Venus Express: The Spacecraft

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The Venus Express project began with the fortunate inheritance of a set of spare spacecraft units and an industrial setup from the Mars Express mission, as it was clear that this second 'Express' mission would only be possible both financially and schedule-wise if new developments were kept to a minimum. Likewise for the payload, the strong legacy from Rosetta and Mars Express in terms of the scientific instruments was equally essential for mission success. Another critical factor was strict adherence to the spacecraft Assembly, Integration and Test campaign schedule, to ensure that the fixed launch window would be met.

Introduction

The main technical challenges faced with Venus Express have been the demanding mission requirements coupled with the need to make maximum reuse of the Mars Express spacecraft design in order to reduce the development risk. Equally challenging was the fact that everything had to be completed within a very short time frame, with the project getting the go-ahead in the autumn of 2002 for a launch in the autumn of 2005.

Consequently, the Venus Express spacecraft is very similar to Mars Express in the following areas:

- Unchanged system concept, with body mounted instruments, fixed antennas and a pair of solar arrays mounted on one-degree-of-freedom drive mechanisms.
- Similar structure with only local changes.
- Fully recurrent propulsion-subsystem and avionics units.

- Similar operational concept, with steady-state Earth-pointing for communications alternated with Venus observations during specific portions of the 24-hour orbit.

There are, however, a number of mission features specific to Venus Express that have required several design changes:

- Some payload instruments not flown on Mars Express had to be accommodated (VIRTIS, VMC, VeRa and MAG), whilst two instruments that were major design drivers for Mars Express are not present on Venus Express (Beagle-2 and MARSIS).
- The thermal environment at Venus is quite severe, with twice the solar flux compared to Earth, which greatly restricts the choice of external materials for the spacecraft.
- Since Venus is an inner planet, the Earth–spacecraft–Sun angle can be up to 360 deg, leading to the need for a dual High-Gain Antenna (HGA) design to ensure that a cryogenic radiator cold surface on the spacecraft can always be pointed away from the Sun.
- The gravity on Venus is 0.81 times that of the Earth (on Mars it is 0.11) and hence a greater velocity increment (delta-V) is needed for the spacecraft's injection into orbit around the planet, requiring the onboard propellant mass to be increased up to the tank limit.
- Venus is closer to Earth than Mars, allowing a proportional reduction in the size of the HGA whilst still maintaining the same performance.

Mechanical Features

The mechanical requirements were driven by the need to reuse the same mechanical spacecraft bus as for Mars Express, with minimal design changes to accommodate the body-mounted 88 kg payload. The interface to the Soyuz-Fregat launcher was unchanged. The maximum spacecraft mass for this launcher was 1270 kg.

Structural Features

The spacecraft's core structure is a honeycomb box 1.7 m long, 1.7 m wide and 1.4 m high, reinforced by three shear-walls and connected to a conical Launch Vehicle Adapter. The solar array is composed of two symmetrical wings to ensure that balanced forces are applied to the arrays and drive mechanisms during the main-engine firing for Venus orbit insertion. This array design would also permit aero-braking if required, for orbit reduction and circularisation.

Four main assemblies were produced in such a way as to simplify the spacecraft development and integration process as much as possible, namely:

- The propulsion module with the core structure.
- The ±Y lateral walls supporting the spacecraft avionics and solar array.
- The shear wall and lower and upper floors supporting the payload units.
- The ±X lateral walls supporting the HGA and radiators.

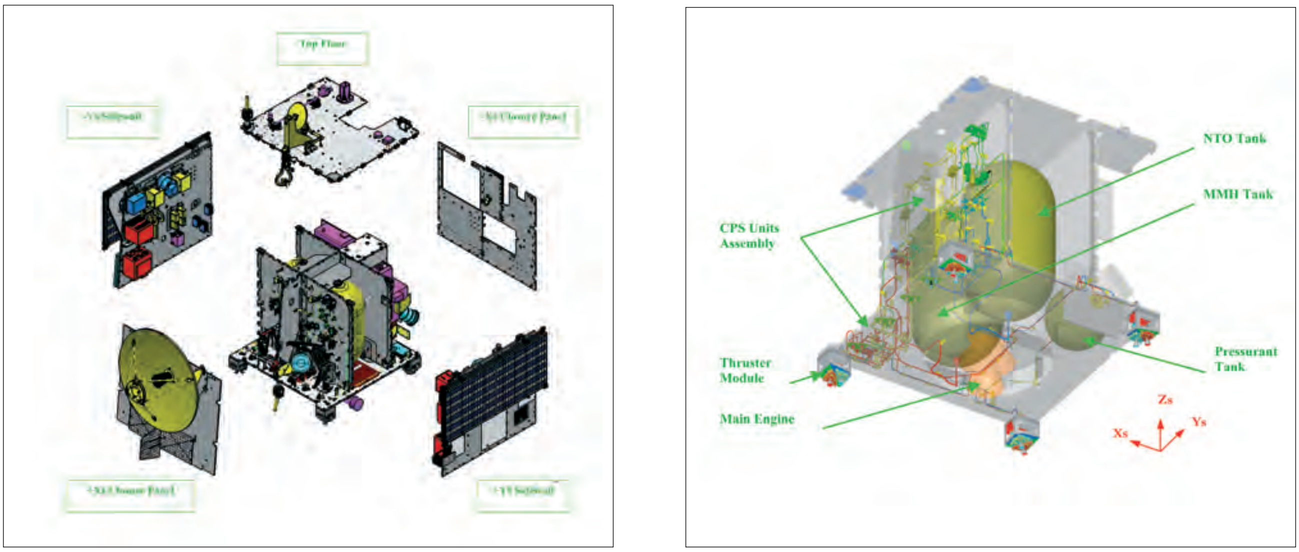
Propulsion Features

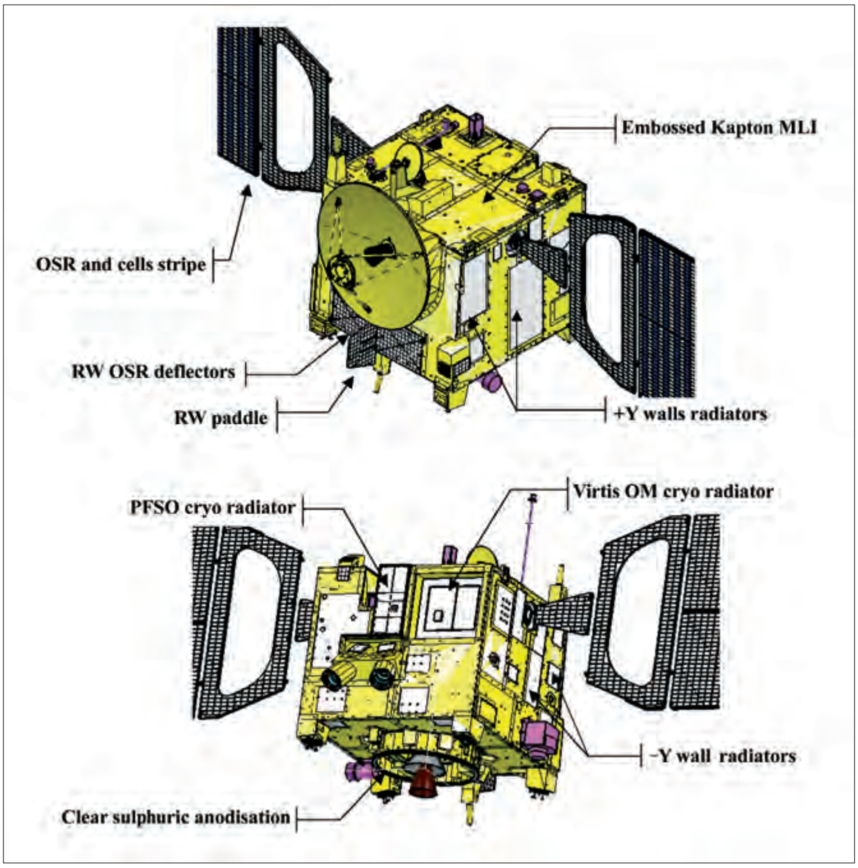
A helium-pressurised, bi-propellant, reaction-control system is used for orbit and attitude manoeuvres by either the 400 N main engine or banks of 10 N thrusters. This is very similar to Mars Express, except for some pipe routing, which was modified due to a change of pyrotechnic valves. In addition, the propellant load at launch was increased to 570 kg due to the increased delta-V requirement; most of it will be used during the 53-minute main-engine burn for Venus Orbit Insertion.

Thermal Features

It was clear from the outset that the Venus Express mission would be very much dominated by the unique thermal design required for this inner planet mission. The thermal requirements were driven by the worst-case cold conditions when in eclipse and the worst-case hot conditions when orbiting the planet, whilst also taking into account the fact that the solar flux would vary from 1320 W/m^2 near Earth to 2655 W/m^2 at Venus. Due to the high

Exploded view of the Venus Express spacecraft and its propulsion system





Views of the top (nadir-facing) and bottom (cryo-radiator) faces of the spacecraft

predicted surface temperatures (up to 250 deg), together with an intense ultraviolet environment, a rapid programme of thermal design, material selection and demonstration was instigated. Because of the severe schedule constraints, it was decided to adopt a conservative margin for the thermo-optical properties of the chosen materials.

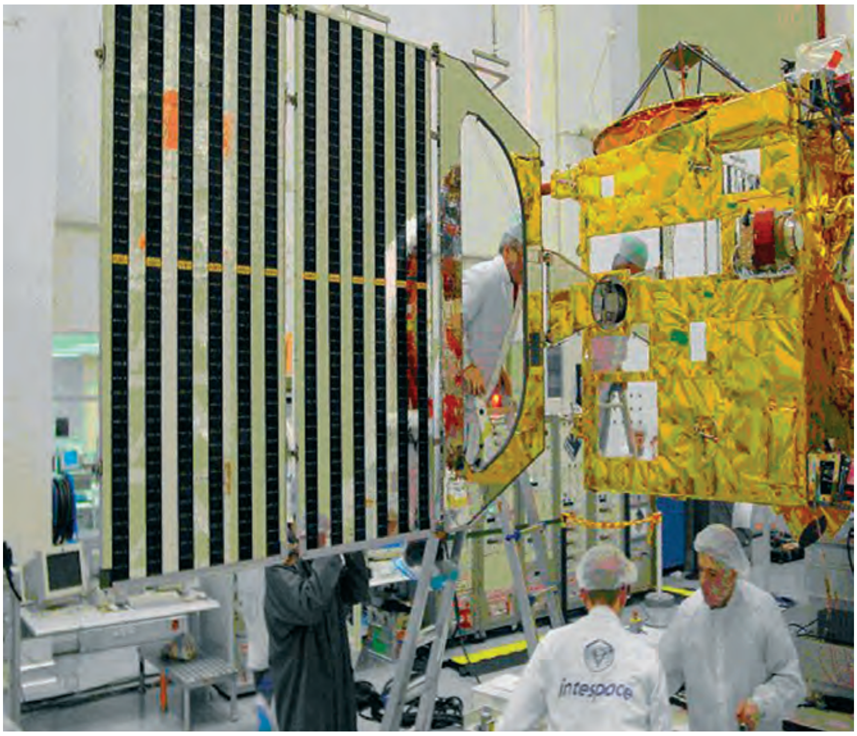
The passive thermal control used on Mars Express has been retained, but the spacecraft's external coatings have been modified to eliminate multiple reflections and avoid solar flux entering the spacecraft directly. In particular, Kapton multi-layer insulation (MLI) covers most of the spsacecraft, while optical solar reflectors (OSRs) are used on the lateral radiators and solar arrays, and sulphuric anodisation on the launch-vehicle adapter (LVA) ring's external surface. The heater power has been increased compared to Mars Express, which at first sight would appear counter-intuitive for a mission to an inner planet, but due to the passive thermal design there is a cold bias to the satellite. The additional heating is particularly required during the mission's early cruise phase and during eclipse.

Electrical Features

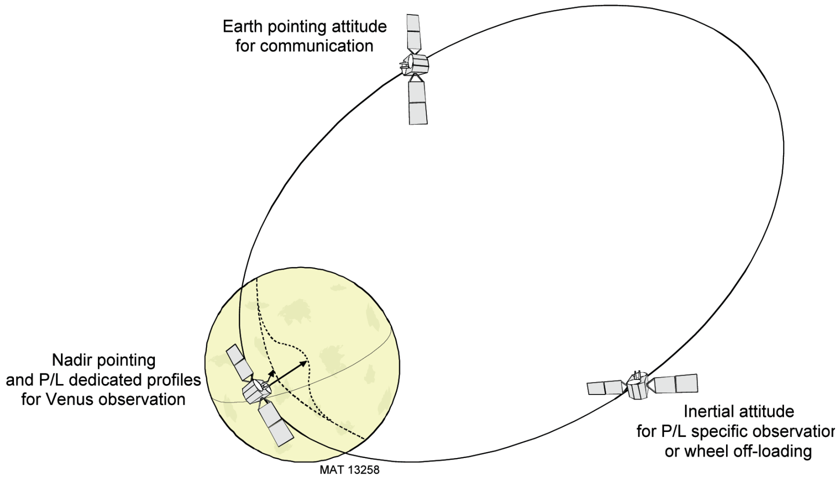
The Venus Express electrical architecture satisfies the needs of an interplanetary mission driven by high-autonomy requirements due to the lack of real-time control, and the highly variable environment in terms of distance, aspect angle, spacecraft attitude, orbit insertion and maintenance, together with the need to collect and format large volumes of science data for return to Earth.

Power subsystem

The spacecraft's onboard power is managed and regulated by the Power Control Unit (PCU) to provide a +28V regulated main supply for use by both the platform and payload units. Power is distributed to all spacecraft units via a Power Distribution



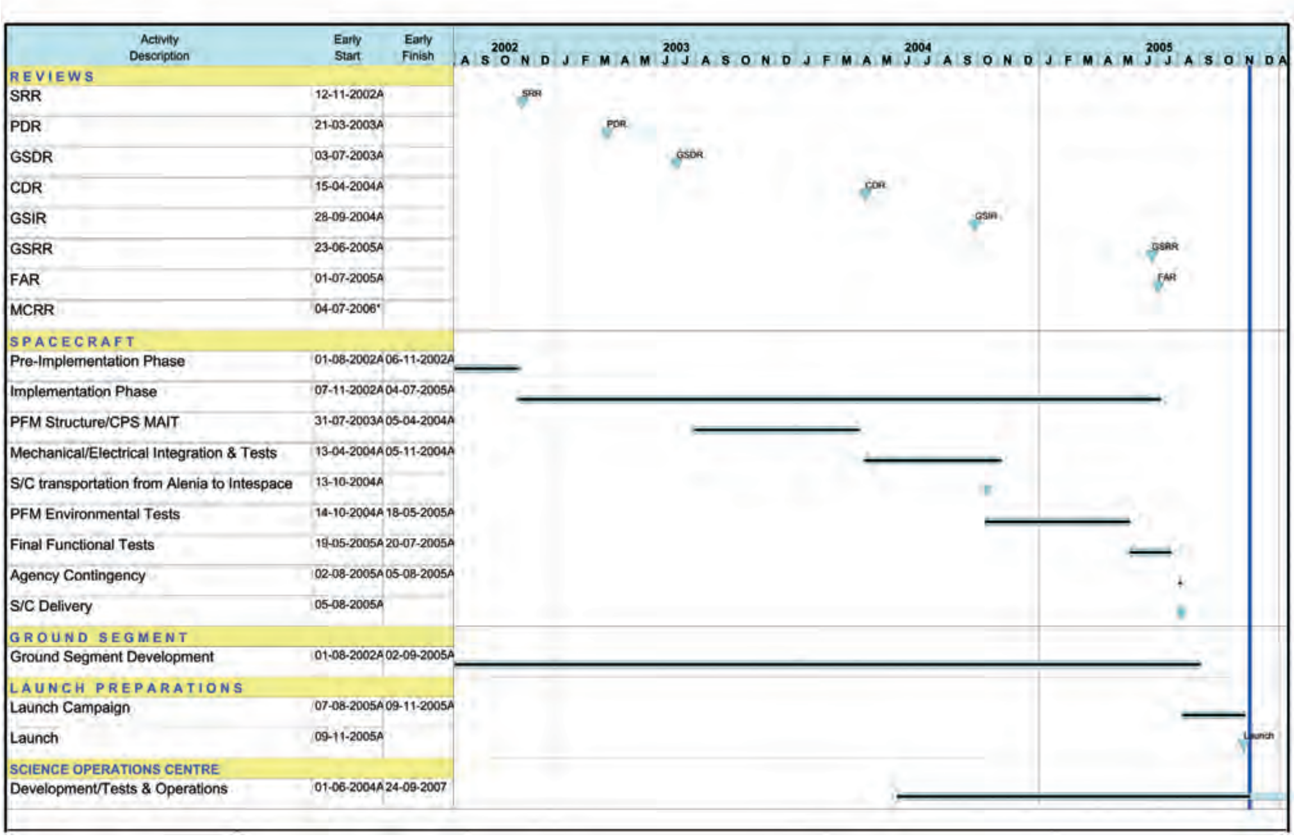
One of the solar-array wings after a successful deployment test at Intespace in Toulouse (F)



Pointing manoeuvres in the Venus orbit

Unit (PDU) that features current limiters for all units. Energy is stored in three low-mass 24 Ah Lithium-Ion batteries for use primarily during eclipse. The pyrotechnic firing circuits are also within the PDU, with the necessary power drawn from the spacecraft's batteries.

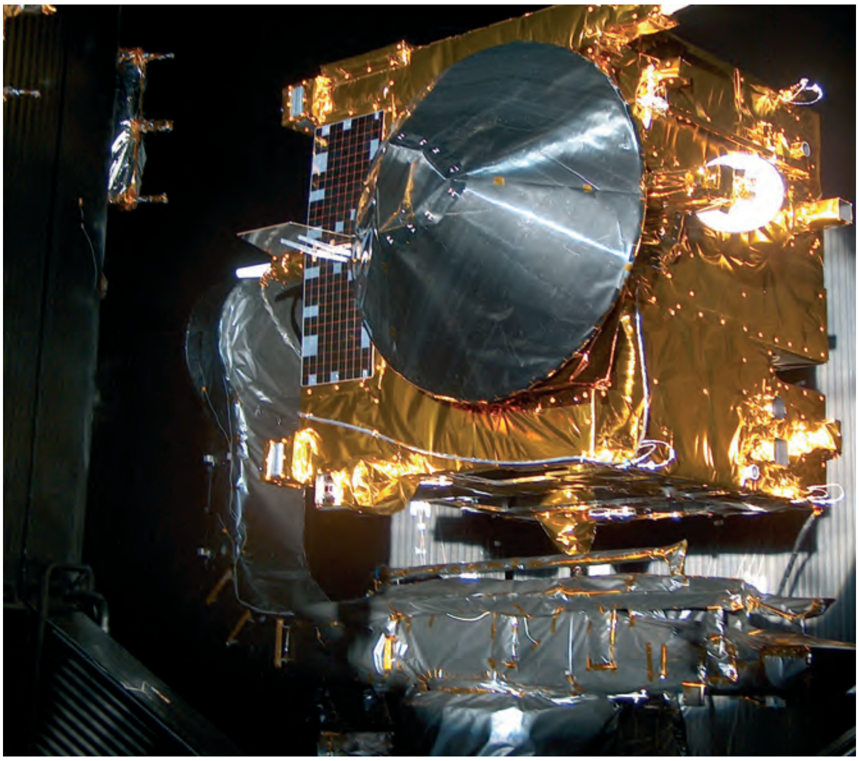
The solar-array power output needed near the Earth is 800 W, while at Venus it is 1100 W. It was decided at an early stage in the project that the silicon-based solar cells used on Mars Express would be unsuitable for Venus Express due to the wide range of temperatures that would be experienced by the arrays, leading to a large voltage range incompatible with the PCU. A trade-off study showed that gallium-arsenide triple-junction ($GaInP_2$/GaAs/Ge) solar cells would be the most suitable for Venus Express. A total of 1056 are mounted on the two wings, each with two panels of two sections, giving each wing a mass of 20.7 kg.



Activity Description	Early Start	Early Finish
REVIEWS		
SRR	12-11-2002A	
PDR	21-03-2003A	
GSDR	03-07-2003A	
CDR	15-04-2004A	
GSIR	28-09-2004A	
GSRR	23-06-2005A	
FAR	01-07-2005A	
MCRR	04-07-2006*	
SPACECRAFT		
Pre-Implementation Phase	01-08-2002A	06-11-2002A
Implementation Phase	07-11-2002A	04-07-2005A
PFM Structure/CPS MAIT	31-07-2003A	05-04-2004A
Mechanical/Electrical Integration & Tests	13-04-2004A	05-11-2004A
S/C transportation from Alenia to Intespace	13-10-2004A	
PFM Environmental Tests	14-10-2004A	18-05-2005A
Final Functional Tests	19-05-2005A	20-07-2005A
Agency Contingency	02-08-2005A	05-08-2005A
S/C Delivery	05-08-2005A	
GROUND SEGMENT		
Ground Segment Development	01-08-2002A	02-09-2005A
LAUNCH PREPARATIONS		
Launch Campaign	07-08-2005A	09-11-2005A
Launch	09-11-2005A	
SCIENCE OPERATIONS CENTRE		
Development/Tests & Operations	01-06-2004A	24-09-2007

The overall schedule for Venus Express

The spacecraft undergoing integration at Alenia in Turin (I)



The spacecraft in the SIMLES facility at Intespace in Toulouse (F)

Communications subsystem

The mission's Telemetry, Tracking and Command (TT&C) requirements were driven by the total volume of scientific data to be returned, and the operational requirements for spacecraft command and telemetry, spacecraft navigation and radio science. Compatibility with both the ESA TT&C Standards and the NASA Deep-Space Network (DSN) was mandatory to allow cross-agency support.

The configuration of the planets during the mission and the need to maintain a cold spacecraft face pointing away from the Sun led to the inclusion of a second smaller High-Gain Antenna (HGA2) that will be used for approximately one quarter of the mission, centred around inferior conjunction when the spacecraft will be at its closest to the Earth.

The TT&C subsystem has at its core two redundant dual-band transponders and two high-power 70 W travelling-wave-tube amplifiers interconnected with a radio-frequency (RF) switching network.

The spacecraft communications system also hosts the VeRa radio-science experiment's high-performance Ultra-Stable Oscillator (USO), which is essential for the one-way downlink experiments.

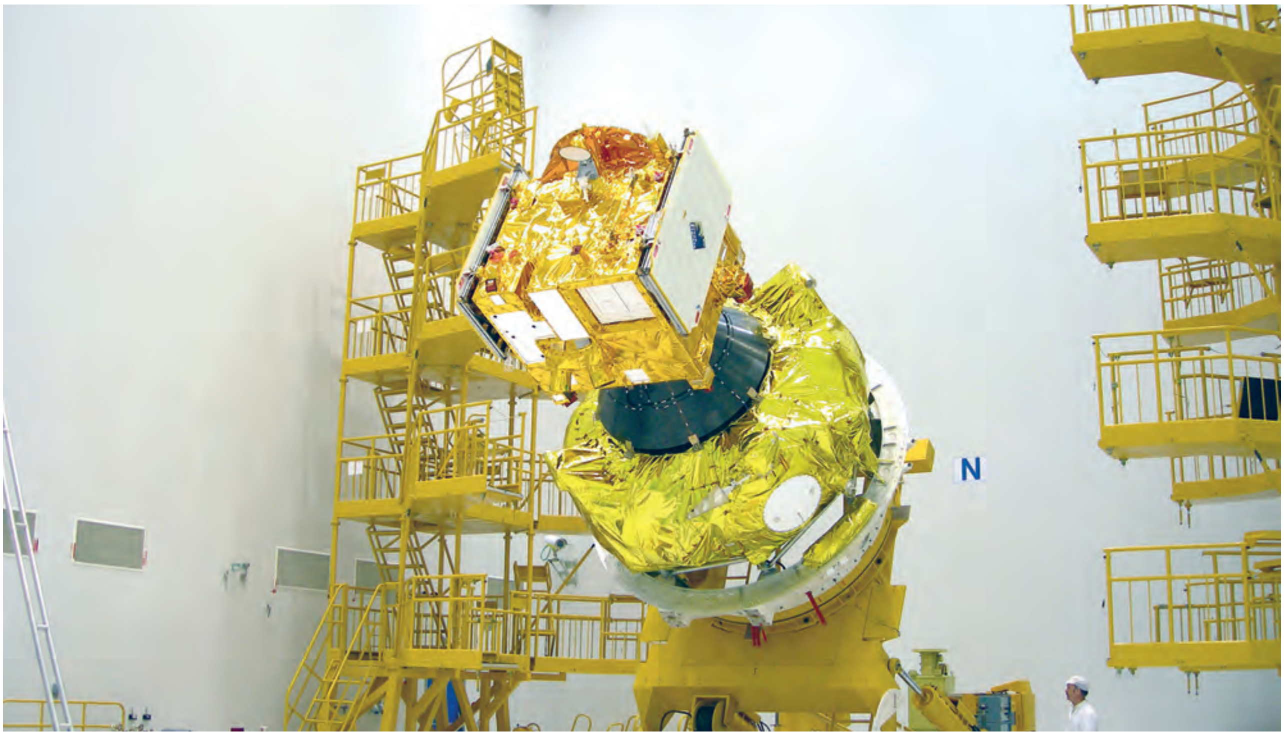
Data-handling subsystem

The spacecraft's data-handling architecture is centred on two Control and Data Management Units (CDMUs), which together constitute the Data Management System (DMS), a Remote Terminal Unit (RTU), an AOCS Interface Unit (AIU) and a Solid-State Mass Memory (SSMM).

The main tasks of the CDMUs are:

- Decoding of the telecommands from the ground and ensuring their execution, onboard housekeeping and science-data telemetry formatting for transmission.
- Execution of DMS software for overall data management, including the mission timeline.
- Execution of the attitude and orbit control system software.

The RTU is the interface between the DMS system and the payload and platform units. Instructions to these units are passed over one of the two redundant OBDH busses. In



The combined stack of the Venus Express spacecraft and Fregat upper stage being readied for launch at the Starsem facilities in Baikonur

the return direction, telemetry from the payload or platform units is gathered by the RTU for return to the DMS.

The SSMM is a file-based 12 Gbit mass-memory store for housekeeping and science data collected by the DMS system. However, two of the payloads, VIRTIS and VMC, generate such large volumes of data at high speed that they have their own dedicated direct links to the SSMM.

Attitude and Orbit Control Subsystem

As the spacecraft is of a fixed-antenna and body-mounted-instrument design and there is the need for a main-engine burn to achieve orbit insertion around Venus, the Attitude and Orbit Control System (AOCS) has to provide a high degree of attitude manoeuvrability. Attitude estimation is therefore based on star-tracker and gyroscope data. There is also a Sun-acquisition sensor for initial orientation of the spacecraft after its separation from the Fregat at launch and for safe modes. Reaction wheels are used for most attitude manoeuvres, thereby reducing fuel consumption.

Testing

The true 'express' nature of the Assembly, Integration and Test (AIT) activities can be appreciated from the fact that the spacecraft structure was delivered to Alenia's integration facility in Turin (I) on 5 April 2004 and the environmental test campaign was successfully completed just 15 months later, on 2 July 2005.

Following the initial integration of all of the platform units, payload units, thermal hardware, spacecraft harness, RF waveguides and antennas, an Integrated Subsystem Test was first completed. The spacecraft was then moved to the Intespace facility in Toulouse (F) in order to complete the system and environmental testing close to Astrium, the Venus Express prime contractor.

Owing to the unique characteristics of a Venus mission and the high solar flux experienced, it was necessary to upgrade the solar simulator facility (SIMLES) at Intespace. The solar flux was temporarily increased by introducing a removable lens into the optical path of the simulator, thereby concentrating the solar beam into a smaller area to illuminate the spacecraft with the higher flux representative of the flight environment.

The first spacecraft Integrated System Tests were run at Intespace at the end of November 2004, and the mechanical vibration and acoustic testing was performed immediately after Christmas. These tests showed that the spacecraft should perform as expected after its ride into space aboard the Soyuz/Fregat launcher.

By the spring of 2005, Venus Express was ready for the Thermal Balance/Thermal Vacuum test campaign. The results of these tests successfully demonstrated that the spacecraft would perform as predicted in the harsh thermal environment to be expected around Venus. The spacecraft underwent radiated Electromagnetic Compatibility (EMC) testing, including an auto-compatibility test to demonstrate that when the spacecraft is transmitting to Earth none of its other functions will be affected. In late spring, the System Verification Test performed by ESOC, and a further Integrated System Test, rounded off the successful Environmental Test Campaign.