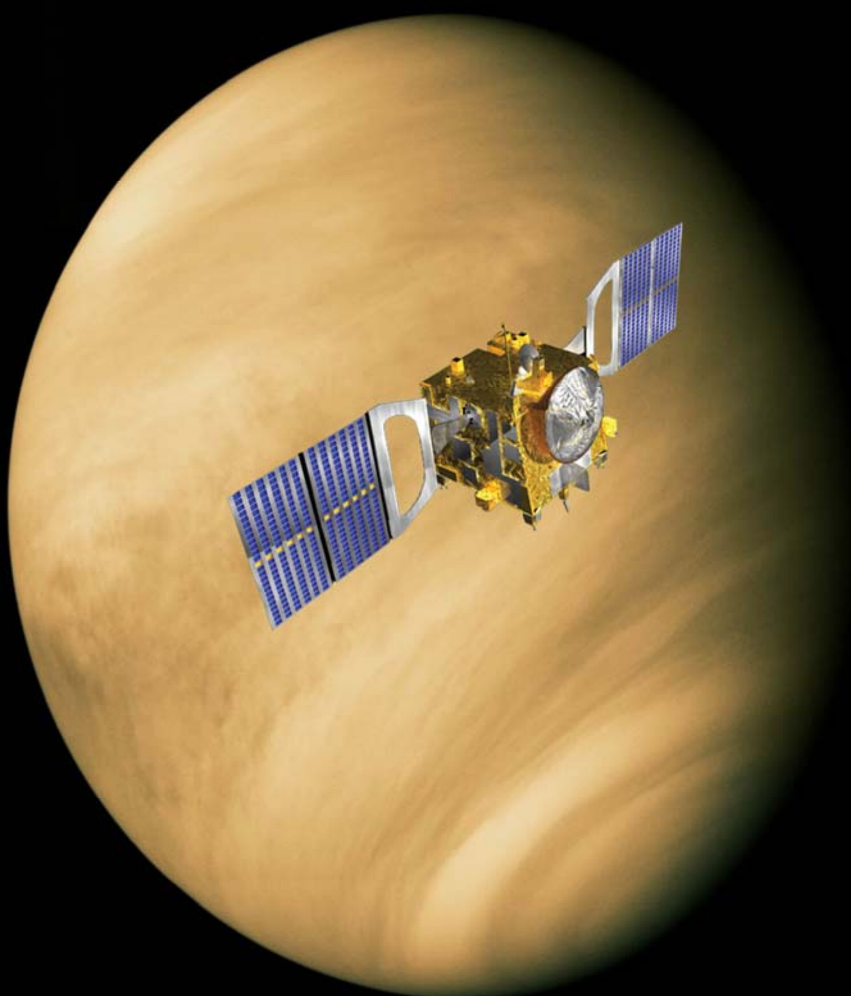
United States–NASA Support of the Venus Express Mission



United States–NASA Support of the Venus Express Mission

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Appendix A: Venus Express Publications Supported by NASA was compiled by Kevin Baines.

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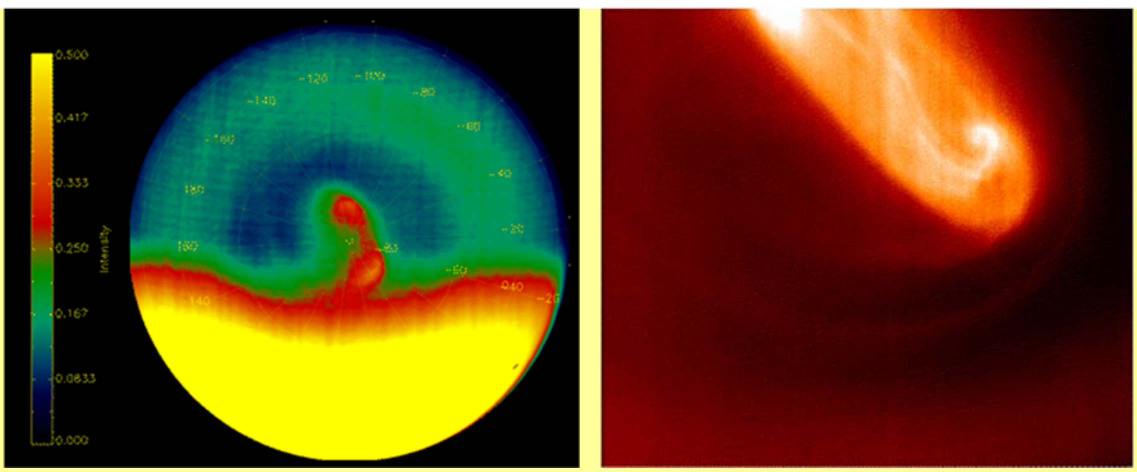
Executive Summary

Venus Express was the first Venus exploration mission undertaken by the European Space Agency. The science mission was conducted from April 2006 until the propellant was exhausted in late November 2014. Venus Express was an outstanding scientific success with its long-term observations of the Venusian atmosphere. These observations provided a substantially better understanding of the atmospheric global circulation and local dynamics, composition and thermal structure, including (1) concrete insights into mechanisms responsible for powering the global super-rotating atmosphere and (2) new insights in the cloud structure and cloud morphology (3) the strongest proof yet for the existence of lightning at Earth-like rates. As well, the mission provided new insights into the planet's evolution, via (4) significant improvements of the measurement of the atmospheric escape into space, and (5) discovering young surface materials in the environs of a volcanic construct, strongly indicating that Venus is volcanically active. This mission, like many international missions, demonstrated how the mutual contributions from two space agencies enhance the overall success of a mission. This report describes the U.S./NASA contributions to this mission.



Polar Vortex Phenomena. Venus Express confirmed that the Venusian South Pole has a complex and variable vortex-like feature, sometimes taking the shape of a dipole, but at other times morphing into tripolar, quadrupolar, and amorphous shapes. Temperatures near the 60-km level are shown in the nighttime portions of 5-µm Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) images, revealing the dipole to be notably hotter than its surroundings, likely due to compression of descending air. (Left image, taken in daytime conditions, is overexposed by the Sun). Right-hand, close-up image shows filamentary nature of the dipole, which changes shape constantly in the dynamically active atmosphere. The dipole is offset from the pole by several degrees of latitude and rotates with a period of about 2.4 days. (Courtesy of ESA)

1. Venus Express Overview

Venus Express was the first Venus exploration mission conducted by the European Space Agency. The mission was proposed in 2001 to reuse the design of the Mars Express spacecraft, with modifications of the solar panels and the thermal control as well as use of some spare Rosetta instruments. It was launched on November 9, 2005 from Baykonur Cosmodrome on a Soyuz-FG/Fregat rocket. It arrived at Venus on April 11, 2006 and achieved its science orbit on May 7, 2006. Venus Express exhausted its propellant in late November 2014 and subsequently disintegrated in the Venusian atmosphere in late January 2015.

The main objectives of the mission were the long-term observation of the Venusian atmosphere in order to provide a better understanding of the atmospheric dynamics, thermal structure and chemistry, the study of the planetary plasma environment, and the study of some aspects of surface physics. Such studies contribute to our understanding of planetary atmospheric dynamics in general, while also providing insights into climate change on Earth. A major feature of the mission was the first full utilization of the infrared spectral windows, making observations through the atmosphere down to the surface possible. Venus Express findings complement those of Pioneer-Venus, the last U.S./NASA mission to Venus in the late 1970s. Venus Express had a near-polar, 24-hour orbit while Pioneer–Venus had a near-equatorial orbit. Venus Express instruments included:

- **ASPERA-4** (**A**nalyzer of **S**pace **P**lasmas and **E**ne**r**getic **A**toms) investigated the interaction between the solar wind and the Venusian atmosphere. It characterized the global distribution of plasma and neutral gas, studied energetic neutral atoms, ions and electrons, and analyzed other aspects of the near Venus environment. ASPERA-4 hardware was derived from Mars Express ASPERA-3 spares. Southwest Research Institute (SwRI) provided the Electron Spectrometer. PI: Stas Barabash (Swedish Institute of Space Physics)
- **MAG**: (Magnetometer) measured the strength and direction of the Venusian magnetic field as affected by the solar wind and Venus itself. It mapped the magnetosheath, magnetotail, ionosphere, and magnetic barrier in high resolution in three dimensions, aided ASPERA-4 in the study of the interaction of the solar wind with the atmosphere of Venus, and identified the boundaries between plasma regions. It also carried out other observations, such as the detection and characterization of Venus lightning. This magnetometer was derived from the Rosetta lander's magnetometer. PI: Tielong Zhang (Graz University of Technology, Austria)
- **SPICAV** (**SP**ectroscopy for **I**nvestigation of **C**haracteristics of the **A**tmosphere of **V**enus) was a spectrometer used for analyzing radiation in the infrared and ultraviolet wavelengths by solar and stellar occultation measurements, and by nadir observations. Compared to SPICAM on Mars Express, SPICAV had an additional channel known as **SOIR** (**S**olar **O**ccultation at **I**nfra**r**ed) that was used to observe at high spectral resolution how direct solar light was modified by passing through the Venusian atmosphere at infrared wavelengths. PI: Jean Loup (Bertaux (CNRS / IPSL / UVSQ, Guayncourt, France)

- **VeRa** (**Ve**nus **Ra**dio Science) was a radio sounding experiment that studied the atmosphere and ionosphere of Venus by transmitting radio waves from the spacecraft, letting them pass through the atmosphere and ionosphere, and observing the modulated radio waves on Earth. It also conducted bistatic radar experiments by transmitting radio waves from the spacecraft, and observing the reflections from the Venusian surface back on Earth. It used the standard on board telecommunication system, enhanced by an Ultra Stable Oscillator.
  PI: Bernd Häusler (Universität der Bundeswehr, München, Germany)
- **VIRTIS** (**V**isible and **I**nfra**r**ed **T**hermal **I**maging **S**pectrometer) was an imaging spectrometer that mapped the planet in a broad spectral range from near UV to thermal IR. It studied atmosphere, surface and surface/atmosphere interaction phenomena. PIs: Giuseppe Piccioni (Institute for Space Astrophysics and Planetology, National Institute for Astrophysics, Rome, Italy) and Pierre Drossart (Observatoire de Paris, France)
- **VMC**: The **V**enus **M**onitoring **C**amera was a wide-angle, multi-channel charge-coupled device imager. The VMC, which accomplished global imaging of Venus, operated in the visible, ultraviolet, and near infrared spectral ranges. It studied atmospheric dynamics by tracking clouds, observed cloud morphology for mapping the surface brightness distribution, and searched for volcanic activity. It also monitored airglow and the distribution of the unknown ultraviolet absorbing phenomenon at the cloud-tops. PI: Wojciech Markiewicz (Max-Planck-Institute for Solar System Research, Goettingen, Germany)

In addition, Venus Express had a Planetary Fourier Spectrometer (PFS), which, unfortunately, failed to operate properly when it was first turned on. This was due most likely to an unexplained blockage of the calibration mirror mechanism, such that the instrument field-of-view was stuck looking at the internal calibration source, and, despite many attempts, could not be coaxed to looking out into space and at Venus.

An overview of Venus Express science, based on a presentation made by Håkan Svedhem (Venus Express Project Scientist) at the Venus Exploration Analysis Group (VEXAG) meeting in November 2012. Science Themes for Venus Express Mission:

- Atmospheric Dynamics: Global dynamics mechanisms, super-rotation, double polar vortex
- Atmospheric Structure: Density and temperature in three dimensions
- Atmospheric Composition and Chemistry: Processes and species in the different regions
- Cloud Layer and Hazes: Behavior and characteristics, UV absorber
- Radiative Balance and Greenhouse Effect: Global thermal balance, greenhouse in past, present, and future
- Surface Properties and Geology: Volcanic and seismic activity, highly radar reflective areas
- Plasma Environment and Escape processes: Evolution of the atmosphere and water, escape history

Key Venus Express scientific accomplishments:

- Significantly improved understanding of the global super-rotation and characterization of the polar vortices
- Characterization of cloud morphology on large and small scales
- Global scale surface temperature map
- Thermal profiles of the atmosphere, from SPICAV/SOIR, VeRa, and VIRTIS
- Profiles of chemical composition: CO, SO_2, OCS, D/H ratio
- Discovery of new atmospheric species: O_3, OH
- Electron density profiles in the ionosphere and meteor layer
- First detection of ionospheric photoelectrons
- Lightning inferred from whistler waves
- Detection of upstream plasma waves
- Possible detection of present-day surface volcanism
- Characterized the loss of hydrogen, oxygen, and helium from the Venus atmosphere to space

Additional salient revelations by Venus Express were:

- Measurements of atmospheric density and its variability in the high atmosphere (130–160 km altitude range) were made during several atmospheric drag experiments conducted during the mission. Variations of a factor of two were regularly seen on daily time scales. Such atmospheric "breathing" was a surprising result.
- Variability in the global zonal winds. During the last few years of the mission, large temporal variability in the zonal wind structure was discovered, with zonal wind velocity varying by more than 20% over many latitudes. These measurements pertain to the cloud-top altitudes near the 60 km.

All of these accomplishments, in turn, have led to:

- Enhanced knowledge in all fields of the above Science Themes
- Progress in understanding of atmospheric dynamics and thermal structure
- Improved knowledge in cloud structure and chemistry
- Progress in understanding of surface properties and geology
- Better understanding of plasma environment, as well as escape processes and rates

The processes on Venus show many similarities to those on the Earth in spite of the large differences in the atmospheric conditions. It is essential to understand Venus in order to understand how the atmospheres of terrestrial planets (including the Earth) operate. Also, Venus Express observations imply that Venus has been recently geologically active, possibly even today.

In addition to these scientific accomplishments, the Venus Express Project conducted two successful engineering campaigns:

(1) Delta-DOR observations in 2007–2014, to improve the Venus planetary ephemeris, and

(2) Drag/Torque measurements and aerobraking, in several successful campaigns in 2010–2014, to provide important experience for future missions.

The Delta-DOR campaign was conducted primarily using European tracking stations located in New Norcia (Australia) and Cebreros (Spain).

Some Venus Express science results are shown in Figures 1–3. Figure 1 shows SPICAV/SOIR Observations that have revealed hitherto unexpected variations in H_2O and HDO with altitude. Figure 2 shows Venus atmospheric temperature profiles that were derived from Venus Express radio occultation experiments. Figure 3 shows images of Venus from the Venus Monitoring Camera. These VMC images were instrumental in significantly improving our understanding of the global super-rotation and characterizing of the polar vortices as well as the cloud morphology on large and small scales.

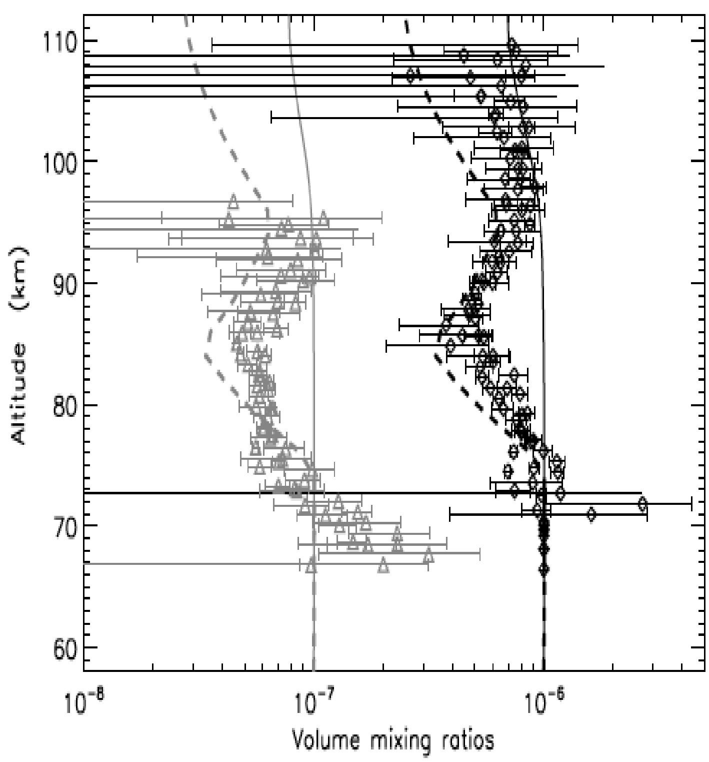


Figure 1. SPICAV/SOIR Observations revealed hitherto unexpected variations in the mixing ratios of H_2O and HDO with altitude.

Variations in H_2O (black) and HDO (gray) show pronounced minima in volume mixing ratios at around 85-km altitude. These features are likely caused by transport by wind that brings water vapor from regions where there has been enhanced destruction. Provided by Yuk Yung, California Institute of Technology. From a Venus Science Nugget posted on the VEXAG website. http://www.lpi.usra.edu/vexag/reports/science_nuggets/

One of the unique Venus Express accomplishments was the collection of hundreds of radio occultations obtained by the Radio Science experiment that covered the planet from pole-to-pole and over all times-of-day and longitudes (Figure 2). These provided accurate temperature profiles down to about the 40-km level, from which thermal winds could be derived. Work still to be completed includes comparing these winds to the winds inferred from remote sensing imaging instruments, which would provide insight into non-equilibrium processes that help power the winds (such as waves, convective updrafts, and meridional advection from Hadley circulation). Global Circulation Models by Venus Express scientists in France indicate that solar heating of the clouds near the 55–60 km altitude level play a major role in powering the large super-rotating zonal winds that flow about 60 times faster than the planet's rotation rate in the cloud region.

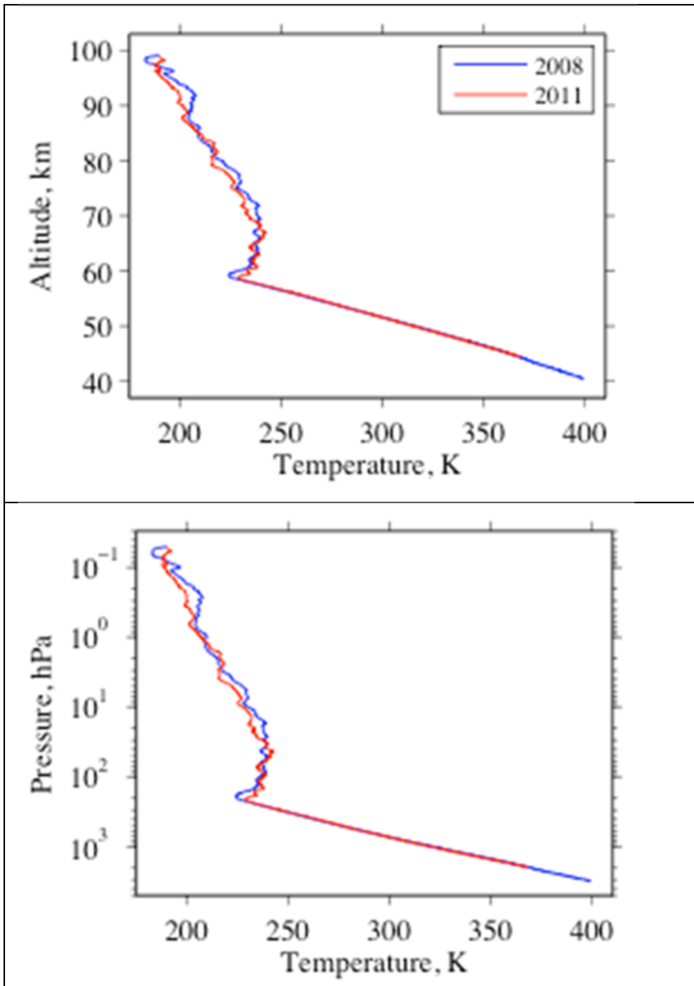


Figure 2. Venus atmospheric temperature profiles from Venus Express Radio Occultation experiments.

Accurate temperature profiles were observed down to about the 40-km level from which thermal winds can be derived. Comparing these winds to the winds inferred from remote sensing imaging instruments provides insight into non-equilibrium processes that power the winds (such as waves, convective updrafts, and meridional advection from Hadley circulation). Provided by Dave Hinson, Stanford University. From a Venus Science Nugget posted on the Venus Exploration Analysis Group (VEXAG) website http://www.lpi.usra.edu/vexag/.

A key U.S.-NASA support of Venus Express was the set of radio science activities that are summarized in Tables 1 and 2. These observations were carried out by the radio science investigators at Stanford University and the DSN teams at JPL. The work of Ricardo Mattei (Universität der Bundeswehr, München) was essential for predicting the pointing of the high gain antenna for the bistatic radar and radio occultation experiments.

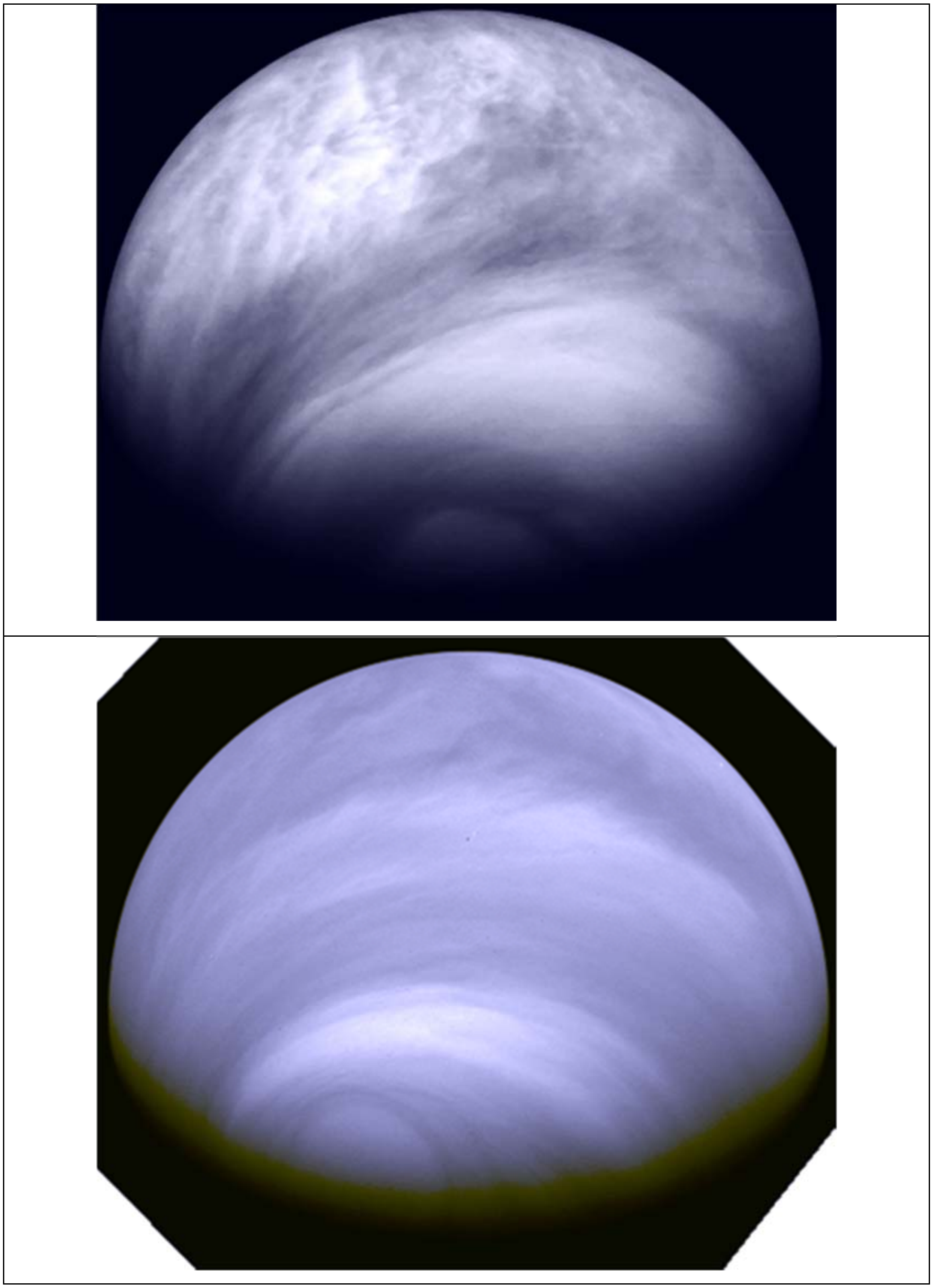


Figure 3. Images of Venus from the Venus Monitoring Camera.

These images were instrumental in significantly improving our understanding of the global super-rotation and characterizing the polar vortices as well as the cloud morphology on large and small scales.

2. U.S. Support of Venus Express

U.S. Support of Venus Express included:

- Participating Scientists (led by Kevin Baines, JPL)
- ASPERA's Electron Spectrometer (provided by SwRI)
- DSN Tracking Support carried out by JPL's Multi-Mission Resource Scheduling Team, Multi-Mission Planning and Sequence Team, DSN Mission Interface Manager, and DSN Operations Group
- Radio Science Experiments carried out by JPL's Radio Science Systems Group, and the Radio Science Participating Scientists
- Navigation Support (led by Don Han, JPL)
- Delta-DOR Support (led by Jim Border, JPL)
- Ephemeris improvements (led by Bill Folkner, JPL)
- Provision of the SPICE ancillary information system, including archive support (led by Chuck Acton, JPL)
- Direct links from the PDS to the ESA/PSA data and archiving of Venus Express data through the PDS Atmospheres Node at New Mexico State University (led by Reta Beebe)
- An educational program with lecture modules for school children that calculated atmospheric wind speed by cloud tracking using real VMC data, by University of Wisconsin (led by Sanjay Limaye).

Tony Carro and Adriana Ocampo, NASA Headquarters, oversaw all of the NASA activities. Participating Scientists were supported under NASA Grants administrated by Goddard and Marshall Space Flight Centers. Support for JPL activities (DSN tracking, navigation, Delta DOR, and ephemeris improvement) was under the auspices of Caltech/JPL Task Plans that were executed in JPL's Solar System Exploration Directorate, reporting to Jim Cutts at JPL. Support for archiving activities at the PDS Atmospheres Node was carried out under the auspices of NASA's Planetary Data System (PDS). Radio Science data archiving by Dick Simpson, Stanford University, was carried out under the auspices of NASA's Venus Express Participating Scientist program. Southwest Research Institute personnel provided ASPERA's Electron Spectrometer and also examined ASPERA data under a Mars–Venus comparative planetology study.

Participating Scientists

U.S. Participating Scientists on Venus Express were selected in two solicitations early in the mission. The European Space Agency in June 2006 issued an Announcement of Opportunity for Venus Express Participating Scientists in order to increase the scientific return of the selected investigations and of the mission as a whole. U.S. Participating Scientists selected jointly by ESA and NASA in October 2006 were:

- Charles Acton, Jet Propulsion Laboratory (SPICE for Venus Express)
- Sushil Atreya, University of Michigan (PFS and VIRTIS)
- Kevin Baines, Jet Propulsion Laboratory (VIRTIS and PFS)

- Pontus Brandt, The Johns Hopkins Applied Physics Laboratory (ASPERA)
- David Crisp, Jet Propulsion Laboratory (VMC and PFS)
- Sanjay Limaye, University of Wisconsin (VMC, VIRTIS)
- Janet Luhmann, University of California, Berkeley (ASPERA and MAG)
- Chris Russell, University of California, Los Angeles (ASPERA and MAG)
- S. Alan Stern, Southwest Research Institute (SPICAV)
- Len Tyler, Stanford University Radio Science (VeRa)

Dave Hinson and Dick Simpson assisted Len Tyler in carrying out VeRa, the Venus Express Radio Science Experiment.

A second set of Participating Scientists (Interdisciplinary Scientists and Support Investigators) was selected via a NASA ROSS solicitation in 2007. These were:

- David Grinspoon, Denver Museum of Nature and Science, Interdisciplinary Scientist for the Venusian Sulfur Cycle
- Yuk Yung, California Institute of Technology, Interdisciplinary Scientist for Chemical Composition and Evolution of Venus
- David Brain, University of California, Berkeley, Support Investigator, Superthermal Electron Measurements
- Robert Carlson, Jet Propulsion Laboratory, Support Investigator, Venus Surface and Clouds
- David Schwenke, NASA Ames Research Center, Support Investigator, Opacity Measurements of Carbon Dioxide

Publications involving these U.S. Participating Scientists are given in the "Venus Express Publications Supported by NASA" document posted on the Venus Exploration Analysis Group's website http://www.lpi.usra.edu/vexag/. (See Appendix A.)

ASPERA Instrumentation

As noted above, ASPERA hardware was derived from Mars Express ASPERA spares. Its Electron Spectrometer was provided by SwRI. During mission operations, SwRI personnel conducted instrument health and safety status checks.

Radio Science Experiments and DSN Tracking Support

A key U.S./NASA support of Venus Express was that provided by NASA's Deep Space Network (DSN). In particular, the DSN tracking stations were used for:

- Radio Science occultations,
- Bistatic radar experiments,
- Solar corona studies,
- Gravity observations,
- Atmospheric drag experiments (before aerobraking),
- Doppler tracking during the Venus Express' aerobraking experiments, and

One final attempt to establish a solid contact with the spacecraft after the propellant was depleted in December 2014.

JPL's DSN Scheduling Group acted as brokers for scheduling the Venus Express' DSN tracking and provided DSN keyword files for the DSN stations translated from Venus Express spacecraft telecom keys files provided by Venus Express spacecraft team at the European Space Operations Centre (ESOC), Darmstadt, Germany. JPL's Radio Science Systems Group led by Sami Asmar provided key JPL support for the Venus Express Radio Science experiments. Special Radio Science receivers were used in recording the Venus Express downlink signals. These data were then delivered to Dick Simpson (Stanford University) for the generation of archival Radio Science datasets that, in turn, were delivered to the Venus Express Radio Science Principal Investigator. DSN usage by Venus Express is summarized in Tables 1 and 2.

Table 1. DSN tracking support for Venus Express.

Start Date	End Date	# Tracks	Comment
22-May-06	18-Jun-06	4	Bistatic Radar
8-Oct-06	5-Dec-06	22	Solar Conjunction
17-Mar-07	19-Mar-07	2	Bistatic Radar
7-May-07	9-Jun-07	5	Radio Occultations
12-Jun-07	3-Aug-07	3	Bistatic Radar
25-Nov-07	25-Nov-07	1	High-Gain Antenna Calibration
30-Jan-08	4-Feb-08	3	Radio Occultations
1-Aug-08	22-Aug-08	8	Atmospheric Drag
4-Nov-08	26-Dec-08	4	Radio Occultations
20-Apr-09	1-Jul-09	11	Gravity
22-Feb-10	28-Feb-10	5	Atmospheric Drag
14-Jun-10	11-Jul-10	14	Radio Occultations
17-Oct-10	19-Oct-10	3	Atmospheric Drag
17-Jan-11	22-Mar-11	10	Radio Occultations
24-May-11	3-Jun-11	6	Atmospheric Drag – Deepest penetration into atmosphere at North Pole Vortex
14-Jun-11	1-Jul-11	8	Radio Occultations
17-Sep-11	23-Sep-11	3	Atmospheric Drag
14-Jan-12	19-Jan-12	6	Atmospheric Drag
4-Dec-12	14-Dec-12	5	Atmospheric Drag
28-Jul-13	28-Jul-13	1	Radio Occultation
20-Nov-13	20-Nov-13	1	Radio Occultation
20-Jan-14	23-Mar-14	19	Radio Occultations
24-May-14	6-Jul-14	22	Aerobraking Campaign
10-Dec-14	10-Dec-14	1	Telemetry Recovery

Table 2. Venus Express DSN radio science observations.

(Provided by Dick Simpson, Stanford University)

Year	Atmos-pheric Drag Experiment	Bistatic Radar	Occultation	Solar Corona	Gravity	Total (by year)*
2006		4		20		24
2007		5	5			10
2008	8		7			15
2009					11	11
2010	8		14			22
2011	9		18			27
2012	11					11
2013			2			2
2014	21		19			40
Totals	57	9	65	20	11	**162**

*Two tracks in Table 1 were not for radio science; three others, although scheduled for radio science, did not yield useful radio science results. Consequently, the totals in this table do not exactly match those of Table 1.

Navigation Support

JPL's Navigation team played the role of middleman between the European Navigation Team (located at the European Space Operations Centre, ESOC) and JPL's DSN Team by providing DSN tracking data for both standard radiometric data and Delta-DOR data. These data that were particularly important for the successful navigation of the Venus Express mission from launch to Venus Orbit Insertion (VOI). Throughout this period, JPL's Navigation Team provided trajectory inputs to the DSN Predict Team based on ESOC's trajectory, monitored DSN's tracking data delivery to ESOC, conducted regular navigation teleconferences between JPL and ESOC, and provided light-time and orbit parameter files to JPL's Multi-Mission Sequence Team for their DSN Keyword File (DKF) generation processes. This support continued after VOI, but less frequently as the number of DSN tracks was reduced.

Delta-DOR Support

Delta-DOR measurements were made during cruise from Earth to Venus for navigation support and VOI targeting and then continued during the orbital phase of the mission for planetary ephemeris improvement. Both DSN and ESA stations made measurements with most of them conducted using the ESA tracking stations at New Norcia in Australia, Cerberos in Spain throughout the mission, and, Malargüe in Argentina during the last years of the mission. Comparisons of DSN and ESA data paved the way to integrating the ESA and NASA tracking networks for Delta-DOR measurements.

Planetary Ephemeris Improvement

One of the key Venus Express engineering experiments was the collection of monthly Delta-DOR data that was collected with ESA's tracking stations in order to improve the Venus planetary ephemeris. JPL and European Navigators generated normal points from the Venus Express Delta-DOR data from 2007 through 2014. Each normal point represents a measurement of one component of the direction from Earth to Venus at the measurement time. The measurement direction is parallel to the vector between the tracking stations used, in New Norcia (Australia) and Cebreros (Spain). A plot of the measurement residuals against the current (DE430) planetary ephemeris is below.

Venus Express Delta-DOR residuals from 2007 to 2009 (Figure 5) have an RMS of 2.8 milli-arcseconds and data from 2009 to 2014 have an RMS of 1.7 milli-arcseconds. Before Venus Express, we had only Magellan Delta-DORs from 1990 to 1994 with an RMS of 3.2 milli-arcseconds. The newest Venus Express RMS values represent an improvement of 47% compared with the Magellan values. Also, the longer Venus Express arc results in a factor of 2–4 improvement in the estimation of the Venus orbit plane.

Range measurements (Figure 6) to the Venus Express spacecraft provided by Trevor Morely, Michael Müller, and Frank Budnick (ESOC) have been very valuable for improving the Venus ephemeris. The residuals to DE430 Planetary Ephemeris are about 8 meters RMS. This is a significant improvement compared with the Venus ephemeris range errors that were about 200 m before Venus Express.

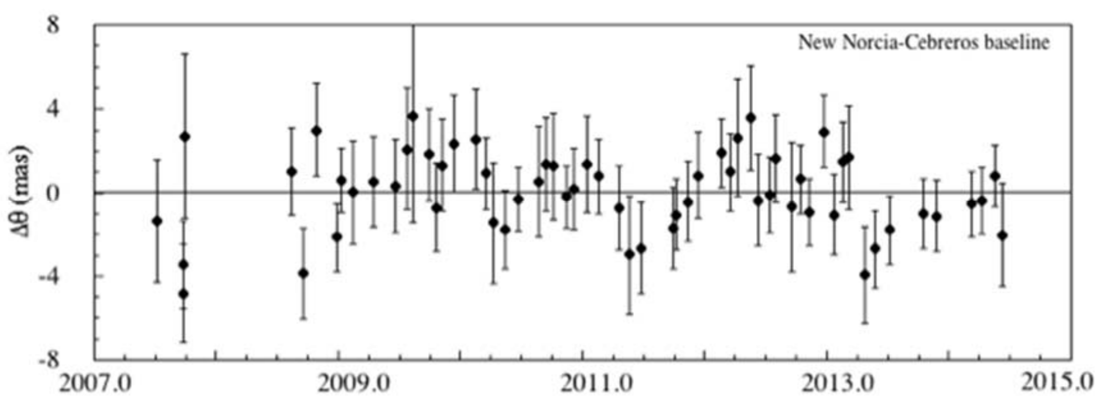


Figure 4. Venus Express Delta-DOR residuals relative to the DE430 planetary ephemeris.

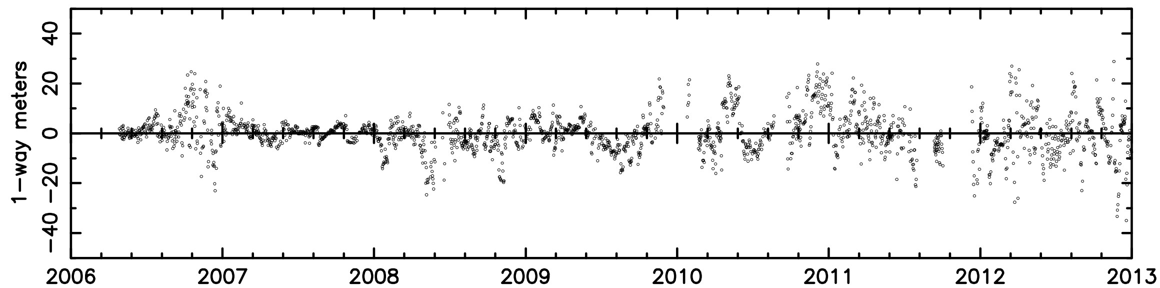


Figure 5. Venus Delta-DOR one-way range residuals for the period of 2008–2013.

NAIF-SPICE

The Navigation and Ancillary Information Facility (NAIF) at JPL provided additional investigator support to ESA's Venus Express mission. This ensured that high-quality, high-accuracy ancillary data were available in a form familiar to U.S. and European investigators. SPICE kernels were made available to support observation planning and science data analysis. An important adjunct to this was providing the Venus Express investigators with the appropriate SPICE and NAIF Toolkit Software. This, in turn, enabled investigators to access and make the best use of those ancillary data. NAIF also conducted peer reviews of each Venus Express SPICE archive increment prepared by Europeans, thus helping to ensure complete, high-quality ancillary data that will be available to any U.S. or European researcher long into the future.

Data Archiving

Another of the key U.S. accomplishments associated with Venus Express mission has been the linking of Venus Express data in the ESA Planetary Science Archive (PSA) to NASA's Planetary Data System. Detailed web pages with direct links to the PSA data sets are provided at the PDS Atmospheres Node at New Mexico State University, led by Professor Reta Beebe (see Figure 7). In addition, selected VeRa data produced by JPL's Radio Science Support Group and delivered to Dick Simpson, Stanford University, have been posted directly on the PDS Atmospheres web site http://pds-atmospheres.nmsu.edu/ve/ to mitigate delays resulting from funding issues along the originally negotiated delivery path to PSA.

Artist's concept of lightening on Venus. Courtesy of ESA.

Quick Searches

- Mercury
- Venus
- Mars
- Jupiter
- Saturn
- Uranus
- Neptune

PDS Web Sites

- PDS
- Atmospheres
- Geosciences
- Imaging
- Navigational & Ancillary Information (NAIF)
- Planetary Plasma Interactions (PPI)
- Planetary Rings
- Small Bodies

PDS Support

- Management
- Engineering
- PDS Phonebook

Data Analysis Proposals Support

- ROSES Research Opportunities
- New Horizons data at the Small Bodies Node

Venus Express

The Venus Express (VEX) spacecraft was built by the European Space Agency to study the atmosphere and the surface of Venus. It was launched in November 2005 and it was inserted into orbit around Venus on April 11, 2006. Venus Express is equipped with seven instruments. Links to more detailed information regarding the instruments on board Venus Express are given below.

The data will be archived in the European Space Agency's Planetary Science Archive. To provide PDS Atmospheres Node users transparent access to VEX data, we are developing an interoperability protocol whereby users can link to the VEX data from this site.

Some of the VEX data are fully ingested into the PSA and are available through this interoperability protocol.

Image Courtesy of ESA

VEX mission phases

Phase Acronym	Phase name	Start Date	End Date	Duration (days)
LEOP	Launch and Early Orbit Phase	09/11/05	11/11/05	3
NECP	Near Earth Commissioning Phase	12/11/05	16/12/05	21
ICP	Interplanetary Cruise Phase	17/12/05	04/04/06	107
VOI	Venus Orbit Insertion	05/04/06	21/04/06	16
VOCP	Venus Orbit Commissioning Phase	22/04/06	03/06/06	42
NMP	Nominal Mission Phase	04/06/06	02/10/07	486
EMP	Extended Mission Phase	03/10/07	on-going	

Data sets are split into the nominal mission (launch to end of nominal mission) and the extended mission (from 2/10/2007).

Figure 6. Screenshot of PDS Atmospheres Node, Venus Express page. (http://pds-atmospheres.nmsu.edu/ve/).

3. Key Personnel

U.S. Project Management

- Adriana Ocampo and Tony Carro, Program Executives and Scientists, NASA Headquarters
- Jim Cutts, Planetary Science Program Support Task Manager, JPL
- Tommy Thompson, Venus Program Support Sub-Task Manager, JPL

European Personnel

- Marcello Coradini, ESA Headquarters
- Håkan Svedhem and Dimitri Titov - Project Scientist/Deputy Project Scientist
- Fred Jansen and Patrick Martin, Mission Managers
- Adam Williams, Octavio Camino, Andrea Accomazzo, and Spacecraft Team - Spacecraft Operations
- Trevor Morely, Michael Müller, Frank Budnick, and Flight Dynamics Team – Navigation
- Miguel Almeida, Michel Breitfellner, Marc Costa, Emmanuel Grotheer, Raymond Hoofs, Nicolas Manaud, Santa Martinez, Donald Merritt, Federico Nespoli, Miguel Perez Ayucar, Stefan Remus – Venus Express Science Operations Centre personnel

U.S. Participating Scientists

- Kevin Baines, Lead
- Charles Acton, Sushil Atreya, David Brain, Pontus Brandt, Bob Carlson, Dave Crisp, David Grinspoon, Dave Hinson, Sanjay Limaye, Janet Luhmann, Chris Russell, David Schwenke, Dick Simpson, Alan Stern, Len Tyler, Yuk Yung,

ASPERA Electron Spectrometer

- David Winningham and Rudy Frahm, SwRI

DSN Tracking Support

- Sami Asmar, Radio Science Support Group Lead, JPL
- Daniel Kahan, Nicole Rappaport, Eugene Goltz, Radio Science Support Group
- Ruben Espinueva, Jacqueline Jai, Marisol Mercado, Cozette Parker, Multi-Mission Resource Scheduling Team (DSN Schedulers), JPL
- Bruce Waggoner, Ricardo Torres, Eva Pereira, and Terry Himes, Multi-Mission Planning and Sequence Team (DSN Keyword Files), JPL
- Padma Varanasi and Dwight Holmes, DSN Mission Interface Managers, JPL
- Jesse Velasco, Scott Riley, Greg Hewitt, DSN Operations

NASA/JPL Navigation Support Don Han, JPL

NASA/JPL Delta-DOR Support James Border, Peter Kroger, JPL

Planetary Ephemeris Improvement William Folkner, JPL

NAIF-SPICE Charles (Chuck) Acton, JPL

NASA Data Archiving

- Reta Beebe, PDS Atmospheres Node, New Mexico State University
- Dick Simpson, Radio Science Data Archiving, Stanford University

4. Summary and Lessons Learned

As noted above, Venus Express was the first exploration mission to Venus conducted by the European Space Agency. The mission was developed quickly after its approval in July, 2002, at the conclusion of an ESA competition for a mission re-using the design and selected spares from Mars Express. For the most part, the scientific instruments were assembled from spare Mars Express and Rosetta components with the VMC camera and the Belgian/Russian-supplied SOIR channel of SPICAV being added to the scientific payload. Just three years after mission approval, Venus Express was launched on November 9, 2005, arriving at Venus on April 11, 2006 and achieving its science orbit on May 7, 2006.

After a nearly flawless 8.5 years of near-continuous science observations, during which it collected more than 5 Terabits of data, Venus Express exhausted its propellant in late November 2014 and subsequently disintegrated in the Venusian atmosphere in late January 2015. As observations over such long periods of time had never been done in previous missions to Venus, this provided a better understanding of how the atmospheric of Venus works. Such an understanding is of great importance not only for Venus, but also for the general understanding of the terrestrial planets and so contributes to a better insight into, for example, climate change on Earth. Also, the Venus Express' observations suggest that Venus is still geologically active. Venus Express was an outstanding scientific success as demonstrated by more than 400 papers published in refereed journals thus far.

In addition to these scientific accomplishments, the Venus Express Project conducted two successful engineering campaigns:

(1) Delta DOR observations in 2007–2014 to improve the Venus planetary ephemeris, and

(2) Drag/Torque measurements and Aerobraking in 2010–2014 to gain important experience for future missions.

NASA contributed to the scientific and engineering successes of the European Venus Express Mission by providing:

- Participating Scientists and Interdisciplinary Scientists
- ASPERA's Electron Spectrometer
- DSN Tracking Support
- DSN Radio Science Support
- Navigation Support
- Delta-DOR Support
- Planetary Ephemeris Improvement
- SPICE Support
- Data Archiving via NASA's Planetary Data System

This mission, like many successful international missions, was a successful quid pro quo. The Europeans provided the spacecraft and skillfully carried out the mission and instrument operations that resulted in vast new knowledge of Venus and its atmosphere. Mutual European–U.S. activities were the navigation support, Delta-DOR analyses, and, most importantly, data archiving in the European and U.S. data archives. Key U.S. NASA contributions were DSN tracking and Participating Scientists. Without these mutual contributions the mission would not have been the international success that it was. Benefits to the Europeans were more robust experiments for Venus Express from the interactions of the US Co-Investigators with the European Principal Investigators and Teams. In addition, NASA DSN tracking support was provided. Benefits to NASA were the availability of Venus Express science data to the U.S. Venus community, as the availability of archival Venus Express science data enables a NASA Venus Data Analysis Program.

One of the lessons learned from this U.S./NASA support of Venus Express is that Participating Scientists should be supported at levels that would allow:

(1) Adequate travel to meet their European colleagues for all important face-to-face interactions, and

(2) Sufficient support for students and postdocs in order to build a cadre of early career scholars involved with Venus studies.

Also, for deployment of the SPICE system to an international partner, face-to-face Technical Interface Meetings are needed to ensure the SPICE products can be correctly produced, and training is needed for the scientists who will use SPICE data products and Toolkit software. It is also important that the international partners allocate sufficient resources to ensure the timely production of correct SPICE data and to provide consultation to the instrument teams and other scientists using SPICE.

5. Reference Documents

Letter to Marcello Coradini (ESA) from Andrew A. Dantzler (NASA) regarding (a) selection of U.S. Participating Scientists on the Venus Express mission and (b) allocation of DSN tracking time, October 17, 2005.

IFMS-OCC Interface Control Document, Issue 12.1.0, (defines JPL/DSN - ESOC Interfaces), European Space Operations Centre, Darmstadt, Germany, December 20, 2007.

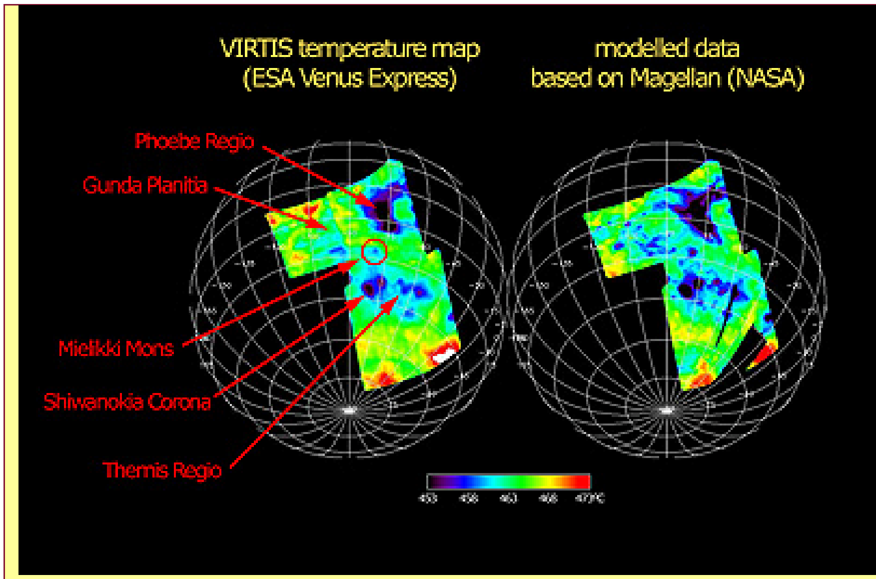
VEX - MGSS Interface Control Document, VEX - ESC - IF - 5007, Issue 2.3, (defines interfaces for generating DSN tracking files), European Space Operations Centre, Darmstadt, Germany, March 2014.

Technical Assistance Agreement (TAA) between the California Institute of Technology and the European Space Agency, Instituto di Fisica Dello Spazio Interplanetario, Instituto di Astrofisica Spaziale e Fisica Cosmica, Observatoire de Paris a' Meudon, Max Planck Institute For Solar System Research, and Institut für Raumfahrttechnik, Universität der Bundeswehr, München, Germany, March 27, 2006.

6. Acronyms and Abbreviations

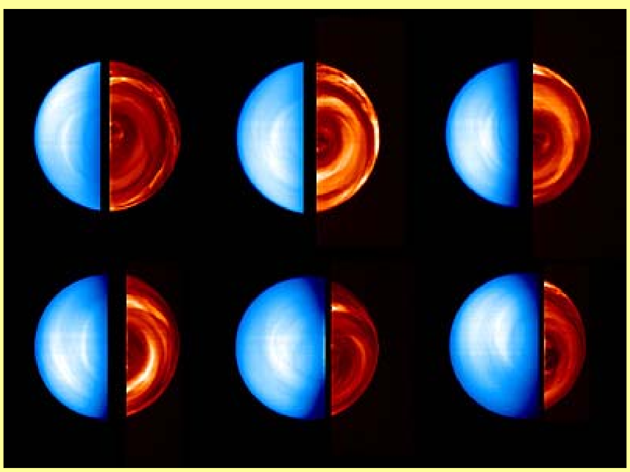
ASPERA	Analyzer of Space Plasmas and Energetic Atoms
Delta-DOR	Delta Differential One-way Ranging
DKF	DSN Keyword File
DSN	Deep Space Network
ESA	European Space Agency
ESOC	European Space Operations Centre
IFMS	Interface and Modem System
JPL	Jet Propulsion Laboratory
MAG	Magnetometer
MGSS	Multi-Mission Ground Support System
NAIF	Navigation and Ancillary Information Facility
NASA	National Aeronautics and Space Administration
OCC	Operations Control Centre
PDS	Planetary Data System (NASA)
PI	Principal Investigator
PFS	Planetary Fourier Spectrometer
PSA	Planetary Science Archive (ESA)
ROSS	NASA solicitation (a precursor to the present ROSES)
ROSES	Research Opportunities in Space and Earth Science
SOIR	SPICAV's Solar Occultation at Infrared (instrument)
SPICE	Space Planet Instrument C-matrix Events
SPICAV	Spectroscopy for Investigation of Characteristics of the Atmosphere of Venus
SwRI	Southwest Research Institute
U.S.	United States
VeRa	Venus Radio Science
VEXAG	Venus Exploration Analysis Group
VOI	Venus Orbit Insertion
VIRTIS	Visible and Infrared Thermal Imaging Spectrometer
VMC	Venus Monitoring Camera

(a)



Surface Temperatures. (left) Black-body temperatures measured for the surface correlate well with topography (right), due to decreases of surface temperature with height. Slight variations in this correlation may indicate differences in the surface rock emissivities. (Courtesy of ESA.)

(b)



Day and night images of the South Pole of Venus. Daytime images (left side of each image) show high-altitude clouds of small particles near the 70-km level. Night images (right side of each image) show thick clouds of relatively large particles near the 50-km level. Clouds at night are seen in silhouette against the glow of Venus' hot lower atmosphere, using near-infrared thermal radiation at 1.7-µm wavelength. Following the dark (cloudy) and bright (less cloudy) regions, as they move around the planet, yields measurements of Venus' winds near the 55-km level. Comparison with 70-km altitude winds as measured by the movements of dayside clouds yields wind shears, providing clues to the processes powering Venus' enigmatic system of super-rotating winds. (Courtesy of ESA)

Venus Express VIRTIS results: excerpts from Venus Exploration Analysis Group (VEXAG) Exploration Themes document posted on the VEXAG website.

http://www.lpi.usra.edu/vexag/ showing (a) surface temperatures and (b) day and night images of the South Pole of Venus.

Appendix A: Venus Express Publications Supported by NASA

Compiled by Kevin H. Baines
Last update: 06-16-2015

Listing of refereed publications authored or co-authored by at least one scientist supported by NASA Venus Express funding.

2006

Baines, K. H. Atreya, S., Carlson, R. W., Crisp, D., Drossart, P., Formisano, V., Limaye, S. S., Markiewicz, W. J., and Piccioni, G. (2006). To the depths of Venus: Exploring the deep atmosphere and surface of our sister world with Venus Express. *Planet. Space Sci*. **54**, 1263-1278.

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2007

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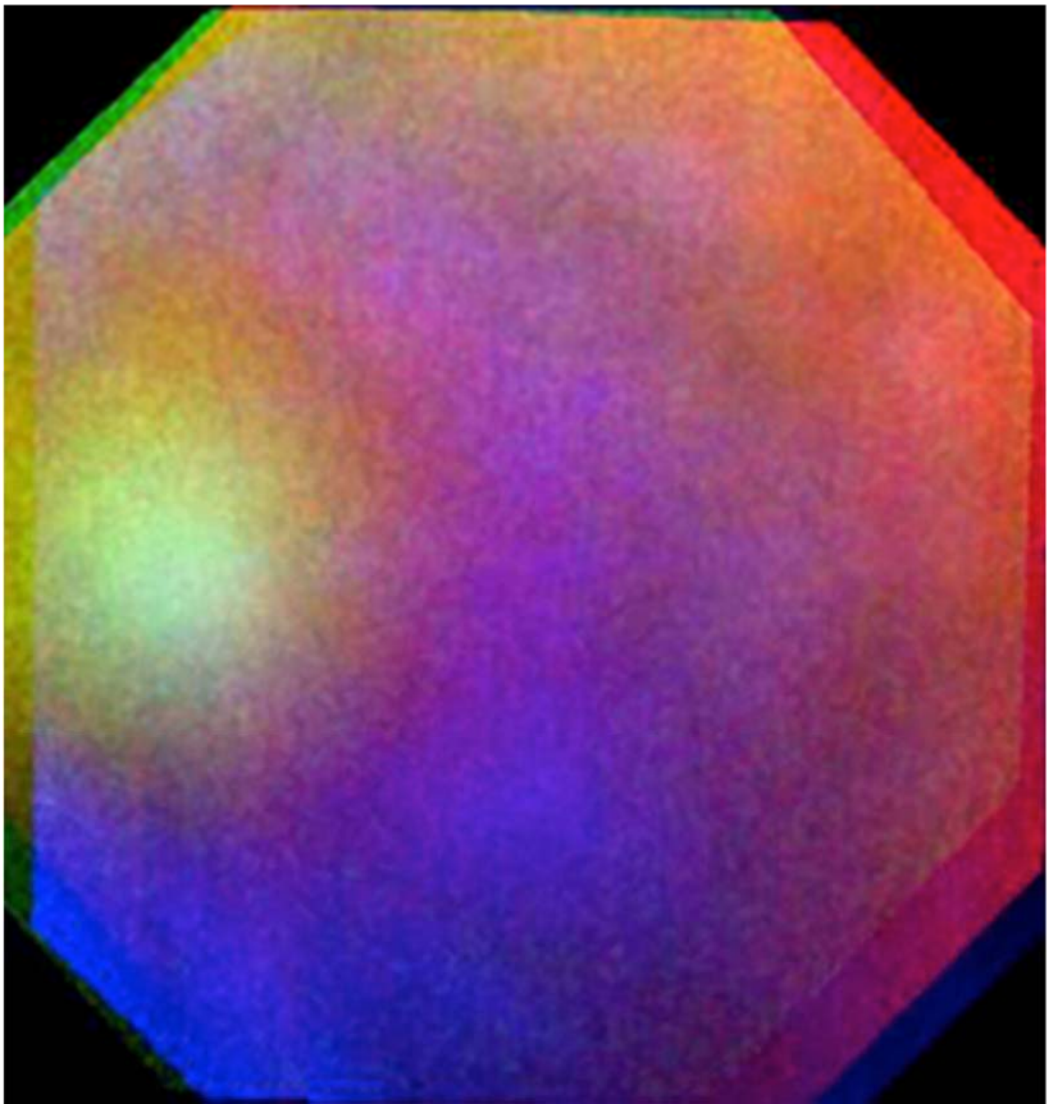

This false color composite image of a Venus 'glory' is composed of three images at ultraviolet, visible, and near-infrared wavelengths from the Venus Monitoring Camera.

The first time that a glory was observed on another planet other than on Earth.

http://www.esa.int/Our_Activities/Space_Science/Venus_Express/Venus_glory

Venus Express launch on a Soyuz-FG/Fregat rocket on November 9, 2005, Baikonur Cosmodrome, Kazakhstan.