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To the depths of Venus: Exploring the deep atmosphere and surface of our sister world with Venus Express

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Abstract

With its comprehensive suite of near-infrared instruments, Venus Express will perform the first detailed global exploration of the depths of the thick Venusian atmosphere. Through the near-daily acquisition of Visible and Infrared maps and spectra, three infrared-sensing instruments—the Planetary Fourier Spectrometer (PFS), the Venus Monitoring Camera (VMC), and the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS)—will comprehensively investigate the Thermal structure, meteorology, dynamics, chemistry, and stability of the deep Venus atmosphere. For the surface, these instruments will provide clues to the emissivity of surface materials and provide direct evidence of active volcanism. In so doing, ESA's Venus Express Mission directly addresses numerous high-priority Venus science objectives advanced by America's National Research Council (2003) decadal survey of planetary science.

Keywords: Venus; Venus Express; Near-Infrared Spectroscopy; Dynamics; Chemistry

1. Introduction

Residing at times just 41.5 million km away from Earth, Venus is our closest planetary neighbor; yet, it is one of the most enigmatic objects in the Solar System. At the dawn of the space age, Venus was thought to be Earth's twin because of its similar size, mass, and solar distance. In the 1960s and 1970s, some of the first interplanetary explorers—including Mariner 2, the first spacecraft to another planet—showed that even though Venus and Earth apparently formed nearby in the solar nebula, sharing common inventories of refractory and volatile constituents, they followed dramatically different evolutionary paths. While the Earth evolved into the only known oasis for life, Venus developed an almost unimaginably hostile environment, characterized by a massive (95 bar) CO_2 atmosphere, a hellish (737 K, 867 °F) surface temperature, a ubiquitous cloud deck of sulfuric acid (H_2SO_4) particles, and an exceedingly energetic global circulation of hurricane force winds. While a few of these differences can be attributed to Venus' closer proximity to the Sun, others—such as the globally super-rotating circulation pattern and bone-dry atmosphere—are so mysterious that they cast serious doubts on our understanding of the formation, evolution, and workings of terrestrial planets.

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Venus Express provides a renewed focus on our Sister Planet, advancing a number of high-priority science goals identified and promoted by a variety of space exploration advocates in recent years (e.g., Crisp et al., 2002), including several proposed Discovery and New Frontiers missions (e.g., the Discovery VESAT Mission, Baines et al., 1995). In particular, Venus Express effectively addresses a number of salient scientific issues embodied by the cross-cutting themes identified in the National Research Council Decadal Survey of Planetary Science (NRCDS, 2003). The NRCDS was developed by the American Space Science Community as a means to assess and determine the priority of goals and approaches for the American Planetary Program for the ensuing decade. As shown in Table 1, by examining the deep atmosphere and surface of Venus, the Venus Express mission directly addresses all of the specific themes and many of the questions posed by the Inner Planets Sub-panel of the NRCDS. Some of the most salient issues of the NRCDS and addressed by Venus Express are:

(1) *Volatiles and organics*: What is the history of volatile compounds, especially water across the Solar System?
   - Did Venus acquire and then lose an ocean of water?
(2) *Origin and evolution of habitable worlds*: Why have the terrestrial planets differed so dramatically in their evolution?
   - When and how did Venus lose its water?
(3) *Processes*: How do processes that shape the character of contemporary bodies operate and interact?
   - What processes maintain the massive atmospheric greenhouse effect and high surface temperatures?
   - Why does the cloud-level atmosphere rotate almost 60 times as fast as the solid surface?
   - What dynamical and chemical processes maintain the global cloud deck?
   - How does Venus release heat from its interior? Is it volcanically active today?

An overarching scientific goal for exploring Venus's deep atmosphere is to understand processes responsible for the current climate on Venus and its evolution over time. Venus Express addresses this concern explicitly. In particular, Venus Express will provide valuable information on the complex coupling between atmospheric dynamics, photo- and thermo-chemistry, and Thermal and surface structure that drive:

- *the global atmospheric circulation*, including mechanisms responsible for polar vortices, Hadley cells, and global atmospheric super-rotation, and their implications for volatile transport, cloud formation, and dissipation,
- the *static stability* of the near-surface atmosphere, and its implications for the efficiency of the greenhouse mechanism, and surface–atmosphere interactions,
- the *sulfur cycle* and associated surface/atmospheric chemical interactions such as *volcanism and surface weathering*, and *dynamical transport of trace gases* throughout the atmosphere.

2. Specific scientific objectives for the deep-atmosphere and surface, and fundamental approach

Venus is a dramatically active planet. Due to the large range of pressures and temperatures encountered in its thick atmosphere, a rich variety of processes continually affects atmospheric chemistry and dynamics. For example, sulfur-bearing gases generated at the surface by volcanic emissions and chemical weathering of surface rocks under high atmospheric pressures and temperatures (95 bar and 737 K) are altered in the lower atmosphere by thermochemistry and in the middle and upper atmosphere by photochemistry to produce vertical, temporal, and spatial abundance variations. Throughout the atmosphere, winds and weather systems transport these gases and cloud formations, revealing a global circulatory system very poorly understood for a terrestrial planet.

Two dynamical phenomena are particularly enigmatic: (1) the rapid, nearly global, zonal super-rotation of the atmosphere near the cloud tops and (2) the complex dipole-shaped vortex at the north pole observed briefly by the Pioneer Venus Orbiter (PVO) (e.g., Limaye and Suomi, 1981; Taylor et al., 1979a). These phenomena and many others are not understood, primarily because of the paucity of observations afforded by previous missions.

To effectively address such issues, Venus Express will view the planet globally and three dimensionally, imaging and mapping—for the first time—the bulk (99.8%) of the atmospheric mass residing below the 70-km level. The key breakthrough capitalized by Venus Express is the ability to observe the lower atmosphere and surface using near-IR spectroscopy and spectral mapping, utilizing spectral windows of transparency largely unaffected by near-ubiquitous CO_2 absorption. Observing the nightside of Venus in these windows enables Venus Express to take effective advantage of the planet's intense surface and lower-atmosphere Thermal emission as sources of indigenous light to measure overlying extinction by the trace gases and clouds found in Venus' deep atmosphere. Initially discovered by Allen and Crawford (1984) and successfully exploited by ground-based observers (e.g., Crisp et al., 1989, 1991a, b; Lecacheux et al., 1993, Pollack et al., 1993), as well as by the Galileo/NIMS and Cassini/VIMS Venus flybys (e.g., Carlson et al., 1991, 1993b; Baines et al., 2000), Venus Express will explore in particular the chemistry and dynamics of the deep atmosphere down to the surface, thus revealing how the exotic environment of Venus works at depth.

Fig. 1 illustrates the kinds of imagery that Venus Express will return on almost a daily basis for large portions of the globe. Cloud-tracked winds will be measured on both the day and nightsides, with imagery supplied by VMC for

Table 1
Venus Express science summary: From decadal study objectives to data products

Decadal study cross-cutting themes	Inner planets panel themes	Inner planets panel, decadal study relevant questions	Relevant priority science investigations	Venus Express PFS, VIRTIS, and VMC Observations		
				Measurements	Instruments	Data products
1. *Origin and evolution of habitable worlds*	*Past*					
Why have the terrestrial planets differed so dramatically in their evolution?	What led to the unique character of our home planet?	a. What are the bulk compositions of the inner planets and variation with solar distance?	1. Determine elemental and mineralogical surface compositions	1-μm surface spectroscopy	PFS, VIRTIS	Surface compositional constraints
		b. What is the internal structure and how did the core, crust, and mantle of each planet evolve?	2. Determine the compositional variations and evolution of crusts and mantles	1-μm surface spectroscopy	PFS, VIRTIS	Surface compositional constraints
2. *Volatiles and organics* What is the history of volatile compounds, especially water, across the solar system?		c. What is the history of water and other volatiles and how did the atmospheres of inner planets evolve?	3. Determine the composition of magmatic volatiles	1-μm surface spectroscopy, lower-atmosphere NIR spectroscopy	PFS, VIRTIS	Surface compositional constraints, lower atmosphere abundances (e.g., SO_2, OCS, HDO)
3. Processes	*Present*					
How do processes that shape the character of contemporary bodies operate and interact?	What common dynamic processes shape Earth-like planet?	a. What processes stabilize climate?	1. Determine the general circulation and dynamics of the inner planets' atmospheres	NIR, UV global/regional movies, IR global/regional daily mapping, thermal profiles	VIRTIS, VMC, PFS	Cloud-tracked windfields at 50, 57, 70 km alt. Daily thermal windfields
				3-D UV, near IR, and IR movies of polar vortices	PFS, VIRTIS, VMC	Polar dipole winds/evolution
				CO tracer monitoring	PFS, VIRTIS	CO tracked winds
				O_2 airglow mapping	PFS, VIRTIS, VMC	O_2 dynamical constraint maps
			2. Determine the composition of the atmosphere, especially trace gases and isotopes	Regional/global near-IR spectral mapping	PFS, VIRTIS	Lower atmosphere abundance maps of H_2O, HCl, CO, SO_2, SO, OCS, HDO
				UV mapping	VMC	Upper atmosphere SO_2 maps
			3. Determine how sunlight, thermal radiation and clouds drive greenhouse effects	NIR spectroscopy/maps of clouds and gases	PFS, VIRTIS	Maps of cloud microphysical properties, mass column abundances

Table 1 (*continued*)

Decadal study cross-cutting themes	Inner planets panel themes	Inner planets panel, decadal study relevant questions	Relevant priority science investigations	Venus Express PFS, VIRTIS, and VMC Observations		
				Measurements	Instruments	Data products
			4. Determine processes and rates of surface/atmosphere interaction	Lower-atmosphere and surface NIR spectroscopy of H_2O, thermal profiles, surface albedo/flux variabilities	PFS VIRTIS	H_2O variability, thermal variabilities, surface variabilities during mission
		b. How do active internal processes shape the atmosphere and surface environments?	1. Characterize current volcanic and/or tectonic activity and outgassing	Near-IR imaging/mapping/movies of surface thermal flux, lower atmosphere trace gases and particulates	PFS VIRTIS	Imaging/mapping/movies of volcanic temperatures, emissions, and plumes
		c .How do active external processes shape environments?	2. Quantify processes in the uppermost atmospheres of terrestrial planets	Near-IR spectral maps, IR global/regional daily mapping	PFS VIRTIS	Atmospheric H_2O loss, O_2 airglow constraints, Daily thermal winds
	Future What fate awaits Earth's environment and those of the other terrestrial planets?	a. What do the diverse climates of the inner planets reveal about the vulnerability of Earth's environment?	1. Characterize the greenhouse effect through meteorological observations	UV–NIR spectroscopy/maps of clouds and gases	PFS, VIRTIS, VMC	3-D thermal and cloud structure, windfields, through time, thermal profiles from upper levels through sub-cloud atmosphere
		b. How do varied geologic histories enable predictions of volcanic and tectonic activity?	1. Assess the distribution and age of volcanism on the terrestrial planets	1–2.5 μm surface spectroscopy, imaging/mapping/movies of volcanic emissions/fluxes	PFS, VIRTIS	Spatial distribution of active volcanism
			2. Search for evidence of volcanic gases in inner planet atmospheres	1–2.5 μm surface spectroscopy, imaging/mapping/movies	PFS, VIRTIS	Surface imaging/mapping/movies of volcanic temperatures, plume aerosols, and gas emissions

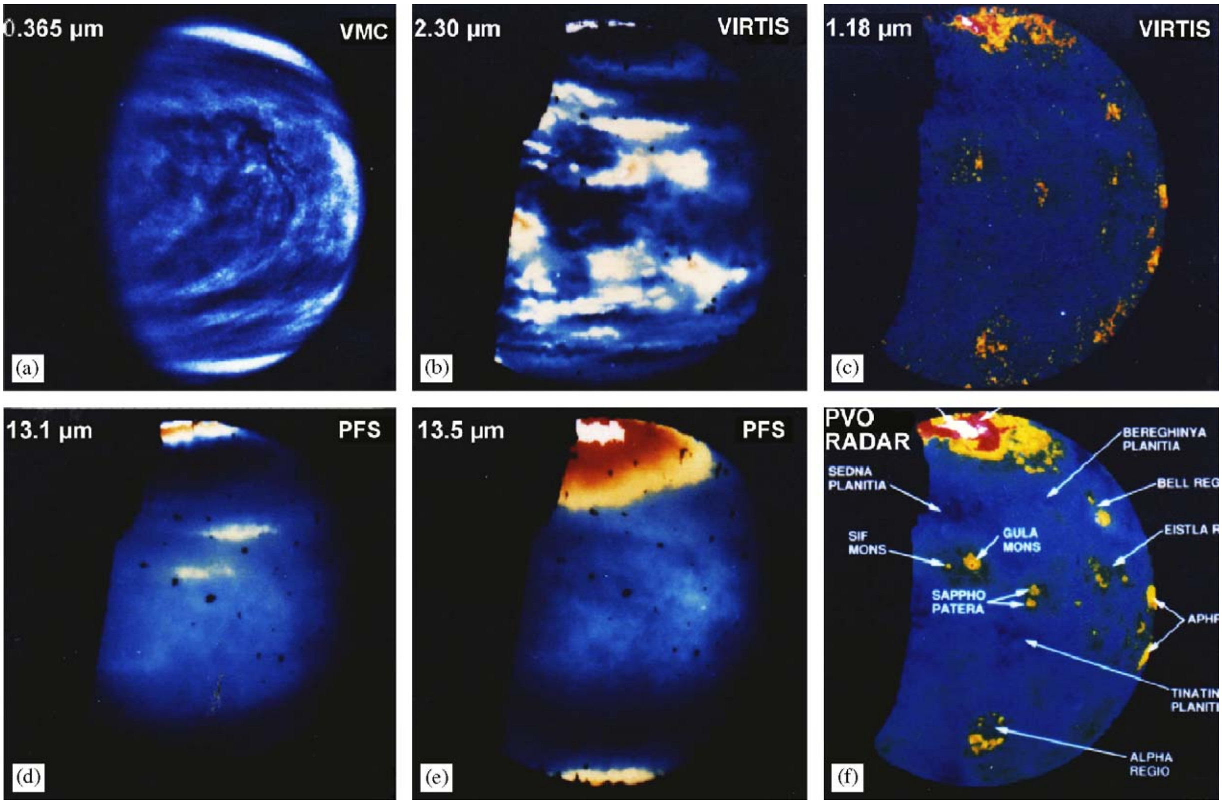

Fig. 1. Representative Venus Express images and maps simulated by Galileo/NIMS and Galileo/SSI Data. (a) VMC 0.365-μm 70-km hazetop image (represented by a 0.42-μm SSI image); (b) VIRTIS 2.30-μm 50-km cloudtop map, and (c) VIRTIS 1.18-μm surface temperature map (both represented by NIMS maps); and (d–e) PFS 13.1- and 13.5-μm thermal emission maps near the 70- and 75-km levels, also corresponding to VIRTIS and PFS 4.56- and 4.84-μm thermal emission maps (here represented by the 4.56- and 4.84-μm NIMS maps). The ability of VIRTIS and PFS to observe surface thermal emissions is demonstrated by the NIMS thermal topographic map (c) which shows remarkable correlation with a Pioneer-based radar altimetry map (f). Venus Express exploits these proven Galileo/NIMS observational techniques with improved spectral, spatial, and temporal sampling and coverage to provide a fully comprehensive set of dynamical measurements.

the dayside, and nightside motions of thermally backlit clouds supplied by Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) images and Planetary Fourier Spectrometer (PFS) scans. Together, the day and night motions of cloud features will provide a comprehensive description of the cloud-layer dynamics, yielding clues to mechanisms responsible for Venus' strong cloud-level super-rotation. PFS mid-infrared spectrometry will yield spatially resolved vertical temperature profiles at levels above the clouds, which will provide unique insights into processes involved in the atmospheric stability and dynamics at those levels. Finally, the present-day influx of gases from the deep interior and surface/atmosphere interaction processes will be evaluated through a comprehensive search for and analyses of volcanic activity, and via novel surface observations obtainable with near-IR surface imagery.

Fig. 2 succinctly summarizes the breadth of science objectives and measurement approaches largely enabled by this technique, utilizing the spectral and imaging power of three infrared instruments, PFS, VIRTIS and VMC (c.f. Table 2), Together these instruments will provide the first global, time-dependent comprehensive description of the thermal structure, composition, and dynamics of Venus. A summary of the array of quantitative physical measurements and the uncertainties expected to be achieved by these instruments is given in Table 3. The measurement techniques themselves are detailed in Section 3. We now discuss specific science objectives and enabling approaches provided by these three instruments on Venus Express.

2.1. D/H isotopic ratio and atmospheric loss

An understanding of the process of loss of oxygen, hydrogen, and other species from Venus is important for understanding the evolution of the atmosphere and climate. Due largely to the runaway greenhouse effect, the atmosphere of Venus today is vastly different from that at Venus' formation. The large ratio of HDO relative to H_2O—some 150 times to that found on Earth (deBergh et al., 1991; Donahue and Hodges, 1993)—attests to the loss of most of its water during its evolution. A key question is the amount of water in the past, estimated to be between 5 and 500 m. The large uncertainty arises from a lack of precise measurements of the D/H ratio, as well as uncertainties in the current loss rate of H and O. The D/H ratio ranges from 0.013–0.025 based on the PVO mass

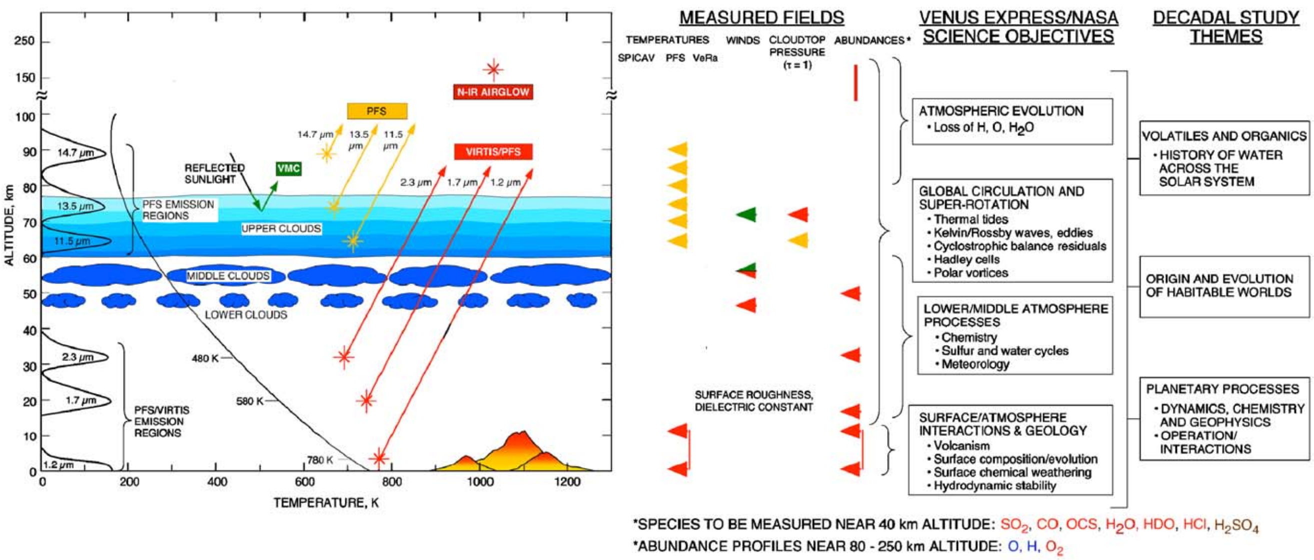

Fig. 2. From photons to processes: Venus Express's visual–infrared instruments (color-coded boxes and arrows) use Venus's strong indigenous thermal- and solar-reflected radiation to sample aerosols, gas abundances, and temperatures at many levels within the planet's extensive atmosphere, including at and near the surface (c.f. example weighting functions at the left-most part of the figure). Infrared instruments (e.g., PFS and VIRTIS) sample photons originating throughout the atmosphere, measuring the overlying extinction indicative of upper-level hazes clouds and middle and lower-level clouds and/or gas abundances (c.f., arrows). These instruments also measure the thermal properties of the upper, middle, and lower atmosphere and thermal properties of the surface. Through such measurements, Venus Express addresses a variety of fundamental science goals of NASA and the Decadal Study of the National Research Council (2003), as shown on the right.

Table 2
Characteristics of Venus Express visual–infrared sounding instruments

Instrument	Wavelength		Spatial FOV (mrad)		Spatial resolution (km)	
	Coverage (μm)	Res (cm^{-1})	IFOV	FOV	At 250 km	At 35K km
PFS-SWC	0.9–5.0	1.4	27.2	27.2	6.8	952
−LWC	5.0–45.0	1.4	48	48	12	1680
VIRTIS-M	0.25–5.0	100–300	1	64	0.25	35
−H	2.0–5.0	2–2.28	1.749	1.749	0.44	61
VMC	0.36, 0.513 0.935, 1.01	~400	0.74	304	0.18	25.8

spectrometer and IR spectroscopy data, considering the full range of uncertainty in the measurements.

On Venus Express, PFS and VIRTIS will each make measurements of HDO and H_2O, utilizing nadir views as well as limb scans and occultations. The two great advantages of (1) observing close-up from space, without having to contend with debilitating effects of telluric absorptions and photon scattering from the bright dayside hemisphere, and (2) extremely high signal-to-noise resulting from several years of near-daily measurements, together will enable dramatic improvement in the measurements of the abundances of both H_2O and HDO. It is expected that the D/H ratio uncertainty will drop from its present factor-of-two uncertainty to about 25%, with the main errors resulting from uncertainties in the behavior of absorption strengths of CO_2 and other gases in the spectral background. This in turn will improve the estimate of water lost from the planet by about a factor of eight, thus providing significant new constraints on the origin and evolution of atmospheric water and the overall climate of Venus.

2.2. Compositional stability of the atmosphere

An important mystery of the atmospheres of Venus and Mars is that their CO_2 atmospheres are stable (except for the known seasonal changes on Mars). This seems puzzling, since CO_2 can be destroyed by photolysis ($\lambda \leqslant 0.2\,\mu m$) on a relatively short timescale on both planets (a few tens of million years for Venus, based on similar calculations for Mars where the entire 6-mb pressure of CO_2 is photochemically destroyed in approximately 6000 years; Atreya and Gu, 1994). Whereas on Mars the hydroxyl radicals (OH) are believed to play a critical catalytic role in maintaining the stability of CO_2 (by recycling CO and O or CO and O_2—formed upon O + O

Table 3
To the Depths of Venus: Measurement Objectives and Uncertainties

Spatial coverage: global (cloud tracking focuses on the southern hemisphere)
Temporal coverage: ~daily for 15 months

Measurement objective		Instruments	Best diagnostic wavelengths (μm)	Spatial sampling at 20K km distance/ typical best temporal sampling (hours)	Measurement precision/accuracy	
Cloud distribution/winds at					m/s*	m/s
50-km alt. (night)		VIRTIS	1.73, 2.30	20.0 km/1.5	1.7	1.7
57-km alt. (day)		VIRTIS	1.72, 2.30	20.0 km/1.5	1.7	1.7
		VMC	0.95	14.8 km/1.5	1.3	1.3
70-km alt. (day)		VMC	0.365	14.8 km/1.5	1.3	1.3
Temperature mapping at					°K	°K
Surface (1–10 km)		VIRTIS	0.85 0.90,1.01,1.10,1.18	50 km/1.5	0.5	3.0
65 km		PFS, VIRTIS	13.1, 4.56	20 km/1.5	0.1	1.5
70 km		PFS, VIRTIS	13.5, 4.84	20 km/1.5	0.1	1.5
75 km		PFS	13.8	960 km/1.5	0.1	1.5
Thermal profiles					°K	°K
65–100 km, 5 km vert. res.		PFS	11–15	960 km/1.5	0.1	1.5
Surface thermal emission		VIRTIS	0.85 0.90,1.01,1.10,1.18	20.0 km/1.5	2%	20%
Airglows						
$O_2(^1\Delta)$ near100 km		VIRTIS, PFS	1.27	20.0 km/1.5	5%	10%
O_2 near 120 km		VMC	0.37, 0.51	14.8 km/1.5	10%	20%
Cloudtop altitude/pressure ($\tau = 1$)					km	km
65 km		PFS	11.5/13.1	544 km/1.5	<0.1	0.2
70 km (day)		VIRTIS, PFS	2.0	20.0 km/1.5	0.2	0.2
Molecular abundances					%	%
Species	Alt. (km)					
H_2O	0–12	VIRTIS, PFS, VMC	1.10–1.18	14.8 km/1.5	5	20
	23	PFS, VIRTIS	1.74	20.0 km/1.5	10	20
	33	PFS, VIRTIS	2.40–2.43	20.0 km/1.5	4	20
HDO	33	PFS, VIRTIS	2.38–2.46	20.0 km/1.5	20	50
	30	PFS, VIRTIS	2.30	20.0 km/1.5	3	20
CO	42	PFS, VIRTIS	2.33	5.0 km/24	3	20
OCS	30	PFS, VIRTIS	2.425	20.0 km/1.5	7	20
	37	PFS, VIRTIS	2.435	20.0 km/1.5	7	20
SO_2	39	PFS, VIRTIS	2.46	20.0 km/1.5 h	9	20
	~70	PFS,	7.4, 8.7, 19.3	960 km/1.5 h	20	30
HCl	39	PFS, VIRTIS	1.74	20.0 km/1.5 h	15	30
H_2SO_4 (liq.)	~70	PFS	8.7, 11.1, 17.2, 22.2	960 km/1.5 h	25	25

*Cloud-tracked wind precisions/accuracies determined from 9-h samples obtained at 50,000 km altitude.

recombination—into CO_2), this mechanism fails on Venus. This is due to the relatively small mixing ratio of water vapor and an efficient removal of the HO*x* along with the depletion of O_2 in the process of formation of the hygroscopic sulfuric acid (net $2SO_2 + 2H_2O + O_2 \rightarrow 2H_2SO_4$) in the Venusian atmosphere. It has been suggested that chlorine in the Venus atmosphere might play a catalytic role similar to OH in the Martian atmosphere (Yung and DeMore, 1982). If that is the case, models predict the presence of several critical chlorine compounds in the atmosphere of Venus, including ClCO, $ClCO_3$, ClOO, ClO, HCl, and Cl_2. Note that chlorine would also participate in the sulfur chemistry, producing a number of species, the most abundant of which is expected to be sulfuryl chloride (SO_2Cl_2) at the ppm level. Both PFS and VIRTIS on Venus Express will be used to (1) detect and measure the abundances of several key diagnostic species (c.f., Table 3), including SO_2, HCl, and possibly Cl_2, as well as to (2) determine associated vertical mixing information. The results will be used in physico-photo-chemical–thermochemical models (e.g., Yung and DeMore, 1982; Wong and Atreya, 2005) to understand the present state of chlorine, sulfur, and water chemistry and to develop detailed models of the evolution, climatology, and the stability of the atmosphere of Venus. As part of this analysis, information on vertical mixing will come from the distribution of key minor constituents, as is routinely done for the giant planets (see e.g., Atreya, 1986; Wilson and Atreya, 2003).

2.3. Global circulation

Multiple-wavelength images and maps acquired by Venus Express will reveal the three-dimensional (3-D) nature of the planet's circulation, providing valuable constraints on the latitudinal and vertical extent of any Hadley cells in the southern hemisphere, the spatial and vertical extent of planetary-scale waves there, and the importance of thermal tides and barotropic instabilities in maintaining Venus' super-rotation. Venus Express will regularly scrutinize the temporally varying 3-D thermal structure and the bulk motions of diagnostic features (e.g., cloud-tracked and vapor-tracer-tracked winds at several levels, waves, the polar dipole(s), and zonal jets). These observations will then be used as inputs to interpretative models and theories (e.g., cyclostrophic balance and thermal tidal models) to derive an improved understanding of the underlying processes driving the circulation.

For such dynamical studies, Venus Express will provide the following observational coverage over four Venus solar days (approximately 500 Earth days), on nearly an Earth-daily basis:

- nightside cloud motions at 50 km (lower cloud) and 57 km (middle cloud) levels from 1.73- and 2.3-μm maps (c.f., Fig. 1(b) for an example 2.3-μm backlit cloud image);
- dayside cloud motions at 70 km (0.365 μm) and 57 km (0.95 μm) levels from VMC and VIRTIS images/maps (c.f., Fig. 1(a) for representative 70-km level cloud image);

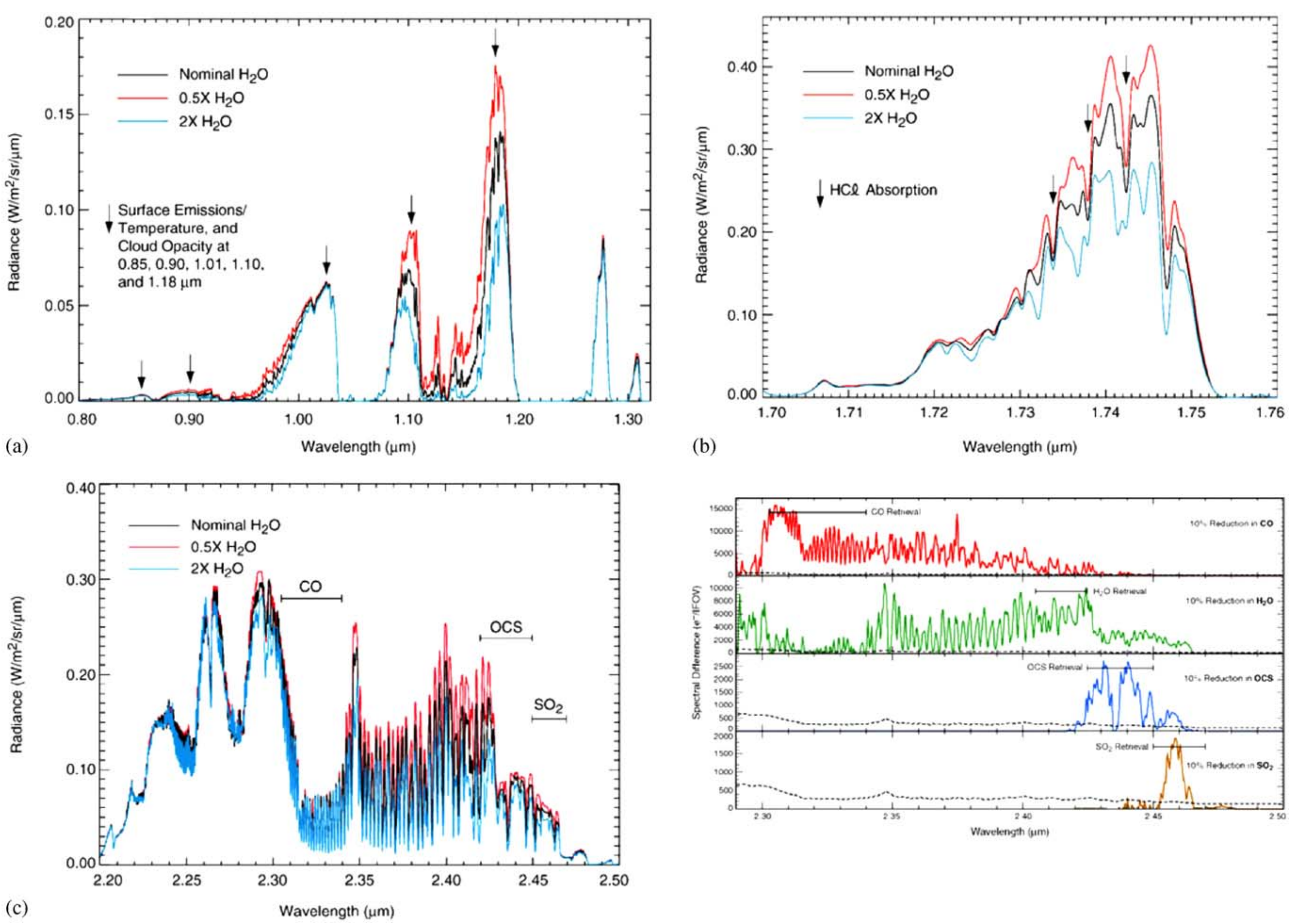

Fig. 3. Simulated PFS Spectra and Sensitivities. PFS's high-spectral resolution reveals numerous trace species in the lower atmosphere. Each major spectral window is shown in panels a–c for a nominal H_2O abundance profile (Meadows and Crisp, 1996; black curves) and for alternative H_2O abundance profiles (blue and red curves). The 1-μm region is particularly sensitive to H_2O and HDO in the deep, near-surface atmosphere, and to surface temperature and emissivity. The 1.73-μm region senses H_2O and HCl in the lower atmosphere near 35 km altitude. The 2.4-μm region senses CO, OCS, and SO_2 near 35 km altitude and H_2O and HDO near 50 km altitude. Lower right-hand panel: PFS's 3000 resolving power at 2.4 μm enables the determination of CO, H_2O, OCS, and SO_2 abundances in the lower atmosphere. Each has strong, distinguishable diagnostic features which are relatively well-isolated from features of other species (bracketed spectral regions). For a 10% change in abundance, variations in spectral features (colored curves) are an order of magnitude more than the instrumental noise (dashed curves). Abundances are retrieved sequentially, progressing from short wavelengths sensitive only to CO through longer wavelengths which are progressively more sensitive to H_2O, OCS, and SO_2, with the analysis focusing on the relatively spectrally-clean bracketed regions.

- nighttime abundance maps of tracers (e.g., SO_2, H_2SO_4, CO, OCS, and H_2O) in the middle-deep atmosphere from PFS, VIRTIS, and VMC (c.f., Fig. 3);
- temperature maps at a variety of levels between 55 and 100 km, altitude, temperature anomalies (e.g., polar dipoles), and thermal winds from VIRTIS and PFS thermal maps (c.f., Fig. 1(d) and (e) for typical 70- and 75-km level thermal maps);
- surface (up to 12 km elevation) global temperature maps from VIRTIS, PFS, and VMC (c.f., Fig. 1(c)).

Fundamental aspects of global circulation to be investigated by Venus Express are (1) global super-rotation, (2) Hadley cells, and (3) polar vortices. Inter-relationships between each of these are likely to be important determinants in the observed character of each. For example, the polar vortices are likely produced as natural endpoints for the Hadley cells, while the Hadley cells themselves are probably major transporters of zonal momentum to the poles that help maintain the super-rotation of the entire atmosphere, including the polar vortices. Venus Express tests specific hypotheses dealing with each of these phenomena, and their inter-relationships, in striving to understand the 3-D nature of Venus' global circulation, as we now discuss.

2.3.1. Global super-rotation

The cloud-level atmosphere on Venus rotates up to 60 times faster than the surface. This phenomenon is a fundamental mystery of planetary dynamics: *What provides the torque that spins the atmosphere faster than the planet itself?* The key unknown here is the process by which the equatorial atmosphere is re-supplied with angular momentum that is lost through friction and the poleward transport of heat and mass. Over the years, a number of hypotheses for powering and maintaining the super-rotation have been proposed. Today, three postulated mechanisms are generally believed to play potentially key roles:

- *Convective motions resulting from diurnal heating.* This "moving flame" model (e.g., Schubert and Whitehead, 1969) uses the phase lag of heating with depth to produce tilted convective motions that accelerate the flow. The flow can be further amplified by a feedback mechanism wherein the inward vertical shear of the zonal wind produces an upward transport of westward momentum (Thompson, 1970), enhancing the westward flow.
- *Eddy coupling between meridional and zonal flows* (Gierasch, 1975; Rossow and Williams, 1979; Del Genio et al., 1993; Del Genio and Zhou, 1996), including eddies produced by the barotropic instability of high-latitude jets associated with Hadley cells. Angular momentum transport occurs latitudinally and vertically via an array of small-scale eddies, large-scale traveling waves, and vertically propagating gravity waves and tides (Leovy, 1973; Held and Hou, 1980; Rossow, 1985; Hou and Farrell, 1987; Hou and Goody, 1985; Gierasch, 1987; Del Genio and Rossow, 1990).
- *Momentum transfer by gravity waves.* Solar thermal tides, which are gravity waves triggered by solar heating, are the main candidate for the transport of momentum in the vertical, and indirectly in the horizontal (e.g., the Eliassen-Palm flux) including the thermal tide (Fels and Lindzen, 1974; Fels, 1986; Baker and Leovy, 1987; Leovy, 1987; Hou et al., 1990).

The second and third mechanisms, involving the solar thermal tide and eddies, are perhaps the most direct and simplest candidates for powering the high-speed zonal circulation. Tides have been detected in (1) the thermal IR from a 72-day record (roughly two thirds of a Venus solar day; Schofield and Taylor, 1983), (2) thermal IR maps from Venera 15 (Zasova et al., 2000), and (3) the day-side cloud level winds (Limaye and Suomi, 1981; Limaye et al., 1982; Limaye, 1988, 1990). Yet, fundamental characteristics of the tidal structure, including the phases and amplitudes of the diurnal and semi-diurnal components at different latitudes and different depths, have not been measured with sufficient precision to constrain hypothesized dynamical mechanisms. Also lacking are the required correlated observations of thermal structure and winds on both the day and nightsides, which enable the determination of the meridional heat and momentum fluxes. Only the dayside cloud motions have been measured at adequate spatial resolution for more than a few days, but with insufficient spatial coverage and sampling rate to estimate adequately the tide-induced eddy quantities.

The Galileo/NIMS flyby data (e.g., Fig. 1) provided proof that a spaceborne near-IR spectrometer can measure winds on the nightside of Venus (Baines and Carlson, 1991; Carlson et al., 1991). Furthermore, the Galileo/SSI CCD camera demonstrated that 0.9-μm imaging on the dayside measures cloud motions in the middle cloud layer (Belton et al., 1991).

Venus Express' nearly continuous mapping of the southern hemisphere at UV (VMC) and near-IR (VIRTIS) wavelengths will enable the determination of circulation at three specific depths in the middle atmosphere, which will be used as inputs to tidal models. In particular, mapping differences in zonal and meridional windspeeds between the day and night hemispheres will provide quantitative characterization of the thermal tidal structure within the clouds. Contemporaneous maps obtained by PFS of the temperature field at and above the cloudtops, also for both the dayside and nightside, will be key additional inputs to the tidal analysis. Indeed, such thermal mapping between approximately the 60- and 95-km levels were performed by the VORTEX experiment on Pioneer Venus (Taylor et al., 1980; Elson, 1983) and the Fourier Spectrometer onboard Venera 15 (Moroz et al., 1986, Oertel et al., 1987), both of which found signatures of diurnal and semi-diurnal tidal structures. Beyond providing data on such thermal structures key to understanding the thermal characteristics of the tides and heat transport, these data also can provide information on the 3-D nature of the zonal winds within and above the clouds, thus providing additional characteristics of tidal structure. Indeed, Venera 15 found that the speed of the wind varied significantly with local time, deriving a semidiurnal component of about 10 m/s (Zasova et al., 2000).

Once the tidal models have been calibrated with the observations of cloud-tracked and thermally-derived wind-speeds and thermal structures, the vertical and horizontal momentum and heat transports will be determined. Based on the foundations of previous work in solar thermal tidal models (Pechman and Ingersoll, 1984; Fels, 1986; Newman and Leovy, 1992), analytical/numerical techniques will be adapted to understand the role of thermal tides in maintaining the atmospheric super-rotation.

2.3.2. Hadley cells

Venus Express will characterize Hadley cells, generally considered to be the primary transporters of heat and momentum from the equator (c.f., Schubert, 1983.) Venus Express will test for consistency with the observed and modeled zonal momentum field and temperature structure at temperate and high latitudes. Meridional cloud motions in the middle and lower atmosphere determined by VIRTIS imagery and the latitudinal variation of CO and OCS in the deep atmosphere near 30-, 37-, and 42-km altitude measured by PFS and VIRTIS spectroscopy will be used to constrain bulk meridional motions and thus the latitudinal extent and depth of the upper and lower branches of the Hadley circulation. Additionally, PFS temperature maps will determine the latitudinal gradient in thermal structure, another key diagnostic of Hadley cell structure. For example, a relatively steep latitudinal gradient would indicate an end of a cell.

2.3.3. Polar vortices

At the poles, Mariner 10 and Pioneer Venus UV images showed that the circulation is organized in a pair of circumpolar vortices. In the middle of the northern vortex, there is a remarkable rotating dipole feature whose behavior is a major atmospheric enigma. Discovered in 11.5-μm Pioneer/VORTEX maps by Taylor et al. (1979a), the limited (72-day) observations of this feature indicate an average 2.7-day rotational period. However, this period varied significantly, and the entire dipolar construct nutated at times, with the rotation axis wandering 500 km from the pole in an Earth day. Large variations also occurred in the detailed structure. Usually, the bright regions had a chevron shape, and often, bright filaments connected the two features, typically crosswise.

Venus Express will provide the higher-quality data required to gain a clear understanding of the polar dipole(s), especially simultaneous measurements correlating thermal maps with cloud imagery. Venus Express will achieve significant improvements in spatial, vertical, and temporal resolution and coverage—including the first views of any southern dipoles (VORTEX did not observe the south pole). Movies made from visible, near-IR, and thermal-IR images and maps acquired over 500 Earth days will detail spatial and temporal changes in temperature and cloud opacity which will reveal the true nature of this complex phenomenon.

2.4. Chemistry, composition, and transport

With the high spectral and spatial resolution capabilities of PFS and VIRTIS, Venus Express will globally and repeatedly map the abundances of reactive species, to diagnose chemical and dynamical processes throughout the upper, middle and lower atmospheres. Venus' atmospheric chemistry involves complex and varied chemical cycles—H_2SO_4 cloud formation from H_2O and SO_2, CO generated by photochemistry, OCS and HCl produced by thermochemistry, and SO_2, H_2O, and HCl in volcanic gases (Prinn and Fegley, 1987).

A global decrease over time in SO_2 above the clouds was first observed by the PVO. This decrease may be due to the dissipation of a volcanic eruption of SO_2 prior to PVO's arrival (Esposito, 1984), or, alternatively, to dynamical processes (Clancy and Muhleman, 1991; Bézard et al., 1993). SO_2 is the third most abundant gas below Venus' clouds, the feedstock for the global H_2SO_4 clouds, the second most important greenhouse gas, and a key tracer of volcanic activity. PFS and VIRTIS measurements of SO_2 and OCS abundance and their spatial and temporal variations will be important for understanding the chemistry and physics of Venus' atmosphere and how the atmosphere is affected by volcanic activity.

Spatial variations in CO abundance appear indicative of global-scale dynamics (Collard et al., 1993). A 35% CO enhancement north of 47 °N observed by Galileo/NIMS has been attributed to concentration by the polar descending branch of an equator-to-pole cell (Taylor, 1995).

The O_2 ($^1\Delta$) airglow on the Venus nightside is a unique tracer of dynamics at ~90 km altitude within the upper mesosphere. There, the super-rotation rate may fall to zero, or be highly variable (Crisp et al., 1996; Zhang et al., 1996). VIRTIS and PFS map this dynamical tracer at 1.27 μm, utilizing the airglow's strong spatial and temporal variability (>20% over an hour, Allen et al., 1992; Crisp et al., 1996) to characterize mesospheric circulation.

H_2O is the third most important greenhouse gas in Venus' atmosphere, is intimately involved in formation of the global H_2SO_4 clouds, and is also a potential tracer of volcanism and dynamics. Spatial variability of cloud top H_2O vapor was detected by PVO/VORTEX (Schofield et al., 1982). On the nightside, the H_2O abundance was below the detection limit (6 ppm) and the equatorial mid-afternoon was the wettest (up to 100 ± 40 ppm vs. <6–30 ppm elsewhere). This enhancement may have been generated by vertical uplift of deeper, moister air via convection and Hadley circulation.

In the deep atmosphere, the observable water inventory is $\sim 10^5$ times lower than Earth's: an important clue for understanding the different evolutionary paths taken by Earth and Venus. Thus, it is important to map the sub-cloud water vapor abundance and to understand its spatial, vertical, and temporal variability. Below the clouds, conflicting water abundance results have been reported from different instruments on the PVO, Venera, and Vega probes. However, the low water vapor abundances found by the Venera spectrophotometer experiments (Ignatiev et al., 1997) are confirmed by the PVO mass spectrometer (Donahue and Hodges, 1992, 1993), and are also supported by Earth-based IR spectroscopy (Bézard et al., 1990; deBergh et al., 1995; Meadows and Crisp, 1996). For example, the Earth-based 1.18-μm spectra of Meadows and Crisp (1996) are best fitted by a profile with 20 ± 15 ppmv H_2O at the 47-km altitude cloud base increasing to 45 ± 15 ppmv at 30 km, and remaining constant at that value down to the surface. Similarly, NIMS data at 1.18 μm give an H_2O mixing ratio of 30 ± 15 ppmv in the lowest 10 km (Drossart et al., 1993). While NIMS showed no horizontal variation exceeding the 20% level over its sparse sampling of 30 sites, intriguing hints of 10% variability remain. The global IR spectra acquired over long time periods with VIRTIS and PFS nightside spectra of water absorption features in the spectral windows near 0.95, 1.05, 1.10, 1.18, 1.74, and 2.4 μm provide new opportunities to characterize the water abundance between the cloud base and the surface.

2.5. Clouds, meteorology, and lightning

Venus Express will investigate the distribution and variability of lower and middle clouds to ascertain the growth and dissipation rates of cloud masses and their constituent particles. As was done by Galileo/NIMS (Carlson et al., 1993a), cloud particle sizes and column abundances will be determined from nighttime measurements of cloud extinction over a wide range of wavelengths. In particular, by measuring the atmospheric transmission in a variety of spectral windows dominated by cloud attenuation rather than CO_2 absorption—such as at 1.31, 1.73, and 2.4 μm—the mean particle radius of the spherical, Mie-scattering cloud particles (c.f., Hansen and Arking, 1971; Hansen and Hovenier, 1974) can be ascertained. At these wavelengths, the lower atmosphere of Venus near 20-km altitude generates a thermal glow against which the attenuation of the overlying silhouetted clouds can be measured.

The Galileo/NIMS "snapshot" of the pole-to-pole distribution of cloud particles found unexpected large variations in mean particle size, with marked hemispherical asymmetry (Carlson et al., 1993a). In particular, particles were found to be ten times larger (by volume) in the Northern Hemisphere compared to the Southern. Explanations for such marked hemispherical differences in cloud particle sizes are uncertain, but likely involve spatial variations in dynamical properties such as temperature, eddy diffusion (turbulence), and strengths of up/downdrafts bringing cloud-forming gases (principally SO_2 and H_2O) into the region. The NIMS results indicate that if cloud particle size is due to mixing of vertically stratified source regions (e.g., photochemical and condensation source mechanisms), then the mixing must be coherent over very large spatial scales, in turn implying relatively small variations in small-scale dynamical regimes. Yet, the distinct regional character of particle sizes may indicate sharp regional variations in the strength of dynamical mechanisms (e.g., turbulence, up/downwelling).

From VIRTIS near-IR maps, Venus Express will obtain particle size and cloud column abundance maps of the nightside several times per week in order to observe the temporal growth and decay of clouds and cloud particles. These observations will be correlated with temporally and spatially varying abundances of parent gases and with the observed wind and eddy fields to ascertain mechanisms explaining the distinct regional differences in particle size.

Lightning—another indicator of dynamics—has been tentatively detected by the Venera 11–14 landers (Ksanfomaliti, 1979, 1983) and by PVO (Taylor et al., 1979b; Russell, 1991) via electromagnetic impulse events. The Venera data suggest that the rate of lightning discharges may be even greater than found on Earth (c.f., Russell, 1991). Yet, only two optical investigations have reported possible lightning detections (Krasnopolsky, 1980; Hansell et al., 1995). Venus Express nightside VMC and VIRTIS imaging will increase coverage in both area and time by orders of magnitude and should positively confirm the existence of terrestrial-strength optical lightning flashes if their frequency in the well-scrutinized southern hemisphere is at least one-tenth of one percent of their frequency on Earth. If their global frequency significantly greater, meaningful constraints on the preferred local time and latitude of lightning occurrence can be made, thus providing further constraints on the nature of meteorology and chemistry on Venus.

2.6. Surface/atmosphere interactions

Venus Express's surface and near-surface thermal and compositional measurements will, for the first time, reveal crucial geological, dynamical, and chemical links between the hot, pressurized surface and the overlying chemically reactive atmosphere. Venus Express near-IR instruments will observe (1) the near-surface atmospheric lapse rate and its spatial/temporal variability and (2) the chemical, dynamical, and thermal effects of active volcanism—if present—on the atmosphere and surface.

2.6.1. Surface atmospheric lapse rate

Direct measurement of temperature lapse rates in the planetary boundary layer (0–12 km) are limited to localized measurements by the Vega 2 probe (Linkin et al., 1987) and the Venera 8–10 probes (Avduevskiy et al., 1983). More recent ground-based near-IR spectral studies (Meadows and Crisp, 1996) suggest that the lapse rate varies considerably over the planet. In particular, measurements of the Beta Regio region indicate that the lower atmosphere is remarkably subadiabatic there, with a lapse rate of 7.5K/km vs. the expected 8.3K/km adiabatic rate. Conversely, theoretical considerations (Dobrovolskis, 1993) indicate that the atmosphere could be statically unstable and turbulent in places, due to the influence of topography on atmospheric winds and small yet significant variations in surface heating caused by variations in slope, surface emissivity/conductivity, and latitude. Pettengill et al. (1996) noted that the critical altitude at which the Venus highlands show low radar emissivity increases by 1.5 km from the equator to high northern latitudes, perhaps reflecting a latitudinal variation in the atmospheric lapse rate. Measurements of the vertical lapse rate and/or horizontal and temporal gradients would directly address whether there is a latitudinally varying vertical lapse rate as well as enable evaluations of mechanical surface weathering due to entrainment of particles in turbulent surface winds (e.g., Dobrovolskis, 1993).

Observations by NIMS (Carlson et al., 1991; Carlson et al., 1993b), Cassini/VIMS (Baines et al., 2000) and ground-based observers (Lecacheux et al., 1993; Meadows et al., 1992; Meadows and Crisp, 1996) in the 0.85-, 0.90-, 1.01-, 1.10-, and 1.18-μm CO_2-free windows detect thermal emissions from the surface of Venus (c.f., Fig. 1(c)). Following Meadows and Crisp (1996), 1-μm flux measurements will be correlated with Magellan-derived surface topography to obtain constraints on thermal profiles from 0 to ~12 km altitude. The degree of near-surface static stability will be ascertained by the thermal gradient measured on mountain slopes, particularly in Ishtar Terra, Maxwell Montes, Alpha and Beta Regio, and Aphrodite Terra. Temporal variations in surface flux will constrain dynamics in the near-surface atmosphere and constrain the thermal emissivity of surface materials. In addition, constraints on the eddy diffusion coefficient in the 0–12 km region will be important for coupled chemical-dynamical models of sulfur gas chemistry and atmospheric oxidation state (Fegley et al., 1997).

Venus Express will produce greatly enhanced coverage and increased thermal accuracy compared to Earth-based measurements, which, due to the Venus–Earth orbital resonance, are restricted to a small range of longitudes every 18 months. PFS and VIRTIS near-infrared maps of the surface temperature over a 12-km range of surface elevation will determine the lapse rate up to ~12 km altitude, while providing improved spatial resolution (~100 km compared to ~250 km from terrestrial observatories), improved signal to noise (>1000), and much more comprehensive spatial and temporal sampling and coverage. Based on Meadows and Crisp (1996), Venus Express will obtain an accuracy of ±0.25K/km in the lowest scale height over much of the globe.

2.6.2. *Volcanism*

The surface of Venus is geologically young (~500 million years). This, and the presence of a highly reactive sulfuric-acid cloud cover with a mean lifetime of two million years (e.g., Fegley et al., 1997), suggests the possibility of current volcanic activity. VIRTIS, PFS, and VMC will all readily observe volcanic activity by its thermal flux, enhanced gaseous absorptions, and increased atmospheric scattering/absorption from ejected dust plumes. Thus, Venus Express presents a real opportunity to quantitatively characterize for the first time volcanic activity on the surface of a terrestrial planet other than Earth (e.g., Hashimoto and Imamura, 2001). Such data will be immensely useful in characterizing the role volcanism plays in climate change and stability and in assessing the character of interior processes within a dry planet. Chemical weathering of high-dielectric-constant surface material generated by volcanism—e.g., perovskite minerals, pyrite, and pyrrhotite—may be observed as a spatially and temporally localized change in surface radiation. Laboratory studies under simulated Venusian conditions of iron sulfide chemical weathering (Fegley et al., 1997) have revealed that FeS_2 and Fe_7S_8 decompose in timescales of weeks to years. At high elevations, high-dielectric materials are ubiquitous at microwave wavelengths (e.g., Pettengill et al., 1988; Pettengill et al., 1992; Klose et al., 1992). Venus Express will map surface thermal emissions within the five surface-detection windows from 0.85- to 1.18-μm (c.f., Baines et al., 2000). The latter observations will be correlated with extant radar-determined surface emissivity and elevation maps—as well as any bistatic radar results achieved by Venus Express—to look for compositional differences among surface basalts. For example, the relative distribution of silicates and sulfides will be mapped as demonstrated theoretically by Hashimoto and Sugita (2003), as well as more exotic volcanic deposits and high-elevation materials.

Any change in the H_2O and HDO abundances associated with volcanic activity would help clarify the long-term evolution of both the atmosphere and the solid planet. The observed atmospheric D/H ratio is ~150 times greater than the telluric ratio (deBergh et al., 1991; Donahue and Hodges, 1993). The hypothetical mechanisms responsible for the higher D/H ratio are currently controversial and range from the loss of a primordial ocean to steady state mechanisms, wherein H_2O supplied by cometary infall and volcanic outgassing is lost by atmospheric H_2 escape and oxidation of Fe-bearing crustal minerals (Grinspoon, 1993). Measurement of magmatic water and HDO released in a volcanic eruption would yield valuable insights into the evolution of the H_2O-poor atmosphere and the efficacy of present theories of global tectonics, insights into volcanic activity, and constraints on the oxidation rate of Venus' crust.

3. Measurements and methodology

Venus Express will acquire mosaics and maps of Venus in over a thousand wavelengths, spanning scientifically relevant spectral regions from 0.365 to 45 μm, representative samples of which are shown in Fig. 1. Except for VMC, all observations for each instrument are typically acquired in all wavelength channels simultaneously. PFS, VIRTIS, and VMC are bore-sighted, allowing simultaneous, geometrically registered imaging and mapping.

Each of the three deep-sounding imagers and spectrometers on Venus Express provide synergistic information which together will provide a new understanding of the nature and evolution of our sister world. The basic characteristics of these instruments are summarized in Table 2. VIRTIS and PFS both exploit seven atmospheric windows between 0.85 and 2.5 μm observed on Venus' nightside to sample the lower atmosphere and surface. VIRTIS acquires 2-D spectral maps which measure surface and atmospheric properties from the surface to ~80 km altitude at spatial scales down to 0.5 km. For VIRTIS, spectral image cubes can be acquired at resolving powers up to $\lambda/\Delta\lambda = 2500$ per line pair. PFS provides a resolution of $1.2\,\mathrm{cm}^{-1}$ throughout its spectral range. For both instruments, well-resolved spectra obtained in the highly diagnostic 1.7- and 2.3-μm windows yield composition (e.g., H_2O, SO_2, CO, OCS, HCl) in the deep atmosphere at altitudes between 30 and 47 km. The intensity gives a combination of cloud opacity and deeper-level temperature. The spatial patterns observed by VIRTIS give motions of the thermally backlit cloud layers at 50 and 57 km altitude, which appear silhouetted against the warmer layers below. Five atmospheric windows from 0.8 to 1.2 μm provide additional information about water vapor throughout the lower atmosphere as well as constraints on the near-surface thermal structure and surface temperature, as validated by the Galileo/Near-Infrared Mapping Spectrometer (NIMS; Carlson et al., 1991, 1993b; Drossart et al., 1993) and the Cassini/Visible and Infrared mapping spectrometer (VIMS; Baines et al., 2000).

Beyond its near-infrared capabilities, PFS is also an IR-spectrometer that measures thermal profiles throughout the middle atmosphere from 65–100 km by sampling the wings of the 4.3 and 15-μm CO_2 bands. Daily coverage of temperatures in the northern hemisphere and daily views of the northern polar dipole (c.f., Taylor et al., 1979a) are primary measurement objectives. Maps of vertical windshear over altitude inferred from the cyclostrophic balance equation will be compared to the winds observed by VIRTIS and the Venus Monitoring Camera (VMC) at 57 and 70 km to look for imbalances diagnostic of dynamical processes, important in particular for the assessment of possible mechanisms responsible for the atmosphere's enigmatic super-rotational state. In addition, the uniquely broad spectral coverage of PFS from 0.9–45 μm, combined with its relatively high spectral resolution, will yield important new information on the distribution of a plethora of important trace species throughout the atmosphere.

VMC is a UV–near-IR, 4-filter camera for cloud-tracked wind measurements at 57 and 70 km altitude, important for measuring zonal windshears, indicative of processes responsible for Venus' super-rotating atmosphere. A 0.365-μm filter images the mesospheric haze and the UV feature motions, which originate between 60 and 70 km altitude in the upper cloud. The 0.935 and 1.01-μm filters image the middle cloud near 57 km altitude, a technique validated by the Galileo/SSI encounter (Belton et al., 1991). From differences observed at these two latter wavelengths, constraints on the water profile below 10 km and surface thermal emission properties can be obtained, giving unique clues to chemical and dynamical processes in the near-surface Venus environment (c.f., Meadows and Crisp, 1996). Such multidimensional coverage is essential for understanding transports of energy and angular momentum.

VIRTIS's M-channel spatial resolution of 1 mrad and VMC's comparable resolution of 0.74 mrad enable wind measurements to better than 2 m/s in 9-h samples near apogee and enable viewing of wave structures at 10-km scales and smaller near perigee. PFS's IFOV of 27 mrad enables 4-μm thermal mapping (*a la* NIMS, c.f. Fig. 1d and e) of the northern polar dipole at better than 100-km scales within 3700 km of perigee—adequate for temperature mapping above the cloud tops. Within 1000 km of perigee over the North Polar Region, this instrument will acquire maps at better than 27-km scales to resolve small, perhaps cloud-induced thermal features in the polar dipole.

Table 3 shows the measurement accuracies and precisions expected for key environmental parameters (e.g., molecular abundances, winds, temperatures), given the instrument capabilities (e.g., spatial, temporal, spectral resolution and coverage, S/N) and the viewing geometries of the Venus Express mission. Here, precision denotes the uncertainty in temporal or pixel-to-pixel spatial variations, and is driven by the S/N of the measurement. Accuracy denotes the uncertainty in absolute quantities, typically driven by uncertainties in the absolute calibration of the instruments and the model in Meadows and Crisp (1996) for temperatures. Precision/accuracy estimates here are based on (1) Carlson et al. (1991), Baines and Carlson, 1991, and Limaye and Suomi (1981) for winds; (2) Carlson et al. (1991) and Crisp et al. (1991a) for abundances, and by (3) Schofield and Taylor (1983), Carlson et al. (1991), and Meadows and Crisp (1996) for pressures and temperatures. As one example of our procedures in developing Table 3, we now discuss the retrieval of gas abundances from PFS data.

The high-spectral-resolution capability of PFS, together with our state-of-the-art atmospheric modeling capability, enables the retrieval of deep-atmosphere molecular abundances with exceptional precision. This is demonstrated in the lower right-hand panel of Fig. 3, which shows the sensitivities of PFS spectra to 10% reductions in the concentrations of CO, H_2O, OCS, and SO_2. For each species, the differences between the modified and nominal cases reveal numerous spectral features which markedly exceed the expected instrumental noise (black dashed curves) of the $39 \times 39\,km^2$ effective IFOV, resulting in a precision of better than 3% for each species when all other species are kept at their nominal concentrations. However, significant spectral overlap exists, especially between H_2O, OCS, and SO_2. A combined analysis of all four species resolves the ambiguities, wherein constituent abundances are derived sequentially, beginning with the well-isolated 2.303–2.34 μm CO spectrum (bracket over red spectrum). Using the derived CO concentration, the H_2O concentration is derived next from the 2.405–2.425 μm portion (bracketed) of the H_2O spectrum (green). OCS is next derived from the 2.425–2.45-μm region (bracketed, blue), using the derived H_2O results. Finally, SO_2 is derived from 2.45–2.47 μm (brown, bracketed) using the H_2O and OCS retrievals. This procedure attains uncertainties of 3%, 4%, 7%, and 9% for the abundances of CO, H_2O, OCS, and SO_2, respectively.

4. Conclusion

Utilizing atmospheric windows in the near-infrared initially discovered in the mid-1980s (Allen and Crawford, 1984), Venus Express will be the first spacecraft to view our sister planet globally and three dimensionally, as it images and maps—for the first time—the bulk (99.8%) of the atmospheric mass residing below the 70-km level. In so doing, Venus Express will directly address numerous high-priority issues of planetary science during its 500-day nominal science mission. The fundamentally increased understanding of dynamical and chemical processes provided by Venus Express will provide dramatic new insights into the nature of global circulation, the evolution of climate, and surface–atmosphere interactions on all terrestrial planets, including the Earth.

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