dr. Sanjay Limaye
  - 10) Provided input for a web story, "Weather on Venus" (venus.wisc.edu) following the discovery of a bright spot on Venus in amateur images of Venus taken on 19<sup>th</sup> July 2009, the same day a comet impact occurred on Jupiter. A screen image of the web story is shown in Figure 5.
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News Features

Weather on Venus?

On July 19, 2009, Frank Melillo took a picture of Venus through an ultraviolet filter from his backyard in Holtsville, New York state and saw a bright spot near the limb, almost at the same time as the first picture of the recent impact on Jupiter taken by an amateur in Australia (Anthony Wesley). Frank was imaging Venus based on an alert to the amateur astronomers put out through ALPO (Association of Lunar and Planetary Observers) that some Venus volcanoes were going to be approaching the terminator.

Surprisingly, Frank's image (Figure 1) showed a brighter than usual spot in the southern hemisphere, far away from the volcanoes. The bright spot in Frank's image and two others were also captured in an image taken about 10.5 hours earlier by George Tasourdis (Figure 1, right image)

Fortunately, the Venus Monitoring Camera (VMC) built at the Max Planck Institute for Solar System Research (Katlenburg-Lindau, Germany) for European Space Agency's Venus Express Orbiter was monitoring Venus during this period. VMC images on July 19th indeed show about 30% brighter than usual "spot" ~1000 km in size located at ~50°S (Figure 2). This bright region appears in one of the southern streaks seen almost every day on Venus which characteristically spirals towards the pole as a part of hemispheric vortex centered on the pole.



Figure 1. Amateur images of Venus taken by Frank Melillo and Paul Maxson compared (left) on July 20, 2009 and George Tasourdis (right) on July 19, 2009 showing brighter than usual clouds in ultraviolet light.

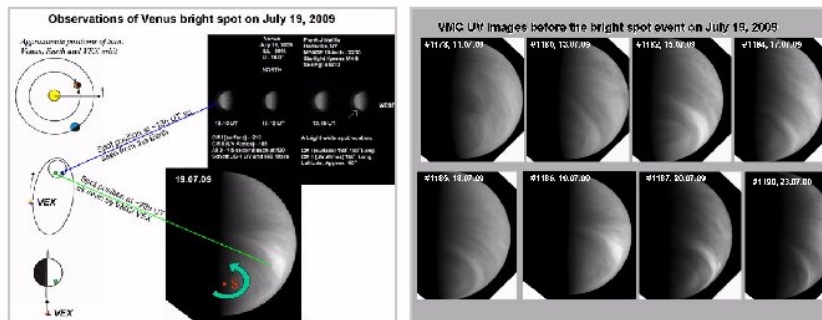


Figure 5. A screen image of the web story on the sudden appearance of a bright cloud on Venus (venus.wisc.edu).

5. PUBLICATIONS AND CONFERENCE PRESENTATIONS

Bullock, M. A.; Senske, D. A.; Balint, T. S.; Benz, A.; Campbell, B. A.; Chassefiere, E.; Colaprete, A.; Cutts, J. A.; Glaze, L.; Gorevan, S.; Grinspoon, D. H.; Hall, J.; Hashimoto, G. L.; Head, J. W.; Hunter, G.; Johnson, N.; Kerzhanovich, V. V.; Kiefer, W. S.; Kolawa, E. A.; Kremic, T.; Kwok, J.; Limaye, S. S.; Mackwell, S. J.; Marov, M. Y.; Ocampo, A.; Schubert, G.; Stofan, E. R.; Svedhem, H.; Titov, D. V.; Treiman, A. H., 2009, A Venus Flagship Mission: Report of the Venus Science and Technology Definition Team 40th Lunar and Planetary Science Conference, (Lunar and Planetary Science XL), held March 23-27, 2009 in The Woodlands, Texas, id.2410, 2009LPI...40.2410B.



Baines, K. H.; Atreya, S. K.; Crisp, D.; Hall, J. L.; Kerzhanovich, V. V.; Limaye, S. S.; Zahnle, K. , 2009. In-Situ Exploration of Venus by Balloon -- Science Objectives and Mission Architecture, 40th Lunar and Planetary Science Conference, (Lunar and Planetary Science XL), held March 23-27, 2009 in The Woodlands, Texas, id.1238, 2009LPI...40.1238B

S. Limaye, W. Markiewicz, D. Titov, and R. Moissl, 2009. Vortex Organization and the Cloud Level Circulation from Venus Monitoring Camera Observations from Venus Express, EGU2009-9412, European Geosciences Union, Vienna, Austria, 19-24 April, 2009.

Limaye, S.; Markiewicz, W. J.; Titov, D.; Moissl, R.; VMC Team, 2009. Venus Atmosphere Observed by the Venus Monitoring Camera on Venus Express, DPS meeting #41, #48.06, American Astronomical Society, Fajardo, P.R.

S. Limaye, W. Markiewicz, D. Titov, R. Moissl, and I. Khatuntsev, 2009, Venus Atmospheric Circulation from VMC Observations, EPSC2009-751, European Planetary Science Congress, 13-18 September 2009, Potsdam, Germany.

Limaye, S. S. , Vortex Circulation of Venus, 40th Lunar and Planetary Science Conference, (Lunar and Planetary Science XL), held March 23-27, 2009 in The Woodlands, Texas, id.2564, 2009LPI, 40.2564L

Moissl, R., I. Khatuntsev, S.S. Limaye, D.V. Titov, W.J. Markiewicz, N.I. Ignatiev, T. Roatsch, K.-D. Matz, R. Jaumann., M. Almeida, G. Portyankina, T. Behnke, S.F. Hviid, 2009, Venus cloud top winds from tracking UV features in Venus Monitoring Camera images, *J. Geophys. Res.*, 114, E00B31, doi:10.1029/2008JE003117.

R. Moissl, J. Borchert, W. J. Markiewicz, D. V. Titov, and S. S. Limaye  
Observations of Small-scale wave-like features in VMC images, EPSC2009-358, European Planetary Science Congress, 13-18 September 2009, Potsdam, Germany.

Limaye, S. S., J. P. Kossin, C. Rozoff, G. Piccioni, D. V. Titov, and W. J. Markiewicz (2009), Vortex circulation on Venus: Dynamical similarities with terrestrial hurricanes, *Geophys. Res. Lett.*, 36, L04204, doi:10.1029/2008GL036093.

W.J. Markiewicz, E. Petrova, D. Titov, N. Ignatiev, S.S. Limaye, R. Moissl, H.U. Keller, T. Roatsch, and K.D. Matz, 2009. Morphology and droplet sizes of the upper clouds of Venus, EPSC2009-720, European Planetary Science Congress, 13-18 September 2009, Potsdam, Germany.

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