The Ground Segment and Mission Operations

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Following launch and its 5-month interplanetary cruise, Venus Express was injected into a 24 h orbit around Venus. It is now conducting science observations for two Venusian days (486 Earth-days). This paper describes the ground system infrastructure, the orbital requirements and mission control parameters, the flight operations concept, principles and implementation for the various mission phases and payload operations, and the mission products to be made available to the scientific community.

1. Introduction

Venus Express was launched on a Soyuz-Fregat vehicle from Baikonur Cosmodrome on 9 November 2005. Mission control is based on a single control centre in association with the Cebreros 35 m ground station near Madrid (E). The New Norcia (Australia) 35 m station was used during Venus orbit injection and again for radio science investigations. The baseline operations philosophy is to acquire scientific data primarily during the 95 min pericentre passes, store the data onboard and downlink them during a single 9.5 h pass each day (even though the pass may last up to 13 h).

The mission is controlled from the Venus Express Mission Operations Centre (VMOC) located at ESA's European Space Operations Centre (ESOC) in Darmstadt (D). The launch and commissioning phase used the Main Control Room at ESOC, with tracking, telemetry and command (TT&C) provided by the ESA ground stations in Kourou and New Norcia.

VMOC is the primary interface with the spacecraft, responsible for monitoring and controlling the entire mission. The principal mode of operations is that all routine payload operations are planned and executed according to an agreed Flight Operations Plan (FOP). There are no realtime payload operations other than near-realtime interactive operations during commissioning (initial turn-on, calibration) and/or contingency situations; the procedures are contained in the FOP. After launch, the performance of all spacecraft subsystems was checked out, followed by a sequential switch-on/commissioning of all the experiments. Cruise operations followed. For all mission phases, the FOP is based on inputs provided through the User Manual.

Facilities and services are provided to the scientific community for planning and executing the acquisition of scientific data. This includes the generation and provision of the complete raw datasets and auxiliary data to the Principal Investigators (PIs).

The Venus Express Science Operations Centre (VSOC), at ESA's European Space Research & Technology Centre (ESTEC) in Noordwijk, The Netherlands, supports scientific mission planning and experiment command request preparation for consolidated submittal to VMOC. VSOC comprises the Payload Operations Service (POS) and the Data-Handling and Archive Service (DHAS). Under the responsibility of VSOC, POS undertakes the short-term science coordination and mission planning, while DHAS makes pre-processed scientific data and the scientific data archive available to the scientific community.

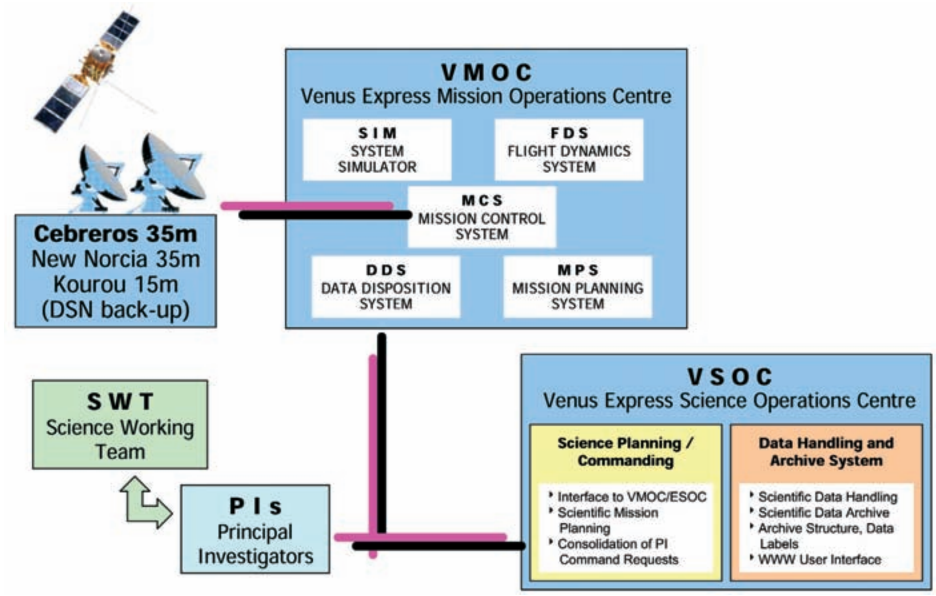


Fig. 1. Overview of the Venus Express ground segment.

2. Ground Segment Systems and Facilities

The ground segment monitors and controls the spacecraft and payload during all mission phases, as well as receiving, archiving and distributing instrument data. The ground segment (Fig. 1) consists of:

— a ground station and communications network performing telemetry, telecommand and tracking operations within the S/X-band frequencies. Telecommand is either at S-band or X-band, and telemetry is switched between the two, with the possibility of transmitting simultaneously in both bands (although only one can be modulated). Only the S-band up/downlink was used during the Launch & Early Operations Phase (LEOP), and is used for the VeRA radio-science campaigns and during emergencies. ESA's Cebreros 35 m-diameter dish (Fig. 2) is being used throughout all mission phases, complemented by the New Norcia 35 m station during Venus Orbit Insertion (VOI) and VeRa campaigns, and the Kourou 15 m station during LEOP. NASA's Deep Space Network (DSN) will be called on only during emergencies.

— VMOC, at ESOC, including:
  - the Mission Control System, to support, with both hardware and software, the data processing essential for controlling the mission, as well as evaluating spacecraft performance;
  - the Data Disposition System, supporting the acquisition and interim storage of raw scientific data, accessible together with raw housekeeping and auxiliary data from PIs at remote locations, and providing for production of all data on a raw-data medium for archiving purposes;
  - the Mission Planning System, supporting command request handling and the planning and scheduling of spacecraft/payload operations;
  - the Flight Dynamics System, supporting all activities related to attitude and orbit determination and prediction, preparation of slew and orbit manoeuvres, spacecraft dynamics evaluation and navigation in general;
  - the Spacecraft Simulator, to support procedure validation, operator training and the simulation campaign before each major phase of the mission, such as LEOP and VOI;

— VSOC, to support through POS the scientific mission planning and experiment command request preparation for consolidated submittal to VMOC. VSOC, which is collocated with VMOC during critical mission

Table 1. Ground station network usage.

Ground Station	*Mission Phase*	*Frequency*	*Remarks*
Kourou 15 m	launch & LEOP	S-band uplink S-band downlink X-band downlink X-band uplink	backup/emergency during near-Earth phase
Cebreros 35 m	commissioning (near-Earth/Venus), cruise, VOI, routine operations	X-band uplink X-band downlink	
New Norcia 35 m	launch & LEOP, VOI, routine operations	S-band uplink S-band downlink X-band uplink X-band downlink	routine operations support only for VeRa dual-band campaigns; emergencies
NASA / DSN	all mission phases	S-band uplink S-band downlink X-band uplink X-band downlink	emergencies backup/add-on during LEOP/VOI routine operations support only for VeRa operations

Note: Perth 15 m was used during LEOP for initial acquisition (S-band).

Fig. 2. ESA's 35 m ground station antenna at Cebreros.

phases, makes pre-processed scientific data and the scientific data archive available to the scientific community through its DHAS;

— a communication network, providing the support services for access to test data obtained during the spacecraft integration and test programme, submittal of command requests to VMOC, retrieval of quick-look mission products kept at ESOC, and potentially to provide electronic data exchange of scientifically processed data, if required.

The ESA/ESOC ground segment elements/facilities are described in the Network Facilities Manual. Existing hardware and software are used to the maximum extent possible. The stations are connected to VMOC via two-way data and voice links provided by ESOC. An overview of the nominal ground station network is given in Table 1.

3. Orbital Requirements and Mission Control Parameters

3.1 Launch, injection, interplanetary trajectory and Venus insertion

The Venus window for a Soyuz-Fregat launch from Baikonur opened on 26 October 2005, and closed on 24 November 2005. After Soyuz burnout, the Fregat upper stage and spacecraft remained in a 200 km coast orbit for about 70 min. Fregat then reignited and injected Venus Express into the required escape hyperbola to Venus with an excess velocity of about 2.8 km/s. The spacecraft separated from Fregat in a 3-axis stabilised attitude with residual angular rates of less than 1°/s.

As soon as the orbit was determined from ground tracking, a trajectory correction manoeuvre corrected for dispersions in the launcher performance. During cruise, small trajectory maintenance manoeuvres ensured optimum arrival conditions at Venus. Some days before VOI, a final arrival trajectory was achieved via further correction manoeuvres. VOI was achieved over the course of a week of critical operations. The initial firing of the main 417 N engine lasted about 50 min, achieving a delta-V of 1251 m/s, to attain a 9-day orbit of 682 x 330 685 km. The final operational orbit was achieved with apocentre

Table 2. The engine/thruster firings of Venus Express to reach its operational orbit.

Date (UT)	*Engine/thruster*	*Burn Type*	*delta-V (m/s)*	*Duration (s)*	*Venus Orbit (i = 90°)*
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: VOI	1251.590	3163	330 685 x 662 km, 9 d
15 Apr 06	10 N	pericentre control	5.806	504	330 685 x 257 km, 9 d
20 Apr 06	400 N	apocentre lowering	200.300	529	99 108 x 259, 40 h
23 Apr 06	400 N	apocentre lowering	105.320	343	70 463 x 268 km, 26 h
26 Apr 06	10 N	apocentre lowering	9.165	670	68 000 x 268 km, 25 h
30 Apr 06	10 N	apocentre lowering	8.035	603	67 000 x 268 km, 24.2 h
3 May 06	10 N	apocentre lowering	1.952	233	66 582 x 268 km, 24.02 h
6 May 06	10 N	pericentre control	3.101	301	66 582 x 249 km, 24.0 h

lowering through a combination of main engine and 10 N thruster firings. Venus Express was then in a 24 h, 90º-inclination orbit, with a pericentre of 249 km at 80º latitude and an apocentre height of 66 582 km. The manoeuvres to reach this final orbit are listed in Table 2. The mission timeline is depicted in Fig. 3.

3.2 Mission phases and duration

The Venus Express mission is divided into distinct mission phases:

Major Events / Mission Phase	*Date*
Launch	9 November 2005
Cruise Phase	
Start Near-Earth Commissioning	12 November 2005
Trajectory Correction TCM-1	11 November 2005
End Near-Earth Commissioning	15 December 2005
Mid-Course Correction	17 February 2006
Attitude adjustment for Venus Capture	29 March 2006
Venus Orbit Insertion (VOI) Phase	
Start VOI	7 April 2006
Venus Capture Manoeuvre (ΔV 1251 m/s)	11 April 2006
Orbit Insertion Manoeuvres (total ΔV 327 m/s)	15 April – 7 May 2006
Venus Commissioning Phase	
Start of Commissioning (Payload)	22 April 2006
End of Commissioning	3 June 2006
Routine Operations Phase	
Start of Science Operations	4 June 2006
Earth-Venus Superior Conjunction (communications outage)	28 October 2006 (21 October – 4 November)

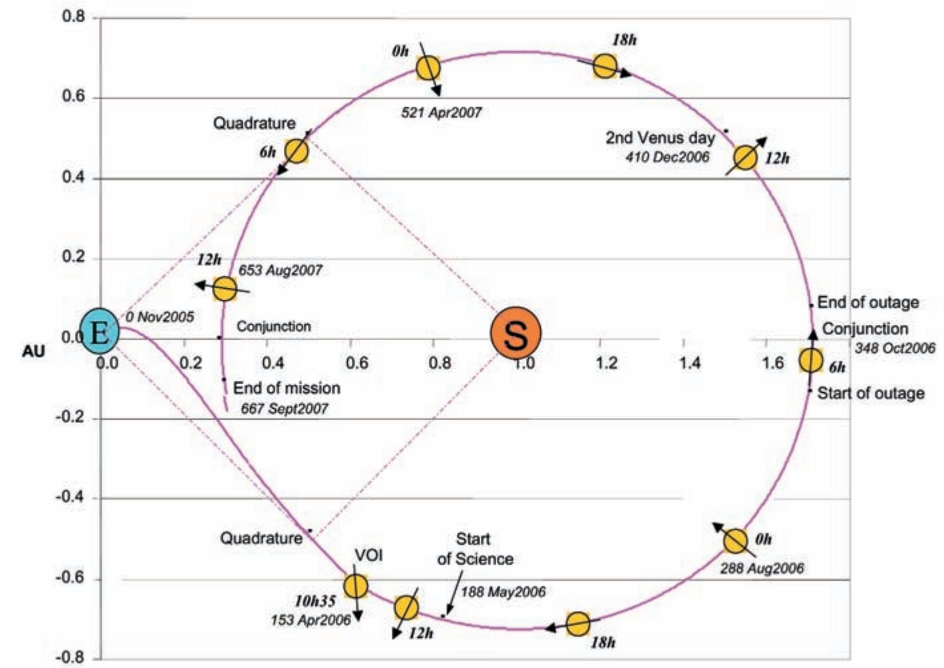


Fig. 3. The mission timeline.

Earth-Venus Inferior Conjunction (communications outage)	18 August 2007 (14–21 August 2007)
End of Mission (baseline)	5 October 2007
Extended Mission Phase (optional) Start of Extended Mission End of Extended Mission	 6 October 2007 30 Jun 2009
Total Mission Duration)	1329 days

3.3 Navigation

Navigation is the function to determine, optimise and control the trajectory on the basis of measurements, estimation and optimisation algorithms. The navigation function for Venus Express is performed at VMOC using radiometric measurements via the TT&C subsystem. VMOC is responsible for defining, according to the User Manual, the manoeuvre strategy for the entire mission, including the launcher dispersion correction, mid-course trajectory correction, Venus orbit insertion (capture and apocentre lowering), pericentre maintenance manoeuvres and any graveyard manoeuvre. It conducts inflight main engine tests as defined by the spacecraft prime contractor, while allowing for navigational constraints.

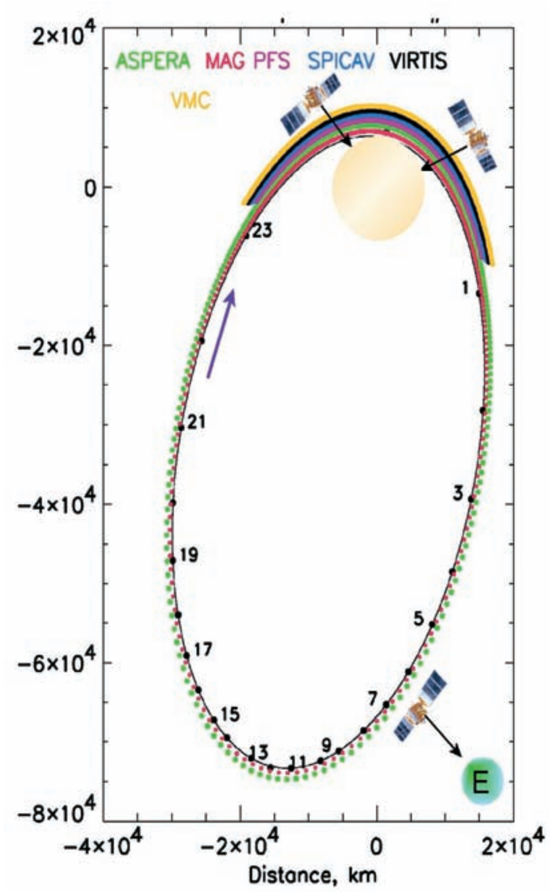
3.4 Attitude pointing accuracy and stability

The requirement for attitude pointing stability and accuracy was driven by the Venus capture manoeuvre, when attitude steering maintained the direction of thrust. The ability to reconstitute scientific observations during pericentre passes is a secondary driver for attitude maintenance. The ground segment requirements take into account the constraints defined in the Experiment Interface Document.

3.5 Venus orbit and attitude constraints

There are a number of constraints on the design of the operational orbit and the

Fig. 4. The orbit around Venus is divided into the different observing phases and Earth communication. The numbers within the ellipse denote the time in hours.



spacecraft attitude related to the planet and Sun directions that affect the flexibility in scheduling payload operations during the routine operations phase.

The period of the typical orbit of Venus Express around the planet (Fig. 4) is held at 24 h according to an agreed strategy of the project, mission analysis, flight dynamics, science and prime contractor teams. The orbit is timed so that the acquisition-of-signal 10º above the horizon at Cebreros occurs 2 h after pericentre passage. After about 14 months, the synodic motion of Venus would move the Cebreros visibility period 12 h earlier (to before pericentre) if the orbit were not adjusted. The pericentre altitude is maintained at 250–400 km, as required by the spacecraft's thermal design. The pericentre would otherwise rise naturally owing to the effects of solar gravitation.

Pericentre maintenance and station-pass phasing manoeuvres are typically scheduled every 40 days, and last about two orbits.

The feasibility of lowering the pericentre height to 150 km, for example, for short periods (several orbits) during the extended mission will be assessed by the project team, ESOC and the Project Scientist/Science Working Team. Spacecraft orbit position and accuracy are determined to within 3 km at the 95% confidence level within 1 h of receipt of tracking data at VMOC during critical operations, and the next working day during routine phases. During LEOP, cruise and VOI, the requirements were dictated by trajectory knowledge requirements.

The attitude constraints are driven by thermal subsystem margins (heat capacity), payload field-of-view requirements and the limited reaction wheel capacity. The attitude of the spacecraft body is defined by pre-set profiles of reference axes in inertial space. This ensures that imaging objectives are met and stability during imaging can be controlled. The ground segment supports the following spacecraft pointing options:

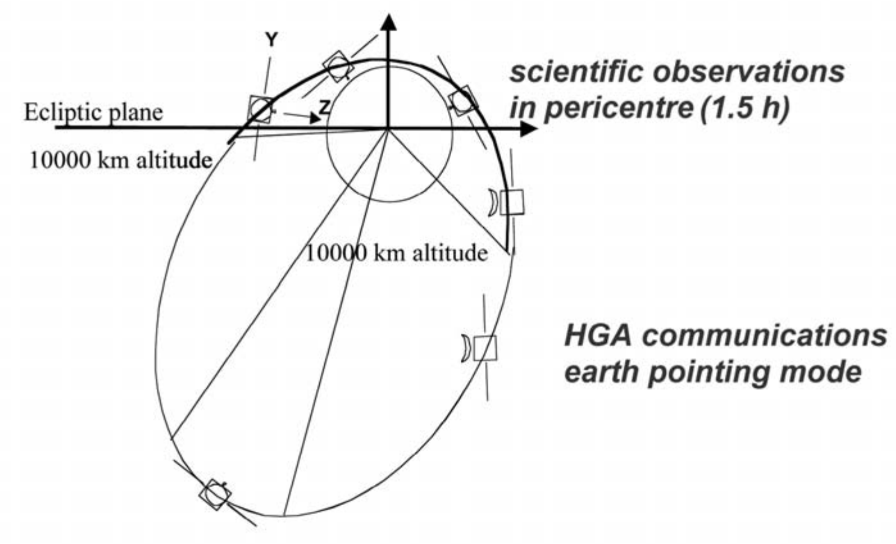


Fig. 5. The spacecraft's different attitudes in Venus orbit.

— Earth pointing: the boresight of the selected HGA points to Earth;
— nadir pointing: the +Z axis is nadir-pointing. A fixed offset (up to 30º) along- and/or across-track, is allowed; different yaw steering laws are supported;
— inertial pointing: the spacecraft points in a fixed inertial direction;
— VeRA custom pointing: the spacecraft points according to the profile provided by the VeRA Principal Investigator;
— VIRTIS mosaic: the spacecraft performs a raster manoeuvre according to the inputs provided by the VIRTIS Principal Investigator.

In the observation scenario used for sizing the subsystems during design, the +Z face of Venus Express nadir-points for the 95 min around pericentre.

During communications passes, lasting a maximum 10 h per orbit, Venus Express is maintained with its HGA (+X face) or HGA2 (–X) pointing to Earth (Fig. 5). Dedicated orbital slots, which are not necessarily compatible with science observations, are reserved outside of the planned ground station passes for spacecraft maintenance activities such as wheel offloading and orbit manoeuvres.

3.6 Scientific payload operations

Payload scientific operations are conducted according to the observation scenarios or feasible combinations of the defined ten science cases (Table 3) whenever they are compatible with the spacecraft and ground segment resources.

The downlinking of stored data is performed during daily station passes, when science observations do not interfere with the Earth pointing. Under nominal conditions, an average of 8.5 h is available continuously daily for downlinking. An average bandwidth of about 7 kbit/s is allocated to the downlinking of stored spacecraft telemetry, assuming a continuous generation rate of 2.5 kbit/s throughout the 24 h for spacecraft housekeeping telemetry.

VeRa radio science observations are conducted during Earth occultations with the spacecraft inertially fixed, for the short periods when the line-of-sight to Earth passes through the Venus atmosphere. Dual-frequency measurements (X/S-bands) to add to the X-band measurements of the Cebreros 35 m station make the occasional use of the New Norcia 35 m and DSN 34 m and 70 m stations. As far as possible, the orbit phasing is such that spacecraft entry into and exit from Earth occultation occur during New Norcia passes. During radio occultation, the spacecraft performs a slew manoeuvre to compensate for ray bending owing to atmospheric refraction.

Table 3. Payload operation scenarios.

ID#	*Observation Scenario*
1	pericentre observation
2	off-pericentre observation
3	apocentre global spectral imaging by VIRTIS
4	VeRa bi-static sounding
5	SPICAV stellar occultation
6	SPICAV/SOIR solar occultation
7	limb observation
8	VeRa Earth radio occultation
9	VeRa solar superior and inferior conjunction
10	Venus gravity anomaly by VeRA

Table 4. Acquisition periods and rates.

Mission Phase	*Ground Station*	*Daily Contact Window*	*Distance to Earth (AU)*	*Prime Spacecraft Antenna*	*Telemetry Rate[1](kbit/s)*	*Telecommand Rate (kbit/s)*
LEOP	New Norcia 35 m Kourou 15m	10 h 10 h	near-Earth	LGA-S	2	2
Near-Earth Commissioning	Cebreros 35 m	8 h	near-Earth 0.1	HGA2-X	26	2
Interplanetary Cruise	Cebreros 35 m	8 h	0.1–0.7	HGA2-X	14–26	2
Venus Orbit Insertion[2]	Cebreros 35 m New Norcia 35 m	10 h 10 h	0.7	HGA1-X	87	2
Routine Science Phase[3]	Cebreros 35 m	max 10 h	0.3–1.723	HGA1-X HGA2-X	22–256	2
Radio Science Investigation	New Norcia 35 m DSN 34 m DSN 70 m	30 d/yr 3 h/pass		S-band	carrier only	–

[1]includes Reed Solomon encoding overhead (net information rate is about 15% less) and commensurate with spacecraft TT&C design constraints (e.g. link budgets).
[2]only during capture phase, same as interplanetary cruise during approach.
[3]routine daily contacts are restricted to 9.5 h passes, with an average of 8.5 h (possibly 9 h best-effort) continuous data downlink to allow for a 1-shift mission control scenario.

3.7 Acquisition periods and bit rates

The acquisition periods achievable with the ground station complement depends on the mission phase; the distance to Earth dictates the maximum bit rates. The maximum available telemetry data rates for the space-ground link are summarised in Table 4. The figures reflect the maximum bandwidth, which has to be shared among all payload instruments and spacecraft subsystems when operational.

4. Flight Operations

4.1 General concepts and principles

The Mission Operations Department at ESOC, on behalf of the Directorate of Science Programme, prepares, plans and executes the Venus Express mission operations.

All operations are conducted by ESOC according to procedures laid down in the Flight Operations Plan, a comprehensive document prepared by the ESOC Venus Express Flight Control Team based on Project/Industry deliverables (User Manual and Database), the Science Operations Plan and agreements with the PIs. Payload operations are based on experiment User Manuals, Procedures and Databases, which the PI teams were required to produce and deliver to the prime contractor, who integrated them into a single Spacecraft User Manual .

Spacecraft operations during all active mission phases (lasting about 2 years, with a possible extension of 1.5 years) follow an offline approach. All activities are pre-planned and the resulting telecommands are uplinked to the spacecraft for time-tagged execution as the onboard Mission Timeline. Telemetry evaluation is mainly offline, with limited quasi-realtime intervention in selected critical and major contingency cases.

There are communication blackouts of up to 2 weeks owing to the spacecraft-Earth-Sun geometry. The communication turnaround time between ground and Venus Express is up to 30 min. The contacts between VMOC at ESOC and the spacecraft are not continuous and are primarily used for pre-programming of autonomous operations functions on the spacecraft, and for data collection for subsequent offline assessment. The downlink is normally configured such that most of the bandwidth is dedicated to dumping the stored telemetry, with limited housekeeping and/or event telemetry transmitted in realtime during the pass. Anomalies are usually detected on the ground only after a delay; the minimum delay is the light travel time, but typically it is of the order of a day. That means on-ground reaction faster than 24 h is not supported.

The PI institutes decide on their instruments' operations. The primary responsibility for developing the payload operations strategy lies with the Science Working Team (SWT). Simultaneous operation of the full instrument complement for 95 min during pericentre passage is the baseline. Operations outside of pericentre are supported for pre-defined attitude and instrument configurations, in scenarios validated (pre-launch) by the spacecraft prime contractor and checked by VSOC. For the remaining mission phases, the baseline is that no ground support is provided for payload operation – the instruments remain inactive or in basic, safe and autonomous low-activity modes.

4.2 Conducting operations

The characteristics of the mission dictate offline mission operations during Venus orbit science operations. Hence, all operations during routine operations are pre-planned and spacecraft health and mission progress monitoring is conducted offline after later recovery of the required telemetry. This implies a high level of onboard autonomy at system, subsystem and instrument level, to achieve the following objectives:

- to implement science operations and maintain appropriate prerequisites on the spacecraft status outside ground contact under nominal onboard conditions;
- to maintain mission-product generation in the event of a first failure affecting a spacecraft function;
- to stop mission-product generation in the event of a second failure, while ensuring spacecraft survival until the ground can intervene.

Following a failure, ground intervention normally takes place long after (depending on the mission phase) intervention by the onboard systems. The ground then collects information on the failure and the actions already taken autonomously onboard, and, if necessary, reconfigures the spacecraft subsystem or instruments to reestablish the generation of mission products. To this end, the spacecraft and payloads provide the ground with extensive information on the decision-process followed and all the actions autonomously carried after detecting a failure. VMOC's reaction requires unambiguous identification of the failure from the telemetry, and depends on the related contingency procedures specified in the spacecraft and experiment user manuals.

Operations of both spacecraft and scientific payloads are conducted in strict compliance with the validated event sequences and procedures documented in the Flight Operations Plan. This encompasses all operations: special and contingency operations as well as routine operations.

4.3 Mission phases

4.3.1 LEOP

LEOP lasted 3 days, starting a few hours before launch and ending with the start of the Near-Earth Commissioning Phase. Launch support began 8 h before launch (L–8 h) and included a final readiness test with the stations. At L–4 h, data flow tests and data confidence tests were performed; the data flowed from the satellite at the launch site to ESOC. This permitted the final verification of the ground system and network readiness an hour before launch and the final go/no-go decision. After Venus Express separated from Fregat at L+90 min, the spacecraft performed a series of configuration activities, including priming the reaction control subsystem, acquiring Sun-pointing, deploying the solar wings and establishing radio contact with the ground stations. These activities lasted about 50 min; ending about 20 min after first acquisition-of-signal by New Norcia at about L+2 h. Post-launch operations started once the separation sequence was completed. At that time, VMOC took control and completed the initial configuration activities, including configuration of the main subsystems (Data Management System; Attitude & Orbit Control System) and activation of the most important functions. In parallel, precise orbit determination was carried out by analysis of the radiometric measurements and the parameters for the first trajectory correction manoeuvre were calculated. The execution of this manoeuvre, on 11 November, concluded this phase.

4.3.2 Near-Earth Commissioning Phase (NECP)

NECP started on L+3 days with the execution of the first trajectory correction manoeuvre (TCM), and ended with the transition to the interplanetary cruise mode on 15 December 2005. Apart from TCM-1 in its early phase, it was dedicated to activation and checkout of the payload, instrument calibration, and verification that the overall system performance met the requirements. This included the checkout of the payload interfaces with the spacecraft subsystems, interference measurements between the payload and of subsystem influences on the payload. All subsystems not immediately used entering LEOP were also commissioned at the beginning of this phase. The detailed procedures were included in the Flight Operations Plan. No special tools were developed for these commissioning activities. The spacecraft was always flown in thermally stable attitudes. Daily planning sessions reviewed the progress of commissioning and eventually handled replanning. HGA2 was nominally used for X-band contact with Cebreros throughout this phase. The participation of instrument specialists was required at VMOC for the initial experiment switch-on operations and performance checkout. The operations performed during NECP included:

— completion of any remaining subsystem initialisation/switch-on, in particular that of payload elements;
— reconstitution and prediction of orbit/trajectory parameters to the accuracy required for subsequent mission phases;
— uplink of attitude control parameters;
— satellite performance surveillance and evaluation.

This involved operating all the instruments in their various operational and calibration modes, followed by analysis of output measurement data and instrument or spacecraft housekeeping. The analysis, carried out by the PIs under the responsibility of the Project, verified the correct functioning of the instruments. Critical operations such as power-up sequences during commissioning were initially performed only during ground coverage periods, when realtime control and monitoring of the spacecraft was possible.

4.3.3 Interplanetary Cruise Phase

The cruise phase began after NECP and ended with the Venus approach phase, defined to begin a month before Venus Orbit Injection. During cruise, Venus Express was kept in a 3-axis stabilised attitude (Sun-facing solar array, HGA2 pointing towards Earth) and communication with the ground was established during each daily pass. Mandatory payload calibration and maintenance activities were scheduled as approved by the Project Scientist. However, there were no science operations during the cruise phase.

4.3.4 Venus Orbit Insertion

VOI began a month before the Venus orbit capture manoeuvre, and ended when the spacecraft reached its operational orbit around Venus. The approach phase lasted about 3 weeks and the capture phase 1 week. The final orbit around Venus was achieved with a burn strategy that included a capture manoeuvre of 1251 m/s to achieve a highly eccentric orbit and the 332 m/s final injection manoeuvres using a combination of 417 N main engine and 10 N thrusters to reduce the apocentre to the final 24 h orbit.

4.3.5 Venus Commissioning Phase

The Venus commissioning phase began after VOI, in parallel with spacecraft activities, and concluded on 3 June 2006 with the start of routine operations in the operational orbit, in accordance with the Master Science Plan (MSP). This was a second payload-commissioning phase during which, after an initial post-cruise checkout, the operational readiness of the spacecraft, payloads and ground segment was verified. The PIs, on-site at ESOC, were provided with mission products and facilities similar to those for NECP. The payloads were operated offline via the onboard Mission Timeline. During this phase, the use of the Mission Planning System (MPS) was gradually phased in. The phase was used as a transition from the pre-defined activity scheme used in all previous critical phases involving the payload, to a more dynamic approach using the full MPS functionality. Finally, a Mission Commissioning Results Review assessed performance and verified the readiness to conduct routine operations of the satellite and ground segment.

4.3.6 Routine Operations Phase

The routine operations phase will last for two Venusian sidereal days (486 Earth-days). Science objectives are being pursued according to the MSP established by the SWT and Science Operations Working Group (SOWG). MSP provides the complete guidelines for the science operations and the selection of orbit and attitude strategies. The mission planning cycle adds details to the MSP and translates it into operations timelines using the MPS. The baseline routine science mission includes operation of the full complement of instruments in a nadir-pointing attitude for the 95 min centred around pericentre passage in each 24 h orbit. The MSP includes other science reference scenarios for attitudes and instrument modes fully validated by the Project and Industry and compatible with the ground segment baseline capabilities.

4.3.7 Mission extension/rundown phase operations/post-mission support

The satellite consumables are sized to support an extended phase of operations lasting an additional two Venusian sidereal days, but this extension is not yet baselined. The rundown operations will begin after the end of the routine/extended operations, the shutdown of instruments and the Project has officially announced the end of the mission. The activities will comprise archiving of software and documentation, and establishing the final cost-to-completion.

4.4 Payload operations support

Venus Express payload operations (Fig. 6) are governed by the rules and guidelines established and periodically discussed by the SWT. The preparation, coordination and execution of science operations are carried out according to the MSP. Two categories of operations are identified: commissioning, and routine science:

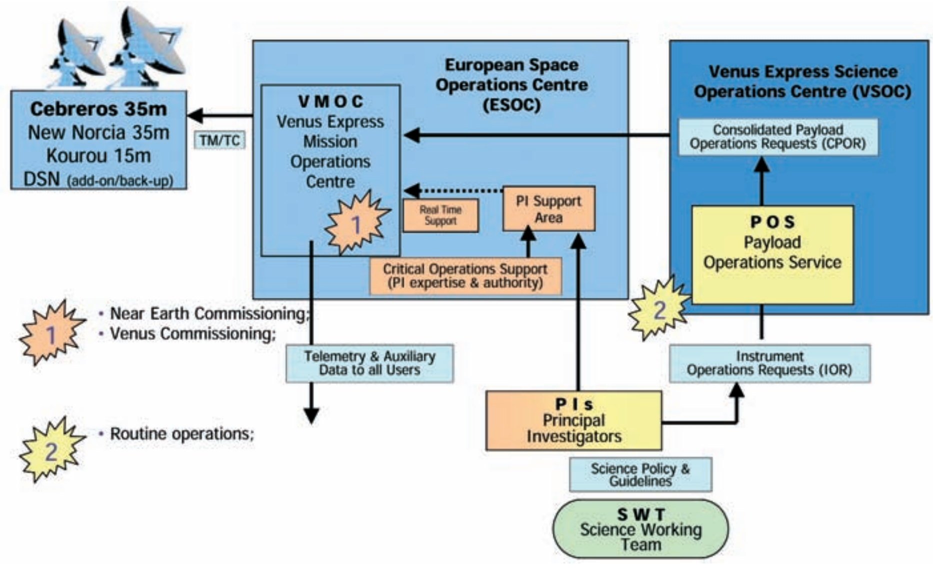


Fig. 6. Venus Express payload operations.

4.4.1 Commissioning operations

During payload commissioning, all experiment operations were executed at VMOC using a detailed timeline and related procedures established before the start of the phase. Timelines and procedures were defined by the SWT and the instrument teams, produced by the ESOC Flight Control Team, and agreed by the PIs. After validation by the system simulator, they were included in the Flight Operations Plan. The PIs and their teams of experts were accommodated at the VMOC during commissioning. The dedicated PI Support Area allowed the experimenter teams to install their support equipment. Payload representatives monitored the operations execution in near-realtime (depending on the availability of data) and supported go/no-go decisions at pre-defined steps in the procedures. The instrument teams could submit change requests to procedures and/or timelines up until to the last planning meeting before the execution time. These requests were discussed with the Flight Control Team in daily operations review and planning meetings under the supervision of the Project Scientist and the Spacecraft Operations Manager.

When the Mission Planning System was introduced during the Venus Commissioning Phase, the relevated VSOC functions were gradually phased in.

4.4.2 Routine science operations

For all the routine science operations, VSOC is in charge of supporting the Project Scientist in planning the science operations schedule and the generation of the coordinated operational command sequences for all instruments and their forwarding to VMOC. All the activities are offline, conducted according to the planning periods and deadlines established in the mission planning concept. The inputs from VSOC are checked by the Flight Control Team mission planners at VMOC against the mission rules and constraints and the available spacecraft and environmental resources, iterated if necessary with VSOC and finally added to the mission timeline for uplinking to Venus Express.

4.5 Mission planning and implementation

All mission operations are performed in accordance with a predefined and agreed plan. In general, inputs for generating the complete plan for each mission phase were submitted several months before the start of the phase. The planning process then continues at a more detailed level, subdividing each phase into planning periods, for each of which a separate deadline for submission of final inputs on the detailed operations is given. Owing to the characteristics of the mission and the offline operations approach, the finalisation of the detailed mission plan for each planning period comes several days before the start of the period. The planning baseline for Venus Express operations has two distinct types of operational planning: those requiring a detailed mission planning system (Category 2) and those that can be handled in a more online way by direct commanding from ground, via time-tag commanding (Category 1). The following groups of operational phases are identified:

Commissioning Mission Planning: a manual approach using the traditional 'timeline' was adopted;

Routine Mission Planning: the approach for all the routine science operations phases are based to the maximum extent possible to that of Mars Express. In a typical scenario, the PI teams provide, at fixed intervals, inputs to VSOC for the requested science operations, and then VSOC passes a consolidated request to VMOC, who checks the requests against mission, environmental and resource constraints. For routine science operations, the timeline of spacecraft attitude and the season (eclipses, occultations, Earth distance, etc.) plays a major role in establishing the constraints against which the payload operations plan has to be checked. This means that the Mission Planning System utilises information coming from the Flight Dynamics System defining the evolution of the spacecraft attitude and the epoch. The constraints on payload operations around Venus meant that a baseline science plan had to be established long before submitting the final science operations requests to mission planning for release to the front-end Mission Control System. The mission planning scenario for routine science operations is therefore divided into different levels:

- long-term planning deals with establishing the baseline science plans. There is input from the SWT and VSOC to VMOC to define the orbit and attitude timeline based on the scientific objectives to be achieved. Typically, one long-term plan is defined for each major payload operations phase of the mission, and the final iteration takes place around 6–12 months in advance of the actual operations of each phase.
- medium-term planning deals with the definition and refinement of an attitude strategy for the next planning period (typically a duration of 1 month). The baseline plan is translated into an attitude timeline (by the Flight Dynamics System) and payload command requests (by VSOC), allowing VMOC to allocate resources and identify conflicts in instruments operations.
- short-term planning. VMOC, using the refined final command requests checked against rules in the MPS, freezes resources and produces the sequences of commands to be uplinked to Venus Express. Deadlines for submitting requests are of the order of a week before the event. The planning period is also of the order of a week.

5. Mission Products

Mission products are made available to the PIs, and include all spacecraft and instrument telemetry data and auxiliary data as specified below. Normally, acquired data are made available at VMOC in engineering format within a minute of reception at the ground station.

5.1 Science telemetry

Upon receipt at VMOC, science data are extracted and stored as raw data chronologically ordered by instrument. They include quality and timing data to enable the PI to correlate them with UTC. Further processing of science data (e.g.

calibration) and verification of the correct functioning of instruments are not performed by VMOC; they are considered to be fully PI responsibilities.

5.2 Other telemetry

All other telemetry packets (typically housekeeping and event packets, telecommand acceptance, execution reports, event messages and anomaly reports, and memory dump packets) are stored as raw data, and are also available to the PIs.

In addition, VMOC can process the telemetry in near-realtime for spacecraft control purposes. The housekeeping and event packets, including the traditional binary and analogue parameters and event messages, are processed using, for example, calibration curves to convert them into engineering and/or functional parameter values needed to monitor the status of the spacecraft subsystems and payload. Special telemetry packets such as diagnostic, command acceptance and execution reports, and memory dump packets are also processed in order to carry out additional functions such as command verification, performance assessment, troubleshooting and supporting onboard software maintenance.

5.3 Auxiliary data

PIs also receive data not contained in the telemetry data to enable them to analyse the science data fully. The auxiliary data are correlated with respect to UTC and are available under subject headings:

— spacecraft ephemeris with respect to Sun and Earth, and Venus;
— spacecraft attitude prediction/reconstitution;
— command history data;
— time-relation history (onboard time/UTC);
— mission planning information.

Auxiliary data are provided in a format and within coordinate systems jointly defined by ESA and the PIs through the SWT. Auxiliary data are stored in a similar way to science data.

5.4 Data access and command request handling

The Data Disposition System (DDS) at ESOC provides quick access to the most recent data over communication lines on a call-up basis. The data include telemetry and auxiliary data, as well as related catalogues. Telemetry data (spacecraft and payload) are provided as raw data – time-stamped packets individually stored on logical files according to Application ID (Process Identifier and Data Type). Auxiliary data generated by VMOC contain the information needed to assist in processing and analysing the science data, and to support mission planning and command-request generation. The data may be stored in different files according to their nature. The catalogues contain a full record of all datasets available on the DDS and the time period to which each dataset pertains. The DDS is a near-realtime processing system that provides data access on a demand-driven basis – the PIs or delegated representatives are responsible for respective data requests. The data/message transmission is via file transfer only. The data are confidential to the related PI. The complete dataset will be kept online for the whole mission, with regular backups made on a Raw Data Medium (RDM). File transfer requires network functions and protocols to be compatible with FTP (TCP/IP). The PIs are responsible for providing the terminals or workstations at the remote host site, and the leasing/rental of public lines. The Data Delivery Interface Document (DDID) governs DDS interfaces, and is agreed with all PIs. The DDID describes the formatting of delivered data down to the necessary level of detail to enable users to retrieve science data and any required housekeeping or auxiliary data.

In addition to data access, the DDS allows for transfer of consolidated command requests from VSOC to VMOC as inputs to the Mission Planning System during routine operations.

5.5 Raw data long-term archiving

Raw telemetry and auxiliary data are being kept by ESOC throughout the mission in the Long-Term Archive (LTA), accessible via the DDS. ESOC produce an RDM with all science and auxiliary data for archive purposes; copies will be kept at ESOC and VSOC for a year after the mission ends. The RDM is offline, with a table of contents in form of a catalogue. However, no processing, data selection or other value-added services are provided. Retrieval from this RDM archive requires 10-20 days. Requests for retrieval require authorisation from ESA and should identify start/stop of pertinent time periods. The DDID governs this interface. Processed scientific and auxiliary data are archived by VSOC according to the Venus Express Archive Plan.

5.6 Data delivery formats

Each data-delivery request to the DDS results in a transfer of a block of data containing three main areas:

— an acknowledgement, including request details and status;
— a catalogue entry giving identification details of the requested data actually supplied (e.g. experiment, date, time);
— the requested data.

A simple packaging within Standard Formatted Data Units is applied, following a recommendation of the Consultative Committee for Space Data Systems. Apart from providing a convenient mechanism for handling the variable length of requested data, this standard also provides administrative support for description of application data.