Venus Express Science Planning and Commanding

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The Venus Express Science Operations Centre (VSOC) has the task of defining and performing, under the direct responsibility of the Project Scientist, the science operations for the mission. VSOC ensures that all the science objectives can be fulfilled within the operational constraints. This paper focuses on the planning and commanding activities, and provides an overview of the VSOC activities, outlines its architecture down to the hardware level, and summarises the science planning process. The data-handling and archiving are dealt with in a companion paper.

1. Introduction

The tasks of the Science Operations Centre (SOC) for any ESA planetary mission are specified in the Announcement of Opportunity and later are documented in the mission's Science Management Plan. For Venus Express, VSOC is responsible for:

- the definition of scientific operations for all mission phases with expert Principle Investigator (PI) team support;
- mission planning and implementation of instrument operation schedules, including resolution of timeline conflicts;
- supporting the PI teams in developing software for payload operations, such as the generation of command sequences;
- the coordination and checking of command sequences generated by the PI teams for their payloads before submission to the Venus Express Mission Operations Centre (VMOC);
- the maintenance and monitoring of a quicklook science data facility;
- together with the PI teams, the creation of a summary of the main scientific results, at regular intervals or for mission highlights;
- the preparation of guidelines for science data archiving and, supported by the PI teams, for the creation of the Venus Express Data Archive;
- make preprocessed data and the scientific data archive available to the scientific community in accordance with approval procedures and schedules as defined in the Experimenter Agreements;
- the definition of material and the planning, supported by the PI teams, for educational and outreach activities during the mission.

In summary, there are two main tasks for VSOC. Firstly, support the PI teams in the preparation of the operational files, the consolidation of the files and sending them to the VMOC for uplink to the spacecraft. Secondly, ensure that all data collected during the mission are archived properly, so that the scientific community can make use of them during and after the mission. This paper focuses on the first topic: the preparation of the operational files. The archiving element is covered by Delhaise et al. (2007) in this volume.

The tasks of VSOC vary during the course of the mission. During the commissioning, the instrument teams interacted directly with VMOC, located at ESOC in Darmstadt, Germany. This ensured a quick turnaround and allowed interactive operation of the instruments. VSOC personnel were collocated with VMOC during that phase and provided general support to the PI teams.

Before launch, VSOC prepared the Pointing and Interference Scenarios for execution directly after payload commissioning.

During the routine science operations phase, VSOC has three planning cycles: long-, medium and short-term planning. The long-term planning began long before launch. For that, VSOC consolidates the top-level science requests and documents them in the Science Activity Plan (SAP). The medium-term planning covers periods of a month and adds more details. In particular, pointing profiles are fixed and the operations have to be known to such a level that the resource requirements can be fixed. The output of this medium-term planning is the Master Science Plan (MSP). The short-term planning covers periods of a week. The MSP is expanded and the final operational files are produced. The main output is the Payload Operational Request (POR) file, containing payload telecommand sequences. The POR file is sent from VSOC to VMOC and, after a final check, uplinked to the spacecraft for execution.

The resulting data are retrieved by the experimenter teams from the Data Disposition System (DDS) at VMOC. After a proprietary period of 6 months, the teams are required to deliver raw and calibrated data (Level-2) to VSOC, where it is validated and ingested into ESA's Planetary Science Archive (PSA). The PSA can be accessed via a web-based interface and allows authorised users to browse, search and request data. The PSA is the legacy of the mission, which will allow future scientists to access and use the Venus Express data (Delhaise et al., 2007).

To support the science operations, VSOC produces Level-1b data from the telemetry coming down from the spacecraft. These data can be visualised by quicklook software and possible issues can be fed back into the operations planning.

2. VSOC Architecture

2.1 Introduction

The VSOC architecture was designed to reuse existing setups wherever possible, fit into the existing structure and workforce distribution of ESA's Research & Scientific Support Department (RSSD), and minimise the number of interfaces. It is physically located at ESTEC/RSSD in Noordwijk, The Netherlands, and is highly integrated with the Science Operations Centres of SMART-1, Rosetta and the Mars Express Project Science Team.

2.2 External relationships

VSOC's relationship with the instrument teams is outlined in Fig. 1, which shows the situation during the nominal science phase. There are three well-defined interfaces:

- A: from the PI teams to VSOC and vice versa;
- B: from VSOC to VMOC and vice versa;
- C: from VMOC to both VSOC and the experimenter teams.

2.3 Interface overview

Interface A is realised via a secure ftp server (sftp). The interface is used by the experimenter teams to deliver their planning file updates and updates to their command database. VSOC puts on this server the command files that need comments from the teams and other information such as the auxiliary data for

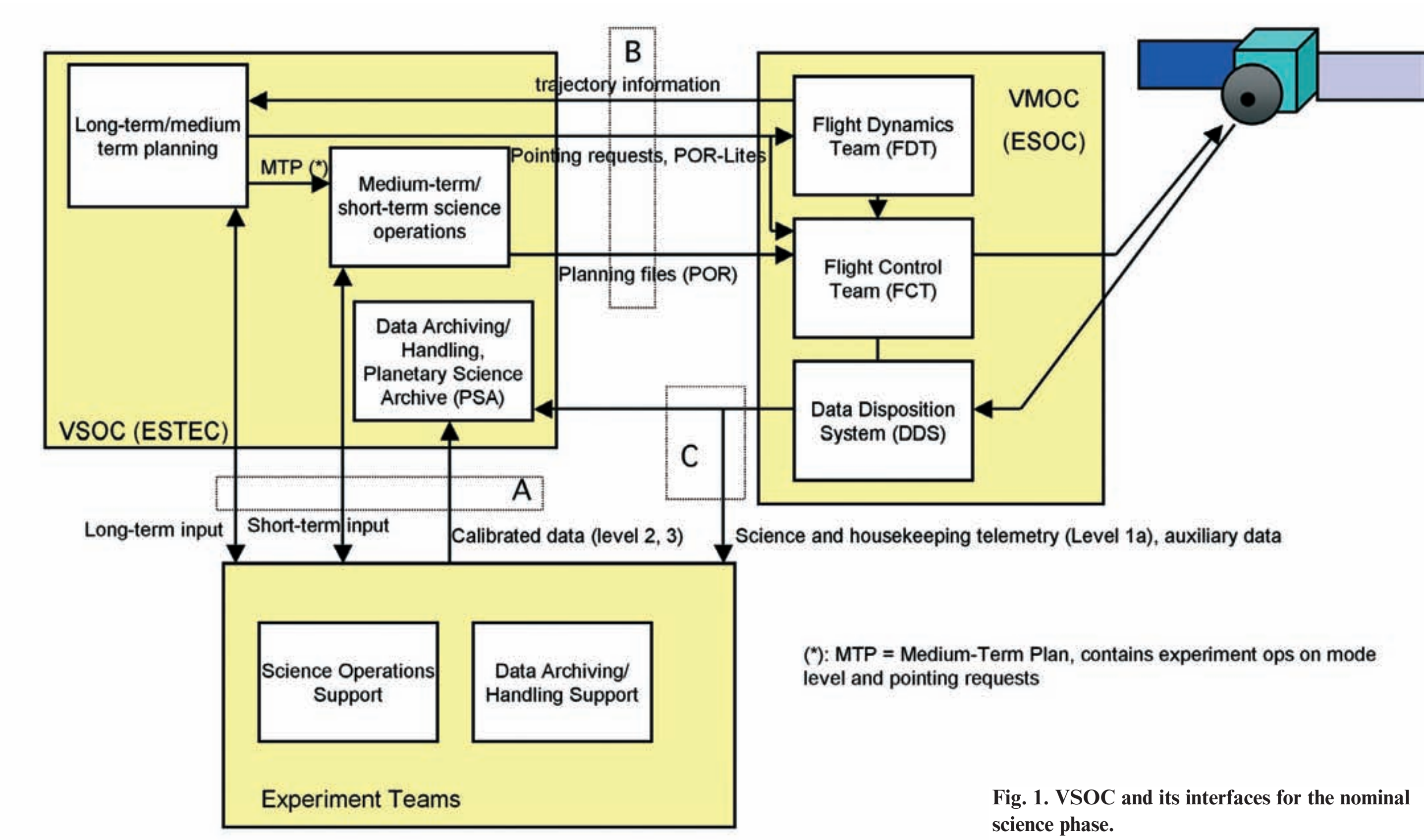

Fig. 1. VSOC and its interfaces for the nominal science phase.

the data archiving. Further information about the physical setup of this interface is given in Section 2.5. After the receipt of science data, the PI teams produce Level-2 (calibrated) data and derived data products such as maps (Level-3 data), and send them to VSOC for ingestion into the long-term archive.

Interface B is realised via the File Transfer System (FTS), which is specialised interface software running at VMOC. VSOC first transmits its files via ftp to a computer physically located at ESOC. On that machine, the FTS software is running and forwarding the files to the designated location, such as the Flight Dynamics Team or the Flight Control Team machine. More information about the physical setup of this interface is given in Section 2.5.

Interface C is realised by the Data Disposition System (DDS) operated and maintained by the VMOC. This server allows interactive, web-based access or files can be requested by sending an XML-formatted request file to a dedicated server. Each PI team and VSOC has a dedicated user account.

VSOC operates an automated data-retrieval system that retrieves spacecraft attitude and trajectory data and converts it into 'SPICE' kernels, a data format that is widely used in the planetary community as a library for geometrical and other calculations.

While the formal submission of operational files is performed via the interfaces as described here, many iterations and discussions of the planning process take place via email, regular teleconferences and the meetings of the Science Working Team (SWT) and the Science Operations Working Group (SOWG).

2.4 Internal architecture of VSOC

VSOC, as part of RSSD's Planetary Missions Division, shares personnel between planetary missions. In particular, the Science Operations Manager and the Data

Archiving Manager are involved in other planetary missions. For mission matters they report to the Project Scientist, but their direct line manager is the Head of the Planetary Missions Division. This ensures maximum reuse of concepts and tools from other planetary missions.

2.5 Physical setup of VSOC hardware

Figure 2 shows the physical setup of the VSOC hardware. Each box represents a physical computer, which normally has a cold-redundant backup machine. In order to maximise the reuse of existing setups, it was decided to use the Rosetta SOC FTS node (the 'FTS machine' in the diagram) as the physical interface between VSOC and VMOC. This computer is located at ESOC. It can be accessed from ESTEC only via one dedicated computer, the 'VMOC i/f', physically located at ESTEC, via a 'WinKey' secure connection.

The interface to the PI teams was realised via a secure ftp server on the PI interface computer. This machine is a dedicated machine used for all planetary missions and separate from the normal departmental ftp server of RSSD.

The typical flow through the system is:

1. VSOC produces the PI Operations Request (PIOR) file based on PIs' inputs and puts it in the outgoing directory on the PI interface computer. From there, it is automatically pushed via sftp to the PI's computer.
2. The PI team analyses the PIOR and submits their updated operational request file (PMRQ file = PIOR Modification Request) to the VSOC sftp area on the PI interface computer.
3. The Operational Request File Acknowledger (ORF-A) automatically picks up the file and checks the filename. For a PMRQ, it launches the Experiment Planning System (EPS) and checks the syntax of the files. It generates an acknowledgement and, if applicable, an error report, which is sent back to the PI teams via sftp. The files are put in a database implemented by a simple directory structure, where they are sorted according to their correctness. A log file entry is generated, which can be viewed on the web via the web interface (VSOCWeb).
4. A Science Operations Engineer picks up the files of the PI teams and consolidates them, possibly iterating the details with the PI teams. The engineer then generates the final PTR or POR files to be submitted to VMOC using the VSOC planning software.
5. The files to be sent to VMOC are transferred to the VMOC i/f computer. It has direct access to the FTS machine at ESOC. The Planner uses the script SubmitFTS to send the file(s) to the FTS computer. SubmitFTS checks the filename and supports the generation of the file's consecutive number. It waits for the Command Request Response (CRR) to come back in and generates a message to the user containing the transmission status of the file. It generates a log entry that can be viewed on the web via the VSOC web interface (VSOCWeb).
6. GetFTS is automatically invoked on the FTS computer when a file is sent by the FTS. In particular, it picks up the CRR files expected after submitting a PTR or POR file and sends it to the VMOC i/f computer at VSOC. It also generates a log entry that can be viewed on the web via VSOCWeb.
7. When data come down from the spacecraft, VMOC distributes it via the DDS. The Automatic DDS Request and Error Handling System (AHRES) polls the DDS (either automatically once per day, or manually) and receives the data as specified in a setup file. In particular, VSOC regularly requests the Flight Dynamics products and converts them via the SPICE conversion tool into the SPICE format. These files are made available on the PI interface computer.
8. The Flight Dynamics products are converted into the format of VSOC's

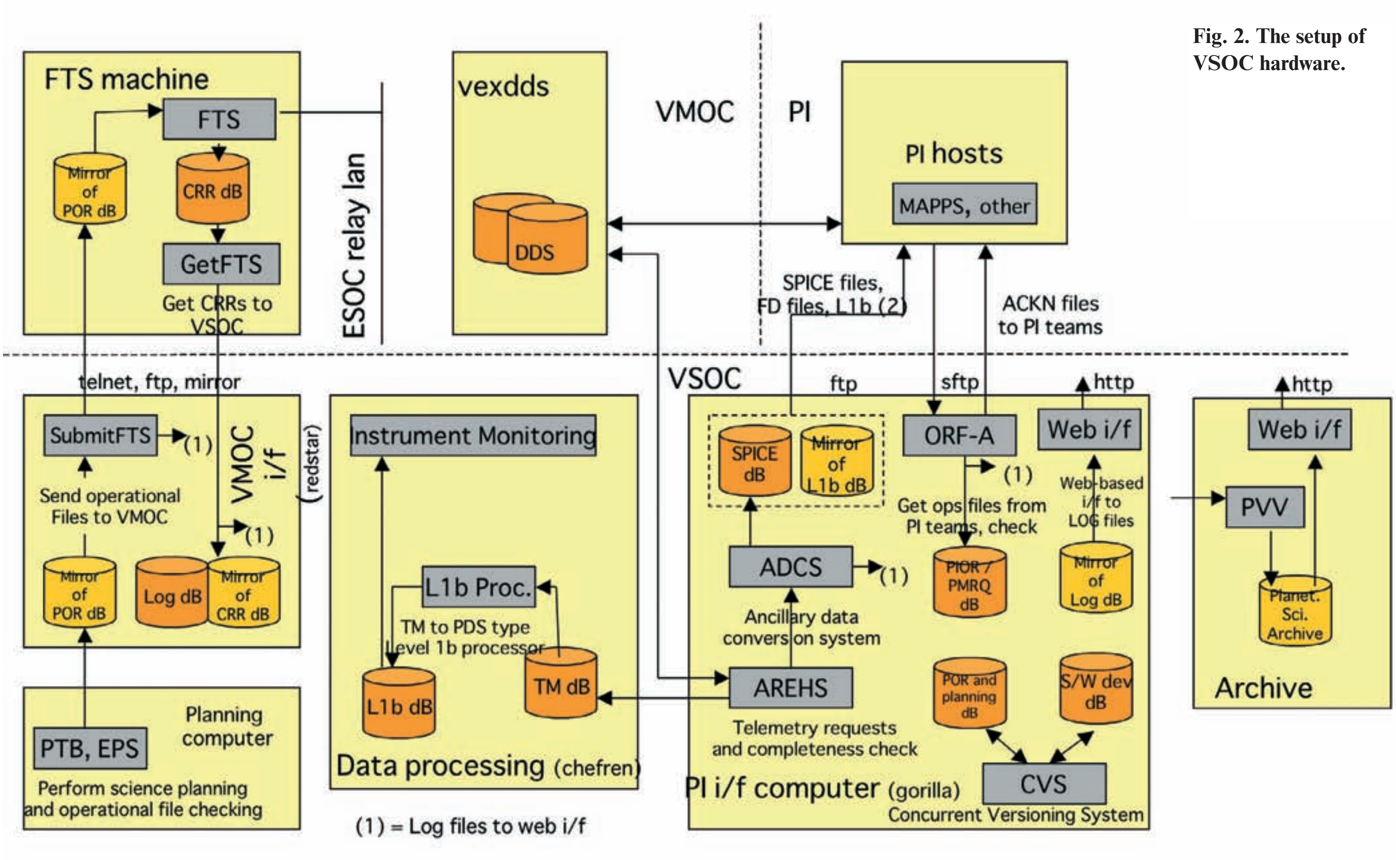

Fig. 2. The setup of VSOC hardware.

Mapping and Payload Planning Software (MAPPS; not shown in Fig. 2). These data are also made available on the PI interface computer. They are transferred to the science planning computers of the different team members to have the latest orbit and attitude files available for science planning.

9. The PI teams calibrate their data and produce Level-1b and Level-2 data. These data are sent to VSOC, where they are verified using the PSA Volume Verifier (PVV) tool and ingested into the Planetary Science Archive for long-term storage. A web-based user interface allows the science community to access these data after a proprietary period.

3. The Team

The VSOC involves the following participants:

— the Project Scientist has the final responsibility for the science operations and archiving activities.
— Project Scientist support by two people working part-time, involved in different areas of Venus studies. They support VSOC in the long-term planning and ensure that the science goals of the mission are fulfilled.
— the VSOC manager is responsible for the implementation and day-to-day management of VSOC. He is involved in the other planetary missions, thus ensuring the maximum reuse of existing concepts, hardware and software.
— three operations engineers collect the input from the scientists, prepare operational skeletons, consolidate the final planning files, iterate them with the PI teams and VMOC, and submit the final operational request files to VMOC.
— two software engineers. One produces the planning software tools, based on

existing software from the other planetary missions. The other produces and tests all interface software and the VSOC web interface.

— the Data Handling Manager is creating a data-handling and archiving concept for Venus Express. He is involved in the other planetary missions and manages the development team for the PSA.

Shared and short-term support:

— PSA software engineers provide the user interface for the PSA. They are shared between all planetary missions.
— a data-handling engineer operates the Level-1b processor, which unpacks the telemetry packets from the spacecraft and produces data that are in an easily readable format compatible with the PSA standard.
— a SPICE engineer develops, tests and maintains the software to produce the SPICE kernels. He is shared between all planetary missions.

The whole team is located at ESTEC, to allow quick interaction between the VSOC members. During the near-Earth commissioning and Venus commissioning phases, at least one Science Operations Engineer was located at ESOC for rapid interaction between the PI teams, VMOC and VSOC.

4. From Science Themes to Operations

Figure 3 shows the concept used for the science planning, the 'Science Themes' concept described in Koschny et al. (2004). It was developed at RSSD during 2004–2006 and is used by all current ESA planetary missions. The left part of the figure describes the science side of the planning process, while the right part covers the operational side. The common denominator is the 'observation'.

The Science Themes define the overall target for the observations of a specific scientific discipline (e.g. atmospheric studies) or phenomena. The top-level Science Themes were derived by sorting the individual science goals of the instruments and the top-level mission science goals. The resulting table was extensively discussed with the Science Working Team to fill in the details. Table 1 shows only the Science Themes and Sub-Themes.

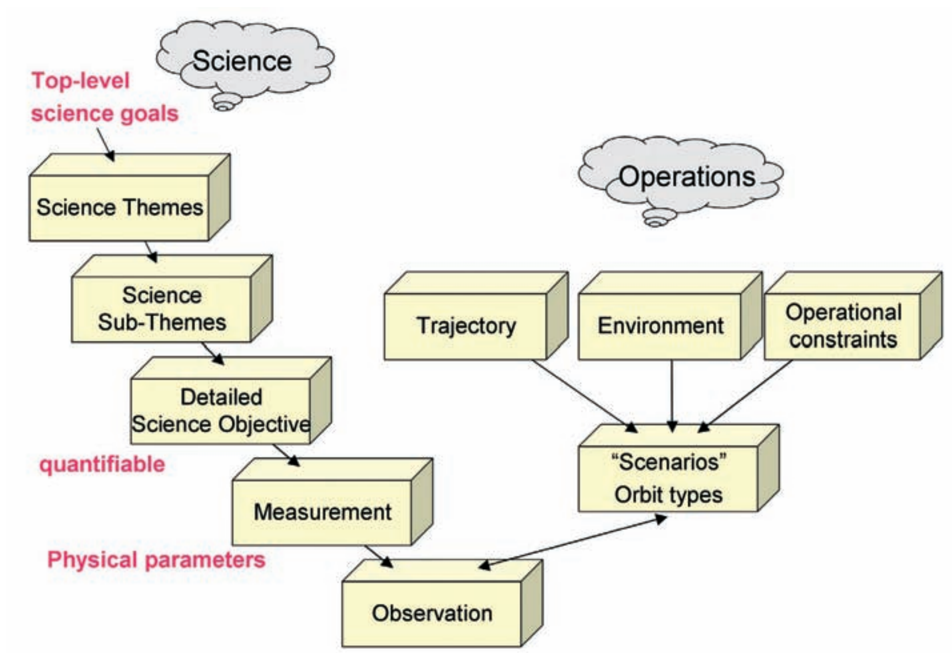

Fig. 3. The 'Science Themes' concept.

Table 1. Venus Express Themes and Sub-Themes.

Science Theme	*Science Sub-Theme*
Atmospheric dynamics	Dynamics of the upper atmosphere Dynamics of the middle atmosphere Dynamics of the lower atmosphere
Atmospheric structure	Structure of the upper atmosphere Structure of the middle atmosphere Structure of the lower atmosphere
Atmospheric composition and chemistry	Chemistry and composition of the upper atmosphere Chemistry and composition of the middle atmosphere Chemistry and composition of the lower atmosphere
Cloud layer and hazes	Optical properties and morphology
Radiative balance	Global balance Greenhouse effect
Surface properties and geology	Surface properties
Plasma environment and escape processes	Plasma and escape

Table 2. Details of the Sub-Themes 'Dynamics of the upper atmosphere' and 'Dynamics of the middle atmosphere'.

Science Theme	*Sub-Theme*	*Science Objectives*	*Measurements*	*Observations*
Atmospheric Dynamics	Dynamics of the upper atmosphere	Temperature and wind distribution	Temperature structure	Solar occultation
	Dynamics of the middle atmosphere	Global circulation	Wind velocity pattern	Stellar occultation
			Temperature and thermal wind fields	Mapping airglow of trace gases
			Vertical, spatial and temporal variability of O2 airglow	Tracking UV features at the cloud top
		Small-scale dynamics and wave phenomena	Morphology of the cloud tops	Temperature sounding in 15 µm and 4.3 µm CO2 bands
			Vertical structure of haze layers above the clouds	Radio occultations
			Fine vertical temperature structure	

The smallest element of a Science Theme is the 'Detailed Science Objective'. For example, the Science Sub-Theme 'Dynamics of the lower atmosphere' can be divided into Science Objectives 'Global Circulation' and 'Temperature structure and atmospheric stability'.

A 'Measurement' is necessary to provide the physical information for the Detailed Science Objective. It can be fulfilled by operating one or more instruments using different 'Observations', possibly over different orbits.

An Observation groups the operations of one or more instruments but contains only one pointing mode (e.g. nadir, mosaic). This allows the geometrical

Table 3. The Venus Express Science Cases.

Case	Title	Description
#01	Observations in pericentre	Spacecraft is nadir-pointing, all optical instruments can observe the planet. Main science goals: high spatial resolution spectral and imaging observations, plasma and magnetic field measurements close to the planet
#02	Off-pericentre observations	Spacecraft nadir-pointing or slightly off-nadir. The main science focus is global atmospheric dynamics and composition
#03	Global spectro-imaging from apocentre by VIRTIS	Done close to apocentre to get complete mosaic of Venus. VMC images and SPICAV spectroscopy support the spectral mapping of VIRTIS. Main science goal: chemistry and dynamics of southern hemisphere
#04	VeRA bi-static sounding	The spacecraft points its main antenna to a specified target on Venus such that the specular reflection of the signal can be received on Earth. This allows characterisation of the surface properties
#05	Stellar occultation by SPICAV	The spacecraft points to a selected star during occultation by the atmosphere. Wavelength absorption allows atmosphere's chemical composition to be inferred as function of altitude
#06	Solar occultation by SPICAV/SOIR	Similar to Case #05 but with the Sun as the source
#07	Limb observations	All optical instruments observe the limb to study the composition and structure of the atmosphere, ionosphere and hazes
#08	Earth radio occultation	As the carrier wave of the radio transmitter slices through the atmosphere of Venus as seen from Earth, the fine structure of the atmosphere and ionosphere can be studied. In particular, the temperature structure in the altitude range 40–100 km is retrieved
#09	VeRA solar corona experiment	This can be done when Venus appears close to the Sun as seen from Earth. The radio carrier wave traversing the solar corona allows its structure and processes to be studied
#10	VeRA gravity experiment	The high-gain antenna is pointed towards Earth. Detailed analysis of the carrier signal reveals the planet's gravity anomalies

constraints to be solved. It is the smallest building block of the operations that can be performed without interruption.

As an illustration, the breakdown of one Science Theme is given in Table 2.

The right-hand side of Fig. 3 takes into account the technical constraints of the mission, such as thermal considerations. For Venus Express, 'Science Cases' were defined long ago to help industrial contractor EADS-Astrium study the mission's feasibility. In Fig. 3, they are called 'Scenarios'. Each Science Case corresponds to a certain pointing mode along one orbit. Table 3 lists all of these Science Cases.

Each Science Case can be considered as containing one or more 'Observations' derived from the Science Themes. The Science Cases are scheduled over the mission and can be used to track how many Detailed Science Objectives were fulfilled.

5. Planning and Commanding

Operations require detailed technical planning and the preparation of telecommand sequences with parameters that are uplinked to the spacecraft to control observations by the instruments. It is the telecommand sequence that commands a certain activity in a payload. For example, there could be a telecommand sequence called 'Acquire Image' for the Venus Monitoring Camera (VMC), with parameters such as 'Exposure time' and 'Compression factor'.

The telecommand sequences are uploaded from VMOC as one large file. VSOC provides the consolidated Payload Operational Request file containing all the telecommand sequences for a specific planning period (typically a week). The file's preparation requires three planning cycles:

— the long-term planning cycle began about 2 years before launch. VSOC and the SWT produce the Science Activity Plan, which outlines the science activities for the complete mission at the top-level (RSSD, 2005a). It includes a list of Science Cases to be flown per orbit.
— the medium-term planning cycle covers a month of activities. Starting from the SAP, the pointing request files (PTRs) are generated. The instrument operations are defined at the mode level (science, calibration, standby) and sent to VMOC as POR-lite files. These files follow the syntax of a POR file, but contain only mode-level operations. All the resources are fixed in this cycle. The Medium-Term Plan (MTP) goes through a number of revisions during the evolution of the planning cycle. In the beginning, it combines and documents the requests from the scientists; the final version is produced after completion of the planning cycle and includes a log of what happened during the month.
— the short-term planning cycle lasts a week. VSOC produces PI Operations Request files from the MTP. These contain the telecommand sequences as a function of time, with instantiated parameters, and are sent to the PI teams for confirmation or updating. The PIs return the PIOR Modification Request to VSOC. Even if there are no changes to the PIOR, VSOC expects a PMRQ to get a positive confirmation by the PI teams for the planned operations. All the PMRQs of all instruments are checked to ensure they follow the correct syntax. Constraints defined in a database are checked. VSOC checks for resource conflicts (which should have already been sorted out in the medium-term planning), syntax errors and conflicts between instruments. Once per week, the conflict-free PMRQs are converted to the syntax of the POR files and sent to the VMOC for uplink.

For a detailed description of science planning and commanding, including definitions of inputs and outputs of the planning cycles, see RSSD (2004).

6. VSOC Software Tools

6.1 The MAPPS tool

The MAPPS tool allows the user to display a 2-D map of Venus to visualise the orbit of Venus Express over the planet. Among other items, it displays the spacecraft position above the target, the Sun and Earth positions, day/night boundaries and the ground tracks of instrument fields-of-view. It also reads in the command files produced by the experimenter teams and displays them in a 'Timeline Visualisation' window. It computes and displays items such as the projected field of view of an imaging instrument on the surface of Venus. MAPPS is a reduced version of the Venus Express Project Test Bed (VEX PTB) that was distributed to the PI teams for their planning purposes.

Figure 4 shows a screen shot from MAPPS. The top part of the image shows the surface of Venus as mapped by the US Magellan radar mission. The blue points are the centre points of Venus Express camera image points. The lower left window is the MAPPS control panel, showing which orbit definition file and

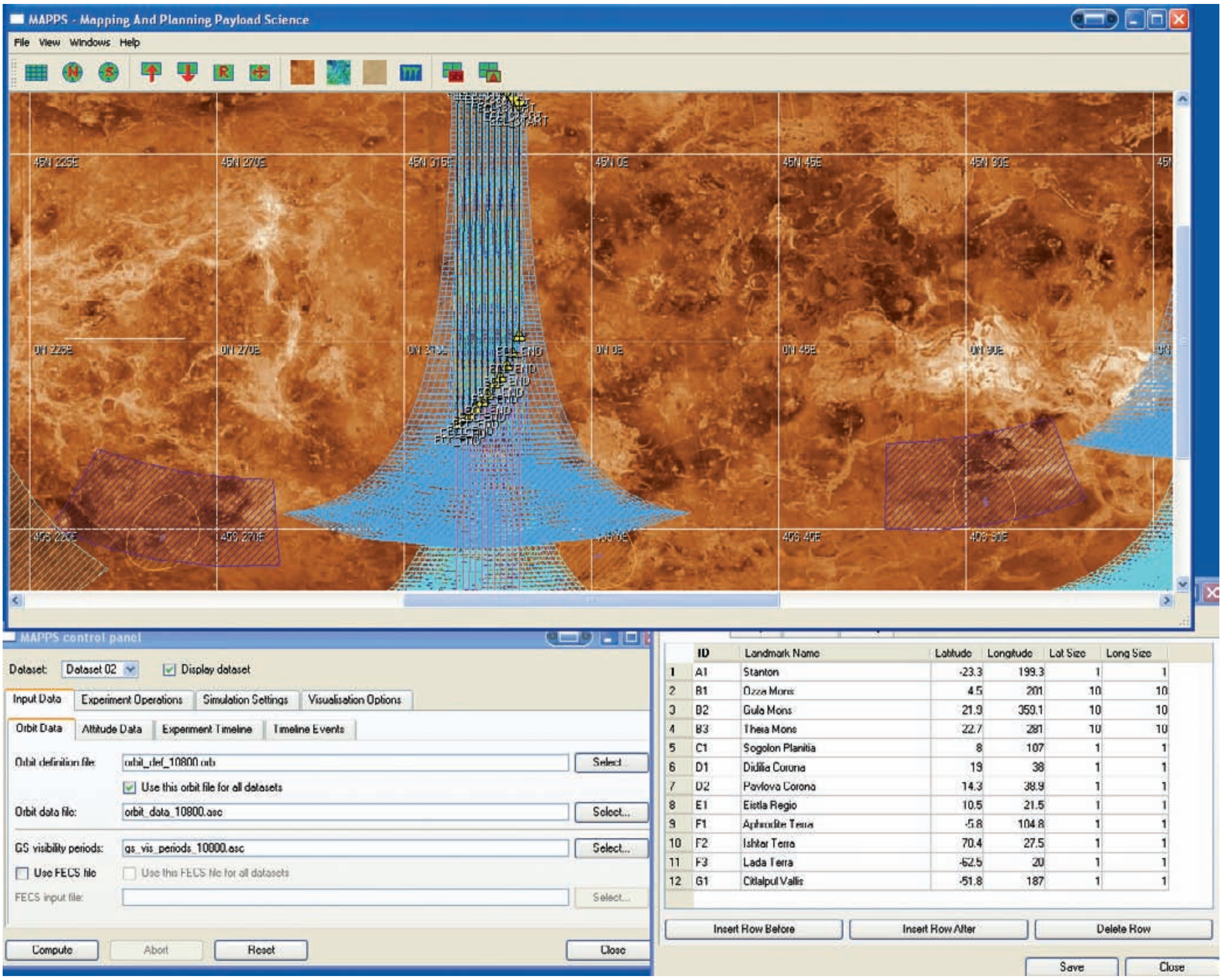

Fig. 4. Screenshot from the Mapping and Payload Planning Software.

ground station visibility file are used. The lower right window shows a number of defined landmarks together with their ID number, the name and latitude/longitude.

6.2 The Experiment Planning System

EPS is a software tool developed by the Planetary Science Operations Team at ESTEC. It accepts as inputs the operational requests from the Experimenters (the PIOR and the PMRQ files). It also reads in the Event Files (EVF) if the PIOR/PMRQ files use events as time markers. It checks the syntax of the input files with respect to the command database and additional constraints as defined in the Experiment Description Files (EDFs).

The experiments are modelled in a simplified way in the EDFs. They list items such as power values and data rates. EDFs are plain ASCII files that are human-readable and are read in by EPS.

The EPS and EDFs developed for each instrument were distributed by VSOC to the experimenter teams for planning purposes. A typical EDF for the ASPERA instrument is shown in Fig. 5.

```
#==================================================================================#
# Filename:   aspera.edf
# Type:                     Experiment description file
#
# Description:              This is the experiment description file for aspera
#
# Author:     VSOC
#                           (for specific version author is specified by initials after date field)
#
#                           name:        Raymond Hoofs (rh)
#                           email:       rhoofs@rssd.esa.int
#
# Date:         May 5, 2003
#
# (c) ESA/Estec
#
#----------------------------------------------------------------------------------#
#
# Version:    1.1
# Date:                     May 5, rh
# Comment:    Initial version for aspera
#
#----------------------------------------------------------------------------------#
Experiment: aspera
Dataflow: TO SSMM
#----------------------------------------------------------------------------------#
# Experiment Modes definition
#----------------------------------------------------------------------------------#
# Here all modes need to be defined together with there power consumption and data rate
            Mode:  mode_name "mode description"
            Equivalent_power: 0 # <average> [<peak> [<low>]] [<unit> (Watts)]
            Equivalent_data_rate: 0 # <average> [<peak> [<low>]] [<unit> (bits/sec)]

# some data acquired from the study cases
#----------------------------------------------------------------------------------#
# VSOC note:
# in case only high and low data-rate are provided VSOC will use high as average untill
# PI teams provide real average data.

            Mode:  OFF "mode description"
            Equivalent_power: 0
            Equivalent_data_rate: 0 [kbits/sec]

            Mode:  SCIENCE "mode description"
            Equivalent_power: 15
```

Fig. 5. An Experiment Description File for ASPERA. Only two modes are defined: OFF and SCIENCE. For each mode, a power value is defined. The hash character '#' denotes a comment line.

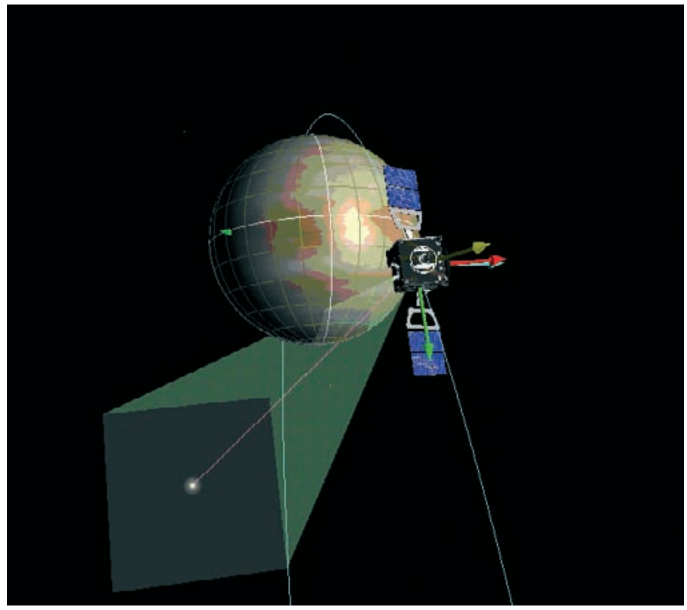

Fig. 6. A screenshot produced by the PTB, showing the spacecraft in front of Venus. The green cone represents the field of view of an instrument observing a star disappearing behind the atmosphere.

6.3 The Venus Express Project Test Bed

The PTB software tool, developed at ESTEC, allows real-time simulations of spacecraft behaviour and the spacecraft environment (Fig. 6). It is used by the VSOC/RSSD team to simulate the mission and get a first idea of possible timelines. It can read in trajectory files provided by the VMOC Flight Dynamics Team or model keplerian orbits. It can read in Pointing Request files to model the spacecraft's attitude. It generates as output Event Files in the format defined by VMOC. It is used in the long- and medium-term planning processes to support the VSOC/RSSD team in generating top-level timelines.

The final environmental conditions are determined and distributed by VMOC, so the PTB is used only for VSOC internal planning purposes.

7. The VSOCWeb

The VSOCWeb is a web-based interface for the PI and VSOC teams, allowing the status of operational files. to be traced It provides the following functionality:

— read access to the experiment models used at VSOC;
— read access to the PIOR files produced by VSOC;
— read access to the PMRQ files submitted to VSOC;
— access to the files logging the transfers between PI teams and VSOC, and vice versa;
— access to the files logging the transfers between VSOC and VMOC, and vice versa;
— for all these files, it allows searches for file types, date ranges, file sources and destinations, for example;
— link to the VEX DDS;
— link to SPICE files produced by VSOC;
— link to the documentation repository (Livelink) of VSOC;
— allow syntax and conflict checking of PMRQ files via an online version of EPS.

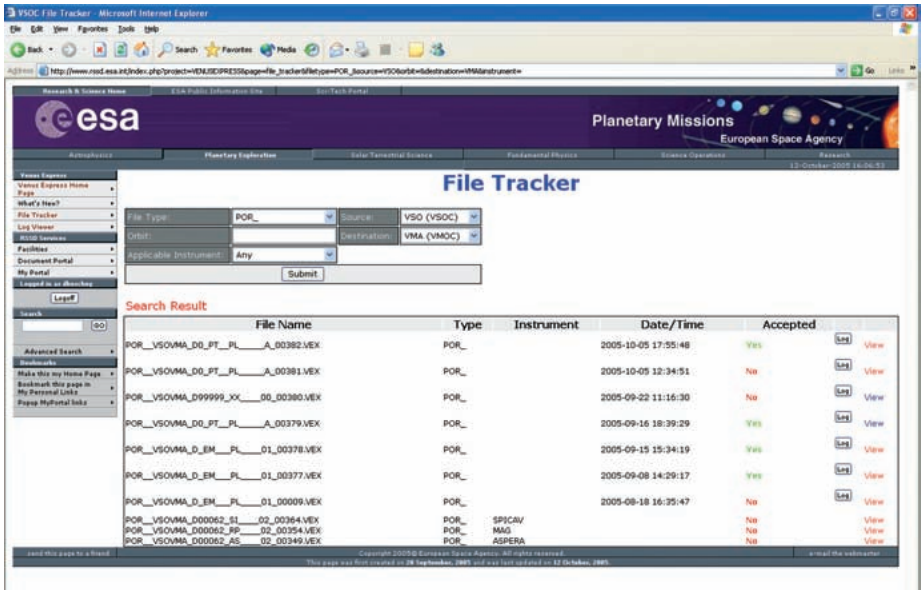

Fig. 7. A screenshot of the VSOCWeb. It shows the file-viewer page for POR files.

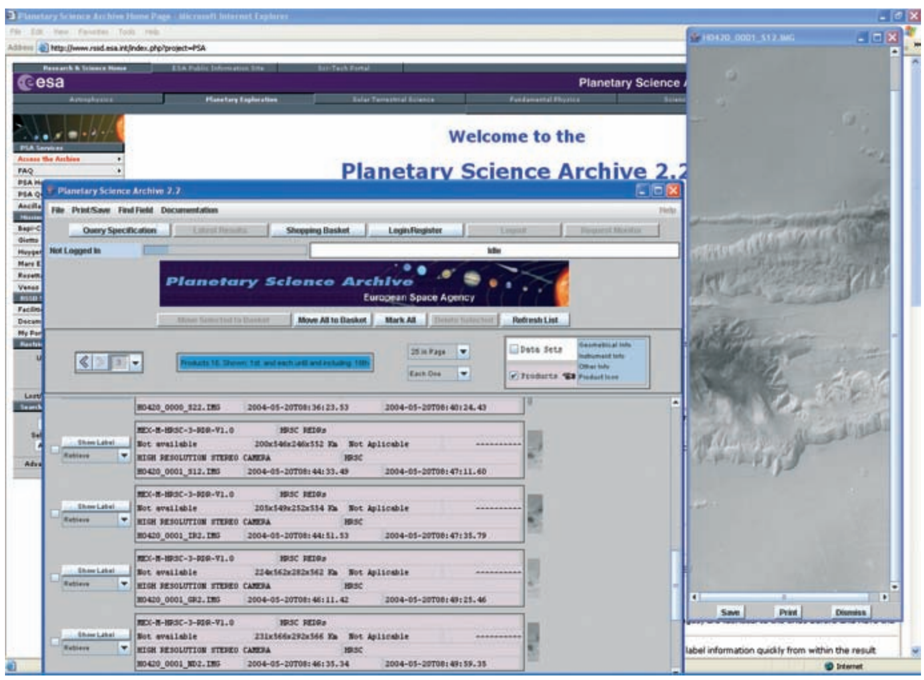

Fig. 8. A screenshot of the Planetary Science Archive, showing Mars Express camera data.

The VSOCWeb can be found at *http://www.rssd.esa.int/VenusExpress*. A detailed requirements list is provided in RSSD (2005b). Fig. 7 shows a screenshot.

The VSOCWeb employs PHP scripts and ties closely into the existing RSSD web infrastructure. All data are stored in an SQL database.

7.1 The Planetary Science Archive

After a proprietary period of 6 months, the raw and calibrated data from the Venus Express payload are ingested into the PSA. From there, they can be accessed by the scientific community, via *http://www.rssd.esa.int/psa*. A screenshot is shown in Fig. 8.

8. Summary and Conclusions

This paper has dealt with the architectural design, physical setup, manpower, planning process and tools of VSOC. It has shown that VSOC is performing its task efficiently by reusing many concepts and tools. Their successful reuse makes them the first choice for upcoming planetary missions such as BepiColombo.

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