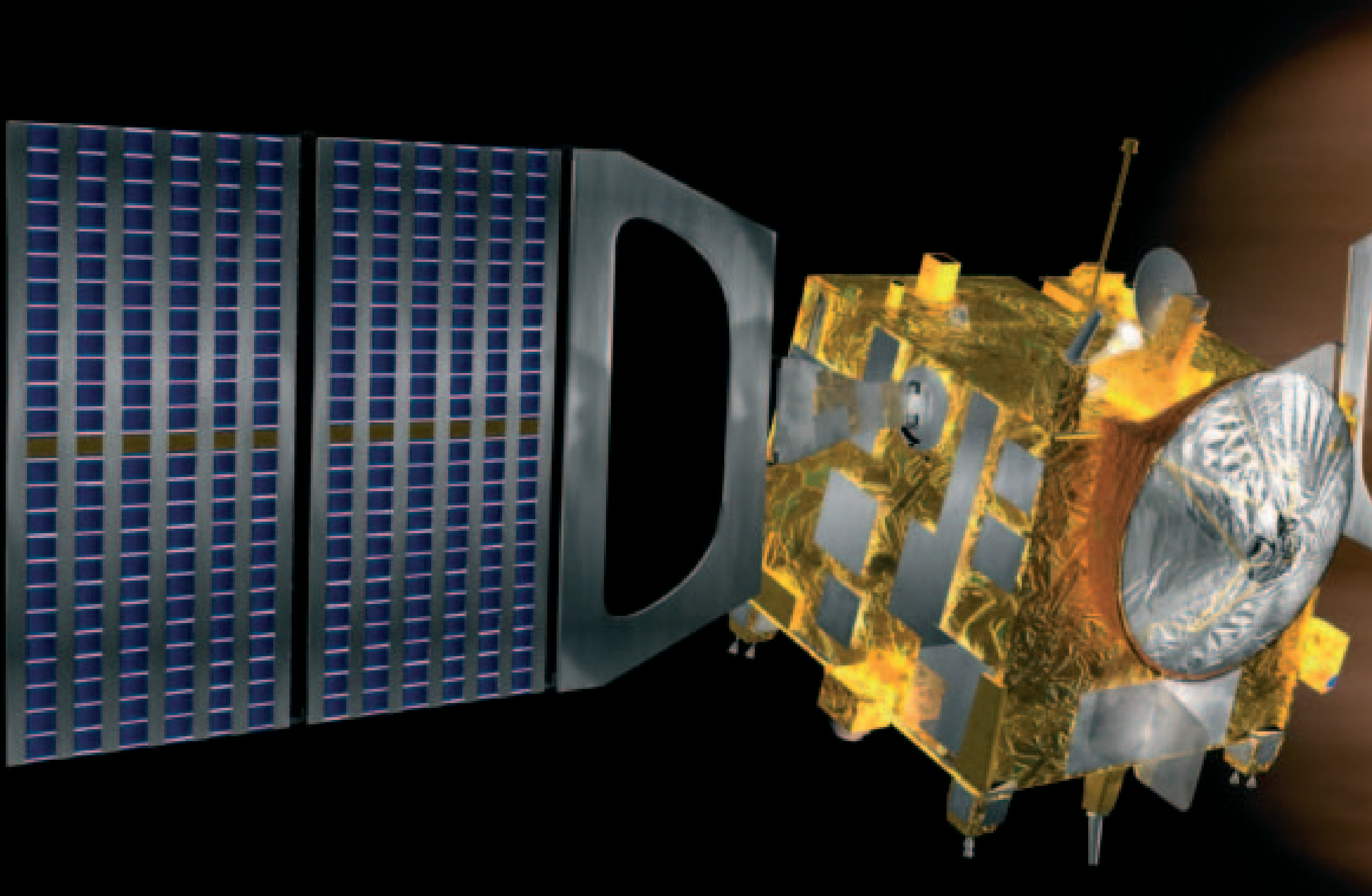
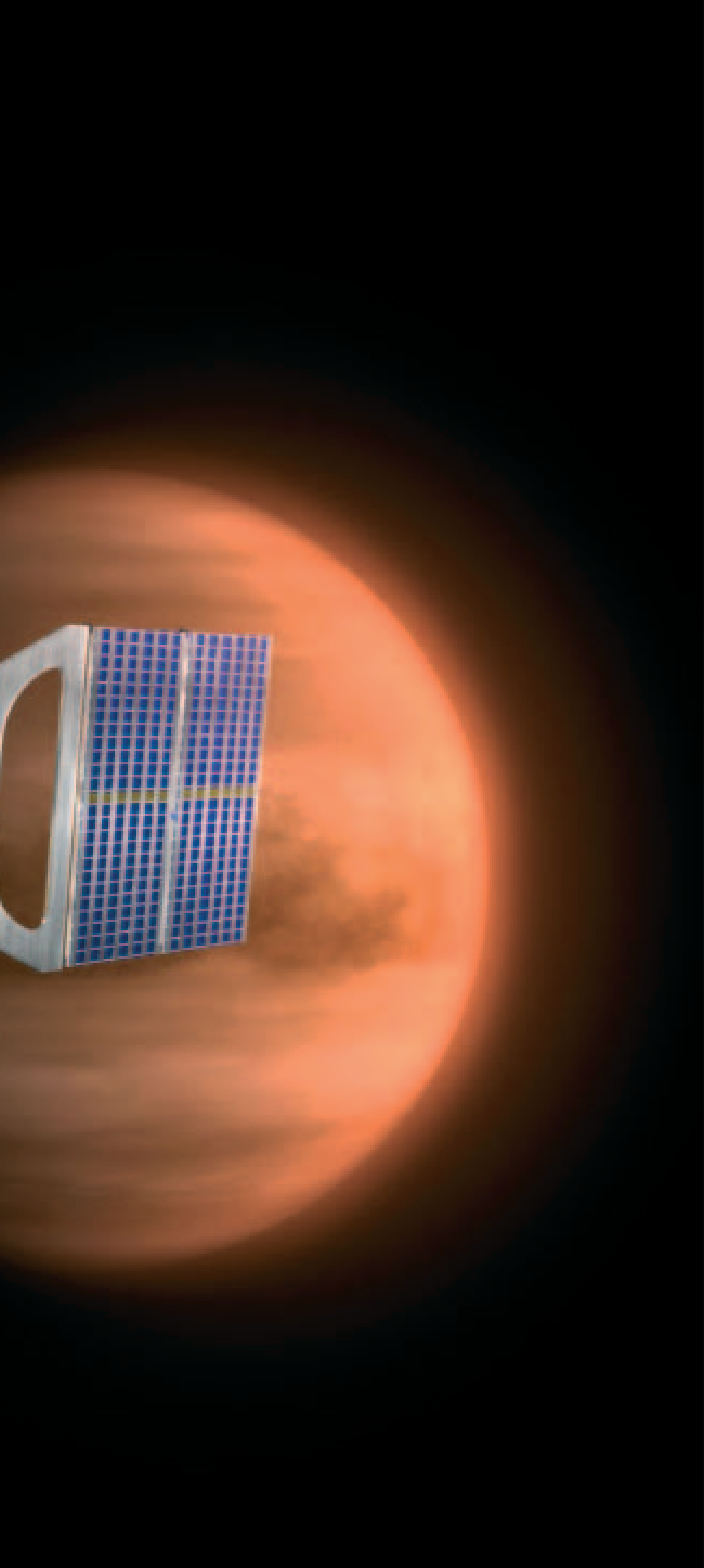
From Earth to Venus





Reaching our Sister Planet

Andrea Accomazzo, Peter Schmitz & Ignacio Tanco
Mission Operations Department, Directorate of Operations and Infrastructure, ESOC, Darmstadt, Germany

In the early morning of 9 November 2005, Venus Express left Earth aboard a Soyuz launch vehicle and headed for Venus. After several months of interplanetary cruise, a perfect capture burn on 11 April 2006 placed the spacecraft in orbit around our neighbouring planet. Only 48 hours later, the first astonishing images of the south pole were received on Earth. A few weeks later, after orbital manoeuvres, Venus Express achieved its operational science orbit ready to begin several years of observations.

Travel Planning

Preparations for the Venus Express mission began in early 2003 at ESOC with the build-up of the Flight Control Team and the definition of the systems required to test, control and monitor the new spacecraft for its flight to and around Venus. Major reuse of the systems developed for Rosetta and Mars Express allowed the ground teams to focus on the required modifications and improvements. The preparation phase went smoothly even though the mission posed new challenges for the operations team, mainly through the thermal

The Cebreros ground station

problems created by the roasting hot environment. In parallel, ESA built a new 35 m-diameter deep-space dish antenna in Cebreros (E) to cope with the workload from the four interplanetary missions operated by ESOC: Rosetta, Mars Express, SMART-1 and Venus Express.

System validation tests were conducted during the summer of 2005, before the simulation campaign of July–October. It was only at the end of this successful campaign that the ground segment was declared 'green' for launch.

Launch and Early Orbit Phase (LEOP)

The first launch attempt was scheduled for 26 October 2005. However, routine inspection of the assembled launch vehicle revealed tiny pieces of insulation deposited on various surfaces of the spacecraft and the Fregat upper stage. Their origin was uncertain, so the launch was postponed to study the unexpected problem. It was quickly determined that hydrazine propellant had damaged Fregat's engine insulation, which had peeled off and was dispersed by the air circulation system inside the fairing. For safety, it was decided to return the entire vehicle to the assembly building and refurbish the Fregat. After frantic repair work, all was well for launch in the early hours of 9 November. This time, everything went according to plan: the Soyuz vehicle and its upper stage operated flawlessly, delivering Venus Express into the targeted escape trajectory with near-perfect precision.

The early orbit phase went smoothly. In the first contact after launch, the signal was acquired from the craft's S-band omnidirectional antennas. The solar wings were deployed automatically following separation from the upper stage, and the reaction wheels were spun up and put into service by the control team. Over the next few ground station contacts, Venus Express was configured for commissioning. Critical activities included switching communications to X-band (for a high data rate) using the spacecraft's second high-gain antenna (HGA2) on the second day, and a small course correction of 3.43 m/s 12 hours later. In total, it took less than 53 hours to complete all these activities, ready for the Near-Earth Commissioning Phase to being immediately afterwards.

Andrea Accomazzo, Spacecraft Operations Manager, in ESOC's Mission Control Room during the launch of Venus Express on 9 November 2005

Near-Earth Commissioning Phase (NECP)

During NECP, the spacecraft systems and payloads were checked out for the first time in space; this took from 12 November to 15 December. Venus Express was still close to Earth, so the brief travel time for the signals allowed very careful near-realtime commanding. Critical checkout operations were conducted during the 7 hours per day of ground station contact using the new antenna at Cebreros.

NECP was split in two parts. The first week was dedicated to a checkout of the spacecraft subsystems, while the remaining 4 weeks were used to test all the scientific instruments.

Subsystem checkout

During the spacecraft checkout, all the units of the radio-frequency (RF) subsystem (transmitters, receivers and antennas) were tested and the HGA-2 radiation pattern was calibrated. For the thermal system, several heater configur-ations were tested to prove that the

The mission control team anxiously await confirmation of orbit capture, ESOC Main Control Room, 11 April 2006

heater lines and heater switches were working properly.

As part of the Attitude and Orbital Control System (AOCS) checkout, a startracker health check was performed together with calibration of the alignment. The Reaction Control System thrusters were fired to test their performance; a 'disturbance torque characterisation' assessed the forces from solar radiation on the spacecraft in various attitudes. Finally, the redundant Solar Array Drive Mechanism was tested by rotating the wings a few degrees.

For the data-handling subsystem, several memory areas of the computers were dumped to serve as a reference ground image of the onboard software. In addition, the redundant Transfer Frame Generator, responsible for the telemetry composition and modulation on the RF signal, was tested.

Payload checkout

During the payload commissioning all the scientific instruments were switched on, tested and calibrated to check the interfaces with spacecraft power, data-handling, telemetry and telecommand systems, and to verify that the overall performance was satisfactory.

On 22 November, after the initial instrument health check of VMC and VIRTIS, the two cameras were pointed towards Earth and imaged the Earth-Moon system from 3.5 million km out. A minor modification to the VMC software was then installed to prepare it for the upcoming pointing and interference campaign. Following this, SPICAV was commissioned.

To accommodate requests from the science community for instrument calibrations with special spacecraft pointing, a dedicated pointing campaign was prepared by the Venus Express Science Operations Centre (VSOC) for 27 November to 3 December. It was also used to validate further the ground segment interfaces between VSOC at ESTEC in The Netherlands and the Mission Operations Centre (MOC) at ESOC in Germany. The PFS, ASPERA and VeRA instruments were then commissioned.

Once all the instruments were checked out separately, a dedicated interference test concluded the NECP on 15 December. Several instruments were operated simultaneously in various modes to look at potential interferences between them and with the spacecraft systems.

Interplanetary Cruise Phase (ICP)

After NECP, the ICP lasted formally until 4 April 2006, a week before the Venus Orbit Insertion (VOI). ICP was initially considered as a quiet period operationally speaking, with only a few spacecraft activities to be carried out in preparation for VOI. However, it soon turned into a very busy period during which many important spacecraft and payload operations were scheduled.

Payload operations during cruise

While only a 1-week payload checkout was originally planned, in mid-January 2006, payload operations in reality had to be scheduled throughout the entire cruise phase. Following the second payload pointing campaign in January, almost all of the instruments were operated several times for various reasons. While the magnetometer was kept on for most of the time, to measure interplanetary magnetic fields, ASPERA was activated periodically to prepare for the routine mission. The Radio Science

ESA Director General Jean-Jacques Dordain congratulates Flight Director Manfred Warhaut upon receiving confirmation thatVenus Express had successfully entered orbit, 11 April 2006 team performed several frequency-drift tests on the onboard Ultra Stable Oscillator to characterise the frequency stability over time. The PFS, SPICAV, VMC and VIRTIS instrument teams took the opportunity to retest, fine-tune and improve their onboard software.

Spacecraft operations during cruise

During the cruise phase, the experiment teams were not alone in using the time to prepare for the routine mission – the Flight Control Team had to get the spacecraft ready for Venus arrival. At the start of ICP on 16 December, the batteries were discharged to 50% for a month to save battery life for the routine mission. During the rest of the month, several navigation tests were performed using NASA's Deep Space Network (DSN) stations and, for the first time, Cebreros combined with the New Norcia station in Australia. Those tests prepared for the intense navigation and tracking campaign later during cruise.

Following the payload pointing campaign, an intense thermal characterisation campaign started on 23 January 2006 to correlate the thermal model with flight data. Venus Express was pointed so that the Sun illuminated the heat-critical faces +Y, –Y, –Z and –X at an angle of 5º each for 24 hours, followed by an equivalent cooling period. This exercise confirmed the thermal tolerances were acceptable for operations. It was noted that the reaction wheel temperatures were higher than predicted after the Sun had been shining at 5º on the –X face. It was soon found that this contributed to some 'outgassing events' that disappeared later on.

In preparation for Venus arrival, the startrackers were checked on 7 and 8 February by pointing them at the same regions of sky as they would see in the days just before VOI.

From 9 February, all activities focused on the mission's next major milestone: the first firing of the main 400 N engine. In preparation for this important event, the thermal system was configured to warm the helium tank, the data-handling system was switched to a special telemetry mode that provided more frequent subsystem data, and the RF system transmitted an S-band carrier signal throughout the engine burn to simulate the operation planned for VOI. On 17 February, the engine firing went perfectly – to the relief of the whole project team! A week later, a small adjustment was made using the 10 N thrusters, tweaking the trajectory change from by the main engine test.

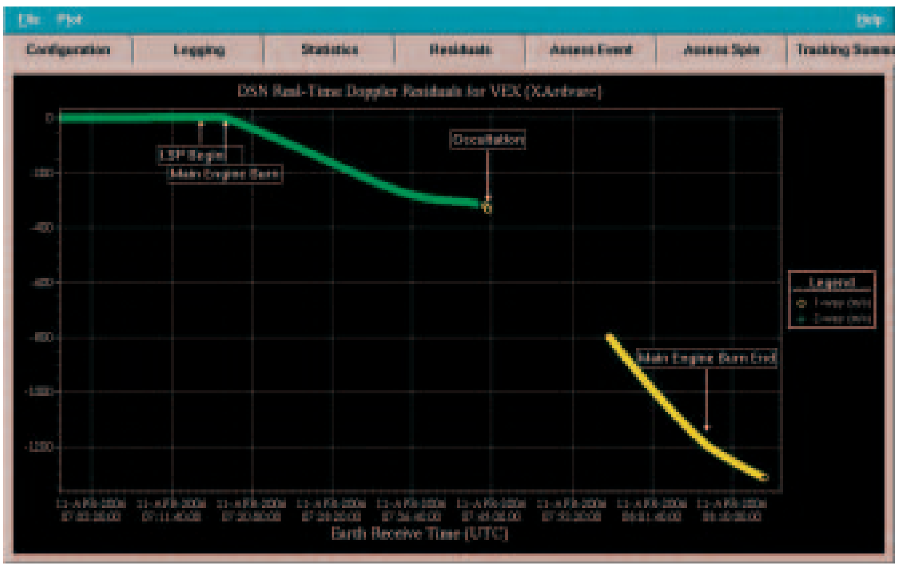
The next milestone was then a rehearsal on 6 March of the VOI operations, performed using the 70 m DSN antenna in Madrid. To train the Flight Control Team and ground station operators from ESA and DSN, and to rehearse the communications aspects of VOI, Venus Express was turned to simulate the same low-gain antenna geometry with Earth. Acquiring the S-band uplink was practised and one-way and two-way Doppler data were monitored. Even the occultation by Venus expected during VOI was simulated by temporarily switching off the onboard S-band transmitter.

From the beginning of March until VOI on 11 April, the navigation and tracking campaign was very intense. Throughout the cruise, about 50 ground station passes in addition to the normal Cebreros communication passes were scheduled with NASA stations to get Doppler and ranging measurements from an independent (non-ESA) source for orbit determination. In addition to the conventional Doppler and ranging methods, the new 'Delta Differential One-way Range' technique was used for navigation. With two ground stations simultaneously measuring the signals from Venus Express and an extragalactic source (a quasar), navigators could determine the position of the spacecraft very accurately.

Venus Orbit Insertion

VOI lasted from one week before the capture burn to 26 days afterwards, when the last of a series of seven orbit-control manoeuvres placed Venus Express in its operational orbit. The main strategy during this phase relied on an early upload of the minimum set of commands necessary to perform the insertion burn (done 4 days before the burn). This set of commands included the slews to and from the burn attitude, the X-band transmitter switched to 'OFF' and 'ON' (as the transmitter was kept off during the burn), and related attitude control mode transitions.

In the final days before insertion, additional slots were reserved for



The Doppler signal from Venus Express during the capture burn, displayed using Jet Propulsion Laboratory/DSN software installed at ESOC specifically for VOI

How Venus Express Reached Operational Orbit

Date (UT)	400/10 N?	Burn Type	Speed Change (m/s)	Duration (s)	Venus Orbit
10 Nov 05	10 N	test	0.500	50	–
11 Nov 05	10 N	launch correction	3.430	211	–
17 Feb 06	400 N	main engine calibration	2.840	154	–
24 Feb 06	10 N	main engine calibration comparison	0.137	14	–
30 Mar 06	10 N	trajectory correction	0.130	14	–
11 Apr 06	400 N	capture	1251.590	3163	330 685 x 662 km, 9 d
15 Apr 06	10 N	pericentre control #1	5.806	504	330 685 x 257 km, 9 d
20 Apr 06	400 N	apocentre lowering #1	200.300	529	99 108 x 259, 40 h
23 Apr 06	400 N	apocentre lowering #2	105.320	343	70 463 x 268 km, 26 h
26 Apr 06	10 N	apocentre lowering #3	9.165	670	68 000 x 268 km, 25 h
30 Apr 06	10 N	apocentre lowering #4	8.035	603	67 000 x 268 km, 24.2 h
3 May 06	10 N	apocentre lowering #5	1.952	233	66 582 x 268 km, 24.02 h
6 May 06	10 N	pericentre control #2	3.101	301	66 582 x 249 km, 24.0 h

trajectory-correction manoeuvres (13, 6 and 2 days before the burn), to correct for minor targeting errors as the spacecraft approached Venus. A ‘last chance’ emergency manoeuvre slot was reserved at 6 hours before the burn. This upload opportunity was to be used only if a trajectory estimation anomaly was identified in the final hours before passage through pericentre (the closest approach to Venus). In that case, an emergency pericentre-raising burn could be commanded if the path was too low (which would plough the craft into Venus), or conversely a longer insertion burn if it was too high. Fortunately, only the first of these slots, 13 days before arrival, had to be used to perform a tiny correction.

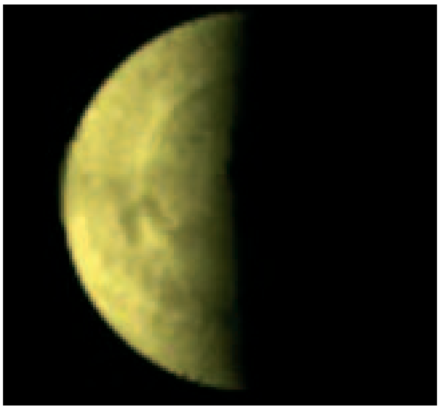
During this phase, Venus Express was gradually commanded into a special, fault-tolerant configuration in which most of the autonomous ‘Failure Detection, Isolation and Recovery’ functions were disabled, thus transferring some monitoring functions to the Flight Control Team. This minimised the chances of an automatic spacecraft reconfiguration being triggered close to or during the insertion burn, which would have resulted in a missed insertion and no possibility of trying again. The various measures taken to increase robustness included turning off monitoring of the power system. Most AOCS and data-management system monitoring was either disabled or allowed only at local level; only low-level reconfiguration possible. Rebooting the Processor Module was forbidden and the Mass Memory was also switched off.

This last point meant that no telemetry could be stored during the burn; in the event of problems, the Flight Control Team would have had very limited information on the possible causes. The last command was sent up to Venus Express 12 hours before the burn.

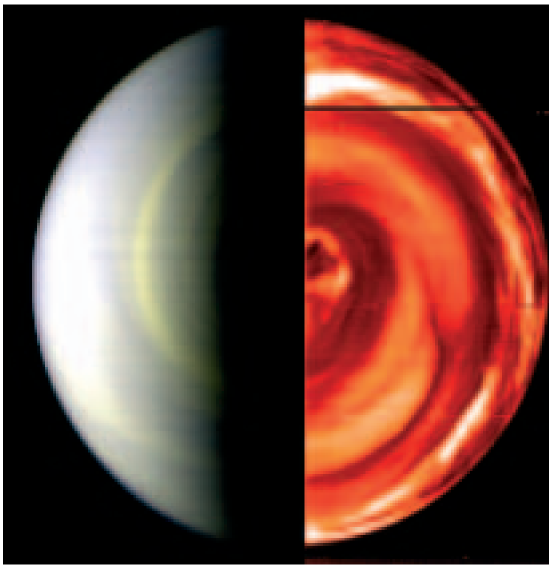
On 11 April 2006, the spacecraft ignited its main engine at 07:10 UT (at the time, the signal took about 7 minutes to reach Earth). During the burn, contact with the ground via the high-gain antenna was not possible owing to its orientation, but the front low-gain antenna was configured with the redundant transmitter to emit an S-band carrier. The 70 m DSN antenna at Madrid picked up this signal, which was relayed in real-time to ESOC to monitor the spacecraft during most of the manoeuvre.

About half an hour into the burn, the spacecraft swung behind Venus, cutting off its signal. It was reacquired on schedule at 07:55 UT, confirming that the capture trajectory was nominal (again, to the relief of controllers). The burn lasted about 50 minutes, and slowed the spacecraft by around 1250 m/s. Venus Express was now in a highly elliptical, 10-day orbit around Venus.

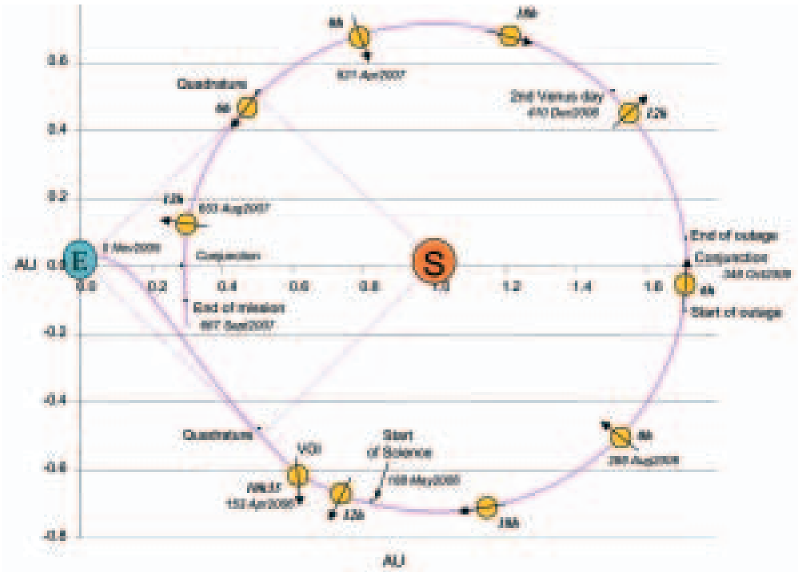
The burn was performed close to quadrature – the Sun and Earth were 90º apart as seen from the spacecraft. Given the spacecraft design, controllers wanted to avoid direct Sun illumination of the craft’s cold faces in order to prevent overheating. This meant swapping high-gain antenna usage from



VMC’s first image of the planet’s south pole. (ESA/MPS, Katlenburg-Lindau, Germany)



VIRTIS first image of the south pole. (ESA/INAF-IASE, Rome, Italy/Observatoire de Paris, France



The Venus Express mission

HGA-2 to HGA-1. Awkwardly, this had to be done during the insertion phase. It was decided that the safest strategy (in order to avoid blinding the startrackers with sunlight reflected from Venus) was to remain on HGA-2 until after capture, and make the swap 24 hours later.

With the spacecraft safely orbiting Venus, the Flight Control Team went ahead with the first batch of science observations of the planet, which were produced and downloaded to the ground only 2 days after having successfully performed the capture burn.

The team then commanded a series of manoeuvres to bring the spacecraft down to a 24-hour polar orbit suitable for science operations. To do this, five manoeuvres were made at the pericentre of the transfer orbit, and two more at the apocentre. Two firings were executed with the 400 N main engine, first slowing Venus Express by 200 m/s and then by 105 m/s. The others used the 10 N thrusters, which will also be called on from now on to maintain the orbit. Finally, on 7 May, the operational orbit was reached and the commissioning of the scientific payloads could be completed on schedule.

Outlook

Venus Express is now orbiting the planet in its routine science operations phase, to end in October 2007 after two Venusian sidereal days (486 Earth days). The spacecraft is operated by the MOC at ESOC with inputs for science activities from the VSOC at ESTEC. Daily contacts with the spacecraft are established through Cebreros. Science data collection has just started and will proceed in the coming months with additional types of observations possible only when the spacecraft is in an Earth-occultation season (July–August 2006) or a solar-conjunction phase (October–November 2006).

After the superior solar conjunction in October, when the Sun is between the spacecraft and Earth, the Earth distance will start decreasing again. This will allow higher data rates for the science downlink. Spacecraft resources have been designed so that an extension of two Venusian days is possible, to January 2009. With the current condition of Venus Express and the propellant margin, it is perfectly feasible and might stretch even further. esa

Acronyms

AOCS: Attitude and Orbit Correction System
ASPERA: Analyser of Space Plasmas and Energetic Neutral Atoms
DSN: Deep Space Network
HGA: High-Gain Antenna
ICP: Interplanetary Cruise Phase
MOC: Mission Operations Centre
NECP: Near-Earth Commissioning Phase
PFS: Planetary Fourier Spectrometer
RF: Radio Frequency
SPICAV: Spectrometer for Analysis of the Venus Atmosphere
VeRA: Venus Radio Science Experiment
VSOC: Venus Express Science Operations Centre
VIRTIS: Visible Infrared Thermal Imaging Spectrometer
VMC: Venus Monitoring Camera
VOI: Venus Orbit Insertion
VSOC: Venus Express Science Operations Centre

Detailed information on Venus Express and its mission can be found in Bulletin 124 (November 2005), pages 8–32. The Venus Express website provides up-to-date information at www.esa.int/venus