ESA-SCI(2001)6
October 2001

Venus Express

An Orbiter for the study of the atmosphere, the plasma environment, and the surface of Venus

Mission Definition Report

European Space Agency
Agence Spatiale Européenne

Foreword

Venus Express, an Orbiter for the study of the atmosphere, the plasma environment, and the surface of Venus, is a mission which was proposed to ESA in response to the *Call for Ideas* to re-use the Mars Express platform issued in March 2001. Venus Express together with two other missions, Cosmic DUNE and SPORT Express, was selected by ESA's Space Science Advisory Committee for a Mission Definition Study. The industrial study of the three missions was conducted in parallel by Astrium-SAS (Toulouse, France) from mid-July to mid-October 2001.

The payload included in the Venus Express Study comprises 5 instruments (ASPERA/MEx, PFS/MEx, SPICAM/MEx, VeRa/Rosetta, VIRTIS/Rosetta) from the Core payload of the original Proposal and the VENSIS/MEx radar in line with the SSWG recommendation. During the Study it was found scientifically reasonable and technically feasible to replace the standard Mars Express engineering Video Monitoring Camera by a scientific instrument, the Venus Monitoring Camera (VMC).

The Mission Definition Report describes the scientific objectives of the Venus Express mission, presents selected payload set, and summarizes the results of the Mission Definition Study. This version of the report covers all science aspects of the mission but contains only a brief summary of the industrial study. The combined industrial study report for all the three missions is published in a separate cover. A complete Venus Express Mission Definition Report, including a comprehensive description of scientific goals, payload, and technical aspects of the spacecraft will be prepared by the end of 2001.

The Venus Express Study was directly supported by the Science Study Team listed below.

Mission science coordination
D.V. Titov, MPAe, Germany
E. Lellouch, DESPA, France
F.W. Taylor, Oxford University, UK
L. Marinangeli, Universita d'Annunzio, Italy
H. Opgenoorth, IRF-Uppsala, Sweden

Principal Investigators
S. Barabash, IRF-Kiruna, Sweden /PI ASPERA
J.-L. Bertaux, Service de Aeronomie, France /Co-PI SPICAM/
P. Drossart, DESPA, France /Co-PI VIRTIS/
V. Formisano, IFSI, Italy /PI PFS/
B. Haeusler, Universitaet der Bundeswehr, Germany /PI VeRa/
O. Korablev, IKI, Moscow, Russia /Co-PI SPICAM/
W.J. Markiewicz, MPAe, Germany /PI VMC/
M. Paetzold, Universitaet zu Koeln, Germany /Co-PI VeRa/
G. Picardi, Infocom Dpt. Univ. of Rome, Italy /PI VENSIS/
G. Piccioni, IAS, Italy /Co-PI VIRTIS/
J. Plaut, JPL/NASA, Pasadena, California, USA
J.-A. Sauvaud, CESR-CNRS, France /Co-PI ASPERA/
P. Simon, BISA, Belgium /CO-PI SPICAM/

The **ESA** members of the Scientific Directorate responsible for the study were:
J-P. Lebreton, Study Scientist, Research and Science Support Department (RSSD), ESTEC
M. Coradini, Science Planning and Coordination Office, ESA HQ, Paris
G. Whitcomb, Future Science Projects and Technology Office, SCI-PF, ESTEC
D. McCoy, Mars Express Project Team, SCI-PE, ESTEC.

The **Industrial** study was lead by:
Ch. Koeck (Study Manager), Astrium, France
with support from:
S. Kemble (Mission Analysis), Astrium, UK

L. Gautret (Payload Interface Engineering), Astrium, France
P. Renard (System Engineering), Astrium, France
F. Faye (Mars Express expertise), Astrium, France.

Support was providing by the following people within ESA:

ESOC:

M. Hechler and J. Rodriguez-Canabal, (Mission Analysis);
R. Van Holtz, (Ground Segment definition)

ESTEC

A. Chicarro (Mars Express Project Scientist), RSSD/SCI-SO
P. Falkner, (payload support), RSSD/SCI-ST
P. Martin (Mars Express Deputy Project Scientist), RSSD/SCI-SO
J. Romstedt (radiation environment analysis & payload support), RSSD/SCI-ST
R. Schmidt (Mars Express Project Manager), SCI-PE
J. Sorensen (radiation environment analysis), TOS-EMA
P. Wenzel (Head of Solar System Division), RSSD/SCI-SO
O. Witasse, (Science support), RSSD/SCI-SO

This report is available in pdf format at: http://solarsystem.estec.esa.nl/Flexi2005/

Requests for further information and additional hard copies of this report should be addressed to:

Jean-Pierre Lebreton: Jean-Pierre.Lebreton@esa.int
Marcello Coradini: Marcello.Coradini@esa.int

Executive Summary

The first phase of Venus spacecraft exploration (1962-1985) by the Venera, Pioneer Venus and Vega missions established a basic description of the physical and chemical conditions prevailing in the atmosphere, near-planetary environment, and at the surface of the planet. At the same time, they raised many questions on the physical processes sustaining these conditions, most of which remain as of today unsolved. Extensive radar mapping by Venera-15,-16 and Magellan orbiters, combined with earlier glimpses from landers, have expanded considerably our knowledge of Venus' geology and geophysics. A similar systematic survey of the atmosphere is now in order. This particularly concerns the atmosphere below the cloud tops, which, with the exception of local measurements from descent probes, has escaped detection from previous Venus orbiters. Many problems of the solar wind interaction, in particularly those related to the impact on the planetary evolution are still not resolved. **The present proposal aims at a global investigation of Venus' atmosphere and plasma environment from orbit, and addresses several important aspects of the geology and surface physics.**

The fundamental mysteries of Venus are related to the global atmospheric circulation, the atmospheric chemical composition and its variations, the surface-atmosphere physical and chemical interactions including volcanism, the physics and chemistry of the cloud layer, the thermal balance and role of trace gases in the greenhouse effect, the origin and evolution of the atmosphere, and the plasma environment and its interaction with the solar wind. Besides, the key issues of the history of Venusian volcanism, the global tectonic structure of Venus, and important characteristics of the planet's surface are still unresolved. Beyond the specific case of Venus, resolving these issues is of crucial importance in a comparative planetology context and notably for understanding the long-term climatic evolution processes on Earth.

The above problems can be efficiently addressed by an orbiter equipped with a suite of adequate remote sensing and *in situ* instruments. Compared with earlier spacecraft missions, a breakthrough will be accomplished by fully exploiting the existence of spectral "windows" in the near-infrared spectrum of Venus' nightside, discovered in the late '80'-s, in which radiation from the lower atmosphere and even the surface escapes to space and can be measured. Thus, a combination of spectrometers, spectro-imagers, and imagers covering the UV to thermal IR range, along with other instruments such as a radar and a plasma analyzer, is able to sound the entire Venus atmosphere from the surface to 200 km, and to address specific questions on the surface that would complement the Magellan investigations. This mission will also tackle still open questions of the plasma environment focusing on the studies of nonthermal atmospheric escape. This issue will be addressed via traditional in situ measurements as well as via innovative ENA (Energetic Neutral Atom) imaging techniques.

The instruments developed for the Mars Express and Rosetta missions are very well suited for this task. The following available instruments: SPICAM – a versatile UV-IR spectrometer for solar/stellar occultations and nadir observations, PFS – a high-resolution IR Fourier spectrometer, ASPERA – a combined energetic neutral atom imager, electron, and ion spectrometer, VIRTIS – a sensitive visible spectro-imager and mid-IR spectrometer, a radio science experiment VeRa, a wide-angle monitoring camera VMC, and subsurface and ionosphere sounding radar VENSIS will form the payload of the proposed Venus Express mission. Taken together, these experiments can address all the broad scientific problems formulated above.

The Mission Definition Study demonstrated the feasibility of the proposed mission to Venus in 2005. The Mars Express spacecraft can accommodate the above mentioned experiments with minor modifications. The launch with Soyuz-Fregat can deliver this payload to a polar orbit around Venus with a pericenter altitude of ~250 km and apocenter of

~45,000 km. This orbit will provide complete coverage in latitude and local solar time. It is also well suited for atmospheric and surface sounding, as well as the studies based on solar and radio occultations. In comparison to the Pioneer Venus spinning spacecraft, Mars Express is an advanced 3 axis stabilised platform which provides significantly enhanced spectroscopic and imaging capabilities. The proposed duration of the nominal orbital mission is two Venus days (sidereal rotation periods) equivalent to ~500 Earth days.

The Venus Express mission will achieve the following **"firsts":**

- *First global monitoring of the composition of the lower atmosphere in the near IR transparency "windows";*
- *First coherent study of the atmospheric temperature and dynamics at different levels of the atmosphere from the surface up to ~200 km;*
- *First measurements of global surface temperature distribution from orbit;*
- *First study of the middle and upper atmosphere dynamics from O_2, O, and NO emissions;*
- *First measurements of the non-thermal atmospheric escape;*
- *First coherent observations of Venus in the spectral range from UV to thermal infrared;*
- *First application of the solar/stellar occultation technique at Venus;*
- *First use of 3D ion mass analyzer, high energy resolution electron spectrometer, and energetic neutral atom imager;*
- *First sounding of Venusian topside ionospheric structure;*
- *First sounding of the Venus subsurface.*

Together with the Mars Express mission to Mars and the Bepi Colombo mission to Mercury, the proposed mission to Venus, through the expected quality of its science results, would ensure a coherent program of terrestrial planets exploration and provide Europe with a leading position in this field of planetary research. The international cooperation formed in the framework of the Mars Express and Rosetta missions will be inherited by the Venus Express and will include efforts of the scientists of European countries, USA, Russia, and Japan. The Venus Express orbiter will play the role of *pathfinder* for future, more complex missions to the planet, and the data obtained will help to plan and optimize future investigations. Venus studies can have significant public outreach given the exotic conditions of the planet and the interest in comparing Venus to Earth, especially in a context of concern with the climatic evolution on Earth.

Table of content

1. Introduction

Since the beginning of the space era, Venus has been an attractive target for planetary science. Our nearest planetary neighbour and, in size, the twin sister of Earth, Venus was expected to be very similar to our planet. However, the first phase of Venus spacecraft exploration (1962-1985) discovered an entirely different, exotic world hidden behind a curtain of dense clouds. The earlier exploration of Venus included a set of Soviet orbiters and descent probes, Veneras 4–16, the US Pioneer Venus mission, the Soviet Vega balloons, the Venera 15, 16 and Magellan radar orbiters, the Galileo and Cassini flybys, and a variety of ground-based observations.

Despite all of this exploration by more than 20 spacecraft, the "morning star" remains a mysterious world. All these studies gave us a basic knowledge of the conditions on the planet, but generated many more questions concerning the atmospheric composition, chemistry, structure, dynamics, surface-atmosphere interactions, atmospheric and geological evolution, and the plasma environment. It is high time to proceed from the discovery phase to a thorough investigation and deep understanding of what lies behind Venus' complex chemical, dynamical, and geological phenomena.

The data from ground-based observations and previous space missions is very limited in space and time coverage, and, prior to the discovery of the near infrared spectral windows, lacked the capability to sound the lower atmosphere of Venus remotely and study the phenomena hidden behind the thick cloud deck from orbit. Thus a survey of the Venus atmosphere is long overdue. Pioneer Venus, Venera-15, -16, and Magellan provided global comprehensive radar mapping of the surface and investigated its properties. The use of penetrating radar can add a third dimension to the earlier investigations.

While a fully comprehensive exploration of Venus will require, in the long term, in situ measurements from probes, balloons and sample return, so many key questions about Venus remain unanswered that even a relatively simple orbiter mission to the planet can bring a rich harvest of high quality scientific results. The re-use of the Mars Express bus with the payload based on the instruments available from the Mars Express and Rosetta projects is very appropriate in this regard. It offers an excellent opportunity to make major progress in the study of the planet.

2. Mission science objectives

The proposed Venus Express mission covers a broad range of scientific goals including atmospheric physics, subsurface and surface studies, investigation of the plasma environment and interaction of the solar wind with the atmosphere. For clarity we divided the atmosphere into three parts: lower atmosphere (0-60 km), middle atmosphere (60 – 110 km), and upper atmosphere (110 – 200 km). The physics, methods of investigation, and scientific goals are quite different for each atmospheric region. However they all can be studied by a multipurpose remote sensing and *in situ* payload in the framework of the proposed orbiter mission.

2.1 Lower atmosphere and cloud layer (0 – 60 km)

<u>Structure.</u> Existing observations of the lower atmosphere hidden below the clouds are limited to in situ measurements, acquired by 16 descent probes mostly in equatorial latitudes**,** by radiooccultations on previous orbiters (Venera 9, 10, 15, 16, Pioneer Venus, and Magellan), and brief glimpses provided by the Galileo and Cassini fly-bys.

The descent probes showed that the temperature structure below 30 km is quite constant all over the planet (Fig. 2.1). However, the temperature structure in the lower scale height is virtually unknown. Mapping the regions of high elevation in sub-micron spectral "windows" at the nightside will determine the surface temperature as a function of altitude (Meadows and Crisp (1996)). Assuming this is equal to the near-surface air temperature, this will *allow a determination of the thermal profile and lapse rate in the 0-10 km range and an investigation of its degree of static stability, constraining the dynamics and turbulence in this region. The thermal structure above 35 km altitude will be obtained from radiooccultations with high vertical resolution.*

<u>Composition.</u> The Venusian atmosphere consists mainly of CO_2 and N_2 with small amounts of trace gases (Fig. 2.1). Although there is very little observational data, the chemistry of the lower atmosphere is expected to be dominated by the thermal decomposition of sulfuric acid, and cycles that include sulfur and carbon compounds (SO_2, CO, COS etc.) and water vapour.

The discovery of the near IR spectral "windows" (Allen and Crawford, 1984), through which thermal radiation from the lower atmosphere leaks to space, allows us to study the composition of the atmosphere below the clouds on the nightside of the planet. The windows at 2.3 and 1.74 µm sound the atmosphere in broad altitude regions centered at 30-35 km and 20 km respectively, while the windows shortward of 1.2 µm (0.85, 0.9, 1.01, 1.10,and 1.18 µm) probe the first scale height and the surface. The detailed appearance of the windows results from the combined effect of composition, cloud opacity, and thermal structure, including the surface temperature (Taylor et al., 1997). High-resolution observations covering all windows simultaneously, along with physical cloud models, should allow retrieval of all the variables.

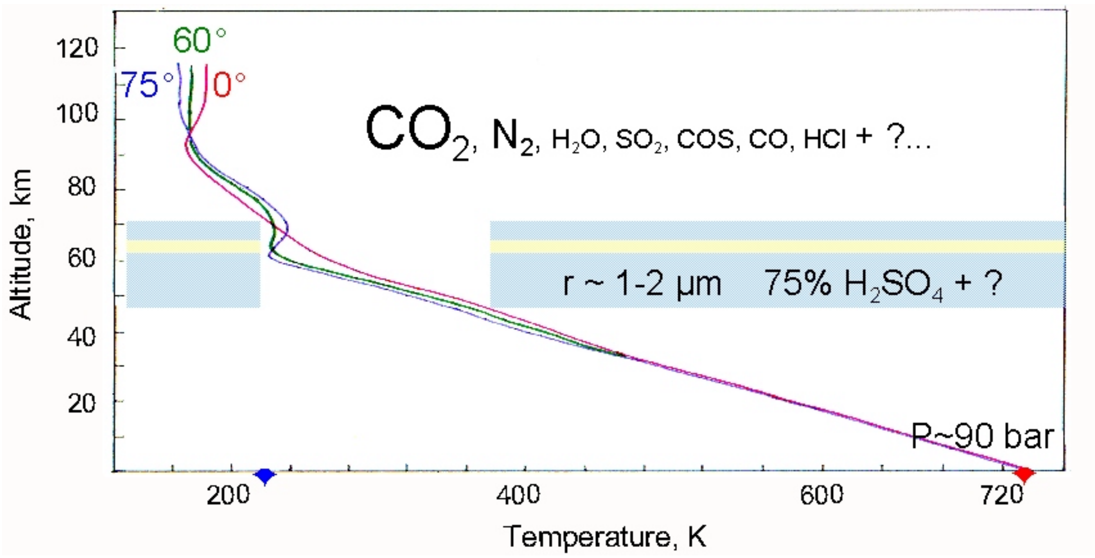

Figure 2.1 Structure and main parameters of the lower atmosphere of Venus.

Water vapour is important not only for chemistry but also as a greenhouse gas. The few existing measurements of the H_2O abundance in the deep atmosphere show no evidence for variability so far. By mapping simultaneously at several wavelengths, corresponding to radiation originating at different altitudes, it will be possible to probe the H_2O profile below the clouds and to search for possible spatial variations, including those that might be the signature of volcanic activity. A precise inventory is also needed to better constrain the origin of the present atmospheric water. The H_2O abundance at the surface has strong implications for the stability of some hydrated rocks.

Carbon monoxide is very abundant in the upper atmosphere due to the dissociation of CO_2 by solar ultraviolet radiation. It is much less common in the troposphere, but it does there show a definite trend of increasing from equator to pole. The source near the poles could be the downward branch of a Hadley cell transporting CO-rich air from the upper atmosphere, an important diagnostic of the mean meridional circulation. More detailed observations of CO at all levels, latitudes and times are needed to confirm this hypothesis and reveal details of the global-scale dynamics. CO is also a key player in the equilibrium between surface minerals and the atmosphere.

The study of the lower atmosphere composition by means of spectroscopy in the near IR transparency "windows" is one of the main goals of the Venus Express mission. More specific objectives include abundance measurements of H_2O, SO_2, COS, CO, H_2O, HCl, and HF and their horizontal and vertical (especially for H_2O) variations, to significantly improve our understanding of the chemistry, dynamics, and radiative balance of the lower atmosphere, and to search for localized volcanic activity.

Cloud layer. Venus is shrouded by a 20 km thick cloud layer whose opacity varies between 20 and 40 in the UV, visible and infrared (Fig. 2.1). The clouds are almost featureless in visible light but display prominent markings in the UV-blue spectral region (Fig. 2.2). Earlier observations showed that at least the upper cloud consists of micron size droplets of 75% H_2SO_4, which is produced by photochemical reactions at the cloud tops. The physical and chemical processes forming the lower clouds are virtually unknown, including major problems like (1) the nature of the UV-blue absorber which produces the features observed from space and absorbs half of the energy received by the planet from the Sun, and (2) the origin of the large solid particles detected by the Pioneer-Venus probe.

The remote sensing instruments on Venus Express will sound the structure, composition, dynamics, and variability of the cloud layer, including:

- *Cloud and haze structure and opacity variations;*
- *Distribution and nature of the UV-blue absorber;*
- *Measurements of atmospheric composition which constrain models of cloud formation and evolution.*

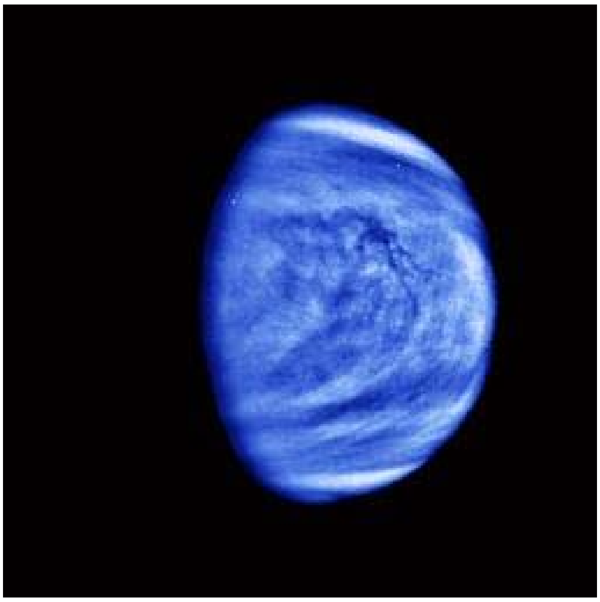

Figure 2.2 Venus images in the violet filter taken by the Gallileo spacecraft.

Greenhouse effect. The high surface temperature of about 735 K results from the powerful greenhouse effect created by the presence of sulphuric acid clouds and certain gases (CO_2, H_2O, SO_2) in the atmosphere (see Crisp and Titov, 1997). Less than 10% of the incoming solar radiation penetrates through the atmosphere and heats the surface, but thermal radiation from the surface and lower atmosphere has a lower probability of escape to space due to the strong absorption by gas and clouds. The result is about 500K difference between the surface temperature and that of the cloud tops, an absolute record among the terrestrial planets (Fig. 2.1). *The measurements of outgoing fluxes over a broad spectral range, combined with temporarily and latitudinally resolved cloud mapping and high resolution spectroscopy in the near IR windows will give an insight into the roles of radiative and dynamical heat transport, and the various species, in the greenhouse mechanism.*

Atmospheric dynamics. The dynamics of the lower atmosphere of Venus is mysterious. Tracking of the UV markings, descent probes, and Vega balloons trajectories all showed that the atmosphere is involved in zonal retrograde *super-rotation* with wind velocities decreasing from ~100 m/s at the cloud tops to almost 0 at the surface (Fig. 2.3). At the same time, there appears to be a slower overturning of the atmosphere from equator to pole, with giant vortices at each pole recycling the air downwards.

What is most puzzling about the regime represented by this scenario is how the atmosphere is accelerated to such high speeds on a slowly-rotating planet. Additional questions include (1) whether the meridional circulation is one enormous 'Hadley' cell extending from the upper atmosphere to the surface, or a stack of such cells, or something else altogether; (2) how the polar vortices couple the two main components of the global circulation and why they have such a complex shape and behaviour; and (3) what the observed (and observable) distributions of the minor constituents in Venus' atmosphere, including the clouds, are telling us about the motions (Fig.2.4).

All attempts to model the zonal super-rotation have been unsuccessful so far, indicating that the basic mechanisms of the phenomenon are unclear. There is an even

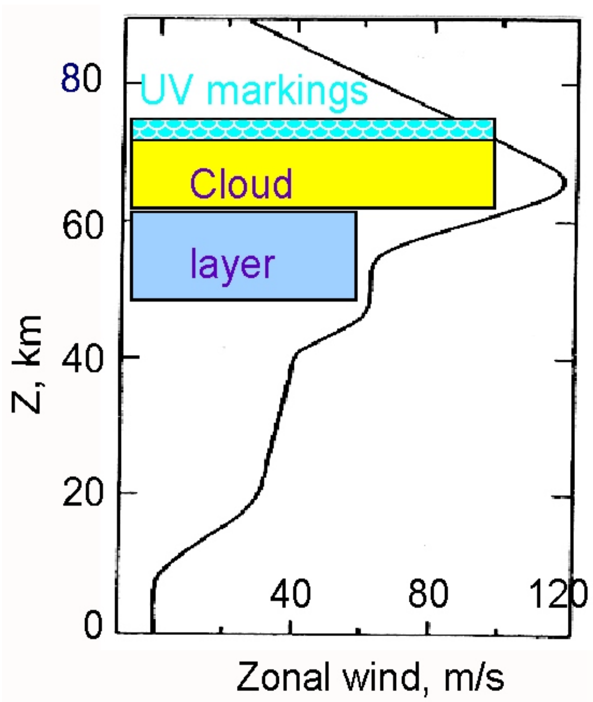

Figure 2.3 Zonal winds in the Venus atmosphere

more basic problem, and that is that we have so few observations of the deep atmosphere that we do not know what to model. The only real solution is to make new observations to gather a more basic description of the lower atmosphere and then to think about the problem again.

Pioneer Venus and Venera-15 observations showed that the polar stratosphere is warmer than the corresponding levels in the tropics, a dynamical effect associated with the zonal super-rotation. We expect the deep atmosphere to be cooler near the poles. How much cooler is not known: this will be a function of the efficiency of the meridional circulation. In theory the most efficient regime would be a Hadley circulation: a single large cell filling each hemisphere and carrying warm air polewards and cooler air equatorwards. The observed movements of the cloud markings would be consistent with such a regime, but whether it actually exists is not known. Discontinuities in the vertical temperature gradient, observed by the Venera, Pioneer Venus, and Vega entry probes at characteristic altitudes, have been interpreted as possible evidence for a stack of Hadley cells on top of each other, rotating in alternate directions.

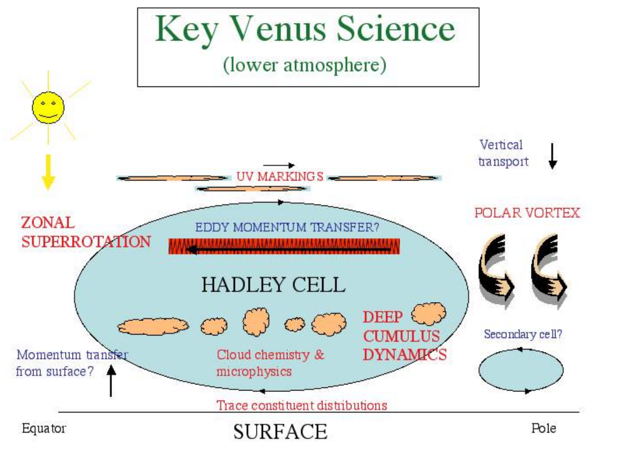

Figure 2.4 Venus atmospheric dynamics

Only the North polar vortex has been observed in any detail. It has a double 'eye' surrounded by a collar of much colder air, the difference in brightness temperature between the two being nearly 100 K at a wavelength of 12.5 µm. The 'dipole' rotates with a period of 2.8 (earth) days. The dynamics of the vortex was derived from a relatively short period of Pioneer Venus observations - 72 days - and with ~100 km resolution mapping only every four days. Attempts to model the structure and dynamical behavior of the vortex have shown only that such limited observations are quite inadequate for the task. *The Venus Express spacecraft orbiting every 10-15 hours and imaging the poles both in the thermal infrared wavelengths, sensitive to the emission from the cloud tops, and the near-IR "windows", which probe much deeper, will allow the production of time- and spatially-resolved movies which would reveal much more information about its behaviour.* Until then, the giant Venusian polar vortices remain one of the great mysteries of the solar system.

A further attribute of Venus' atmospheric dynamics, which also defies explanation, has been revealed in the post-Pioneer and Venera era following the discovery of bright near-infrared markings on the night side of the planet (Allen and Crawford, 1984**).** The best view of these was obtained by the NIMS on the Galileo spacecraft *en route* to Jupiter in February 1990 (Carlson et al, 1991) (Fig. 2.5). The red features are thermal emission from the surface and deep atmosphere of Venus, while the blue markings are regions of relatively high cloud opacity in the main deck, obscuring the emission. This shows that the clouds on Venus are highly inhomogeneous, both horizontally and vertically. The origin of the contrasts must be dynamical and is probably due to variable condensation of cloud material in large-scale cumulus-type dynamics in

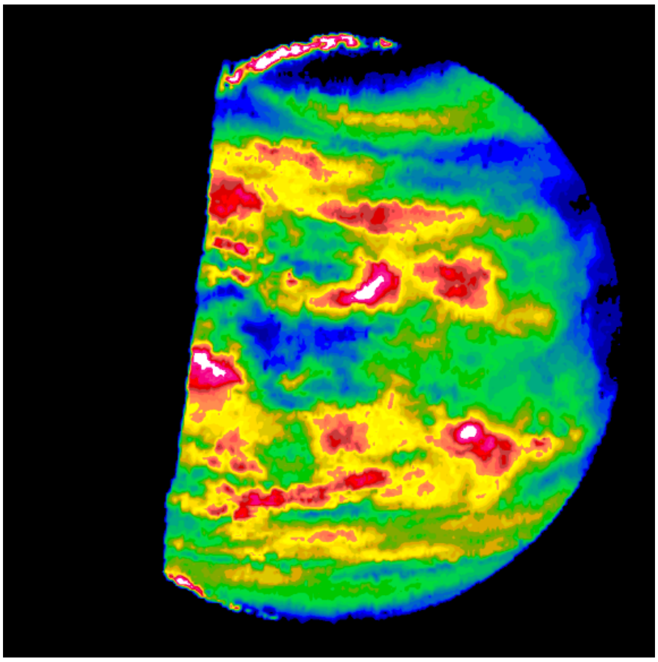

Figure 2.5 False colour image of lower cloud taken by NIMS/Galileo 2.3 µm "window".

the deep atmosphere of Venus. What drives this we can only guess; however, it may be a manifestation of vertically-propagating waves, a possible carrier of the momentum which we observe in the middle atmosphere as the zonal super-rotation.

To understand what is really happening will require new and systematic observations from orbit. Galileo flew by Venus so quickly that only two full maps of the planet's nighttime northern hemisphere were possible, hardly an adequate sample for calculating wind velocities and directions. *The Venus Express with similar instrumentation onboard will globally track the time and space evolution of the clouds with precision over an extended period of time.*

Lightning. The Venus clouds consist, at least in part, of sulphuric acid particles, which have the ability to form highly charged droplets and offer the potential of lightning. Reports of optical flashes have been made based on terrestrial telescopic sightings and orbital data, and very low frequency waves generated in the atmosphere have been reported from the Venera landers and the Pioneer Venus orbiter. Radio frequency spherics were reported during the Galileo flyby of Venus but no lightning was detected from the Cassini flyby. Thus the nature and occurrence, and even existence of lightning on Venus remains a topic of much debate (Grebowsky et al. 1997). Resolving this debate with new data is important both for understanding how the atmospheres of the terrestrial planets become electrified and discharge and to determine if lightning is important in the chemistry of the Venus atmosphere. *Venus Express will provide a long-term set of electromagnetic and optical observations to determine the strength of the flashes and their rates of occurrence, and hence to investigate the nature of lightning on Venus.*

2.2 Middle atmosphere (60 – 110 km)

The Venera and Pioneer Venus orbiters observed this region in the UV and thermal infrared, but with relatively poor coverage in spectral range, latitudes and local solar time (Lellouch et al., 1997).

Temperature structure. The temperature structure of the middle atmosphere shows significant latitudinal variability (Fig. 2.1) which is probably driven by the dynamics but remain poorly understood. Systematic monitoring of the upper mesospheric (70-100 km) temperature field would help to unfold the nature of cyclostrophic balance and the highly variable zonal winds above the cloud tops.

Composition and chemistry. The mesosphere is the region where photochemical dissociation of CO_2 and SO_2 occurs, followed by cycles of carbon dioxide recombination and formation of sulphuric acid. The mesospheric chemistry is described by a chain of reactions that involves HO_x, ClO_x, SO_x, and C_x. H_2O exhibit a remarkable variability in the mesosphere. Pioneer Venus found a high concentration of water vapour in a localized region in the mid-afternoon local time, perhaps due to a dynamical phenomenon, in which convection driven by a local heating maximum transports relatively moist air from beneath. A steady decline of SO_2 from about 400 ppb to ~100 ppb at the cloud tops was observed to occur between 1979 and 1989 (Esposito et al., 1997), possibly attributable to a volcanic eruption at the end of the seventies. Also the SO_2 mixing ratio seems to increase towards the poles. The water vapour and sulfur dioxide should be studied in more detail to understand both chemistry and dynamics of the mesosphere, as well as the processes of cloud formation.

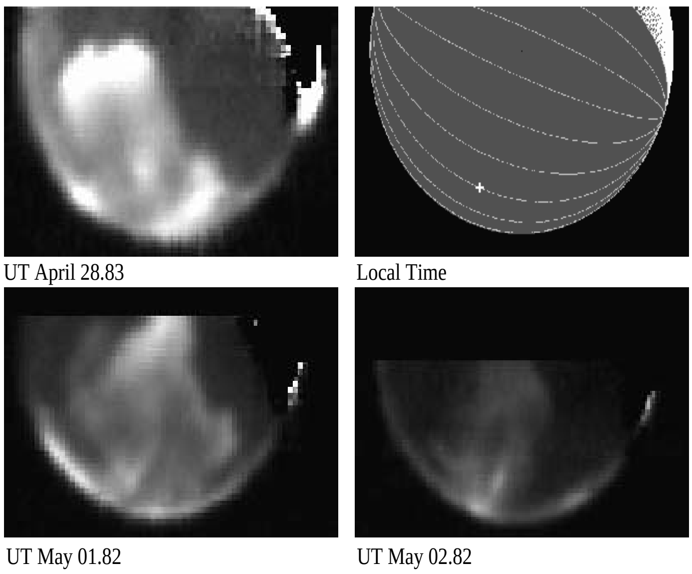

Figure 2.6 AAT/IRIS images of 1.27µm O_2 airglow (Crisp et al., 1993). North is to the right. Bright spots map the regions of strong atmospheric downwelling.

Dynamics. The middle atmosphere is a transition region between the zonal super-rotation regime in the lower atmosphere and solar-antisolar circulation in the upper atmosphere, but how the transition occurs is virtually unknown. The lower mesosphere is characterized by deposition of significant amount of solar energy due to the presence of unknown UV-blue absorber in the upper cloud (67-60 km). Tracking the motions of the UV features from orbit is a powerful tool to study the global circulation and wave phenomena in the lower mesosphere. Mesospheric dynamics was also studied indirectly by Venera-15 and Pioneer Venus orbiters that measured the 3-D temperature field with subsequent derivation of zonal wind field assuming cyclostrophic balance (see Lellouch et al., 1997; Esposito et al., 1997). The zonal wind is dominated by the strong midlatitude jet with speeds up to 150 m/s. This jet located at ~50 N in the vicinity of the cloud tops shows tidal variability. Two weaker jets were also identified at ~85 km and ~65 km.

The O_2 airglow in the near IR (1.27 μm) and visible ranges (0.4-0.8 μm) are formed from the recombination of atomic O produced on the dayside from the CO_2 photolysis at 100-120 km and transported to the night side by the subsolar-to-antisolar flow. They nominally probe the 95-110 km region (IR airglow) and 100-130 km region (visible airglow), and their intensities and spatial distributions are strongly dependent on the mesospheric/ thermospheric circulation, and specifically on the zonal wind profile, the Rayleigh friction controlling the subsolar-to- antisolar flow, and the nightside eddy diffusion coefficient. Simulations (Bougher and Borucki 1994) reproduce the gross structure of the O_2 airglow, but not its detailed appearance. In particular, the few 1.27 μm images in hand (Fig. 2.6) show that the distribution is generally not latitudinally symmetric, often exhibits a multiplicity of local maxima, and shows a striking variability on a 1 hour timescale. These features suggest the existence of local chemical and/or dynamical processes, with the brightest regions being possibly areas of downwelling.

The Venus Express orbiter will investigate the mesosphere by means of global, simultaneous, and spatially resolved spectroscopic observations ranging from UV to thermal IR and will:

- *Study the wind and dynamic phenomena by tracking the motions of UV cloud features;*
- *Measure the 3-D temperature and thermal wind fields;*
- *Study the abundance of SO_2,SO, H_2O,HCl, CO and other species;*
- *Mapping the O_2 infrared and visible airglow as dynamical tracer.*

2.3 Upper atmosphere (110 – 200 km)

Structure and composition. Pioneer Venus remote observations of UV airglow and in situ Probe measurements of neutral densities (CO_2, CO, N_2, O, N, He), and the derived temperatures (Fox and Bougher, 1991) show relatively low (≤ 300 K) dayside temperatures above 140 km despite the small distance of Venus to the Sun, and a sharp collapse across the terminators to very cold nightside temperatures (110 K). This is in stark contrast to expected thermospheric behavior and has no counterpart anywhere else in the solar system. Our knowledge of the structure of Venus' thermosphere remains incomplete because (i) in-situ measurements provide limited spatial sampling (ii) airglow features typically probe broad (15-20 km range) vertical regions, i.e. have poor vertical resolution (iii) most of the information is restricted to equatorial latitudes. Magellan drag measurements provided only limited and tantalizing information regarding high latitude structure. Thus, a global characterization of density and temperature structure is still needed.

Dynamics. The large day-to-night temperature (and corresponding pressure) gradients in the thermosphere were expected to drive very strong (nearly 400 m/s) subsolar-to-antisolar (SS-AS winds). However, from the available data (neutral density and temperature contrasts, UV, visible, and IR airglow maps), the global circulation of the Venus upper atmosphere is inferred to be much weaker, and can be decomposed into two distinct flow patterns : (1) a generally stable subsolar-to-antisolar (SS-AS) circulation cell driven mostly by solar EUV/UV heating, and (2) an asymmetric retrograde superrotating zonal (RSZ) flow that seems to vary greatly over time [Bougher et al. 1997, Kasprzak et al. 1997]. The processes responsible for maintaining and driving variations in the thermospheric winds are still not well understood or quantified. It is apparent that some type of deceleration mechanism, perhaps the breaking of upward propagating gravity waves, is necessary to slow the upper atmospheric winds, but a viable gravity wave drag mechanism must still be found.

Minor constituents with intermediate chemical and photochemical lifetimes yield clues about the atmospheric dynamics at different levels. Large nightside helium and hydrogen bulges near 165 km altitude occur, while smaller bulges of CO are visible at lower thermospheric (100-120 km) altitudes.

The NO UV chemiluminescent nightglow is a tracer of the thermospheric circulation pattern at 115-150 km, and atomic O and H airglows occure near 150 km.

The 3-D modeling tools presently being used to examine the density/temperature/airglow distributions seem to suffer from an inability to reproduce the observed structure and its variations with a unique set of wind fields and eddy/wave-drag parameters. This may reflect missing physical processes, like exospheric transport, that impact the diurnal variations of key tracer species. Nevertheless, the modeling task would be much improved if simultaneous temperature, density and wind measurements could be made above 100 km.

The key science problems related to the thermosphere are summarized as follows. (1). What are the processes responsible for maintaining (and driving variations in) the SS-AS (symmetric) and superrotating (asymmetric) global winds in the Venus upper atmosphere? (2). What is the self-consistent (unique) solution of the global wind, temperature, and density variations of the Venus thermosphere?

Venus Express will address these questions by:

- *Measurements of the atmospheric structure up to 180 km with high vertical resolution from solar/stellar occultations, especially in middle and high latitudes;*
- *Mapping the airglows of O_2, NO, O, and H as global circulation tracers;*
- *Studying the dynamical processes that link the middle and upper atmosphere (tides, planetary and gravity waves, etc.)*

2.4 Plasma environment and escape processes

The study of escape processes from the upper atmosphere has direct implications for the origin and evolution of the Venus atmosphere. Venus is similar to Earth in size and density, and it is likely that it contained initially similar amount of volatiles. The main question how did the atmosphere evolve under the combined effects of escape and interaction with the solid planet? Why the two neighbouring planets became so different? At present, there is evidently no water in significant amount on Venus, possibly explained by intense hydrogen escape at early epochs. Similarly, the lack of molecular oxygen in the present Venus atmosphere requires extremely strong escape in the past and/or massive oxidation of surface material. Current understanding of these processes based on relative abundance of noble gases and isotopic ratios is rather poor.

The history of water on the planet is recorded in the value of the D/H ratio. Deuterium is found to be ~150 times more abundant on Venus than on Earth (Donahue et al., 1997). This enrichment of D/H, explained by preferential escape of H atoms from the upper atmosphere. The present water content and D/H ratio can be interpreted either as the signature of a lost primordial ocean, or a steady state in which water is continuously supplied to the surface by comets or volcanism, or a non-steady regime combining the two sources. The present lifetime of the atmospheric water is highly uncertain but is likely less than 1 Myr so that the primordial ocean is probably not the sole source of the present water. It may however be possible to derive constraints on the primordial water abundance by measuring precisely the atmospheric escape of water (i.e. of H atoms), and the fractionation factor describing the efficiency of D relative to H escape (Gurwell, 1995). The escape rate of D and other atoms from the planetary exosphere depends, first, on their abundance in the upper atmosphere and, second, on the peculiarities of the interaction of the solar wind with the atmosphere. The measurements of atom abundance and their vertical profile would be extremely important to quantify the escape processes. No previous mission to Venus was suitably equipped to address this issue. An additional possible complication is the fact that HDO may undergo vertical fractionation (as occurs on Earth). This makes vertically resolved HDO/H2O measurements highly desirable.

The absence of a planetary magnetic field leads to important differences between Venus' and Earth's atmospheric escape and energy deposition processes. The upper atmosphere of Venus is not protected by the magnetic field from direct interaction with the solar wind. As a result, a large portion of the exosphere resides in the shocked solar wind flow; the photo ionisation, charge exchange and electron impact ionisation effectively remove ionised exospheric components by the plasma flow. The tailward convection of the plasma mantle, situated between the shocked solar wind flow and the ionosphere, leads to another type of atmospheric loss. The ions gyrating around the magnetic field embedded in plasma may re-enter the atmosphere causing its massive sputtering (Luhmann and Kozyra, 1991). Finally, erosion of the Venusian ionosphere under varying solar wind condition provides an additional loss mechanism of atmospheric constituents. The solar wind interacts with the top of the ionosphere to form complex array of plasma clouds, tail rails, filaments and ionospheric holes on the night side through those a substantial amount of material leaves the planet. Figure 2.7 illustrates associated electrodynamics processes and plasma domains of the Venus upper ionosphere. It is not known whether this picture, obtained for solar maximum conditions, is valid for solar minimum when the ionospheric structure becomes different. The escape mechanisms induced by the solar wind are the dominant ones for the loss of heavy atmospheric gases such as oxygen because the planetary gravitational force inhibits the Jeans escape even for non-thermal components.

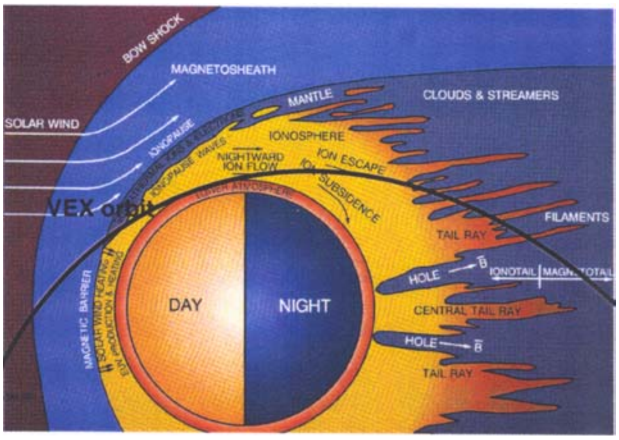

Figure 2.7. Structure of the Venus ionosphere induced by the solar wind interactions. The black line shows the Venus Express orbit.

The Venera and Pioneer Venus orbiters found that the current induced by the solar wind electric field forms a magnetic barrier that deflects the most of the solar wind flow around the planet and leads to the formation of the bow shock (Russell and Vaisberg, 1983). This bowshock compresses the ionosphere on the dayside causing rapid anti-sunward convection and tail rails on the nightside. However, the short lifetime of the Venera-9,-10 orbiters, and insufficient temporal as well as the absence of mass resolution in the Pioneer Venus plasma instrument did not allow a study of the mass exchange between the solar wind and the upper atmosphere of Venus and energy deposition to the upper atmosphere in sufficient detail. Moreover, studies of the atmospheric escape via in situ measurements are inherently limited by spatial coverage of a spacecraft and can be performed only statistically. Only though global imaging techniques such as ENA imaging by ASPERA, instantaneous observations of the global distribution of the escaping plasma can be provided (Williams et al., 1992).

While the plasma dynamics in the near-Venus space is governed by the interplanetary magnetic field, the plasma transport in the ionosphere is fully determined by the local magnetic field, originating from a pileup of the interplanetary magnetic field around the planet, and secondary magnetic fields due to local currents in the ionospheric plasma. Through such currents the magnetic field structure around Venus is closely associated with the formation of the main plasma boundaries and domains such as magnetosheath, magnetic barrier, the ionopause, and the magnetotail. In turn the geometry of the structures constrains possible plasma escape channels. Therefore it is obvious that it will be difficult to interpret the in situ plasma measurements and associated ionospheric structures below, without the help of magnetic field measurements. The investigation of vertical distribution of species in the exosphere and plasma/magnetic field/energetic neutral atoms environment near Venus is very important in order to understand the evolution of terrestrial atmospheres and to understand better what was the Earth's environment during the epochs of weak magnetic field.

Venus Express will address the problems of atmospheric escape and plasma environment by

- *in situ measurements of the energetic neutral atoms, ions, electrons, and magnetic field and inference of escape rates;*
- *active radar sounding of the vertical structure of the topside ionosphere;*
- *high-resolution spectroscopic observations of CO_2 and H_2O to derive ratios of C, O, and H isotopes from the cloud tops up to ~200 km;*
- *Remote sounding of the solar wind turbulence.*

2.5 Surface and surface-atmosphere interaction

Geology. The Magellan images surprisingly revealed that Venus is among the most geologically active planets in the Solar System. Volcanic activity and tectonics have strongly affected the Venusian surface [Solomon et al., 1992] forming highly deformed plateau (Tesserae) and large lowlands (Planitiae). The Planitiae, which are volcanic plains, cover about 80% of the surface. Although there is evidence that the majority of the observed tectonic and volcanic features of Venus formed in a short period of time close to 500 My ago [Shaber et al., 1992; Strom et al., 1994], other volcanic and tectonic features appear to be formed very recently, suggesting that the internal activity of the planet may be ongoing (Fig. 2.8). Geological models for the crustal resurfacing of Venus suggest that the surface is relatively young and does not record the first 90% of the geological formation of the planet. Many scientists favour a catastrophic global resurfacing of the crust, a mechanism unique among the terrestrial planets.

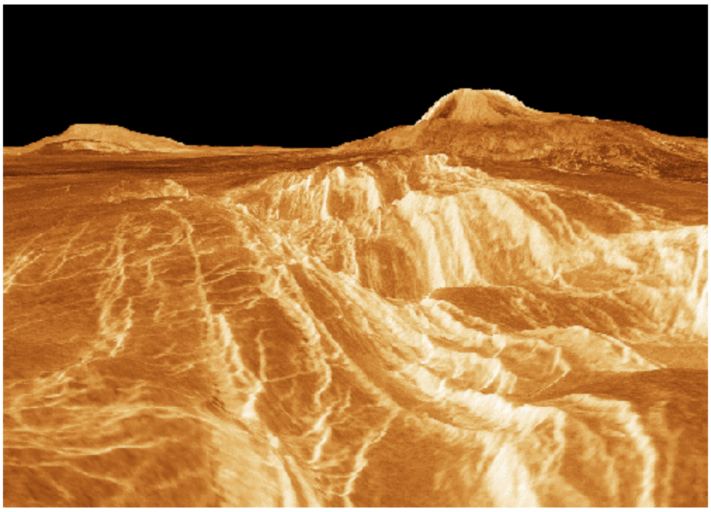

Figure 2.8 Young volcanoes Sif and Gula and Guor Linea rift zone as potential objects for subsurface sounding by VENSIS /Magellan mosaic. Courtesy of NASA/.

Magellan raised new mysteries about the geological evolution of the planet. What was the global geodynamic style within the last 0.5-1 b.y. of the geologic history of this planet? Were the observed tectonic structures formed in global-wide pulses with a specific strain environment or did tectonic resurfacing occur in episodes more distributed in space and time? What are the volumes of old and recent volcanism? What were the rates of volcanism in different geologic epochs? Is there ongoing volcanic and tectonic activity? What is the true scale of exogenic processes controlling, at least partly, surface microrelief?

These questions arise in part because Magellan and previous missions could not determine the sub-surface relations of the geological bodies due to using the frequencies that limited the measured characteristics of the surface to certain scales. The Venus Express radar experiment VENSIS and radio science investigation VeRa meet these challenges and will strongly complement the Magellan observations. *The mission will perform subsurface sounding of the Venusian landforms to 1) outline the internal 3D geometry of tectonic and stratigraphic relationships between geological bodies, (2) provide new data on surface properties, (3) provide new altimetry data complementing Magellan imagery.*

<u>Surface properties and surface-atmosphere interactions.</u> The surface of Venus is geologically young and the presence of sulphuric acid clouds together with the large abundance of SO_2, likely more abundant than allowed by chemical equilibrium with the surface [*Fegley et al.*, 1997], suggests the possibility of current volcanic activity, either episodic or sub-aerial. Observations in the sub-micron spectral "windows" (Fig. 2.9) will search for regions of volcanic activity through enhanced surface temperatures and possibly enhanced gaseous absorption (SO_2, H_2O, HCl, for instance). Measuring the abundance of these gases in the lower atmosphere will also provide constrains on the models of the surface-atmosphere interaction. In particular, reactive gases, such as HF and HCl, are thought to be buffered by chemical assemblages on the Venusian surface.

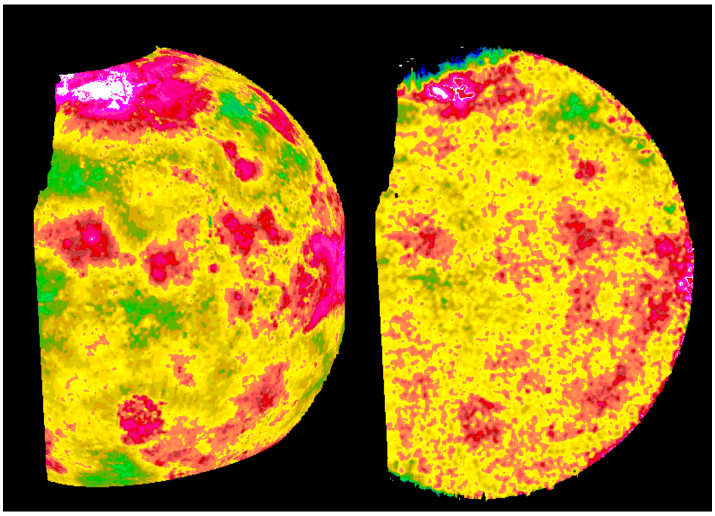

Figure 2.9 Venus altimetry as observed by Pioneer Venus (left), compared to 1.18µm Galileo/NIMS image (right). High altitude terrain (Ishtar Terra in the North, Aphrodite at right) correspond to lower thermal emission, due to the lower temperature of the surface.*(L. Kamp and the NIMS team,JPL, priv. comm.)*

Monitoring the HCl abundance and searching for possible horizontal variations through nightside observations at 1.7 µm will permit to check the effectiveness of this chemical buffering. If variations were detected, they would point to dynamical effects associated with unknown atmospheric chemistry and would thus have strong implications on the halide chemistry and mineralogy. *Venus Express will significantly contribute to this problem by providing high-resolution spectroscopic, spectro-imaging, and mapping in the near-IR spectral "windows".*

Venus seismic activity. Venus might be the site of significant seismic and volcanic activity. Volcanic and tectonic deformation features are broadly distributed globally, unlike plate boundary concentrations typical of Earth. The tectonic disruption of craters and other geologic features seems to indicate that Venus has been tectonically active throughout its history.

It is known that quakes generate seismic waves in the solid planet which are transferred in the atmosphere of the planet (Artru et al., 2001). However, due to the much higher density of the atmosphere (66 kg/m^3 instead of about 1.2 kg/m^3 on the Earth), the transmission coefficient of seismic waves between the solid and atmospheric part of the planet is expected to be about 30 times higher that on Earth. Close to the epicenter, pressure/temperature perturbations could be detected, particularly in the sensitive 4.3 µm CO_2 band where non LTE fluorescent or LTE thermal emissions are highly sensitive to the upper atmospheric perturbations. Although tentative, this objective is highly motivating for a new discovery of Venus internal activity, and is included in the observations of the payload instruments. *A continuous survey of the upper atmosphere of Venus will be performed by the multi-spectral IR mapper, and this will enable a seismic reconnaissance, enabling the localization of the most active part of the planets and to determine the rate of activity, magnitude and position of the strongest quakes.*

3. Scientific payload

The Venus Express scientific payload described in this document is, in line with the *Call for Ideas* issued by ESA in March 2001, the payload proposed for selection at the same time as mission selection. The payload is composed of seven instruments:

- ASPERA: Analyser of Space Plasmas and Energetic Atoms
- PFS: High-resolution IR Fourier spectrometer
- SPICAM: UV and IR spectrometer for solar/stellar occultations and nadir observations
- VeRa: Venus Radio science instrument
- VIRTIS: UV-visible-IR Imaging Spectrometer
- VENSIS: low frequency radar sounder
- VMC: Venus Monitoring Camera

A brief description of each experiment is provided below. Performance characteristics and interface parameters of the instruments are collected in the Tables 3.3 and 3.4 respectively. The Mars Express flight pare units will be used for ASPERA, PFS, SPICAM, VENSIS experiments onboard Venus Express. VeRa and VIRTIS will be built from Rosetta flight spares. VMC is a newly developed instrument that will replace the Mars Express engineering Video Monitoring Camera. It will use existing interfaces of the Mars Express bus.

Minor modifications of some instruments in order to adapt them to specific tasks at Venus are foreseen within the time schedule imposed by the delivery of Flight Units in March 2004. Despite low costs they can significantly increase the scientific output. The modified versions of the instruments will be manufactured in parallel with existing spares in order not to jeopardize the mission schedule. In the following sections we separate current characteristics of the instruments from their possible future modifications and emphasize resulting scientific gain.

3.1 ASPERA (Analyzer of Space Plasmas and Energetic Atoms)

Precursors: None of the previous missions to Venus carried energetic neutral atom imager. The ASPERA instrument on Venus Express provides a new method for studying the interaction process between the Venus atmosphere and the solar wind, and its impact on the atmosphere evolution. Plasma analyzer on Pioneer Venus did not have the possibility for mass discrimination and covered small solid angle being a solar wind monitor. Thus it gave only basic idea about the physics of solar wind – Venus interaction. The electron instrument on Pioneer Venus was restricted to the 0.5 keV energy and limited in coverage.

ASPERA/Mars Express. The ASPERA-3 instrument comprises four sensors: the Neutral Particle Imager (NPI), the Neutral Particle Detector (NPD), the electron spectrometer (ELS), and ion mass analyser (IMA). The baseline performance of the ASPERA instrument is presented in the Table 3.1. It will be assembled from spare units available as a spare kit for the ASPERA/MEX instrument.

ELS is a conventional top-hat analyser in a very compact design. IMA is a mass analyser following a top-hat analyzer with the electrostatic sweeping to provide the sufficient angular coverage. NPI is a simple ENA direction analyser based on the secondary emission principle. NPD is an advanced ENA detector using the reflection and conversion surfaces for ENA identification and UV suppression. Mechanically ASPERA consists of two units, IMA and Main Unit which includes ELS, NPI, NPD, digital processing unit and a scanner to provide 4π coverage.

Table 3.1 ASPERA-4 baseline performance

	NPI	NPD	IMA	ELS
Particles to be measured	ENA	ENA	Ions	Electrons
Energy range, keV	0.1 - 60	0.1 - 10	0.01 - 40	0.01 - 20
Energy resolution, ΔE/E	No	80%	10%	7
Mass resolution,	No	H, O	M/ΔM=5	No
Intrinsic field of view	9° × 344°	9° × 180°	90° × 360°	10° × 360°
Angular resolution (FWHM)	4.6° × 11.5°	5° × 30°	5° × 22.5°	5° × 22.5°
G-factor / pixel, cm^2sr	2.5×10^{-3} (no ε)	6.2×10^{-3} (no ε)	3.5×10^{-4} (ε included)	3×10^{-4} (ε included)
Efficiency, ε, %	1%	1 – 25%	N/A	N/A
Time resolution for full 3D, s	32	32	32	32

The ASPERA-4 instrument will measure energetic neutral atoms (ENA), ions, and electrons. The experiment will (1) investigate the interaction between the solar wind and Venus atmosphere, (2) characterise quantitatively the impact of plasma processes on the atmosphere, (3) obtain global plasma and neutral gas distribution, (4) identify the mass composition and quantitatively characterise the flux of the outflowing atmospheric materials, (5) investigate the plasma domains of the near-Venus environment, and (6) provide undisturbed solar wind parameters.

Modifications for Venus. No major modifications for Venus are foreseen for the baseline instrument. The higher radiation dose for Venus Express will require point shielding which will results in a small (< 300 g) increase in mass. During the next study phase (pre-phase-B), the addition of a magnetometer sensor to ASPERA has been highly recommended by the Venus Express Study team. The inclusion of a magnetometer sensor to be mounted directly on an existing spacecraft structure will be investigated during the pre-phase B activities. The instrument can be easily available for delivery to the Venus Express industrial contractor in March 2004. However, the impact on the ASPERA mass should be further investigated since addition of extra components is obviously required. To cope with the new thermal environment the heater power will be increased by 6W compared to Mars Express. The detailed thermal analysis to be performed under phase-B will show whether or not addition radiators and heat – pipes should be introduced and the accommodation changed. Introducing these elements will result in the mass increase up to 500 g.

3.2 PFS (High resolution IR Fourier spectrometer)

Precursors. The precursors of PFS long wavelength (200-2000 cm^{-1}) channel at Venus was the Fourier transform infrared experiment onboard Venera-15,-16 satellites. The instrument worked for about 2 months and recorded about 1700 spectra of Venus thermal emission. Despite short duration of the mission and limited coverage in latitude and local solar time that experiment demonstrated the power of thermal emission spectrometry at Venus. The complete coverage of the near IR part of the spectrum (8300-2000 cm^{-1}) has never been done before from Venus orbit.

PFS/Mars Express. PFS is a high-resolution Fourier transform spectrometer covering broad spectral range from near IR to thermal IR. The proposed Vex instrument is based on the existing Flight Spare model for Mex. A complete synthetic spectrum of PFS at Venus is shown in Figure 3.1. It consists of two parts: (1) reflected solar radiation (ν>3000cm^{-1}) and thermal radiation (ν<3000cm^{-1}). In both parts the radiation comes from the cloud tops and the spectrum shows the characteristic spectral features of atmospheric gases above the cloud and clouds themselves. At Venus PFS will cover the following scientific objectives (V) marks the scientific goals after modification for Venus):

- Global 3-D measurements of the temperature field with subsequent determination of the zonal component of the wind (thermal wind) in the altitude range 55-100km;
- Monitoring of the upper cloud structure;
- Measurements of abundance of SO_2, CO, H_2O, HDO, HCl, HF and search for H_2S, CH_4 and other gases at 60-70 km;
- Monitoring of the $O_2{}^1\Delta$ airglow at 1.27 μm;
- Measurements of the outgoing thermal spectral fluxes (radiative balance);
- Study of the atmospheric composition (CO, COS, H_2O, SO_2, HCl) below the clouds V) (Table 3.2);
- Study of the cloud opacity and its variations V);
- Measurements of the temperature gradient at 0-10 km and surface temperature V);
- Search for volcanic activity V).

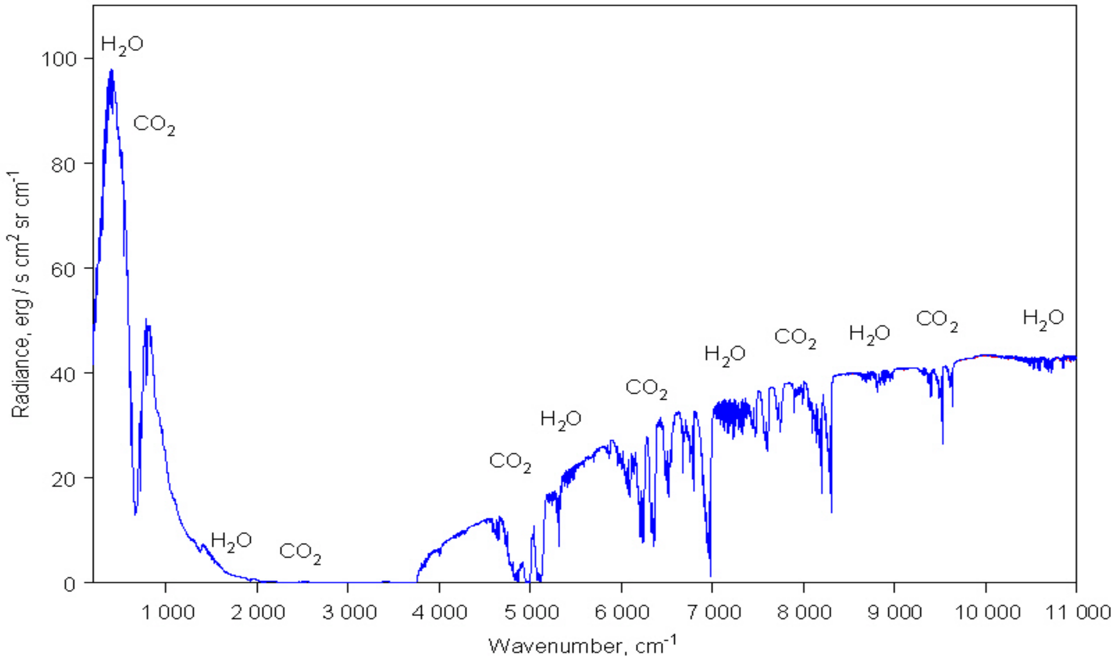

Figure 3.1 PFS synthetic spectrum of Venus dayside. A spectrum similar to that shown at ν<2000cm^{-1} will be observed also at the night side. The near IR emissions of the nightside are shown in Figures 3.4 and 3.2.

Modifications for Venus. The shortwavelength channel of PFS (8300 – 2000cm^{-1}) can be modified in order (1) to increase the sensitivity and to (2) to extend the spectral range to 0.9 μm. The first option will allow PFS to measure weak nightside emissions with high spectral resolution which is crucial for composition analysis. The latter will result in covering of the 1.0, 1.1, and 1.18 μm "windows", in which radiation comes from the lower scale height of the atmosphere and even from the very surface. The near IR spectrum expected from PFS at the night side after modifications is shown in the Figure 3.2 with 1.0 μm "window" presented in Figure 3.4. The modified PFS will provide high resolution measurements of night side emissions in all near IR "windows". After modification PFS will be the only instrument in the Venus Express payload to cover the 1.7 μm "window" with high resolution. Since the "windows" sound different altitudes (Table 3.2) these observations will give the H_2O vertical profile in the lower atmosphere and will help to discriminate between the surface and cloud contribution. The modifications of the PFS shortwavelength channel will include:

1. Change of the PbSe detector for PbS. This would increase the sensitivity in the 0.9 – 3.3 μm (11,000 – 3000 cm^{-1}) range at the expense of loosing the part of the spectrum between 3.3 and 5 μm (3000-2000 cm^{-1}) which is of minor importance at Venus (see Fig. 3.1);
2. Change of the laser diode and entrance window.

These modifications require low costs and will significantly improve scientific return of the experiment and the whole mission.

.

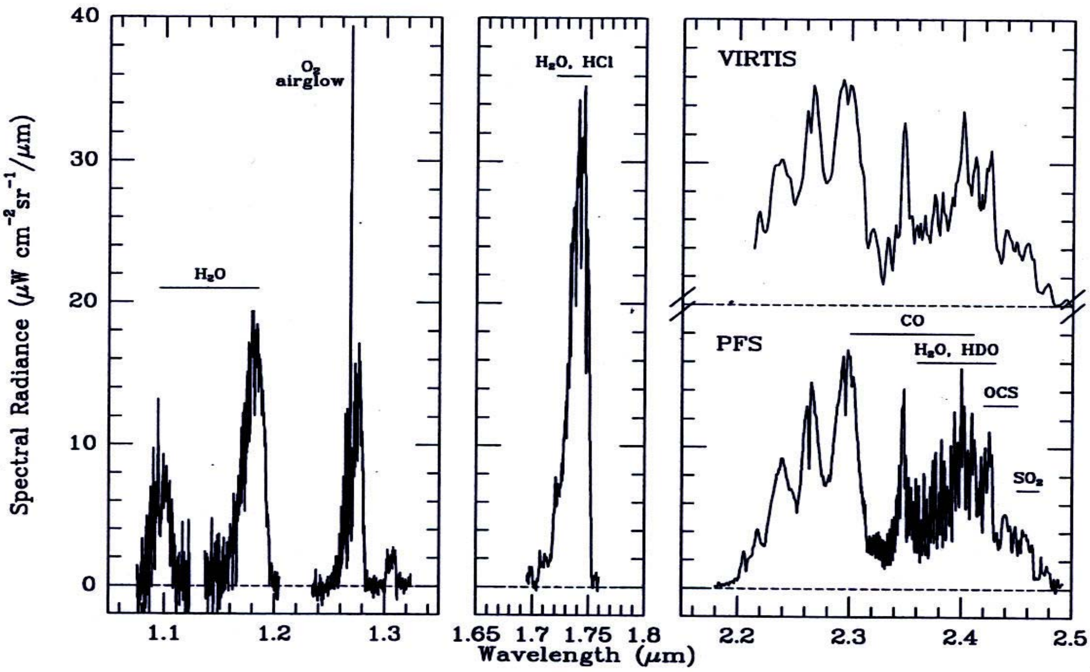

Figure 3.2 Spectra of the nightside emission obtained from the ground by FTS/CFHT and reduced to the spectral resolution of PFS and VIRTIS. Synthetic spectrum in the 1 μm 'window" is shown in the Fig. 3.4

3.3 SPICAM (UV and IR spectrometer for solar/stellar occultations and nadir observations)

Precursors. The Pioneer Venus UV spectrometer (PVO-UVS) has monitored the tops of Venus' clouds and mesospheric airglow in the UV range. SPICAM will be the first instrument at Venus to implement the solar/stellar occultation technique that has been proven to be very effective in the studies of the atmospheres of Earth, Mars, and outer planets. In the near IR range, Galileo and Cassini fly-bys provided short insights beneath the cloud deck of Venus by mapping the nightside emissions in the near IR spectral "windows". SPICAM IR will systematically measure the nightside spectra at high spectral resolution and with high sensitivity.

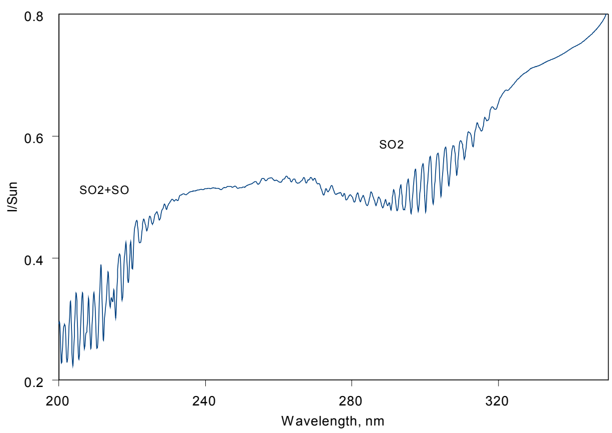

Figure 3.3 Synthetic Venus UV spectrum at 0.4 nm resolution.

SPICAM(UV&IR)/Mars Express. The instrument is a versatile spectrometer that consists of UV and IR channels. SPICAM-UV and a close prototype of SPICAM-IR are included in the science payload of Mars Express ESA mission, integrated in SPICAM Light instrument.

The SPICAM-UV is a highly sensitive instrument in the range 110-310 nm. The detector is an intensified CCD operating in photon-counting mode. Synthetic spectrum of Venus in the UV at SPICAM resolution is shown in Figure 3.3. The SPICAM-UV addresses the following objectives:

- Measurements of SO_2 and SO abundance above the clouds (nadir);
- Determination of the UV albedo (nadir);
- Measurements of the vertical profiles of atmospheric density up to 170-180 km in stellar occultations.

The miniature IR spectrometer of SPICAM (0.8-1.7 nm) with a resolving power of 1500 is based on Acousto-Optic Tuneable Filter (AOTF) technology. The scientific goals of SPICAM-IR at Venus are the following ($^{V)}$ marks the scientific goals after modification for Venus):

- Determination of the H_2O abundance above the clouds (nadir, day side);
- Sounding the surface in 0.7-1.3 μm "windows" (nadir, night side)$^{V)}$;
- Measurements of H_2O content below the clouds (nadir, night side) $^{V)}$;
- Monitoring 1.27 μm $O_2{}^1\Delta$ emission (limb, day and nightside);
- Study of H_2O and aerosol vertical distribution (limb, dayside)

Solar and stellar occultations operations planned for Venus Express, as well as limb sounding have successfully passed preliminary industrial study. Two complete flight models of SPICAM Light will be manufactured for Mars Express mission, so that the spare flight model can be easily refurbished for delivery for the Venus Express mission in March 2004.

Modifications for Venus in SPICAM-IR. For Venus the spectral range of the SPICAM/Mex will be extended to 0.7 μm with enhanced sensitivity at 0.7-1.1 μm to measure the radiance from the atmosphere below clouds and the surface of Venus on night side (Fig. 3.4) with high spectral resolution. This will complement low resolution spectral mapping by VIRTIS in the same spectral range. One of important goals of the SPICAM IR modification is to measure the H_2O contents by high-resolution spectroscopy ($\delta\lambda$=0.5 nm at 1 μm) with high sensitivity (expected S/N > 500 at 1 μm night side). In order to achieve this task we will increase the sensitivity in 1.0-1.7 μm range up to ~0.05 erg $s^{-1}cm^{-2}sr^{-1}\mu m^{-1}$ (1-s measurements) and extend the SW spectral range to 0.7 μm by replacing both detectors by the bi-color detector (Si-InGaAs) and keeping the capability to measure polarisation. Thanks to these modifications we get access to important spectral range at very high sensitivity. Modifications to the existing hardware will be minimal. If the modification is not made, the current sensitivity at 1-1.7 μm (~3 erg $s^{-1}cm^{-2}sr^{-1}\mu m^{-1}$) still permits to observe 1.1-1.3 μm window at longer exposures. No modifications for Venus are foreseen in the UV channel, however, during the pre-phase B study, scientific discussions might orient toward an optimisation for Venus of spectral resolution, or spectral band, without changing the interfaces with the spacecraft. We may for instance increase the spectral resolution for a better SO_2 retrieval, but at the expense of a narrower spectral interval.

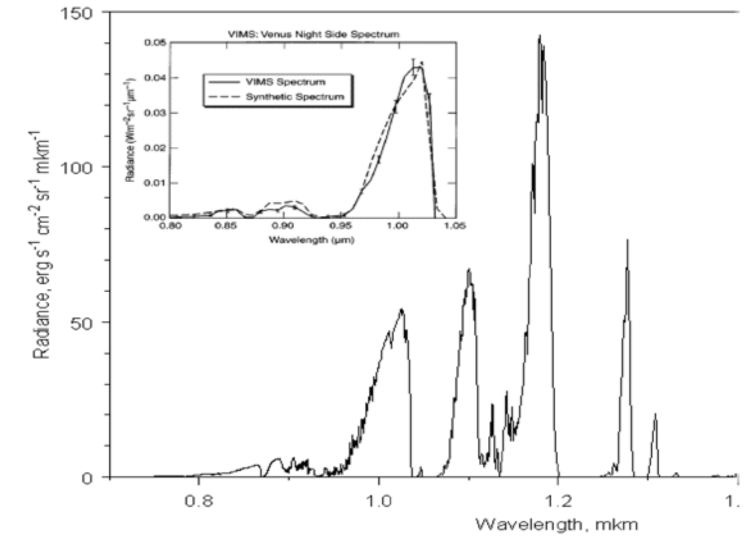

Figure 3.4 Synthetic spectrum of the nightside emission from at spectral resolution of SPICAM IR. Cassini/VIMS spectrum (Baines et al, 2000) is shown for comparison in the upper window.

Modifications for Venus: adding SPICAM-SOIR channel. The Venus Express Study Team endorsed inclusion of SOIR channel in SPICAM experiment. This channel will observe solar occultations in the near IR (1.8-4 μm) at very high spectral resolution (R~15000). It is recommended to study the SOIR accommodation during the pre-phase B activities in the beginning of 2002. The SOIR unit with mass of ~ 4 kg will be placed on top of currently accommodated SPICAM instrument and will use the same solar port. The inclusion of SOIR channel will be studied in parallel with manufacturing of the flight model of SPICAM and will not jeopardize the mission schedule.

The prime scientific objective of SPICAM-SOIR will be to measure the vertical profile of D/H ratio from combined HDO and H_2O measurements. This will provide a key constraint on the relative escape rates of D and H and therefore on the history of Venus water. Other scientific goals of SOIR include:

- Precision profiling of H_2O, CO from the cloud top up to high altitudes (~180 Km);
- Measurements of COS, H_2S, HCl, and HF and their vertical distribution above the clouds;
- Study of hazes above the cloud top (z>70 km);
- Quasi-3D mapping of atmospheric density, temperature, and turbulence up to 180-200 km;
- Search for new trace gases in the atmosphere of Venus (CH_4, C_2H_6 and other organic molecules).

3.4 VeRa (Venus Radio Science)

Scientific goals. The direct radio communication link between the spacecraft and the ground station on Earth can be used as a powerful tool for the radio sounding of neutral and ionized media. The scientific objectives of the Venus Radio Science experiment (VeRa) are:

(1). Radio sounding of the Venusian ionosphere from ~80 km altitude up to the ionopause (300 km to 600 km altitude depending on solar wind conditions) to derive vertical profiles of electron density, to determine the altitude of the ionopause, to study the solar wind interaction with the Venusian ionosphere as a function of local time, planetary latitude and solar wind activity (occultation experiment). The anticipated accuracy will be in the order of 100 el/cm^3 and the height resolution will be in the order of 100 m or better.

(2). Radio sounding of the neutral atmosphere from the cloud deck (35 – 40 km) to 100 km altitude to derive vertical profiles of neutral mass density, temperature, and pressure as a function of local time, planetary latitude and season (radio occultation experiment). Temperature accuracy is anticipated to be in the order of 0.1 K at the base and 10 K at the top layers. Subsequent analysis of these result would give constrains on the composition and thermal wind field.It is proposed to conduct the above mentioned observations using the one-way radio link between the orbiter and the ground station. The inclusion of an Ultrastable Oscillator, USO, (Rosetta heritage) is required in order to improve considerably the accuracy and sensitivity compared to the Pioneer Venus observations (1978-1992).

(3). Dielectric properties, roughness, and chemical composition of the Venusian surface by means of a bistatic radar experiment.

(4). Studies of coronal and extended coronal structures and solar wind turbulence during inferior and superior solar conjunctions of Venus using radio carrier signals propagating in the inner solar system.

Technique. VeRa will make use of the spacecraft radio carrier signals at X-band and S-band transmitted simultaneously by the spacecraft radio subsystem via the High Gain Antenna in the one-way mode. It is mandatory to add an Ultrastable Oscillator (USO, Allan deviation 10^{-13} for 3 s integration time) as a highly stable onboard frequency reference source to be used when performing occultation and bistatic radar measurements. The internal transponder oscillator (TCXO) cannot be used for these kind of observations. The frequency spectrum of interest with respect to the central carrier frequency will extend to some 10 Hz off the RF-carrier. The USO added to the Vex radio subsystem is space qualified and was tested recently successfully during the Rosetta IST. A modification of the USO synthesizer is required in order to convert the USO output frequency to the required transponder downlink frequency. This modification is needed because the Rosetta and Venus Orbiter transmission frequencies shall and have to be different.

Operations and Antenna Pointing. In contrast to most of the other proposed orbiter instruments which will do their observations in spacecraft Nadir pointing, VeRa requires the HGA pointed toward the Earth for the atmospheric and ionospheric sounding observations and the solar wind propagation studies. In this constellation, the other instruments will not be able to conduct their observations in general. The bistatic radar observations require the pointing of the HGA toward the Venus surface. The transmitted radio signals will be reflected from the surface and the echoes will be received at the ground station on Earth.

Spacecraft occultations (the s/c will be occulted by the planetary disk as seen from the Earth) will occur in a near polar orbit in "occultation seasons" with one occultation in every orbit. Prior to and after occultation in every orbit, the direct radio link between the spacecraft and the ground station will propagate through the ionosphere and atmosphere (or vice versa) and two occultation profiles at entry and exit, at different local times and seasons can be observed. The total number of occultation profiles depends on the final orbit selection but it is expected that the number will be higher than those from Pioneer Venus. In order to receive a clean carrier spectrum not corrupted by telemetry signals, TM modulation of the carrier has to be switched "off" during the measurements described above (15 min prior and 15 min past occultations).

Ground segment. From the ground station, the sounding observations and bistatic radar experiments have to be conducted in the so-called open-loop receiver mode which makes it necessary to use the dedicated Radio Science IFMS receiver system at the Perth ground station. This system (funded by BMBW/DLR) is already available and currently being tested by ESOC. In a similar way as foreseen for Mars Express and Rosetta the raw open loop data will be stored at the ground station and transferred to the VeRa science center located at University of Cologne.

3.5 VIRTIS (UV-visible-near IR imaging spectrometer)

Precursors: First attempts of imaging spectrometry on the Venus night side from space in the near infrared were made by NIMS/Galileo in 1990 (Carlson et al, 1990) and VIMS/Cassini in 1999 (Baines et al, 2000) (see Figure 3.4). These fast fly-bys gave the idea how powerful this method of investigation could be at Venus. Unfortunately, the limited duration of the fly-bys allowed only limited investigations, in particular on the meteorological evolution of the clouds. Observations of Venus with the a new generation imaging spectrometer like VIRTIS would provide a unique opportunity to continue these investigations on an extended basis.

VIRTIS/Rosetta. VIRTIS consists of two channels

- VIRTIS/M channel: mapping spectrometer with moderate spectral resolution (R ~ 200) and high spatial resolution of 0.25 mrad (250m at 1000 km altitude), which uses two detectors (1) CCD (0.25 - 1 μm) and (2) IR FPA (1-5μm);
- VIRTIS/H - echelle high resolution spectrometer (R ~ 1200) using an IR FPA detector (2-5μm).

The IR/FPA are high sensitivity detectors (HgCdTe arrays of 270 x 438 pixels) specially designed to provide high sensitivity and low dark current (10 fA at 80 K), with a read noise lower than 500 e^-. For 1 sec integration, the noise equivalent spectral radiance is of the order of $5\ 10^{-5}$ W $m^{-2}sr^{-1}\mu m^{-1}$) for 1 sec integration (for both Virtis H and M) is expected at 2.3 μm. According to the figures above, the Venus flux expected on the night side in this window is as high as 0.15 W $m^{-2}sr^{-1}\mu m^{-1}$. The FPA of both channels is actively cooled by cryocoolers down to the operating temperature of 80 K. On Rosetta, the spectrometer is passively cooled down to T= 130 K by the radiator on the cold panel pointing to the deep space. Due to the thermal constraints on Venus Express, and the comfortable Signal to Noise ratio expected on Venus, the specification on the Optical Module temperature can be relaxed. Simulations on Virtis H show that a temperature of T=150 K on the optical module still provide a S/N higher than 100 for a 1 sec integration time. The spectrum expected from VIRTIS/H is shown in Figure 3.2. VIRTIS-M will systematically obtain maps of surface brightness distribution similar to that shown in Figure 2.9.

Table 3.2. Expected parameters of the measurements of the atmospheric composition below the clouds by VIRTIS-H and modified PFS SW channel and SPICAM IR channels.

Trace gas	**Wavelength, μm**	**Altitude, km**
H_2O	1.1- 1.18 1.74 2.40-2.43	0-12 23[1)] 33
HDO	2.38-2.46	33
CO	2.3	30-40
COS	2.43	30-40
SO_2	2.46	40
HCl	1.74	23

[1)]PFS SW[V)] and VIRTIS-M

The main scientific goals of VIRTIS at Venus are the following:

- Study of the lower atmosphere composition below the clouds and its variations (CO, OCS, SO_2, H_2O) (see Table 3.2 and Figure 3.2) from night side observations (Collard et al., 1993; Drossart et al., 1993);
- Study of the cloud structure, composition, and scattering properties (day side observations) (Roos et al., 1993);
- Cloud tracking in the UV (~70 km, day side) and IR (~50 km, night side);
- Measurements of the temperature field with subsequent determination of the zonal wind in the altitude range 60-100km (night side);
- Lightning search (night side);
- Mesospheric sounding: understanding the transition region between troposphere and thermosphere

(1) non-LTE O_2 emission (night/day side) at 1.27 µm (95-110 km) (Drossart et al., 1993);
(2) CO_2 fluorescence (day side): non LTE emissions at 4.3µm (>80km) (Roldan et al., 2001)
(3) limb observations (CO, CO_2): atmospheric vertical structure (> 60 km) (day/night side);

- Search for variations related to surface/atmosphere interaction, dynamics, meteorology, and volcanism;
- Temperature mapping of the surface, search for hot spots related to volcanic activity;
- Search for seismic waves from propagation of acoustic waves amplified in the mesosphere: search for high altitude variations of pressure/temperature in CO_2 4.3 µm band (Artru et al, 2001).

VIRTIS will also provide true colour high definition images of Venus that are of great value for public outreach programme.

Observation strategy for VIRTIS. To achieve the scientific objectives, VIRTIS must observe both day and night side, and to work with full imaging spectroscopy capabilities, VIRTIS must be able to reconstruct spectral images from the orbit of Venus Express. With the orbit of Venus express, the spatial resolution of VIRTIS is always better than 13 km at apoapsis. This spatial resolution is consistent with the science objectives of cloud structure (Galileo/Venus global observations had a 15-30 km resolution). It is also consistent with surface studies in the IR, because the scattering in the Venus clouds blurs the thermal flux coming from the surface over a scale range comparable to the cloud height (30 km). Therefore, the altitude of the S/C is not a limiting factor for VIRTIS observations.

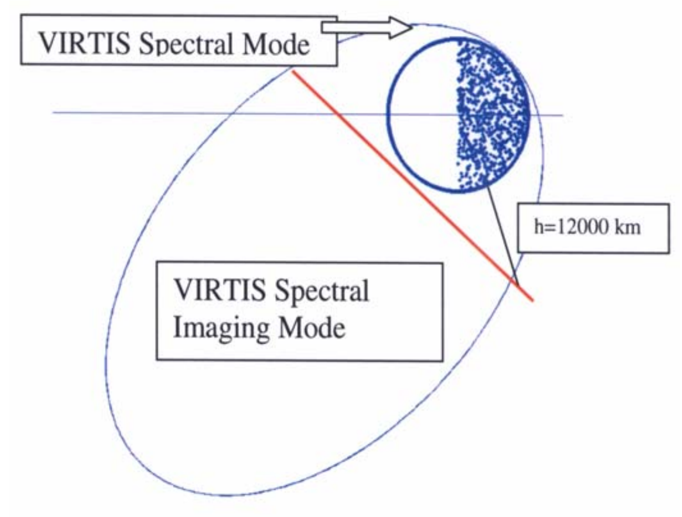

Figure 3.5 VIRTIS modes of observations.

Due to a minimum repetition time between two VIRTIS spectral images of the order of 2.5 sec, the observation strategy is divided into two parts on the orbit, depending on the dwell time on Venus being shorter than the repetition time (no image reconstruction) or larger (image cubes can be obtained). Therefore, the VIRTIS observations are separated into two categories, corresponding to altitudes lower than 12000 km (spectral mode) or higher (spectral imaging mode) (Figure 3.5):

1) Spectral mode (h < 12000 km): This mode will be used for joint VIRTIS/PFS observations. Only a partial coverage of the surface is obtained in this mode, but the coverage reaches about 15% of the surface after 7 orbits, covering a statistically significant part of the disk. In particular, the cloud variability and related atmospheric composition variability will be tracked, as in the Galileo/NIMS studies (Collard et al, 1993; Drossart et al, 1993). Data volume ~ 144 Mbits/hour of observation.
2) Spectral Imaging mode (h > 12000 km): cube reconstruction is possible by scanning mirror operations. Data acquisition can be made in two observation modes:
   - nominal observation mode, with the spectral slit parallel to the S/C motion. The scanning motion is perpendicular to the slit, and orthogonal to the S/C motion
   - "telecommunication mode", with the spectral slit orthogonal to the S/C motion (always nadir pointing). Since the apocenter part of the orbit has to be shared with ground communications, the observations in this mode will require less S/C reorientation than from the nominal observation mode. Data volume: total amount of 240 to 600 Mbits.

Repetition of observations. Due to the atmospheric rotation in 4 days, an atmospheric program will consist in observation campaigns to cover the time variability in short medium and long term. A definition of science operation strategy will of course need a global discussion between instrument teams and satellite operator, to define the best compromise for science return.

3.6 VENSIS (Low frequency radar for surface and ionospheric studies).

Precursors. Due to optically opaque atmosphere, radar is the best way to observe the surface of Venus from orbit. Magellan has obtained global SAR imaging, as well as altimetry and emissivity maps. Major questions raised by the Magellan data concern the nature and formation style of the Venusian crust and the relation between the young planitiae and the older tesserae. Deformation zones are another major problem. The behavior of the Venusian crust, probably dominated by vertical movements, is remarkably different from the Earth's crust. For this reason, only scant examples of Venusian analogue features can be recognized on Earth. This makes nearly impossible to interpret the deformation styles, and thus the dynamic of the crust, using only SAR images.

VENSIS/Venus Express. VENSIS is low frequency radar derived from the MARSIS/Mars Express instrument. The Experiment will obtain fundamentally different kinds of geologic information than Magellan. Mapping of interfaces of geologic units (e.g. tessera, plains, lava flows, impact debris) at low frequencies that penetrate into the surface down to the depth of 1-2 km could be extended into the third dimension. Reflectivity variations recorded at the surface by Magellan are likely to extend into subsurface, providing dielectric contrast at interfaces. Another major geophysical puzzle is the nature of large circular features called coronae.

The VENSIS instrument would also allow detailed characterization of the Venus ionosphere using active sounding in a frequency range of 100 kHz to 7 MHz. In a passive mode, VENSIS can be used to detect lightning, the presence of which remains both controversial and critical to understanding the behavior of the atmosphere and the possibility of present day volcanism.

All these problems require penetrating below the surface. A subsurface investigation of the first 1-2 km will show the internal deformations of the Venusian surface and will depict the structural styles of old crust which are essential to define the crust dynamics. Improved understanding of the evolution of complex Venusian features is a key to understanding the geological evolution of the planet.

Thus the primary scientific objectives of VENSIS experiment are the following:

- Probe the subsurface of Venus to 1-2 km depth with spatial resolution 5-10 km to detect and map geologic materials and large scale structures at planetary scale;
- Characterize surface roughness, composition and electrical properties at long wavelengths (orders of magnitude longer than Magellan).

A secondary objective is to probe the vertical structure of the ionosphere to characterize interactions between the solar wind and the Venusian ionosphere and atmosphere, and search for lightning.

VENSIS potential surface targets. Current Venus Express orbit give possibility to investigate the latitude zone centered at ~60N. The area comprised between 60-70 N of the northern hemisphere of Venus shows a large variety of geological features which are crucial for understanding of the crustal evolution of the planet including planitiae Atalanta and Audra, mountain chains, coronae, ridge belts and tesserae. The potential targets of the penetrating radar investigation can be summarized as follows:

TARGET 1. Ishtar Terra, the most enigmatic highland of Venus, formed by a large volcanic plateau, Lakshmi Planum, surrounded by four orogens (Maxwell, Akna, Freyja, Danu Montes). Ishtar Terra also consists of a large exposure of Venusian old bedrock, Fortuna Tessera, bounded by young volcanic plains. The nature of this complex is not understood yet and is very controversial. VENSIS will help to understand the nature and evolution of this highland and the behavior of the crust and interior of Venus.

TARGET 2. Atalanta Planitia is among the larger lowlands of Venus and shows very interesting linear deformation zones, ridge belts, which have no counterparts on Earth. The only way to understand the ridge belt formation is to look at their subsurface structure.

TARGET 3. Coronae and volcanoes. The area between 60-70N comprises very interesting volcano-tectonic features. For example, Anahit and Pomona Coronae are among the most well-preserved and large coronae features. Also, Sacajawea and Coletta Paterae are large volcanic edifices, which have been probably active in recent time. The subsurface investigation will provide critical information to understand the evolution of these unique features.

TARGET 4. Impact craters, deposits and structures. About 1000 impact craters were identified in Magellan data. Many of them have enigmatic deposits with unusual radar signatures associated with them. These include the high dielectric "parabola" features, and smooth interior "flooded" surfaces.

VENSIS data will be used to probe the subsurface structure of these features. Old impact craters subsequently buried by lava flows may be detected, especially if the high dielectric deposits are preserved in the subsurface.

VENSIS ionospheric studies. The ionosphere of Venus has been studied fairly extensively by Pioneer-Venus using radio occultation and Langmuir probe techniques. The maximum electron density in the Venus ionosphere on the dayside should be about $5{\cdot}10^5$ cm^{-3}, which corresponds to a plasma frequency of 6.4 MHz. The nightside electron density is much lower, about 10^4 cm^{-3}, possibly as low as 10^2 cm^{-3} in the regions called ionospheric holes, which would correspond to plasma frequencies of 900 kHz and 90 kHz, respectively.

The behavior of the plasma frequency (i.e. the distribution of the ionospheric electron density) vs. solar zenith angle should be very similar to the well-known Mars behavior, where the dayside plasma frequency should be lower of 4.5 MHz. Therefore we assume that the compensation for ionospheric distortion, which is used in MARSIS, can basically be reused in VENSIS. Furthermore for implementation of a wider range of an active ionosphere mode we can try to improve the performance using a frequency range between as low as 100 kHz and a frequency higher than 6.4 MHz. In the Active Ionosphere Sounding mode MARSIS will transmit a sequence of pulses with a bandwidth of 10,9 KHz, shifted around a central frequency stepped between 0.1-5.4 MHz with 160 step. For VENSIS the ionospheric sounding frequency range can be expanded from 6 MHz to 7 MHz without extensive design changes. This will allow VENSIS to sound the dayside ionosphere from its density peak at 140 km to the ionopause at 300 to 600 km, depending on the Solar wind conditions. In the polar regions and on the nightside the low frequency range will allow to sound from the peak altitude (~140 km) to basically the altitude of the orbit (at least up to 800 km), where a close connection of structures could be made with the ASPERA in situ measurements. The altitude and spatial resolution of VENSIS ionospheric sounding will be about 15 km and 30 km correspondingly.

In its standard subsurface sounding mode MARSIS is able to transmit 1 MHz signal bandwidth around the following frequencies: 1.8, 3, 4, 5 MHz: a 1 MHz bandwidth allows a vertical resolution of 150 m in vacuum which corresponds to 50-100 m in the subsurface, depending on the wave propagation speed in the crust. The multi frequency observations of VENSIS will allow the estimate of the material attenuation in the Venusian crust and will give significant indications on the dielectric properties of the detected interfaces.

3.7 VMC (Venus Monitoring Camera)

Precursors. Imaging of the Venus disc at different wavelength was carried out by the Pioneer Venus orbiter, during the fly-bys of Mariner-10 and Galileo, and from the ground. These data was used to study the atmospheric dynamics at the cloud tops (UV), to investigate the thermospheric dynamics (UV, visible, and near-IR airglow), to map the surface brightness and to study cloud opacity variations (near-IR). However, these observations lacked global spatial and temporal coverage as well as spatial resolution. At the same time they demonstrated the power of the global imaging in the study of dynamical processes in the Venus atmosphere.

VMC/Mars Express. The Video Monitoring Camera (VMC) onboard the Mars Express is a monochrome wide-angle CCD camera that was designed to take the video sequence of Beagle-2 lander leaving the Mars Express spacecraft at Mars.

VMC/Venus Express. The Study Team has recommended to modify the Mars Express camera into a wide-angle multi-channel Venus Monitoring Camera. The modification will consist of adding several narrow band filters in the UV, visible, and near-IR spectral ranges that would allow the camera to provide support imaging for the whole mission, achieve additional science goals, and contribute to the public outreach programme. Preliminary study showed that the modification of VMC will not specify additional requirements to the Mars Express bus and will be fully compatible with spacecraft interfaces. More detailed elaboration of the technical, programmatic, and financial issues related to the VMC modification and accommodation on the spacecraft will be done by the VMC team, Astrium, and ESA during the pre-Phase B study in the beginning of 2002 if the mission is approved. The modified VMC will be prepared in parallel with available VMC/Mars Express in order not to jeopardize the schedule of the mission. In case of failure to modify VMC in time VIRTIS will be able to cover significant part of the VMC goals so that the achieving of the mission objectives would be secured.

The VMC camera will be capable of achieving scientific goals in atmospheric dynamics and surface studies by means of global multi-channel imaging. An example of UV image expected from VMC at Venus is shown in Figure 2.2. Sequence of such images would allow one to visualize the motions of the cloud tops and to study the general circulation and wave phenomena at the altitude of ~70 km. Images of the Venus disc taken every 30 min will be used to create movies of the cloud motions and propagating waves that would be extremely valuable for investigation of the atmospheric dynamics. Figure 2.6 shows an example of image that VMC will take in the visible at night. The monitoring of airglow patterns that originate at 90-110 km is an efficient tool to study the dynamics of the Venus upper atmosphere. The VMC observations in the 1 μm transparency "window" will give the images similar to those shown in Figures 2.5 and 2.9. These images have two types of features. Some of them belong to the surface and result from the temperature and emissivity variations. Second type of markings originates in the main cloud deck and indicates cloud opacity variations. The movies based on such imaging will be used to study global atmospheric dynamics at ~50km.
To summarize, VMC will fulfill the following scientific goals:

- Support imaging, i.e. global imaging context for the whole mission;
- Observations of the global cloud motions in the UV and near-IR spectral ranges;
- Study of distribution of the unknown UV absorber at the cloud tops;
- Monitoring the UV and visible airglow and its variability as dynamical tracer;
- Mapping the surface brightness temperature distribution and search for volcanic activity.

Besides important scientific goals the VMC imaging and movies will significantly contribute to the public outreach programme.

3.8 Synergy of the payload.

The experiments included in the Venus Express payload provide comprehensive and versatile investigation of various phenomena in the atmosphere, plasma environment, and on the surface of Venus. Combination of different observational tools gives the mission high level of synergy and redundancy ensuring the achieving of mission scientific objectives.

The *temperature sounding* of the atmosphere will be carried out in PFS, VeRa, VIRTIS, and SPICAM experiments. PFS measurements in the thermal infrared range will provide most unambiguous and accurate sounding of the mesosphere. VIRTIS will support these measurements in the apocenter portion of the orbit due to its narrow field of view. VeRa will expand the temperature sounding down to 35 km with vertical resolution of ~100 m that will give an opportunity to study small scale wave phenomena. Solar and stellar occultations by SPICAM will cover the altitudes from the clod top up to ~180 km.

The atmospheric composition will be investigated by VIRTIS, SPICAM, and PFS. In particular the lower atmosphere will be studied by spectroscopy and spectro-imaging in the near-IR transparency "windows". High-resolution measurements by VIRTIS in 2.3 μm "window" (H_2O, CO, COS, SO_2 at 30-40 km) will be complemented by SPICAM spectroscopy in the "windows" at $\lambda \leq 1.7$ μm that sound deeper in the atmosphere (H_2O at 0-20 km). After modification PFS will be able to study the 1.74 μm "window" (H_2O and HCl at ~20 km) and sub-micron emissions (surface and atmosphere above it) with even higher resolving power up to 5000. The three experiments will provide additional data on the composition at the cloud top. Especially valuable will be high-resolution SPICAM observations in solar and stellar occultations that will give the atmospheric composition and isotope abundance up to the altitudes of ~180 km.

The atmospheric dynamics will be studied by tracking the motions of the cloud features in the VIRTIS and VMC images corresponding to the altitudes of 50 and 70 km. These observations will combine advantages of local imaging with moderate spectral resolution with global view of the planet taken in few spectral channels. These measurements will be complemented by the thermal wind field retrievals from the temperature sounding by PFS, VeRa, and VIRTIS. Comparison of simultaneous direct and indirect observations of winds will allow one to verify the hypothesis of cyclostrofic balance in the Venus atmosphere. Thermospheric dynamics will be derived from the airglow patterns observed by VIRTIS and VMC in the UV, visible, and near IR.

The *escape processes* will be investigated by the ASPERA imaging of the charged particles outflow via associated ENAs as well as by direct detection of the escaping ions supported by the measurements of magnetic fields imbedded in the plasma at orbit altitude. These observations in combination with vertical distribution of trace gases and their isotopes measured by SPICAM will help to derive escape rates of different molecules that is of crucial importance for understanding the atmospheric evolution.

The processes in the near Venus plasma environment will be studied by ASPERA, VENSIS, and VeRa. Combination of *in situ* plasma flow measurements by ASPERA and complementary remote sensing of ionospheric structure by VENSIS and VeRa will significantly contribute to our understanding of mechanisms of ionospheric composition, plasma transport, ionosphere-“magnetospheric” coupling, and the origin of the nightside ionosphere of Venus. These observations will be supported by local magnetic field measurements provided by the magnetometer included in the ASPERA instrument. Solar wind parameters measured by ASPERA and simultaneous VENSIS sounding of the ionosphere will give comprehensive picture of the interaction of the solar wind with Venus atmosphere. All three experiments will study the behavior of ionosphere as function of local solar time, latitude and solar wind conditions.

The *surface* investigations will be carried out by the low frequency radar VENSIS. This experiment will sound the subsurface of Venus down to the depth of 1-2 km. This will allow one to study the contacts between different geological units and unveil the history of Venus. Bi-static sounding in VeRa experiment will complement the study of surface properties. Spectroscopic, spectro-imaging, and imaging instruments onboard Venus Express (VIRTIS, PFS, SPICAM) will study the composition of the lower atmosphere and near surface lapse rate that will help to constrain the models of surface-atmosphere interaction. Mapping the surface temperature by VIRTIS and VMC would allow us to search for evidences of *volcanic activity*. Spectroscopic measurements in the upper atmosphere by VIRTIS and PFS will be able to detect waves indicative of the *seismic activity* on the planet.

3.9 Payload accommodation

The accommodation of the instruments on the Mars Express spacecraft is shown in Figure 3.6. Most of the instruments (ASPERA, SPICAM, PFS, VENSIS) are originally from the Mars-Express project. They will keep their places on the Venus Express spacecraft. VMC will also occupy the same place as the camera on Mars Express, i.e. inside the spacecraft close to the upper (+Z, or ”nadir”) wall. The largest of new experiments, VIRTIS, was accommodated in the spacecraft compartment that belonged to OMEGA and HRSC on Mars Express. VeRa will be placed on the left (Y) wall of the spacecraft. The SPICAM-SOIR unit will be mounted on top of the main SPICAM module and will use the same solar port for observations.

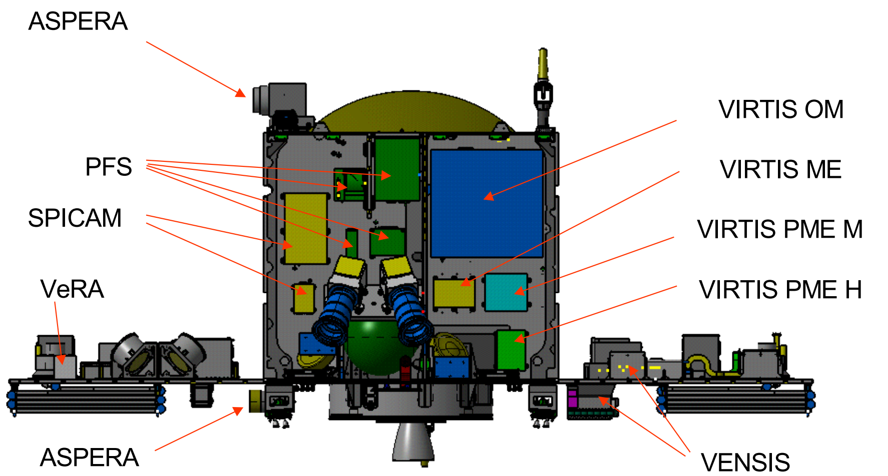

Figure 3.6. Accommodation of the Venus Express instruments on the spacecraft. VMC is not shown.

3.10 Mission and payload schedule

Figure 3.7 shows the mission schedule. The main peculiarity is that the Electrical Model campaign is not foreseen. Atsrium will proceed directly to the integration of the flight units. This becomes possible due to the fact that most of the Venus Express instrument are from the Mars Express project and have already passed the EM tests with the spacecraft. The Rosetta experiments (VIRTIS and VeRa) are compatible with the Mars Express interfaces since they use the same OBDH bus.

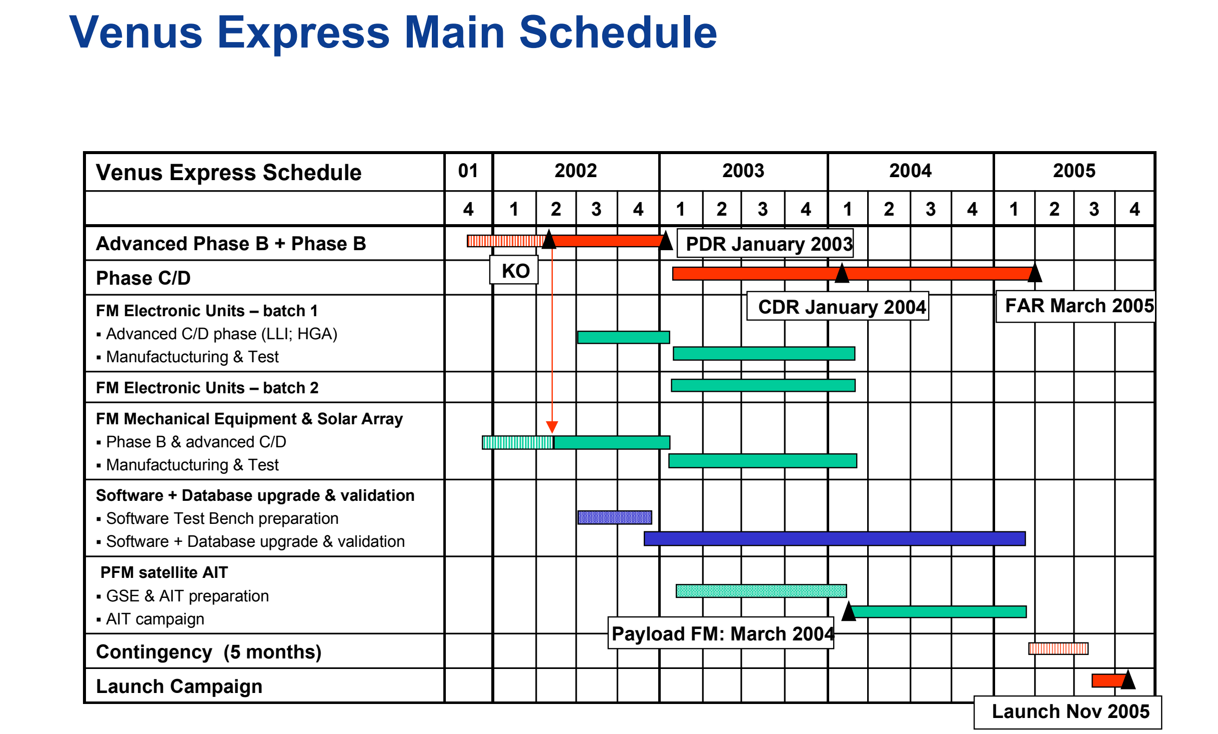

Figure 3.7 Venus Express mission schedule.

Most of the instruments for Venus Express will be refurbished from the Mars Express and Rosetta flight spares that will be ready by mid 2002 according to the schedules of these projects. After additional tests and calibrations they will be ready for delivery in March 2004 (Figure 3.7). Modification of the instruments will be done in parallel with availability of original flight spares without changing the interfaces with the spacecraft. These changes will in no way jeopardize the mission schedule. It is recommended to work out a detailed payload schedule prior to the start of Phase B. Preliminary schedule of the Venus Express payload preparation is as follows:

- 12.2001 - payload approval by SPC together with the mission selection;
- 01-05.2002 - payload pre-Phase B activities;
- 05-06.2002 - payload design review;
- 03-04.2003 - payload critical review;
- 01-02.2004 - payload flight acceptance review ;
- 03.2004 - payload delivery.

3.11 Payload Teams

For most of the experiments the payload teams were formed in the frames of the Mars Express and Rosetta projects. The Teams will be slightly modified for Venus Express. Preliminary list of the experimental teams and cooperating institutions is presented in the Table 3.5. Complete lists of Co-investigators will be finalized after the mission is approved.

Table 3.3 Instrument performance characteristics

V) parameters of the modified instruments

Experiment	**Scientific goals**	**Spectral range, μm**	**Spectral resolution**	**λ/Δλ**	**Imaging**	**FOV, mrad**	**NER, erg/s/cm²/sr/μm**
SPICAM (UV+IR+SOIR)	• SO_2, SO abundance at 60-70 km, and CO_2 (occultation) • NO, O, H, C, CO and O_2 airglow • Atmospheric density and temperature at 80 – 180km • Vertical profiles of H_2O, HDO, $^{13}CO_2$, $^{14}CO_2$, O, OCS, H_2S, HF from cloud tops up to 100-180 km V) (solar occultations) • H_2O at ~ 70 km and at 0-20 kmV) • Surface emissionV) • Search for new trace gases (CH_4, C_2H_6, etc.)	0.11-0.31 1.0-1.7 0.7-1.7V) 1.8-4.0V)	0.8 nm 0.5 - 1 nm 0.2-0.5cm^{-1}	~300 ~1300 ~15000	Yes No No	55x8.7 0.2/pix ∅17.5 0.3-3	0.1 kR/nm (4s) 0.05(0.7-1.05 μm), 3(0.9-1.7 μm) Solar radiance
PFS	• Temperature and cloud structure (55-100km) • Trace gases above the clouds (SO_2, H_2O, HCl, CO, COS, HF, HDO) • O_2 ($^1\Delta$) airglow at 1.27 μm • Minor constituents below the cloudsV) • Temperature gradient at 0-10 kmV) • Surface emission at ~ 1. μmV)	1.2 – 5. 5. - 45 0.9 - 3.3V)	2 cm^{-1} 2 cm^{-1} 2 cm^{-1}	4000– 1000 1000 – 100 5500-1500	No No No	~35	500 – 20 200 – 2 ~0.5 V)

VIRTIS	• CO, COS, SO_2, H_2O at 30-40 km • Cloud structure, composition, and dynamics • Surface temperature mapping • Temperature structure (70 – 90 km) • Density profiles in the upper atmosphere • H_2O and CO at ~70 km • O_2 airglow at 0.3 - 1.27 μm • Search for lightning • Fluorescence in 4.3 μm CO_2 band	0.25 - 1.0 1 – 5.0 2.0-5.0	~3 nm ~30 nm ~3 nm	100 – 200 100 - 200 1000- 2000	Yes Yes No	0.25 0.25 0.5-1.5	~0.1 0.5 – 1.0 0.5 – 1.0 (1s integration time)
ASPERA **1. ENA** **2. Ions** **3. Electrons**	• Solar wind -atmosphere interaction • Characterisation of the impact of plasma processes on the atmosphere • Global plasma and neutral gas distribution • Mass composition flux of the outflowing atmospheric materials • plasma domains of the near-Venus environment • undisturbed solar wind parameters.	0.1-10keV 0.01-40keV .01-20keV	ΔE/E 0.8 0.1 0.07	NA	Yes	Degrees 9x344 (NPI) 9x180 (NPD) 90x360(ions) 10x360(el)	NA

VeRa	• High resolution vertical profiles of pressure, density, and temperature of the neutral atmosphere (35–100 km) • High resolution vertical profiles of the ionospheric electron density in the range of 80km to ionopause (300-600km depending on solar wind conditions) • Dielectric properties, roughness, and chemical composition of the surface • Radio sounding of coronal and extended coronal structures in the inner solar system at superior and inferior conjunctions	NA	NA	NA	NA	NA	NA
VMC	• Mission support imaging • Dynamics at 50 and 70 km • Unknown UV absorber • Airglow • Surface temperature	6filters: 0.23, 0.28, 0.36, 0.5, 0.97, 1.0	~5 nm	----	Yes	500 (total) 0.5 (per pixel)	--
VENSIS	• Subsurface sounding; • Surface characteristics and altimetry • Active ionospheric sounding • Passive ionospheric sounding	1.3-5.5 MHz 0.1-7 MHz 10kHz-5.5MHz	NA	NA	Yes	5x10 km footprint	NA

Table 3.4 Instrument interfaces and requirements

Experiment	Mass, kg	Power, W	Size,cm	Data rate	Radiator	Sun in the FOV	Observations at, km
SPICAM(UV+IR+SOIR)/MEx	9	21+10 for 10 mn per orbit	40x28x23 14x16.5x15.5	~18 Mbyte/orbit 20-60 kbps	No	Nadir FOV: 15° away from the Sun	Pericenter <1000km Limb 500-5000km Occultations anywhere
VIRTIS/Rosetta	31+2(harness)	66	59x65x38 22x25x10 20x25x19	~40kbps (spectral mode) 240-600 Mbits total (spectro-imaging)	Yes, pointing to space	No	Entire orbit
PFS/MEx	31.2	35-45	45x35x27, 20x20x15	24-64 kbps	Yes	No	2 hours at pericenter
ASPERA/Mars Express	9	15 + 10(TBC) heaters	23.2x34.8x2518.6 x28x15.1	0.7 – 22.6 kbps	No		Entire orbit (Nadir <12000km)
VeRa/Rosetta	1.5	5	15.2x12.2x13	NA	No		Earth occultations (HGA to Earth) Bistatic radar (HGA to Venus)
VMC	1.1	4	~10x10x10	~10kbps	No	15° away from the Sun	Entire orbit
VENSIS (MARSIS/MEX)	18	Max 60	Ant.: Dipole 40 m Monopole: 7 m	10 – 80 kbps	No		SSSM <800km IASM <1200 km

NOTES: V) After modification for Venus;

Table 3.5. Payload teams and cooperation

Experiment	Team	Cooperation
ASPERA	**S. Barabash** (PI)	Institute of Space Physics, Kiruna, Sweden
	H. Andersson (Experiment Manager)	
	J.-A. Sauvaud (Co-PI)	CESR-CNRS, Toulouse, France
	Co-Investigators	
	R. Lundin, M. Yamauchi, M. Holmström, A.Grigoriev	Institute of Space Physics, Kiruna, Sweden
	A. Fedorov	CESR-CNRS, Toulouse, France
	A. Coats	Mullard Space Science Laboratory, UK
	M. Grande	Rutherford Appleton Laboratory, Oxfordshire, UK
	P. Bochsler, P. Wurz	University of Bern, Switzerland
	R. Cerulli-Irelli, S. Orsini	IFSI-CNR, Rome, Italy
	H. Koskinen, E. Kalio	FMI, Helsinki, Finland
	N. Krupp, J. Woch	MPAe, Katlenburg-Lindau, Germany
	R. Frahm, J. Sharber, D. Winningham	SWRI, San Antonio, USA
	J. Luhmann	SSL, University of California, Berkley, USA
	E. Roelof	APL, John Hopkins University, Laurel, USA
	C.C. Curris, K.C. Hsieh, B.R. Sandel	University of Arizona, Tucson, USA
	S. McKenna-Lawlor	ST Ltd, National University of Ireland, Ireland
	W. Baumjohann, T. Zhang,	IFW, Graz, Austria
PFS	**V. Formisano** (PI)	IFSI-CNR, Rome, Italy
	R. Terenzi (Experiment Manager)	IFSI-CNR, Rome, Italy
	Co-Investigators	
	A. Maturilli, D. Grassi, D. Carruba, M. Giuranna	IFSI-CNR, Rome, Italy
	G. Piccioni, A. Coradini	IAS, Rome, Italy
	F. Angrilli, B. Saggin	University of Padova, Italy
	L. Colangeli, E. Palomba	OAC, Naples, Italy
	S. Fonti, V. Orofino, A. Blanco	University of Lecce, Italy
	V. Moroz, D. Patsaev, A. Grigoriev, B. Moshkin, A. Kiselev, Yu. Nikolsky, A. Ekonomov, V. Gnedykh, L. Zasova, D. Titov, N. Ignatiev, I.Khatuntsev	IKI, Moscow, Russia
	V Nechaev	NIITP, Moscow, Russia
	A. Jurewicz, M. Blecka, P. Orleanski, M.Michalska	CBK, PAN, Warsawa, Poland
	G. Arnold, H. Hirsch	PE-PP, DLR, Berlin, Germany
	E. Lellouch, A. Marten, Th. Encrenaz	DESPA, Paris, France
	J. Lopez-Moreno, J. Rodriguez	IAA, Granada, Spain
	S. Atreya	University of Michigan, USA
SPICAM	**J-L. Bertaux** (PI),	Service d'Aéronomie du CNRS, France
	E. Dimarellis (Technical Manager)	
	P. Simon (Co-PI)	Institute for Space Aeronomy, Belgium
	O. Korablev (Co-PI)	IKI, Moscow, Russia
	Co-Investigators	
	G.Durry, M. Cabane, E. Chassefiere, J.-P. Dubois, A.Hauchecorne, F. Leblanc, P. Rannou, F.Lefevre, F. Montmessin	Service d'Aéronomie du CNRS, France
	D. Nevejans, E. Neefs	Institute for Space Aeronomy, Belgium
	N. Ignatiev, V. Moroz, A. Rodin, S. Stepanov, D. Titov, L.Zasova	IKI, Moscow, Russia
	F. Forget	LMD, Paris, France
VeRa	**B. Haeusler** (PI)	Uni. der Bundeswehr Muenchen, Germany
	M. Pätzold (Co-PI)	Uni. zu Koeln, Germany
	Co-Investigators	

	R. Treumann	MPE, Garching, Germany
	M. Bird	Universitaet Bonn, Germany
	R.A. Simpson, D. Hinson	Stanford University, USA
VIRTIS	**P. Drossart** (Co-PI)	Observatoire de Paris, France
	A. Semery (VIRTIS-H Project Manager)	
	G. Piccioni (Co-PI and Technical Manager)	IAS, Rome, Italy
	A. Coradini (Deputy PI)	
	G. Arnold (Deputy-PI)	PE-PP, DLR, Berlin, Germany
	J. Benkhoff, (VIRTIS-Main Electronics Project Manager)	
	A.Cisbani·(Project and Program Manager)	Officine Galileo, Italy
	E. Suetta (System Engineer)	
	J.-P. Bibring (Calibration Manager)	IAS, Paris, France
	Co-Investigators from ⇒	Observatoire de Paris, France
		IAS, Rome, Italy
		IFSI-CNR, Rome, Italy
		PE-PP, DLR, Berlin, Germany
		JPL/NASA, USA
		Lisbon Observatory, Portugal
		Space Research Institute (IKI), Russia
		SRC, Poland
VENSIS	**G. Picardi** (PI)	University of Rome "La Sapienza", Italy
	J. Plaut (Co-PI)	JPL/NASA, USA
	W.T.K. Johnson (Experiment Manager)	JPL/NASA, USA
	F. Provvedi (Co-Experiment Manager)	Alenia Spazio, Italy
	Co-Investigators	
	D. Biccari, T. Bucarelli	University of Rome "La Sapienza", Italy
	F. Cappacioni, P. Cerroni, A. Coradini, P.Lombardo, R. Orosei, M. de Sanctis, R. Seu	Istituto di Astrofisica Spaziale- CNR, Roma, Italy
	P. Edenhofer	Ruhr-Universitaet Bochum, Bochum, Germany
	K. Foellmi	University of Neuchatel, Switzerland
	G. Franceschetti	IRECE-CNR, Naples, Italy
	J.E. Guest	University College London, UK
	D.A. Gurnett	University of Iowa, Iowa, USA
	L. Marinangeli	Università "G. D'Annunzio", Pescara, Italy
	E. Nielsen	MPAe, Katlenburg-Lindau, Germany
	P.T. Melacci	Università degli Studi di Perugia, Perugia, Italy
	D. Plettemeier	Univ. of Bochum, Germany
	N. Reeh	Technical University Denmark, Lyngby, DK
	A. Safaeinili, E.R. Stofan	JPL/NASA, USA
	S.B. Serpico	University of Genova, Genova, Italy
	M.J. Siegert	University of Wales, UK
	I. Williams	University of London, UK
		Niels Bohr Institute, Copenhagen, DK
		Mullard Space Science Laboratory, UK
VMC	**W.J. Markiewicz** (PI)	MPAe, Katlenburg-Lindau, Germany *)
	Co-Investigators	
	B. Grieger, N. Hoekzema, H.U. Keller, N. Thomas, D. Titov	MPAe, Katlenburg-Lindau, Germany
		Technical Univ. of Braunschweig, Germany
	D. Crisp	JPL/NASA, USA
	S. Limaye	University of Wisconsin, USA
	N. Ignatiev	IKI, Moscow, Russia
	S. Okano, S. Watanabe	ISAS, Japan

*) VMC: pending internal approval at MPAe.

4 Mission overview

This section presents the summary of the assessment study carried out by Astrium-SAS and published in detail in a separate document.

4.1 Mission scenario

The Venus Express mission scenario is presented in the Table 4.1. The spacecraft is planned to be launched in the beginning of November 2005 by Soyuz/Fregat from Baikonur. In April 2006 after ~150 days of cruise the spacecraft will be inserted into highly elliptical polar orbit around Venus. The observational phase will begin after about one month of commissioning phase.

Table 4.1 Mission scenario

Day Number	Activity
0 (=L)	Launch on Soyuz Fregat , injection into interplanetary transfer orbit
L+60	Trajectory correction
L + 150	Attitude adjustment for Venus Capture
L + 153	Venus Capture Burn
L + 158	Apoapsis Lowering Burns
L + 158(=V)	Entry to Operational Orbit
V+0 – V+30	In Orbit Commissioning
V+30 – V+273	Observations over 1 Venus sidereal day
V+59	Eclipse Season end (Max Duration = 34minutes)
V+122- V+156	Eclipse Season (Max Duration = 51minutes)
V+191 – V+211	Communication Outage (Earth-Venus superior conjunction)
V+215 - V+283	Eclipse Season (Max Duration = 34minutes)
V+280	Optional Periapsis Lowering Burn (Reduce Periapsis from 420 -> 250)
V+280 – V+523	Observations over second Venus sidereal day.
V+346 - V+380	Eclipse Season (Max Duration = 51minutes)
V+439 - V+507	Eclipse Season (Max Duration = 34minutes)
V+487 – V+507	Communication Outage (Earth-Venus inferior conjunction)

The orbit around Venus is inertially fixed, so that the full coverage of planetocentric longitudes will be accomplished in one Venus sidereal day (243 Earth days). The proposed nominal mission orbital life-time is two Venus sidereal days. The first day will be devoted to the global latitude, longitude, and local time coverage of the planet. The second day will provide opportunity for filling observation gaps suffered during the first year, for returning and studying in more details selected objectives, for observing specific surface or atmosphere locations, for looking at time variability of phenomena observed during the first year. Favorable conditions for solar/stellar occultations and subsurface sounding by VENSIS will occur in seasons during each of two Venus days.

4.2 Launch, delta-V, and mass budgets

The Soyuz/Fregat launcher will inject Venus Express directly into interplanetary orbit. It has a launch capability of 1260 kg for a Venus transfer orbit. However, the Mars Express spacecraft is designed for a maximum launch mass of 1200 kg. This latter number has been used for the mission design described in this document.

Table 4.2 Delta-V budget

Component	Delta-V (m/s) for 30,000 km apocenter	Delta-V (m/s) for 45,000 km apocenter
Launcher dispersions/ mid-course correction between Earth and Venus	40	40
Initial orbit capture (incl. losses due to non-impulsive burn)	1250	1250
Apocenter lowering	652	400
Station keeping (pericenter maintainance)	17	17
Total	1959	1707

Venus has a synodic period of 16 months; therefore an optimum launch window to Venus occurs every 16 months. The launch opportunity in November 2005 with the launch window of about 2-3 weeks is assumed for Venus Express. The capture burn at Venus (Delta-V) is large. Therefore an initial capture burn will be followed by a series of apoapsis lowering maneuvers. A highly elliptical orbit with pericenter at ~250 km altitude a period of approximately 5 days, can be reached with a burn of approximately 1250 m/s. The apoapsis is then lowered to the operational orbit altitude. A nominal value of 30 000km requires a further 650m/s. Delta V can be reduced by increasing the operational orbit apoapsis. 45 000km requires only 440 m/s. A delta V budget for two operational orbits with different apocentre altitudes is shown in the table 4.2. The second column of the Table 4.2 represents the nominal case for Venus Express payload and takes into account necessary margins. Each kilogram of “dry” mass added to the spacecraft would result in about 400 km apocenter increase.

4.3 Operational orbit

The Venus Express mission aims at exploring the Venusian atmosphere, the plasma environment and the surface geology of Venus from orbit. The selected orbit is quasi-polar with a pericentre at ~250 km and apocentre in the range 30 000-45 000 km with a period of 9.6 to 16 hours. A high-inclination elliptical orbit provides complete latitudinal coverage and gives the best compromise for allowing both high-resolution observations near pericenter and global observations during the apoapse part of the orbit, and for in-situ measurements of the Venusian environment and its interaction with the solar wind. The altitude of the apocenter, hence the length of the orbit period depends upon the fuel load that can be embarked within the launcher lift capability. The lower the apoapse, the more fuel is required to achieve the final orbit. The range of acceptable apocentre altitudes provides a degree of flexibility for the development phase, and allows one to cope with the uncertainties that have been designed in the current mass budget, which includes a comfortable margin. The lower apocentre is preferred from the point of view of scientific return. It is preferable to have pericentre at about 60-70 N in order to study all latitudes in at least one hemisphere with high spatial resolution (Fig. 4.1). The selected baseline orbit provides full latitude and local solar time coverage for the atmospheric observations and convenient conditions for tracking the cloud features from the apocentre. This orbit allows radar and other high-resolution surface observations of high latitudes in the northern hemisphere. For example, it allows good coverage of Ishtar Terra – the region of prime interest for detailed radar investigations.

The final choice of the apocentre altitude at Venus orbit injection will be made later during the spacecraft development, and could even be adjusted during the transfer phase to Venus. It will be the result of trade-offs, balancing observation requirements with telecommunications periods, payload and spacecraft performances, and available fuel after trajectory correction about 60 days after launch.

Due to the low value of the J2 term of Venus gravity field, orbit apse rotation and nodal regression are very small. The only major orbit perturbation is the effect of solar gravity, which raises the periapse. Over one Venus sidereal day (243 Earth days) the periapse will raise by approximately 170 km. Fuel has been budgeted to lower the periapse as needed over the duration of the mission.

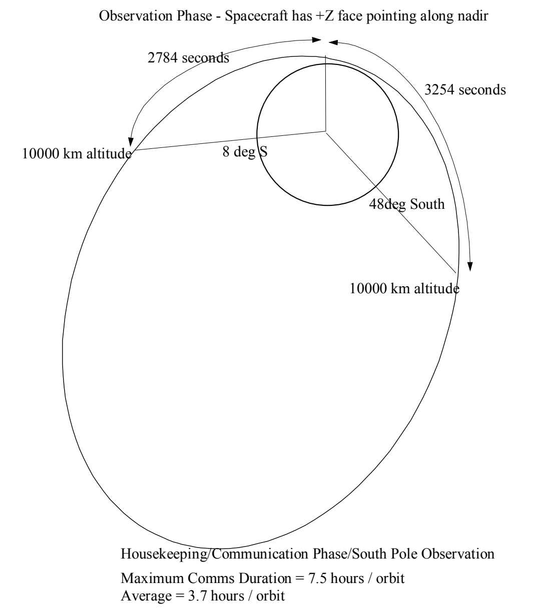

Figure 4.1 Typical Venus Express orbit.

4.4 Orbital science operations

The "store and forward" concept of the orbital operations, implemented for the Mars Express and the Rosetta missions, fits the Venus Express requirements. The experiments will collect the data in the vicinity of pericentre and store them in the mass memory. The apocentre part of the orbit will be shared between global remote sensing observations, in-situ observations and data transmission periods. Some of the experiments will be designed for collecting data in the apoapse part of the orbit when it does not interfere with the downlink to the Earth. The solar/stellar occultation experiments will operate in short time slices per orbit off pericentre. The radio occultation experiment VeRa requires the high-gain antenna to point to the Earth or to Venus for providing radio occultation measurements of atmospheric structure or bistatic sounding of the Venus surface. This experiment will require pure carrier signal with telemetry "off". The radar VENSIS will operate at altitudes less than 800 km and with preference on the nightside for surface and subsurface sounding and Venus lightning detection, and both dayside and nightside for ionospheric topside sounding and for local plasma measurements.

4.5 Telecommunications

Venus Express is an Orbiter mission. Orbit period between 10 and 16 hours is envisaged depending upon the delta-V budget available for lowering the apocentre from the initial high-apocentre capture orbit. The baseline orbital period will be selected during the development phase of the spacecraft. It could also be adjusted after launch, during the transfer phase. The mission operations will be based on one downlink per orbit. The Venus Express minimum downlink data rate is about 63 kbps at Venus superior conjunction (1.73 AU). This data rate allows one to downlink 1.36 Gbits/day during 6 hour contact. The maximum TM rate is 228 kb/s, which allows 4.9 Gbits/day with 6h contact. Communication outages will occur during both superior and inferior conjunctions. During these periods the data will be stored in the

Table 4.3 Recording capability during telecommunication outages.

	Superior conjunction 20 days comms outage	Inferior conjunction 10 days comms outage
Storage rate to saturate SSM	500 Mbits per day	1 Gbit per day
Time to download SSM	8 days at 63kbps	2 days at 228kbps

10 Gbit Solid State Memory (SSM) at a rate compatible with the outage duration and the downlink capability after outage. Examples are shown in Table 4.3.

4.6 Thermal control

The Venus Express orientation during the communication phases that would last for about 10 hours per orbit is driven by thermal aspects. Satellite and payload thermal requirements have been assessed and fed into the spacecraft and mission designs to the extent possible during the short study phase. Satellite pointing strategies for the major operation modes have been designed which satisfy the spacecraft and payload thermal requirements with sufficient confidence at this level of the study. It is proposed to tilt the HGA by about 30 deg. to cope with most of the Sun exposure constraints. Transient solar exposure of the instrument radiators may be allowed for short parts of the mission of a few days. The modifications that need to be implemented in the instruments have been clearly identified and have been taken into account in the proposed instrument schedule. No show-stopper has been identified from the thermal point of view. However, more detailed thermal studies will be required in the early design phase of the mission to fully implement the pointing modes proposed in this study.

4.7 Radiation requirements

Preliminary assessments of the Venus Express radiation environment showed that the instruments need to be designed for a qualification level of 20 krad, which is not significantly different from the requirements of the Mars Express and Rosetta mission. No major problem is anticipated to meet this requirement.

4.8 Ground segment implementation and operations support

The Ground Segment implementation for the Venus Express mission can basically follow the same lines as for Mars Express. For the initial support after launch, use can be made of the standard ESA 15 m S/X-band network, typically Kourou, Perth, and Villafranca.

For the longer distance support, larger antennas in the 30 m range will be necessary. The ESA network has a 32 m S/X-band station at New Norcia. As this station will be used for a number of other missions (ROSETTA, Mars Express, Herschel/Planck, Bepi Columbo), and the NASA DSN is also heavily loaded, a second 32 m antenna is under consideration by ESA (near Madrid). These 2 stations can function as the primary ones for Venus Express too. When during certain calendar periods station scheduling conflicts are foreseen (e.g. during the upgrade of the New Norcia station to Ku-band support), temporary complementary support may be arranged from other 30 m antennas (e.g. the NASA/DSN Goldstone, or DLR's Weilheim.) Also, during the period when Venus and Earth are in superior conjunction, the temporary use of even larger antennas (>60 m) is considered in order to speed up the retrieval of on-board stored data, which will be accumulated during the long period of communications outage. Such large antennas may further be of interest when conducting radio sounding experiments with the VeRa instrument.

The Mission Control Centre design and implementation for Venus Express can borrow heavily on those of Mars Express and ROSETTA, given the intended heritage of both platform and payload. This will hold true particularly for the real time support system and the software satellite simulator. Major project specific developments/customizations are primarily expected in the areas of flight dynamics, mission planning, and timeline validation (in view of the stringent thermal conditions of the Venus Express mission).

As to operations analysis and flight operations procedure development, although large inheritance will exist from the Mars Express and ROSETTA missions, significant adjustments are unavoidable to reflect the peculiarities of the Venus Express mission. On the positive side, for the actual conduct of operations a high synergy should be well within reach when pursuing close cooperation with the Mars Express and ROSETTA operations teams. This should enable an around the clock support for the mission - as needed - at minimal delta cost.

4.9-Miscellaneous

Aerobraking. Peculiarity of the orbits at Venus is that there is no natural precession of the pericenter. So being once inserted in a certain orbit the spacecraft will be locked on a certain position of the pericenter with other locations observed from large distances. Circularizing the orbit by aerobraking could give a chance to cover all latitudes at high spatial resolution. However this option is not considered in the mission baseline and should not be considered as a mission and spacecraft design requirement.
Magnetic cleanliness. A magnetometer sensor may be added to ASPERA. It will be designed such that no boom will be required, and it will not impose special magnetic cleanliness requirements of the spacecraft.

5. Science operations, data analysis, and archiving

5.1 Science Operations Concept

The mission will be operated following a scheme similar to that of Mars-Express and Rosetta. A Mission Operation Centre (MOC) will be located in ESOC. A Science Operation Centre will be set-up in the early development phase of the mission. An effort will be made to design the Venus Express SOC so as to fully exploit the instrument operation knowledge that will reside within the PI and Co-I institutes which was acquired during the development of the MARS EXPRESS and Rosetta Science Operation Plans.

5.2 Principal Investigators

The Venus Express payload put forward in the report is considered to be the selected Venus Express Scientific payload as indicated in the ESA AO calling for mission proposal issued in March 2001. It is anticipated that the payload will be endorsed by the SSWG and SSAC and confirmed by the SPC at the time of the Flexi 2005 mission selection in Dec. 2001.

The Venus Express Study Team recommends that further work be initiated prior to the start of the industrial phase-B activities in order to finalise the payload interface requirements and to allow further work on the identified modifications on the existing payload instruments.

The Principal Investigators (PI's) of each of the seven proposed payload instrument are considered as the Venus Express PI's.

5.3 Interdisciplinary Scientists (IDS)

It is anticipated that ESA will issue a call for Venus Express Interdisciplinary Scientists (IDS) to support the development phase of the mission; one of the primary tasks of the IDS will be to coordinate the development of the Science Operation Plan from the science point of view. It is expected that up to 4-5 IDS's will be selected within one year after mission approval.

5.4 Science Working Team

After mission approval, ESA will nominate a Venus Express Project Scientist who will be responsible for coordinating all scientific aspects of the Venus Express mission. The Venus Express Science Working Team (VexSWT) will be composed of all PI's and IDS's. The VexSWT will be chaired by the Project Scientist.

The VexSWT will meet on a regular basis during the development of the mission and during the flight operations phase, typically 2-3 times/year, nominally at ESTEC. VexSWT meetings may also take place at PI institutes, ESOC or at the spacecraft contractor premises. A Venus Express Science Operations Working Group (VexSOWG) will be formed to support the development of the Science Operation Plan. The VexSOWG will be composed of all IDS's and one representative for each PI-team.

5.5 Science Operation Team

The Venus Express Project Scientist will be supported by a Science Operation Team (VexSOT), that will be based at ESTEC. Taking full advantage of the MARS EXPRESS and Rosetta experience, ways to optimize the coordination between the Science Operations Team and the PI-institute based instrument operations teams will be looked at during the early development phase of the mission.

5.6 Science Operation Plan

The planning of the first year observation will be such that it provides both global and local time coverage. The first year of the Science Observation Plan (SOP) will be developed before launch, with the objective of flying it as developed. Whereas the observation planning of the second year will be more flexible. A skeleton will be developed before launch but it will be finalised only during the first year of orbital observations.

During the first Venusian year, the observation programme will be based on several "templates" that will be reusable full-orbit sequences according to the objectives of the observation programme. An effort will be made to minimize the number of templates so as to minimize the number of observation sequences. The observation sequences will be prepared before launch. Selected observation sequences will be used for ground testing and end-to-end validation of the MOC including the SOC. Data transfers between MOC and SOC and PI-institutes will use public networks.

5.7 Data analysis

Instrument data will delivered to the PI-team institutes by the MOC. Instrument data reduction and analysis will be the responsibility of the Venus Express PI-Teams. Trajectory and ancillary data will also be provided by the MOC. The SOC will help coordinating the data analysis and will prepare summary reports for each orbit that will be distributed to all teams.

The PI-teams will have proprietary data rights for a period of 6 months. It is expected however that teams will facilitate data exchange among all teams. After the proprietary period, the data will be archived in a public archive and made easily accessible to the wider science community. The data archive format will follow the one adopted by Mars Express and Rosetta.

5.8 Science Management Plan

A Venus Express Science Management Plan will be prepared within TBD months after the selection of the mission. Inter alia, the SMP will define all the responsibilities between ESA and the PI's.

5.9 Complementary Venus Ground-based Observations

Venus is a relatively easy planet to observe from ground. Wind measurements and lightning detection are but two objectives that could be pursued from ground based observatories that would complement and support the Venus Express in-orbit observations. Venus is also accessible to amateur astronomers with a modest-size telescope. As part of the outreach programme, the possibility to involve amateur astronomers to support Venus Express scientific objectives will be investigated. A Venus-watch programme may be envisaged.

6. Programmatic validity

Venus Express and the ESA Science Programme. Mars Express has been the cheapest and maybe the fastest mission to Mars ever programmed. We show in this proposal that this success and experience can be directly applied to a Venus mission. Through innovative programming and an original scientific approach, ESA could add a host of totally new exciting discoveries about the planet Venus to its achievements, for a low cost. Explanations of ESA's Horizon 2000 and 2000+ programmes emphasize the need to achieve large scale savings through new creative methods. Venus Express would provide a perfect demonstration of this principle; rare will be the opportunities to gain so much scientifically about two completely different subjects for so little outlay.

The main motivation of planetary studies of terrestrial planets is to compare the physical conditions on the planets, to understand the forces that drive the differences, and to make conclusions concerning our own planet Earth. Adding the Venus mission to already approved ESA missions to Mars and Mercury would comprehensively complete the European study of terrestrial planets. This would result in a global and coherent programme of planetary research and provide Europe a leading role in this field.

We clearly realize that the physics of Venus is very complex and its study would require a long-term and coordinated effort. We consider the proposed orbiter as a pathfinder that will provide many important insights into Venus' surface, atmosphere and plasma environment that will help to formulate the objectives of the future missions including descent probes, balloons, and sample returns.

The science team has had interest expressed by about 50 potential collaborators from 10 different countries. The list of potential instruments includes 18 instruments designed and manufactured in 10 European countries, USA, Japan and Russia. The readiness and availability of the instruments is such that the payload will have no negative financial or programmatic impact on other ESA science programme missions.

Venus Express and other Venus missions. Venus Express will be natural continuation of the first phase of Venus exploration by the Soviet and American spacecraft. A decade, that passed since the first phase was completed, was extensively used by the planetary scientists to analyze the data from the previous missions and to formulate the tasks for the next step.

Comparison of the proposed Venus Express mission with Venus Orbiter mission, which was recently approved by Japanese Space Agency and that will arrive at Venus in 2009, allows several conclusions. Firstly, Venus Express has much broader scientific capabilities expanding beyond pure atmospheric dynamics, covering also compositional, plasma, and surface studies. Secondly, both missions are quite complementary with respect to investigation of atmospheric dynamics. This is provided by selection of orbits: equatorial for the Japanese orbiter and polar for Venus Express. Simultaneous and coordinated observations by two spacecraft at Venus, that is not excluded, would give unprecedented opportunity in Venus investigations. The overlap in scientific goals of both missions can be transferred into broad scientific and hardware co-operation.

7. Science communication and outreach

7.1 Goals

Each planetary mission should have a component that is interesting and important for the public. A mission to Venus would offer a unique opportunity to excite and enthuse the public. The Science team under the coordination of ESA would aim to:

- Increase public knowledge of Venus
- Increase public enthusiasm for planetary exploration and science
- Increase public knowledge of ESA and its scientific programmes

It is the responsibility of all scientists to engage in activities which will encourage and help create the scientific workforce of the future. An occasion such as a mission to Venus will provide a new set of resources which can be used to expand the conventional scientist's role of supporting graduate and postgraduate education, to one of improving teaching and learning of science, in particular planetary science, at all levels.

7.2 Scientific Themes

Venus is the brightest object in the sky after the Sun and Moon, the closest and the most easily recognizable planet. Venus is the twin sister of Earth with similar size and mass and yet it is drastically different and demonstrates a set of exotic phenomena: carbon dioxide atmosphere, sulfuric acid clouds, extremely high surface temperatures, hurricane winds circling the planet, giant vortexes, direct interaction of the solar wind with the atmosphere in a way typical for comets. It is therefore a natural laboratory to study atmospheric dynamics, chemistry, radiative balance, and plasma effects. Perhaps the most puzzling aspect of Venus' history is the evolution of its atmosphere, which one might have expected to be similar to the Earth's. Yet at some point the evolution on each planet took drastically different paths. Venus has the powerful greenhouse effect that is absolute record in the Solar system: the increase of surface temperature by about 500 degrees C is due to the presence of certain gases and clouds in its atmosphere. Is this the future of our planet if the atmospheric pollution continues growing on the Earth? How stable is our own climate system? How did the Earth manage to squeeze between Scilla and Haribda of cold Mars and hot Venus? Many of the questions that we would like to solve for Venus apply to Earth as well. We believe that these and other topics give the Venus studies great communication potential.

7.3 Implementation

The Venus Express mission will attract much public interest. Hence, the importance of careful advance planning of Communications and Public Outreach activities. Each Principal Investigator will provide material for public outreach and other public communications in various ways. Dedicated media and communications experts will coordinate such activities.

During the Development Phase of the mission, ESA is expected to set up a Web home page on the Venus Express mission as an information tool for the scientific community and the general public. After launch, a more elaborated home page will include the latest news on the mission as well as preliminary scientific results obtained by the orbiter instruments as soon as they become available.

The details of an outreach programme would be developed by ESA in consultation with the PIs, but some ideas might include:

A. Travelling Venus Express exhibition – a collection of images, videotapes, posters, maps, mission planning charts, slide sets, factsheets and digital imagery from the mission which can be loaned to libraries, museums and public groups.

B. Teacher Resources –providing access to materials such as images, videos etc. as well as assistance in understanding of the scientific background.

C. Image Library – a selection of the most striking images produced by the mission, along with explanatory captions for press and writers to use.

D. Website – a dedicated mission website regularly updated for the public to follow mission progress/discoveries, with animations and interactive activities along the lines of that provided, for example, by NASA's Pathfinder and NEAR missions.

E. Diverse media such as posters, brochures and ESA Special Publications.

F. In the case of selection the Venus Express Team would propose ESA to run an open competition over Europe for the best name of the mission. People can submit a short essay describing their proposal. The winning essay can be printed on a chip which will be fixed to the spacecraft. This would help to attract the attention to the Venus mission and ESA planetary programme.

ESA will have overall responsibility for planning and carrying out Communications and Public Outreach activities related to Venus Express. The active cooperation of all scientists involved in the Venus Express mission is essential for the success of the Communications and Public Outreach activities. For this purpose, the Project Scientist will initiate and identify opportunities for publishing project-related progress reports and scientific results. Materials suitable for release to the public will be provided by the Science Working Team at any time during the development, operational and post-operational phases of the mission. The PIs have the obligation to supply ESA with such materials. The exact nature of these materials is to be defined at the appropriate time.

8. International cooperation

The idea to use the Mars Express bus for an orbiter mission to Venus has found a vivid resonance among the planetary community in Europe, USA, Japan, and Russia. The broad cooperation already formed in the Mars Express, Rosetta, and Cassini missions will be extended to Venus. In the present moment the potential payload include 18 instruments designed and manufactured in about 10 European countries, USA, Japan, and Russia (Table 8.1).

In addition to the provision of Venus Express orbiter instrumentation by ESA member states and international partners, the scope and scientific return of the mission will largely benefit from an augmented international collaboration. In particular, the three main international collaborations for the Venus Express mission would be.

Japan. In a similar manner to the close collaboration between Mars Express and ISAS' Nozomi mission, both in terms of scientific complementarity and simultaneous observations of the planet Mars, Venus Express could be linked to the recently approved ISAS' Venus mission to be launched in 2007. Venus Express will be located in a polar orbit with emphasis on the study of the atmospheric composition, structure, and dynamics, surface and ionized environment, while the Japanese mission will be placed in an equatorial orbit and focus on atmospheric dynamics. Simultaneous observations could even become possible during an extended mission lifetime of Venus Express. The hardware cooperation in the VMC camera experiment is foreseen. Following in the footsteps of Mars Express, the collaboration at Venus will pave the way for a more ambitious undertaking at Mercury with BepiColombo.
United States. All the instruments on Venus Express inherited from Mars Express include American Co-Is providing hardware and/or scientific analysis, and in particular the MARSIS radar is a major joint collaboration between NASA/JPL and the University of Rome. In addition, as for Mars Express, the availability of NASA's DSN could enhance the scientific data downlink capabilities as well as support the spacecraft during critical mission operations;
Russia. As most of the Mars Express instruments were originally developed for the Mars-96 mission, and subsequently adapted or improved for Mars Express, all the PI teams proposing a Mars Express flight spare instrument include Russian investigators. Thus, Russian scientists will continue to play an important role in the development of Venus Express instruments, that could even be enlarged if conditions inside Russia allow. Also, Venus is a planet of great interest in Russia as the Venera missions played a pioneering role in our current understanding of Venus.

Table 8.1 Geography of Venus Express cooperation

	A	**B**	**Ch**	**Fi**	**Fr**	**D**	**DK**	**J**	**Ir**	**I**	**P**	**Pl**	**Rus**	**S**	**Sw**	**UK**	**USA**
SPICAM		•			•								•				
PFS					o	•				•		•	•	o			o
VIRTIS					•	•				•	o	o	o				o
VeRa						•											
VMC						•		o					o				o
ASPERA	•		•	•	•	•			•	•					•	•	•
VENSIS			o			o	•			•						o	•

• - Both hardware and scientific participation
o - Only scientific participation

9. References

Allen, D, and J. Crawford . Discovery of cloud structure on the dark side of Venus. Nature, 307, 222, 1984

Artru J., P. Lognonné, and E. Blanc, Normal modes modeling of post-seismic ionospheric oscillations, Geophys. Res. Letters, 28, 697, 2001

Baines et al (2001) (2000). Detection of Sub-micron radiation from the surface of Venus by Cassini/VIMS. *Icarus*, **148,** 307-311.

Bougher, S. W., and Borucki, W. J. Venus O_2 visible and IR nightglow: implications for lower thermosphere dynamics and chemistry. J. Geophys. Res. 99, 3759, 1994

Bougher, S. W., Alexander, M. J. , and H. G. Mayr. Upper atmosphere dynamics: global circulation and gravity waves . In "Venus II", Univ. of Arizona Press, p. 259, 1997

Carlson R.W. et al. Galileo infrared imaging spectroscopy measurements at Venus. Science, 253, p. 1541, 1991.

Collard et al (1993). Latitudinal distribution of carbon monoxide in the deep atmosphere of Venus, *Planet. Space Sci.* **41**, 487.

Crisp, D. and D.V. Titov, The thermal balance of the Venus atmosphere, In "Venus II", Univ. of Arizona Press, p. 353, 1997.

Donahue, T. M., Grinspoon, D. H., Hartle, R. E., and Hodges R. R. Jr. Ion neutral escape of hydrogen and deuterium: evolution of water, In "Venus II", Univ. of Arizona Press, p. 385, 1997.

Drossart et al (1993). Search for spatial variations of the H2O abundance in the lower atmosphere of Venus from NIMS Galileo. *Planet. Space Sci.* **41**, 495.

Esposito, L.W., J.L. Bertaux, V. Krasnopolsky, V.I. Moroz, and L.V. Zasova . Chemistry of lower atmosphere and clouds. In: Venus II, Eds. S.W. Bougher, D.M. Hunten and R.J. Phillips, Univ. of Arizona Press p.415, 1997.

Fegley, B., Jr., Klingelhoeffer, G., Lodders, K. and T. Widemann. Geochemistry of surface-atmosphere interactions on Venus. In "Venus II", Univ. of Arizona Press, p. 591, 1997.

Fox, J. L., and S. W. Bougher, Structure, luminosity, and dynamics of the Venus thermosphere, Space Sci. Rev., 55, 357, 1991.

Grebowsky, J.M., Strangeway, R. J. and D. M. Hunten. Evidence for Venus lightning. in "Venus II", Univ. of Arizona Press, p. 125, 1997.

Gurwell M.A. Evolution of deuterium on Venus, Nature, 378, 22, 1995.

Kasprzak, W. T., G. M. Keating, N. C. Hsu, A. I. F. Stewart, W. B. Coldwell, and S. W. Bougher, Solar Cycle Behavior of the Thermosphere, in "Venus II, Univ. of Arizona Press, 225, 1997.

Lellouch, E., T. Clancy, D. Crisp, A.J. Kliore, D. Titov, and S.W. Bougher,. Monitoring of mesospheric structure and dynamics. In: Venus II, Eds. S.W. Bougher, D.M. Hunten and R.J. Phillips, Univ. of Arizona Press. p.295, 1997.

Luhmann, J. G., and J. U. Kozyra, Dayside pickup oxygen ion precipitation at Venus and Mars: Spacial distributions, energy deposas well as the absent of mass s Moreover, studies of the and consequences, J. Geophys. Res. 96, 5457, 1991.

Meadows, V. S. and D. Crisp. Ground-based near-infrared observations of the Venus nightside: the thermal structure and water abundance near the surface. J. Geophys. Res. 101, 4595, 1996.

Pettengill, G.H., Ford, P.G., and R.A. Simpson, Electrical properties of the Venus surface from bistatic radar observations. Science, Vol.272, 1628-1631, 1996

Roldan et al (2000) Non-LTE Infrared Emissions of CO2 in the Atmosphere of Venus. *Icarus*, **147**, 11.

Roos et al (1993). The upper clouds of Venus: determination of the scale height from NIMS-Galileo infrared data, *Planet. Space Sci.* **41**, 505.

Russell, C.T. and O.L.Vaisberg, The interaction of the solar wind with Venus, in *Venus.* Univ. of Arizona Press, p. 873, 1983.

Solomon, S.C. et al. Venus tectonics: an overview of Magellan observations. J. Geophys. Res. 97, 13256
Schaber, G.G. et al. Geology and distribution of impact craters on Venus: what are they telling us? J.Geophys.Res, 97, 13257, 1992
Strom , R. G., Schaber G.G. and D.D. Dawson. The global resurfacing of Venus. J. Geophys. Res. 99, 10899, 1994
Taylor, F. W., Crisp, D., and B. Bézard. Near-infrared sounding of the lower atmosphere of Venus. In "Venus II", Univ. of Arizona Press, 325, 1997.
Williams, D. J., E. C. Roelof, and D. G. Mitchell, Global magnetospheric imaging, Rev. Geophys., *30*, 183, 1992

10 Acknowledgments

The Venus Express Proposal and the Mission Definition Study are the result of joint efforts of a great number of specialists from the scientific community, industry, and ESA. The contribution of the following colleagues is highly appreciated:

H.Alleyne, University of Sheffield, UK
G. Arnold, PE-PP, DLR, Berlin, Germany
J. Artru, Institut de Physique du Globe, Paris, France
S. Atreya, University of Michigan, USA
K. Baines, JPL/NASA, USA
M. Balikhin, University Sheffield, UK
J. Banting, Astrium, UK
A. Basilevsky, Vernadsky Institute, Russia
W. Baumjohann, IWF, Austria
G. Bellucci, IFSI-CNR, Rome, Italy
C. de Bergh, DESPA, France
L. Berthoud, Astrium, UK.
B. Bezard, DESPA, France
D. Biccari, Infocom Univ. Rome, Italy
S. Bougher, University of Arizona, USA
M. Bullock, Southwest Research Institute, USA
E. Chassefiere, LMD/CNES, France
A. Coradini, IAS, Rome, Italy
D. Crisp, JPL/NASA, USA
L. Esposito, LASP, Boulder, USA
P. Gough, University of Sussex, UK
B. Grieger, MPAe, Katlenburg-Lindau, Germany
D. Grinspoon, Southwest research Institute, USA
D. Gurnett, University of Iowa, USA
P. Hartogh, MPAe, Katlenburg-Lindau, Germany
N. Ignatiev, Space Research Institute (IKI), Russia
N. Johnson, Washington University, St.Louis
G. Keating,, Washington University/NASA / Physics of the upper atmosphere/
H.U. Keller, MPAe, Katlenburg-Lindau, Germany
I. Khatuntsev, Space Research Institute (IKI), Russia
M. Kreslavsky, Vernadsky Institute
S. Limaye, University of Wisconsin, USA

P. Lognonné, Institut de Physique du Globe, Paris, France
J.J. Lopez-Moreno, Instituto de Astrofisica de Andalucia, Spain
R. Lundin, IRF-Kiruna, Sweden
V.I. Moroz, Space Research Institute (IKI), Russia
A. Nagy, University of Michigan, Ann Arbor, USA
E. Nielsen, MPAe, Germany
K. Oyama, ISAS, Japan
M. Parrot, LPCE, Orleans, France
A.Rodin, Space Research Institute (IKI), Russia
R. Rodrigo, Instituto de Astrofisica de Andalucia, Spain
C.T. Russell, University of California, Berkeley, USA
S. Savin, Space Research Institute (IKI), Russia
M. Smith, Astrium, UK
O. Talagrand, LMD/CNES, France
N. Thomas, MPAe, Katlenburg-Lindau, Germany
P. Travnicek, IA, Prague, Czech Republic
R. Treumann, MPE Garching, Germany
E. Ustinov, JPL/NASA, California, USA
O. Vaisberg, Space Research Institute (IKI), Russia
J.E. Wahlund, IRF, Uppsala, Sweden
H. Waite, University of Michigan, Ann Arbor, USA
I. Yoshikawa, ISAS, Tokyo, Japan
L.V. Zasova, Space Research Institute (IKI), Russia
T. Zhang, IWF, Graz, Austria