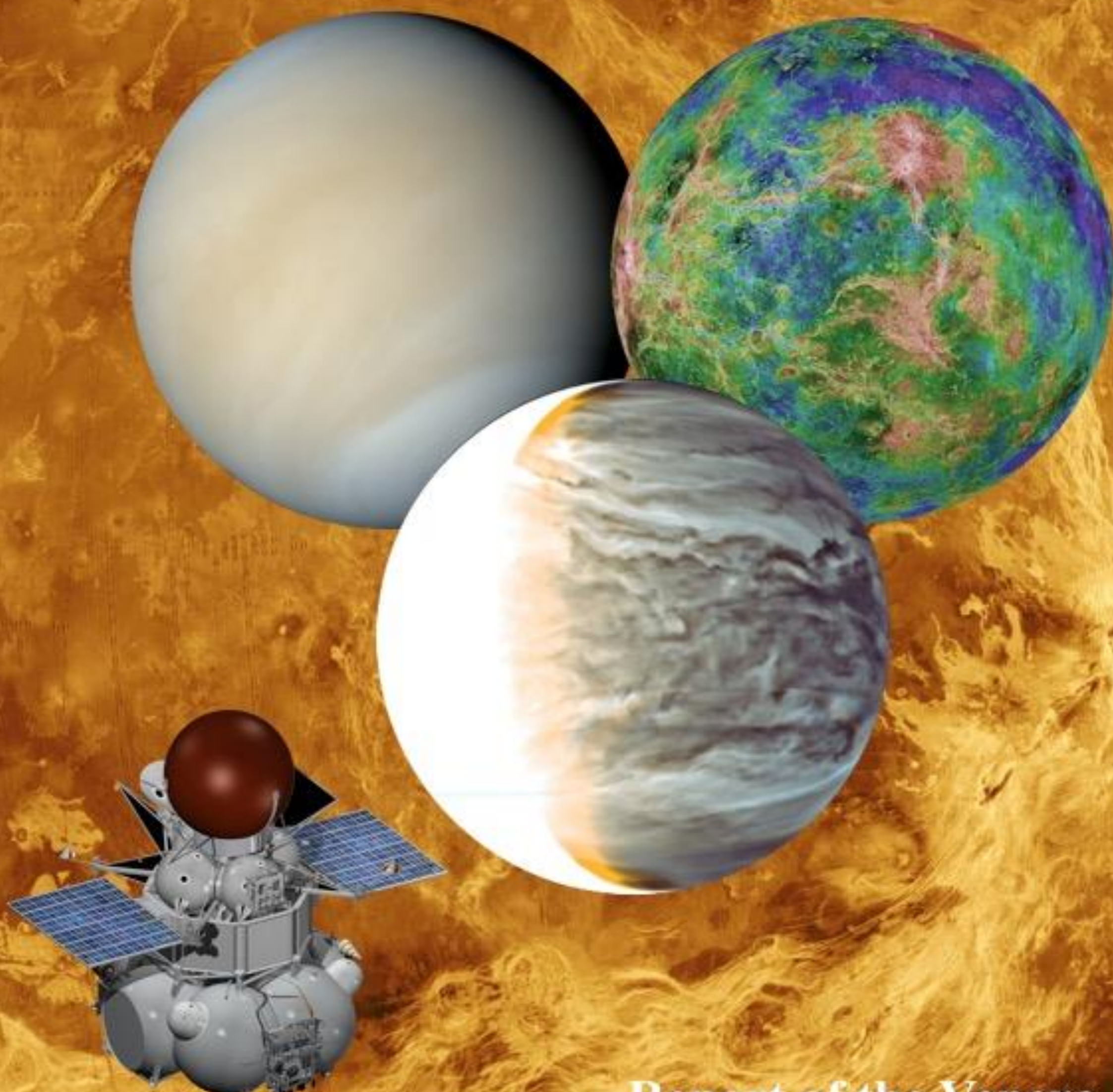
Venera-D: Expanding our Horizon of Terrestrial Planet Climate and Geology through the Comprehensive Exploration of Venus



Report of the Venera-D Joint Science Definition Team

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Venera-D: Expanding our Horizon of Terrestrial Planet Climate and Geology through the Comprehensive Exploration of Venus

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1 Executive Summary

Background. Formed in the inner solar system out of the same protoplanetary material as the Earth, Venus is considered Earth's twin. Although these siblings have nearly the same size, mass, and density, unlike the Earth, Venus' climate is fueled by a massive CO_2 atmosphere producing an enormous greenhouse effect with a surface pressure of 90 bars and a near-surface temperature of 470°C. Shrouded in clouds of sulfuric acid, the surface lacks water and has been sculpted by volcanism and deformed by faulting and folding forming belts of mountains and rifts. The lack of an intrinsic magnetic field suggests the planet's interior structure may also be different than that of the Earth.

These differences indicate that the Earth and Venus took substantially different evolutionary paths. Because the Earth, with its abundant water supply, is currently our only known example of a planet hosting an active biosphere, we are compelled to understand when the evolutionary paths of these twin planets diverged, as well as understand how and why the divergence occurred. Answers to these questions can help us determine if conditions ever existed on Venus that could have fostered the origin of life and in turn help us understand what makes a planet habitable. Thus, the study of Venus will aid in better understanding the past and possible future of our climate. In particular, answering questions regarding the instability of our climate and the increase in amount of greenhouse gases: Can we be slowly going the Venus' direction? These questions may be addressed through the Venera-D mission concept consisting of an orbiter and a lander.

Venera-D Concept and Architecture. The concept of Venera-D (Venera-Dolgozhivuschaya (long-lasting)) is the next step in the highly successful series of Venera and VEGA missions of the 1970s and 1980s (Avduevskii et al. 1977; Marov et al. 1973, 1978; Florensky et al. 1977; Barsukov et al. 1982, 1986; Moroz et al. 1985, 1990, 1996; Surkov et al. 1984; Sagdeev et al. 1986, 1992). The baseline mission concept would consist of an orbiter and lander with advanced, modern, instrumentation. A list of possible "contributed mission elements" was also studied. The science objectives of the mission would address key questions about the dynamics of the atmosphere with an emphasis on atmospheric superrotation, the geological processes that have formed and modified the surface with emphasis on the mineralogical and elemental composition of surface materials, and the chemical processes related to the interaction of the surface and the atmosphere. For each baseline mission component, the following goals would be addressed:

Focused Orbiter Goals:

- Study of the dynamics and nature of superrotation, radiative balance, and the nature of the greenhouse effect;
- Characterize the thermal structure of the atmosphere, winds, thermal tides, and solar locked structures;
- Measure the composition of the atmosphere, study the clouds, their structure, composition, microphysics, and chemistry;
- Investigate the upper atmosphere, ionosphere, electrical activity, magnetosphere, and the escape rate

Focused Lander Goals:

- Perform chemical analysis of surface materials and study the elemental composition of the surface, including radiogenic elements;
- Study of interaction between the surface and the atmosphere;
- Investigate the structure and chemical composition of the atmosphere down to the surface, including the abundances and isotopic ratios of the trace and noble gases
- Perform direct chemical analysis of the cloud aerosols;
- Characterize the geology of local landforms at different scales

Venera-D Joint Science Definition Team. To refine the mission science goals, priorities, and architecture, NASA and IKI/Roscosmos established in 2015 a Joint Science Definition Team (JSDT) to evaluate the Venera-D concept with the following objectives:

1. Identify, prioritize and develop science goals, investigations, and measurements consistent with the current Venera-D concept;
2. Assess the Venera-D mission architecture including possible modular options (e.g., subsystems) for collaboration opportunities and required instrumentation capabilities. Assess technology readiness level to implement the mission concept and identify areas for which development is required;
3. Identify mission components (mission elements/subsystems/instruments) that best lend themselves to potential collaboration. Outline a general maturation schedule needed to support a Venera-D mission for launches in the post-2025 time frame;
4. Assess the precursor observations and instrumentation validation experiments needed to enable or enhance the Venera-D mission (e.g., instrument testing in a chamber that emulates the chemistry, pressures and temperatures found in the atmosphere or at the surface of Venus);
5. Evaluate how Venera-D will advance the scientific understanding of Venus and feed forward to future missions with the ultimate goal of sample return.

As part of its task, the JSDT traced the baseline Venera-D science to the science outlined in the NASA Planetary Decadal Survey (SSB, 2011) and further mapped it to the specific objectives and investigations identified by the Venus Exploration Analysis Group (VEXAG) (Herrick et al. 2014). As part of this analysis, the JSDT identified areas where important VEXAG science may not be addressed by the baseline concept and generated a list of "contributed" options, (in order of interest by the JSDT and IKI) to fill these "science gaps" ranging from:

- Specific instruments such as a Raman Spectrometer and an Alpha-Proton X-Ray Spectrometer (APXS);
- Possible flight elements such as:
  - A maneuverable aerial platform;
  - A small long-lived surface station;
  - A balloon;
  - A small subsatellite (Roscosmos contribution); or
  - A small aerial platform

Technology Assessment. The extremes of temperature and pressure make the operation of a spacecraft in the Venus environment a unique challenge. The JSDT assessed and prioritized areas where technology maturation is required. Key among these are (1) the lander sample handling/processing system, (2) the need for facilities to test and qualify a full-scale lander, and (3) maturation, testing, and validation of instruments that would need to operate in Venus ambient conditions. Additional flight components such as a maneuverable aerial platform and the small long-lived stations offer great promise for the advancement in scientific understanding, but require maturation to reach flight readiness Technical Readiness Level (TRL).

To ensure scientific success of the Venus science goals, laboratory experiments will be fundamental to validating results. Among the high priority analysis needed to be performed include studies of (1) spectral line profiles under high pressures and temperatures (orbiter); (2) optical properties of the lower Venus atmosphere in the visible to near infrared (lander); (3) evaluation of the compositional change of the trace gas components due to the temperature and pressure drop during atmospheric sampling (lander); (4) trace and noble gases enrichment procedure (lander); (5) atmosphere (pressure / temperature) effects on remote sensing instruments (lander); (6) supercritical properties of Venus like atmospheres (lander); and (7) UV absorption experiments to identify absorbers and identify insolation energy deposition (aerial platform).

JSDT Findings and Recommendations. The JSDT identified priorities for the science goals and objectives. Based on these priorities, a baseline mission would consist of a single highly capable orbiter and a single highly capable lander. Each would address science questions regarding the composition and dynamics of the atmosphere. In regard to surface and surface-atmosphere interactions, the lander would be the primary mission element to address these objectives while the orbiter, making surface observations in the near-infrared would provide global-scale data to address questions related to recent volcanic activity and compositional variability of terrains. In the assessment of possible mission enhancements, in situ measurements, both at the surface and aloft made over an extended period of time (many hours to months) are enabling, especially for understanding the processes that drive the atmosphere. Mobility within the atmosphere was also deemed of high priority in terms of understanding the location of the UV absorber and identifying its composition.

In formulating a strategy for the development of Venera-D, the JSDT identified areas where investments would need to be made to bring the mission concept fruition. For an anticipated launch in the post 2025 timeframe, activities of the following nature would be needed to ensure mission success:

- The types of instruments to achieve the Venera-D science require various levels of validation and maturation to ensure robust and successful operation in the Venus environment (470°C and 90 atm.)
- Laboratory work to characterize the chemistry of the Venus atmosphere at high temperatures and pressures
- Development of capable facilities to test mission enabling instruments and the spacecraft at the component and system level in a simulated Venus environment
- Continued development regarding all potentially “contributed” mission elements

Mission Element Trades. As the Venera-D concept matures and resources (mass, power, volume, funding to name a few) are better defined, trades will need to be made that impact science. In anticipation of this, a set of potential architectural options ranked as *Ambitious, Adequate, and Minimal*, were identified that achieve no less than the core baseline science.

Ambitious: The most ambitious option contains the most flight elements, the highest potential science return, and offers the greatest range of potential contributions. Its complexity due to the large number of elements results in a high level of technical and scientific risk.

Adequate: The adequate mission option, composed of three flight elements, would be a challenge from the standpoint of complexity, interfaces, testing, validation, and operation. However, like the ambitious option, the opportunity for potential mission element "contribution" is very high.

Minimal: The minimal concept would produce significant science results focusing on the core objectives, but the set of potential mission element "contributions" would be reduced relative to the ambitious and adequate architectures.

Framework for Future Work. The Venera-D JSDT has completed its formulation (*pre-Phase-A*) of science goals and priorities along with its assessment of key area for technology maturation. The next phase (*pre-Phase-A*) of development would focus on a deeper examination of the science and instruments along with the definition of spacecraft requirements. Within this context, specific areas have been identified that deserve attention. These include the following:

1. Definition of a focused mission architecture concept;
2. Definition of the lander and orbiter operations concept including a timeline of science observations, strategy for sample acquisition, handling and analysis, data flow and downlink;
3. Refinement of instrument capability relative to the ability to achieve the science goals;
4. Refinement of envelope (mass, power, volume) for a potentially contributed element;
5. Maturation of the small station concept; instrumentation and concept for targeting and deployment—if provided as a contribution;
6. Aerial platform accommodation and deployment optimization along with science priorities and instrumentation—If provided as a mission element "contribution".

To achieve a number of these items, a greater engagement of the broader Venus science community is recommended. Current discussion has focused on holding workshops in both the United States and Russia to understand the limitation and needs of current models (e.g., General Circulation Models or GCMs and interior structure models), landing site selection, and the types of measurements needed to more adequately constrain parameters in the models and experiments. This would, in turn, form a basis to better identify the types of instruments needed to achieve the important science of Venera-D. The Venera-D mission would provide a major step in understanding our sister planet, and the origins of the solar system.

2 The Allure of Venus

2.1 Introduction

Formed in the inner solar system out of the same protoplanetary material as the Earth, Venus is considered Earth's twin sister. Although these siblings have nearly the same size, mass, and density, unlike Earth, Venus' climate is fueled by a massive CO_2 atmosphere producing an enormous greenhouse effect with a surface pressure of 90 atmospheres and a temperature of 470°C. The atmosphere undergoes superrotation, with the upper clouds rotating at a rate 60 times faster than the surface. Shrouded in clouds of sulfuric acid, Venus' surface lacks water and has been sculpted by volcanism and deformed by faulting and folding forming belts of rifts and mountains. The lack of an intrinsic magnetic field suggests the planet's interior structure may also be different than that of the Earth. These differences indicate that the Earth and Venus had substantially different evolutionary paths. What remains unanswered is when, why and how the paths diverged. Additionally, it remains that the Earth stands as our only known and verified example of a planet with an active biosphere.

Therefore, we are compelled to explore and understand the differences in the evolutionary path of these twin-planets. Indeed, the study of Venus will help us to better understand both the past and possible future evolution of our own climate. In particular, answering questions regarding the instability of our climate and the increase in the amount of greenhouse gases: can we be slowly going in Venus' direction? Additionally, solving these mysteries will help us determine if conditions ever existed on Venus that could have fostered the origin of life and also help us more clearly understand and define what pathways that lead to a habitable planet. The Venera-D mission concept is designed to address these provocative and timely questions.

2.2 The Venera-D Concept

The concept of Venera-D (Venera-Dolgozhivuschaya (long-lasting)) was born out of the highly successful Venera and VEGA missions of the 1970s and 1980s (Sagdeev et al. 1986, 1992). Venera-D was proposed by Vasily Moroz to the Russian Academy of Sciences in 2003 as a long-lived (30 days) lander on the surface and it was included in the Russian Federal Space Program 2006–2015. However, detailed analysis showed that high temperature electronics, previously available in Soviet Union, were no longer being produced in Russia. The concept of Venera-D was changed to a baseline mission consisting of an orbiter and short-lived (2–3 hours) VEGA-style lander with advanced instrumentation on both elements. A list of possible "contributed mission elements" was also studied including, balloons, a subsatellite, and a long-lived (24 hours) surface station.

Building on the results of the Venera, VEGA (Avduevskii et al. 1977; Marov et al. 1973, 1978; Florensky et al. 1977; Barsukov et al. 1982, 1984; Surkov et al. 1984; Moroz et al. 1990, 1996; Sagdeev et al. 1986, 1992), Magellan (Saunders et al. 1992), Venus Express (Svedhem et al. 2009) and now the Akatsuki mission (Nakamura et al. 2011), a comprehensive mission is proposed that would answer key questions about the dynamics of the atmosphere with emphasis on atmospheric superrotation, the geological processes that have formed and modified the surface with emphasis on the mineralogical and elemental composition of surface materials, and the chemical processes related to the interaction of the surface and the atmosphere.

2.3 Baseline Venera-D Concept and Science Priorities

2.3.1 Mission Elements

The baseline Venera-D mission concept would consist of an orbiter that would be instrumented to make observations focused on atmospheric dynamics and chemistry. The mission scenario would place the spacecraft in a polar orbit with a period of 24 hours. The expected lifetime of operation of the orbiter would be greater than three years. Depending on the science to be achieved, there is flexibility in trading orbiter period to gain greater communication time with other mission elements or to gain system mass. The architecture of the lander component of the Venera-D mission concept is envisioned to be similar to the VEGA lander of the 1980s but with modern scientific instruments. The lifetime of the lander on the surface is expected to be greater than two hours with time allocated such that the baseline science could be achieved in one hour with the second hour allocated as margin for continuing or repeating measurements. Previous studies and the current JSDT study also assessed other components as potential augmentations to the Baseline Venera-D concept which will be discussed in detail in this report. These elements include, a free-flying aerial platform, a balloon, a subsatellite, and small long-lived surface stations. The JSDT also considered the case where a small long-lived station could be incorporated as an instrument on the lander—operating for a period long after the main lander ceased to make measurements.

2.3.2 Prioritized Overarching Science Goals

Baseline Venera-D Goals and Objectives. The science goals of the baseline (orbiter and lander) Venera-D concept address key outstanding questions related to the Venus atmospheric and surface science. To direct the development of the mission concept, the JSDT prioritized (high, medium, and low) the goals and objectives for both the orbital and landed components of the mission. The four focused goals defined in the summary (see below) for the orbiter are all of high priority. Orbiter objectives (**Table 2.3-1**) that are related to the goal of understanding the structure, dynamics, and chemistry of the atmosphere are of highest priority while the orbiter objectives that focus on the ionosphere, magnetosphere, solar wind interactions, and particle environment are of medium priority. In terms of the defined lander goals, those of highest priority focus on surface material composition, interaction between the surface and the atmosphere, and the structure and chemical composition of the atmosphere. The goal to search for volcanic and seismic activity is of low priority as it was concluded that the relatively short period of time (two or more hours) for which measurements could be made would be insufficient for positive detections. At the objective level (**Table 2.3-2**), lander objectives related to atmospheric composition are of high priority and those to assess atmospheric structure and dynamics and properties of aerosols are of medium priority. All lander objectives related to geologic investigations are high priority except those related to the search for seismic activity and electromagnetic fields; where the latter exception is best done from orbit.

Focused Orbiter Goals:

- Study of the dynamics and nature of superrotation, radiative balance and nature of the greenhouse effect;
- Characterize the thermal structure of the atmosphere, winds, thermal tides, and solar locked structures;

- Measure the composition of the atmosphere, study the clouds, their structure, composition, microphysics, and chemistry;
- Investigate the upper atmosphere, ionosphere, electrical activity, magnetosphere, and the escape rate

Table 2.3-1. Venera-D Science from Orbit.

Objective Title	Science Objectives	Measurements	Instrument	Priority
O1. Vertical structure of mesosphere and cloud-born gases	Characterize the three-dimensional atmospheric composition, including SO_2 and H_2O, temperature field, cloud structure and thermal winds, thermal tides, thermal balance in 55–100 km on both the day and night sides	1) Measure the spectrum in the range of 5 to 45 μm with a sampling of Dv = 1 cm^{-1}; 2) Depending on latitude and local time, retrieve the temperature profiles at 55 to 100 km to recover the dynamics, structure and composition of the upper clouds, altitude of upper boundary of clouds and scale height, upper boundary of the middle clouds, SO_2, H_2O in the range of 55 to 75 km.	Fourier Transform Spectrometer (PFS-VD)	High
O2.Atmospheric dynamics and airglow	1) Determine the limb and nadir detailed UV spectral characteristics to identify the "unknown" UV-absorber; 2) To study of small scale atmospheric dynamics, cloud structure and cloud tracking; 3) Analyze cloud components (SO_2, SO, "unknown UV absorber") and search for night side airglow.	1) Measure spectra and perform imaging at 190 to 490 nm with a sampling of Dl<= 0.4 nm; 2) Map the SO_2 and SO abundance in the wavelength range of 0.19 to 0.32 μm; 3) Map the 'unknown' UV absorber in the 0.32 to 0.49 μm range with high spectral and spatial resolution (~100 m); 4) Map the cloud structure and wind speed from imaging at 0.19 to 0.49 μm; 5) Measure NO, CO, O_2 to study night glow.	UV imaging spectrometer (e.g., UVMAS)	High
O3.Structure, composition, and dynamics of clouds, hazes, and surface thermal emissivity	1) Determine the structure, composition, dynamics, thermal balance, structure of the clouds and haze (0–100 km) on the night side), upper boundary of clouds, and composition above clouds on the day side; 2) Dynamics in the transfer region between zonal and SS-AS modes of circulation (90–110 km) 3) Surface emissivity, search for thermal activities 4) Dynamics and polar vortices.	1) Measure spectra and perform imaging in the wavelength range of 0.4 to 5.1 μm (0.4 to 1.9 μm –VIS-NIR, 1.5 to 5.1 μm –IR; with spectral sampling of Δλ=0.002 and 0.005 μm, respectively); 2) Map the thermal structure, distribution of minor constituents, clouds, surface emissions, non-LTE emissions, and wind speeds; 3) Measure CO, H_2O, OCS and SO_2 abundance; 4) Measure winds at different altitudes through cloud tracking at 350 nm and 980 nm in the day side; 1.74μm (at 50 km) on the night side; 5) Map the three-dimensional temperature field on the night side of Venus at 65–90 km altitude; 6) Mapping the non-LTE O_2, OH, O, NO, CO_2 dynamics at 90–140 km; 7) Measure the surface temperature and search for possible emissivity anomalies.	UV-IR imaging spectrometer (e.g., VENIS)	High
O4. Vertical structure and composition of the atmosphere	1) Study the vertical structure and composition of the atmosphere and thermosphere, including La, HDO, H_2O, CO, SO_2 and SO, COS, HCl, HF etc. (and infer O and H escape rates); 2) Study the hazes above the clouds (70–160 km).	1) Measure IR spectra in the wavelength range of 2.2 to 4.4 μm with a spectral sampling of Δλ =0.1 nm; 2) Measure UV spectra in the wavelength range of 118–320 nm with a spectral sampling of Δλ =1.3nm.	UV & IR solar and stellar occultation spectrometer	High

Objective Title	Science Objectives	Measurements	Instrument	Priority
O5. Dynamics of UV and UV- absorbers	1) Track clouds to constrain the dynamics of UV and UV-absorbers ('unknown' and SO_2, SO); 2) Map surface thermal emissions at 1 µm to evaluate surface geology.	Perform imaging at 0.285 µm, 0.365 µm, 0.500 µm, and 1 µm.	Imaging System	High
O6. Ionosphere and atmosphere	1) Determine the free electron and neutral gas density in the ionosphere and thermosphere; 2) Characterize the interplanetary medium; 3) Determine the electron density (profiles) of the ionosphere; 4) Determine the temperature, pressure, concentration of sulfuric acid vapor (profiles) of the atmosphere; 5) Determine the surface scattering properties, permittivity and density of the surface material.	Measure the amplitude, phase and frequency of radio signals in two frequency ranges of L and X (S) band, emitted from the orbiter, reflected from the surface and passing through the atmosphere.	Radio-science two-frequency occultation in L- and X-bands	Medium
O7. Structure, composition, and dynamics of the atmosphere (20–60 km altitude)	Determine the structure, composition, dynamics, thermal balance of the atmosphere in the altitude range of 10–60 km.	Perform measurements between 10–90 GHz (0.3–3 cm) using three channels and several zenith angles to measure temperature profiles, mixing ratios of H_2SO_4 and SO_2.	Millimeter-radiometer	High
O8. Atmospheric density, temperature, wind velocity, mesospheric minor constituents, and CO_2 dayglow	1) Determine density and temperature vertical profiling in the altitude range 80–160 km by means of solar occultation; 2) Determine wind velocity in the altitude range 90–160 km; 3) Map wind velocities in the Venus mesosphere; 4) Determine the concentration of minor constituents in the Venus mesosphere (vertical profiles); 5) Characterize CO_2 dayglow on the Venus limb	1) Measure atmospheric absorption spectra in the 10–11 µm spectral range in nadir geometry and solar occultation mode with a resolution of λ/Δλ ~107–108; 2) Doppler measurements of component along the spacecraft's orbit plane by means of solar occultations; 3) Perform nadir single-point and imaging spectroscopic measurements; 4) Imaging spectroscopy of atmospheric absorption in the 10- to 11 µm spectral range in nadir geometry with resolving power λ/Δλ ~107-108; 5) Measure dayglow in the 10- to 11 µm spectral range in nadir geometry and solar occultation mode with resolving power λ/Δλ ~107–108.	Infrared heterodyne spectrometer	High
O9. Venus magnetospheric interactions	1) Characterize the Interplanetary magnetic field (during cruise to Venus); 2) Characterize the interaction between the solar wind and the induced magnetosphere at Venus (boundaries, pick-up processes); 3) Determine the structure of Venusian magnetic wake;	Measure magnetic field vector(s) in the amplitude range of ±1000 nT in the frequency range of 0 to 32 Hz with a sensitivity of 0.1 nT.	**Plasma package--** Magnetometer (e.g., FM-V)	Medium

Objective Title	Science Objectives	Measurements	Instrument	Priority
	4) Characterize any ULF waves resulted from possible discharges in Venus atmosphere.			
O10. Solar wind ionosphere interactions	1) Monitor plasma parameters in solar wind and Venusian magnetosheath with a high resolution (32 Hz); 2) Characterize the interaction between solar wind and Venus ionosphere (bow shock, magnetosheath, ionopause and wake boundary).	1) Measure the total ion flux between 5×106 and 1×1010 cm^{-2}s^{-1} with incident angles of total ion flux within 40° from central direction; 2) Measure the energy distribution of ions between 0.2 and 4.0 KeV; 3) Measure the bulk velocity of solar wind between 200 and 850 km/s; 4) Measure the Ion temperature between 1 and 100 eV. Plasma density between 0.1 to 200 cm^{-3}.	**Plasma package**--Solar wind monitor (e.g., BMSV-V)	Medium
O11. Interaction between the solar wind and Venus	Investigate the interaction between the solar wind and Venus by evaluating: 1) The accretion magnetosphere of Venus, pick-up of planetary ions; 2) The bow shock and pike-up ion influence on its structure; 3) The boundary layers at Venus their fine structures; 4) The acceleration processes in Venusian wake; 5) The total losses of Venusian atmosphere resulted from its interaction with solar wind.	1) Measure the three-dimensional ion and neutral energy-mass spectrometer for the energy range of 30 eV to 5 keV; 2) Measure Electrons between 10 eV and 5 keV.	**Plasma package**--Panoramic plasma analyzer (e.g., ARIES-V)	Medium
O12. Venus particle environment interactions	1) Determine the energy spectra of protons and electrons with high time and energy resolution in the solar wind (cruise phase) and at orbits around Venus; 2) Constrain the fine structure of ion beams resulting from transient acceleration at discontinuities in the solar wind and interaction between solar wind and Venus plasma environment.	1) Measure protons at energies between 20 and 1000 keV; 2) Measure electrons at energies between 20 eV and 400 keV.	**Plasma package**--Electron and proton spectrum analyzer, (e.g., ASPECT-V)	Medium
O13. Electromagnetic fields	Characterize the electromagnetic fields, electrical activity and conductivity of the atmosphere of Venus	Measure the spectrum (two-channel spectrum analyzer) in the low frequency range between10 Hz and 15 kHz.	**Plasma package**--(e.g., GROZA-SAS2-O)	Medium

Lander Goals:

- Perform chemical analysis of the surface material and study the elemental composition of the surface, including radiogenic elements;
- Study of interaction between the surface and atmosphere;
- Investigate the structure and chemical composition of the atmosphere down to the surface, including abundances and isotopic ratios of the trace and noble gases
- Perform direct chemical analysis of the cloud aerosols;
- Characterize the geology of local landforms at different scales;
- Search for volcanic and seismic activity and search for lightning

Table 2.3-2. Venera-D Descent and Landed Science.

Objective Title	Science Objectives	Measurements	Instrument	Priority
Atmospheric Science				
L1. Atmosphere composition during descent	Determine the composition, chemistry, greenhouse, photochemistry, origin and evolution of the atmosphere, dynamics, atmosphere-surface interaction.	In situ measurements of chemical composition of the atmosphere including abundances of gases SO_2, CO, COS, H_2O, NO_2, HCl, HF, their isotopologues and isotopic ratios D/H, 13C/12C, 18O/17O/16O, 34S/33S/32S during descent from 65 km and after landing.	Multi-channel tunable diode laser spectrometer	High
	Determine the content and isotopic composition of light and noble gases in the atmosphere. Verify CO_2 and N_2 gradient at altitudes below 120 km.	During the descent, measure the chemical composition of the Venus atmosphere and of aerosols of clouds.	Chemical analyses package (CAP)--Gas Chromatograph Mass Spectrometer (GCMS)	High
L2. Atmosphere Composition at the surface	Determine the chemical composition of the atmosphere, clouds.	At the surface, measure the chemical composition of the atmosphere.	Chemical Analyses Package (CAP)--Gas Chromatograph Mass Spectrometer) (GCMS)	High
L3. Atmospheric structure and dynamics	Determine atmospheric structure, dynamics, turbulence, convection, thermal balance	Measure temperature, pressure, wind speed, temperature gradient, and acceleration from 120 km altitude to the surface and at the surface.	Temperature-Pressure-Wind (TPW) package (nephelometer, accelerometer/altimeter, photometer)	Medium
L4. Physical properties of atmospheric aerosols	Evaluate aerosol microphysics, composition, vertical profile, cloud formation and chemistry, thermal balance	Measure atmospheric aerosol particle number density, size distribution and optical properties.	Nephelometer – particle counter (e.g., NEFAS)	Medium
Surface Geology and Geophysics				
L5. Surface structure and morphology	Characterize surface structure, morphology, and relief elements at the scale of 100–10-m/pixel during descent; on the surface, characterize the surface at the scale of 1-m to 0.01 m/pixel. Localized characterization to better than 0.2 mm/pixel	1) Surface imaging during the descent phase and measure the optical properties of the atmosphere; 2) Imaging on the surface and measure the optical properties of the near surface atmosphere; 3) Stereo imaging of the surface (FOV 30° to 45° and angular	Imaging System (Descent imager; panoramic camera; microscopic imager)	High

Objective Title	Science Objectives	Measurements	Instrument	Priority
		resolution ~0.0005 rad) starting from an altitude of several kilometers and while on the surface; 4) Panoramic stereo imaging of the surface. Detailed stereo imaging of surface with the spatial resolution better than 0.2 mm.		
L6. Surface elemental composition	Determine the elemental composition of surface rocks with emphasis on trace elements including the radioactive isotopes of K, U and Th.	1) Measure the Gamma-ray spectrum of the surface induced by the flux of neutrons with energies 14 MeV; 2) Spectrum of gamma radiation from natural radioactive elements of the surface. X-ray Fluorescence (XRF) spectra to determine the elemental composition. 3) Chemical composition of a rocky sample (which must be delivered inside the lander)	• Active Gamma-spectrometer (e.g., AGNESSA); • XRF mode of Mössbauer spectrometer; • Chemical Analyses Package (CAP)	High
L7. Mineral phases	Identification of mineral phases, containing Fe (Fe2+, Fe3+, Fe6+). To address atmosphere and surface evolution along with surface minerals (search for any possible bound water e.g., philosilicates?).	Measure Mössbauer spectra of the surface rocks	Miniaturized Mössbauer spectrometer (e.g., MIMOS2A)	High
L8. Global and regional seismic activity	Assess global and regional tectonic activity	Measurement of planetary seismic background and self-oscillations to constrain crustal thickness	Seismometer	Low
L9. Electromagnetic fields	Determine electromagnetic fields, electrical activity and conductivity of the atmosphere of Venus	Measure of emissions in the range of 10 Hz to100 kHz	Wave package (e.g., GROZA-SAS2)	Low

2.4 Venera-D Joint Science Definition Team

As the stated science goals of Venera-D are consistent with those outlined in the NASA Planetary Decadal Survey (SSB, 2011) and the detailed objectives and investigations identified by the Venus Exploration Analysis Group (VEXAG) (Herrick et al. 2014), a joint IKI-Roscosmos/NASA science definition team was formed to prioritize science objectives, codify investigations that would be of mutual interest to both IKI-Roscosmos and NASA, provide an initial assessment of a mission architecture, identify technology needs and areas of needed laboratory experiments, and elements for collaboration and contribution. The members of the Joint Science Definition Team (JSDT) and their roles are provided in **Table 2.4-1** and **Figure 2.4-1**.

Table 2.4-1. Members of the Venera-D Joint Science Definition Team.

SDT Member	Institution	Expertise
L. Zasova, Co-chair	IKI	Atmosphere
N. Ignatiev	IKI	Atmosphere
O. Korablev	IKI	Atmosphere—IKI POC
N. Eismont	IKI	Ballistics
I. Lomakin	Lavochkin Assoc.	Technology
M. Gerasimov	IKI	Surface & atmosphere chemistry
M. Ivanov	GEOKHI	Surface geology
A. Martynov	Lavochkin Assoc.	Technical
I. Khatuntsev	IKI	Atmosphere
D. Senske, Co-chair	JPL, Calif. Inst. of Tech	Surface geology
S. Limaye	Univ. of Wisconsin	Atmosphere
K. Lea Jessup	SWRI	Atmosphere
T. Economou	Univ. of Chicago	Chemical analysis (APXS)
T. Kremic	GRC	Technology
L. Esposito	LASP	Atmosphere
A. Ocampo	NASA HQ	NASA Study Scientist

Figure 2.4-1. Group picture from the third Venera-D JSDT meeting. Attendees included the director of IKI, representatives from Lavochkin Association, and the NASA office in Moscow.

To direct the work of the JSDT, a joint NASA/IKI charter was established. The tasks of the JSDT are as follows:

1. Identify, prioritize and develop science goals, investigations, and measurements consistent with the current Venera-D concept;
2. Assess the Venera-D mission architecture including possible modular options (e.g., subsystems) for collaboration opportunities and required instrumentation capabilities. Assess technology readiness level to implement the mission concept and identify areas for which development is required;
3. Identify mission components (mission elements/subsystems/instruments) that best lend themselves to potential collaboration. Outline a general maturation schedule needed to support a Venera-D mission for launches in the post-2025 time frame;
4. Assess the precursor observations and instrumentation validation experiments needed to enable or enhance the Venera-D mission (e.g., instrument testing in a chamber that

emulates the chemistry, pressures and temperatures found in the atmosphere or at the surface of Venus);

5. Evaluate how Venera-D will advance the scientific understanding of Venus and feed forward to future missions with the ultimate goal of sample return.

To address these tasks, the JSDT organized itself into three sub-groups, Atmosphere, Surface/Surface atmosphere interaction, and Technology. In the course of its work, individual sub-groups held telecons or had splinter meetings during the full JSDT face-to-face meetings. The full JSDT discussed issues during telecons that took place every other week.

This report of the JSDT is structured in the following manner, Science background and current open questions that can be addressed by Venera-D; Mission architecture; Technology Assessment, Enablers, Challenges, and opportunities for Laboratory Work; Potential Contributions to Venera-D; JSDT Findings and Recommendations; and a Framework for Future Work.

3 Science Background, Current Open Questions and Relation to Venera-D

3.1 The Venus Atmosphere

3.1.1 What We Know About the Venus Atmosphere and Open Questions

Our knowledge of Venus' basic atmospheric properties (temperature, pressure, thermal structure, etc.), and how different it is from Earth has come through the success of the Soviet, U.S., ESA and now, JAXA missions to Venus and began with the discovery of the planet's atmosphere by Lomonosov during its transit across the disk of the Sun in 1761 from St. Petersburg. Earth-based observations of Venus have continued to make significant contributions towards our knowledge of its surface, atmosphere with its global cloud cover, and the thermosphere. The discovery of new knowledge about Venus has brought us more questions than answers.

Venus hosts one of the most extreme atmospheric environments in our inner solar system and one that is dramatically different from that of the Earth at present. The predominantly CO_2 atmosphere with a small amount of N_2 exerts a pressure of about 92 bars on the surface, which is responsible for a surface temperature of ~735 K due to the greenhouse effect despite the planet reflecting almost 80% of incident solar energy back to space. The planet is covered entirely with sulfuric acid haze and clouds, and the atmosphere also harbors other gases such as H_2O, CO, and SO_2, which all have strong absorption bands in the infrared spectral range and trap some of the thermal emission from the surface and the lower atmosphere. With only a slight tilt to the rotation axis, Venus' atmosphere experiences very weak seasonal forcing. The atmosphere is also known to be superrotating relative to the solid planet surface. The Venus atmosphere, at present, has five orders of magnitude less water, than Earth, but Venus could have harbored liquid water on the surface for as long as 2 billion years and could have been the first habitable planet (Way et al. 2016). From a comparative planetology perspective, we are compelled to understand when and how the evolutionary paths of the two planets diverged since both planets were formed from the same region of the protoplanetary disk and the physical properties of the solid bodies are nearly identical in terms of mass, size and density.

Despite the many successful missions to Venus, fundamental questions about the atmosphere remain, primarily because of the constraints of previous observing platforms in terms of altitude access, spatial access, temporal continuity and instrument resolution, and occasionally the lack of suitable or capable instruments for certain altitude regions.

At present, the most prominent open major questions we have about Venus' atmosphere are:

- Why does the atmosphere of Venus rotate faster than the solid planet?
- What is the composition and nature of the UV absorber, and what determines its spatial distribution and evolution?
- When and why did Venus take a different evolutionary path compared to the Earth and what are the mechanisms responsible for Venus' evolution and the process that led to the present climate?
- What are the processes of surface-atmosphere interaction?
- Why aren't the two primary consituents of the atmosphere (CO_2 and N_2) well mixed in the troposphere and show a vertical gradient?

To answer each of these questions, it is paramount that measurements are made using capable instruments both remotely and in situ. The Venera-D baseline mission consisting of an orbiter in a high inclination orbit and a lander descending to the surface has the potential to obtain many of the measurements needed to address a significant set of the outstanding questions listed above about the Venus atmosphere. The science return of the mission might be further enhanced by supplementing the baseline architecture with a capable aerial platform (altitude changing UAV lasting many months or a balloon lasting several weeks)—providing long-term monitoring of the ambient atmospheric circulation within the cloud layer at a small range of altitudes. Additionally, a long-lived surface station could provide critical additional measurements at the surface-atmosphere boundary over a full Venus solar day (~117 Earth days). Inclusion of a long-lived aerial platform or a long-lived surface station could provide for the first time continuous monitoring of the atmosphere over a full Venus solar day. These types of sustained long-term observations are needed for the successful achievement of Venera-D's primary atmospheric science goal: to investigate the superrotation of Venus' atmosphere. In the following sections, we describe how Venera-D could achieve this goal and improve our understanding of the atmosphere.

3.1.1.1 Atmospheric Circulation

Why does the Venus atmosphere rotate faster than the surface everywhere it has been measured in the deep atmosphere? Superrotation of Venus' cloud top atmosphere was discovered more than half a century ago from ground-based images. Its global and vertical structure has now been inferred from UV and NIR images (Mariner 10, Galileo Orbiter, Venus Express and now Akatsuki), and from tracking of the Venera landers, Pioneer Venus entry probes, and VEGA balloons (**Figure 3.1-1**). The Venus Express mission has provided some new facets of the atmospheric circulation and now Akatsuki data are providing new perspectives. One of these is that both the cloud cover and the cloud motions both exhibit periodicities with periods ranging

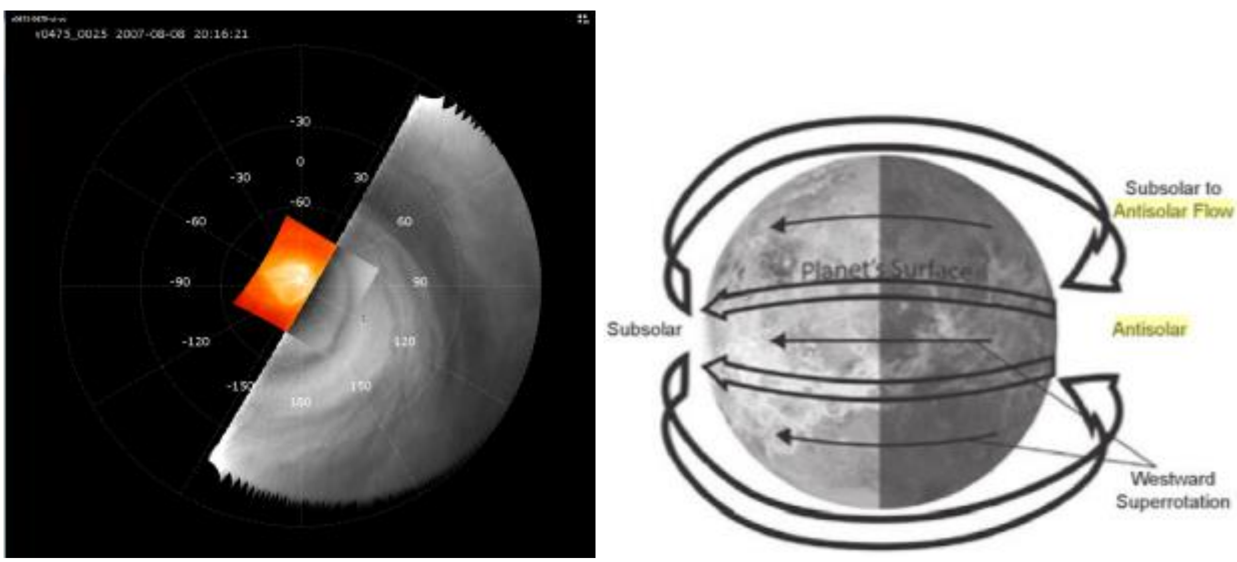

Figure 3.1-1. (*Left*) A composite of VIRTIS image showing the night side view of the polar region and dayside view of the sunlit hemisphere superposed on a 365 nm image taken from the VMC, both mapped in a polar stereographic projection. The dynamical instability shows up in the NIR 5 μm image in the core region of the hemispheric vortex seen in the VMC image which extends to the equator. **(*Right*)** A schematic image of the general circulation of atmosphere of Venus. Zonal flow is indicated by the arrows from right to left on top of these winds is the sub-solar to anti-solar point circulation above the cloud tops (from Bullock and Grinspoon 2013). Zonal super rotation returns at higher levels (>115 km) when the meridional temperature gradient again changes sign.

from the period of superrotation, one Venus solar day, to as long as the Venus rotation period (Kouyama et al. 2013; Khatuntsev et al. 2017; Lee et al. 2015; McGouldrick 2017). Another new discovery is that somehow the cloud level atmosphere is influenced by the surface topography resulting in cloud level albedo variations (Bertaux et al. 2016) and standing gravity waves (Fukuhara et al. 2017).

Thus, the current wealth of observations has raised many tantalizing questions about the maintenance and the global structure of the superrotation. To answer these questions, we need the following:

1. Critical measurements of the wind fields at all possible altitudes, over a lifetime long enough to reliably characterize the mechanisms controlling the atmospheric flow;
2. Detailed mapping of the global characteristics of the solar energy deposition at all possible altitudes;
3. Critical measurements of the spectral properties and temporal evolution of substances that absorb the major fraction of the incident solar radiation in the clouds, particularly at wavelengths between 0.32–0.55 µm;
4. Measurements that are able to characterize the meridional transfer of momentum and heat. Additionally, these measurements need to be made with sufficient spatial coverage over time to resolve the contributions from transports by thermal tides and other waves.

While issues of the radiative balance and energy deposition are discussed in Section 3.1.1.5 we discuss below the results of previous observations of circulation and wind speeds at each altitude level, and the limitations of these observations that we hope to overcome with Venera-D.

Cloud Level and Below. Vertical profiles of wind velocity from the surface up to 60 km were measured by all spacecraft including the Venera and VEGA landers along with the Pioneer Venus probes (the latter down to 12 km). It was found that the wind speed increased from 0.5–1.5 m/s near the surface to 60–70 m/sec at 60 km. Wind speeds at the cloud top and in the low cloud can be directly mapped by tracking cloud motions (Kerzhanovich and Limaye 1985; Gierasch et al. 1997). Venus' circulation patterns, wind speeds, and planetary waves are derived by the analysis of UV images taken on the dayside from the Mariner 10 (Murray et al. 1974), Pioneer Venus (Rossow et al. 1980, 1990; Limaye et al. 1988), and Venus Express (VIRTIS, VMC) (Hueso et al. 2012; Khatuntsev et al. 2013; Moissl et al. 2009), while images in NIR spectral windows allow such measurements on the night side (Sanchez-Lavega et al. 2008). Other measurements related to the cloud levels were achieved through Earth-based tracking of the VEGA 1 and 2 balloons (Sagdeev et al. 1992). This provided insight into the zonal motions at the altitude level of about 53–55 km while floating for 48 hours between midnight and a little after 6 a.m. local time at low latitudes north and south of the equator (Sagdeev et al. 1986). The VEGA 2 balloon (7.5°S) traveled through areas with high instability. It was determined that the highest instability was observed above Terra Aphrodite (Blamont 1986) and, in turn, Young et al. (1987) explained that the motions were affected by gravity waves, generated by the mountains. The wind speed from cloud tracking in UV-images obtained by VMC (Khatuntsev et al. 2013) as well as albedo measurements in the UV (Berteaux et al. 2016) together with cloud top brightness temperature results from Akatsuki data (Fukuhara et al. 2017) confirm the influence of topography on the dynamics in upper clouds.

All these data are sparse and were obtained at different epochs. The most complete is the VMC VEX data (8 years of observations of predominantly the southern hemisphere), but gaps still exist in the coverage of latitude, local time, and longitude. Akatsuki is now providing an equatorial view to fill in some of these gaps. Measurements within the atmosphere have not been made since the VEGA landers descended to the surface in 1985. All in all, we only have several wind profiles below the clouds that were measured by landers and from the VEGA 1 and 2 balloons in the middle clouds. ***A long-lived atmospheric platform (>30 days) is needed to map the circulation, planetary waves and wind speed to estimate the structure of the thermal tides and other waves and turbulence (within the floating altitude ranges) that are important to understanding momentum transports. Venera-D has the opportunity to provide the required long-term element. Monitoring of the temperature structure on the day and night sides below the clouds in the mm-spectral range (down to 10–20 km) will also help to understand the circulation below the clouds.***

From the Venera-D orbiter, information about the winds at low cloud levels can be obtained by images in the NIR spectral windows on the night side. These together, with dayside winds from cloud tracking in the UV and NIR would improve upon our knowledge of the circulation in the cloud layer.

Mesosphere (60–90 km). Venus is a slowly rotating planet and on average the atmospheric flow is believed to be close to being in cyclostrophic balance. Estimates of the ambient wind have been made by the calculation of the balanced wind under cyclostrophic balance from a limited number of radio occultations obtained from the Pioneer Venus and Venus Express orbiters (Newman et al. 1984; Piccialli et al. 2012). The geometry of the radio occultations do not allow for systematic measurements, so the calculation of the cyclostrophic wind from these data must be done after zonal averaging. Thermal zonal (cyclostrophic) winds in the northern hemisphere mesosphere were obtained from thermal IR spectrometry via the OIR on Pioneer Venus (Schofield et al. 1983), the Fourier Spectrometer on board Venera-15 (Zasova et al. 2007), and the VIRTIS VEX (Piccialli et al. 2008). The local time behavior of the zonal wind speed (also in the mid-latitude jet) was observed by Venera-15 (FS-V15).

The cyclostrophic balance breaks down at 80–90 km because the dynamical regime becomes more complex and cannot be described by simple equations of cyclostrophic balance. Observations indicate that below these levels the temperature increases from the equator to the pole nearly monotonously and the meridional wind is directed mainly from the equator to the pole. Below 60–65 km, the temperature decreases from the equator to the pole and the meridional flux is directed to the equator. This may represent a Hadley cell at the cloud level. Direct measurements of the wind (VMC, Khatuntsev et al. 2013, 2017) confirm the direction of the meridional wind at 65 km to the pole and at 55 km to the equator. Thus, strict cyclostrophic balance cannot be occurring on Venus all of the time as it would preclude meridional transport of heat and momentum, both required to maintain the observed circulation.

Upper Atmosphere above 90 km. The main method to study the circulation above 90–140 km has been through nadir observations of the distribution of the non-LTE emissions of O_2 (Piccioni et al. 2009), NO (Stiepen et al. 2013), and CO_2 (Drossart et al. 2007). Additionally, gravity waves were identified in the vertical profiles of the O_2 nightglow at 90–100 km (Altieri et al. 2015) and in the horizontal distribution of the CO_2 dayglow at 150 km (Drossart et al. 2007). Atomic hydrogen is used as a tracer of thermospheric activity (Chaufray et al. 2012; Hodges and Tinsley 1982) and Doppler shifts of spectral lines can provide some clues about the sub-solar anti-solar circulation near 110 km level (Clancy et al. 2012).

No previous observing campaign to date has provided the wind, temperature, pressure, and atmospheric structure data needed at the required vertical, horizontal and temporal sampling continuously over the duration of one Venus day. Consequently, the processes that drive the superrotation remain ill defined. As stated above, to resolve these issues requires both a study of the circulation patterns and an understanding of energy transfer. This latter issue relates both to our knowledge of the thermal structure discussed in detail in below in §3.1.1.2 and the importance of Venus' UV absorber which is discussed in detail in §3.1.1.5.

Previous missions were unable to achieve the required global coverage or vertical resolution. Venera-D has the opportunity to provide the required long-term and systematic measurements needed to map the upper atmosphere wind speeds. The choice of the orbit and the instrument capabilities required will need to be investigated further.

3.1.1.2 Atmospheric Thermal Structure

Characterization of the thermal structure of the atmosphere is crucial to understanding the processes that drive the superrotation both from the implied pressure field that actually drives it and also to estimate the energy balance. Ideally, we would measure the temperature fields in coordinates of latitude, longitude and local solar time with high accuracy, from the surface to thermosphere, simultaneously while measuring the composition of the atmosphere, cloud properties and thermal balance. As of now, these measurements have been only obtained in very specific altitude ranges at varying local times from infrared remote sensing, radio, solar infrared and stellar ultraviolet occultations, and from entry probes.

Vertical profiles of temperature, pressure, density in the troposphere (below 60 km) as well as the surface temperature, were measured by the Venera and VEGA-2 landers (Linkin et al. 1987) and the Pioneer Venus probes (Seiff et al. 1980). In addition, measurements were obtained up to the low thermosphere. The VEGA-2 temperature profile was obtained with a high vertical resolution and accuracy of 1 K. The temperature profiles, obtained before VEGA, were summarized in the Venus International Reference Atmosphere, VIRA (Seiff et al. 1985). The VEGA 2 static stability profile confirmed that the atmosphere is generally stable except for two altitude intervals, 50 to 55 km, and 18 to 30 km while the peak of high stability is observed around 15 km, which is present in the VIRA profile, but is not very pronounced. Below this peak, the VEGA 2 profile shows the highest instability in the of range 2–4 km altitude. Above the tropopause level the Venus atmosphere is stable.

The difference between temperatures at isobaric levels, measured by different probes, was found typically to be within 10K. There is insufficient information to identify the reason for the difference but it may be due to temporal, local time, spatial variation, thermal tides, or different kinds of waves as well as uncertainties in the measurements.

The Pioneer Venus, Venera-15 and Venus Express orbiters have also provided observations that have shed insight into how the thermal structure is forced by diurnal variations. The three dimensional thermal structure of the atmosphere has been inferred from the Pioneer Venus OIR (Taylor et al. 1980), Venera-15 Fourier spectrometry (Zasova et al. 2007) data on both the day and night sides, and VIRTIS VEX (Migliorini et al. 2012) on the night side using the absorption profiles of the CO_2 (4.3 or 15 µm band). The spectral range, spectral resolution, and observation geometry gave Venera-15 the ability to retrieve from each spectrum, in self-consistent way, vertical temperature profiles (55–100 km) along with aerosol and SO_2 and H_2O profiles in the clouds. Solar related behavior has also been identified in the temperature and aerosol profiles of the mesosphere along with the distribution of the thermal tides vs. latitude and altitude and the solar related dependence of the altitude of upper clouds.

The thermal tides result from the absorption of solar energy, deposited on Venus, in the upper clouds (within 10 km) by an ‘unknown’ UV-absorber(s) which provides energy to support the superrotation. Therefore, to solve the superrotation problem, it is crucial to obtain detailed maps of the phases and amplitudes of the diurnal, semi-diurnal tides, and smaller scale waves in the thermal structure and winds distribution in coordinates (pressure, latitude) with high vertical and horizontal resolution extending from the surface to upper atmosphere.

There are additional unique features in Venus’ thermal and dynamic structure that need further investigation. In the mesosphere at high latitude (>75°) the core region of the hemispheric vortex circulation of Venus (“eye of the vortex”), has been observed in the thermal IR, and is characterized by temperatures higher than the surroundings by 10 K. An “S” shaped dipole feature was discovered by OIR Pioneer Venus (Taylor et al. 1980) over the north pole. A similar feature was observed over the south pole by Venus Express (Piccioni et al. 2007). This feature has been explained as a dynamical instability (Limaye et al. 2009) common to vortex circulations such as in tropical cyclones. But many details of the vortex organization of the circulation are unknown. The vertical temperature profiles (FS-V15) allowed the position of the temperature maximum in the vortex to be identified at 58–60 km, but the vertical circulation in the core region remains unknown. The core region of the vortex in Southern hemisphere was seen to be asymmetric and not precisely centered over the pole by VIRTIS VEX (Luz et al. 2011) and similar behavior was seen from VMC.

Another puzzling structure is the existence of a “cold collar” between 65–75° latitudes in both hemispheres. The cold collar exhibits a tidal nature. The diurnal and semidiurnal amplitudes exceed 10 and 6 K respectively (at latitude of 70°N, altitude of 62 km). It lies below 72 km, above this level the temperature generally does not differ from its surrounding (Zasova et al., 1992). The maximum difference in temperature between areas near the evening and morning terminators was observed to be 30 K (FS-V15), with a higher temperature in the afternoon. Above 90 km, in the transition region, the temperature variation is also connected to the thermal tide with diurnal and semidiurnal amplitudes both of 5 K, at low latitudes, providing temperature difference in excess of 20 K at 95 km with lower temperature in the afternoon, compared to the morning terminator (Zasova et al. 2007). Gravity waves are also generated in this region, revealed through airglows. The Pioneer Venus OIR (Schofield and Taylor 1983) also observed solar related behavior of the cold collar, as well as thermal tides above 85 km. The thermal tides have also been detected as well from cloud motions in data returned from Mariner 10 to Venus Express (Limaye and Suomi 1981; Limaye, 1988, 2007; Toigo et al. 1994; Peralta et al. 2007, Sanchez-Lavega et al. 2008; Khatuntsev et al. 2013) and modelled (Pechman and Ingersoll 1984).

The measurements described only provide part of the picture relative to the nature of the thermal tides and the thermal structure that supports it. The available data pose new questions that help define the objectives of the Venera-D mission. Overall**,** the goal of Venera-D is to fill the gaps in the spatial and temporal coverage and vertical resolution from previous observations of both the circulation and the thermal structure of Venus’ atmosphere so that questions about the dynamics of the atmosphere that remain open or have been created by these new observations can be addressed. Currently, these questions are:

1. How does the meridional and vertical transport of angular momentum that is required to maintain the superrotation take place in the atmosphere?

2. What is the vertical and meridional transfer of heat that is required to maintain the radiative balance of Venus?
3. What is the exchange of angular momentum between the surface and the atmosphere?

These open questions can only be answered by sustained, systematic measurements of the ambient wind and temperature (proxy for pressure) in three dimensions for at least a few solar days at all latitudes and longitudes. Needless to say, a single mission such as the baseline Venera-D cannot expect to make such comprehensive measurements and hence we must compromise by using remote sensing observations from orbit (3 years) supplemented by in situ atmospheric measurements at least in the achievable altitude range to add to the in situ measurements to be made by the Venera-D lander during its descent to surface. The ensemble measurements would enable the spatial and vertical structure of the winds to be determined. A variety of techniques and instruments in orbit, on a lander, and in the atmosphere would be required. Cloud motion measurements at different wavelengths in reflected solar and emitted short wave infrared images have been shown to yield reasonable estimates of the ambient wind as a function of different vertical levels at day and night. However, cloud motions on the *day and night* hemispheres cannot be obtained *at the same altitude or pressure level* by currently available capability and hence in situ measurements are required in order to determine the precise structure of planetary scale waves (including thermal tides) as well as smaller scale waves that contribute to the meridional and vertical transports of energy and angular momentum.

Measurements of the circulation from an orbiter and an atmospheric platform is expected to shed light on other significant aspects of the Venus atmosphere such as:

- Characteristics of the Hadley circulation
- The temporal behavior of the global circulation in hemispheric vortices
- Structure of the thermal tides
- Circulation links to the surface topography and the responsible mechanisms

3.1.1.3 Composition of the Atmosphere

To characterize the origin and evolution of Venus, from its formation to the present, accurate assessment of the composition of the atmosphere is essential. Like the Earth and Mars, the atmosphere of Venus seems to have substantially evolved from its original composition. Whether the major processes that shaped the atmospheres of the Earth and Mars—such as impacts of large bolides and significant solar wind erosion—also occurred on Venus is largely unknown. Detailed-chemical measurements of the composition of the atmosphere, in particular, the noble gases and their isotopes along with light elements and isotopes, will aid in understanding if the modern (secondary) atmosphere is a result of degassing from the interior, or if it resulted from impacts by comets or asteroids. Likewise, it is imperative to determine how the atmospheric abundances of water, sulfur dioxide, and carbon dioxide change under the influence of the exospheric escape of hydrogen, outgassing from the interior, and heterogeneous reactions with surface minerals.

Another issue that must to be resolved is the accurate measurement of the vertical profile of Venus' bulk atmosphere constituents. Currently available measurements of the bulk composition of the atmosphere provide surprising and conflicting results that contradict our expectations of the atmospheric structure and need further investigation to be adequately explained. For example, the highest accuracy measurements of N_2 concentration have come from the Pioneer Venus Large Probe (PVLP) (Oyama et al. 1980) and MESSENGER (Peplowski and Lawrence 2016). Combining these observations implies that a vertical gradient in the N_2 concentration (%) exists such that the value decreases with altitude from 5.5 at 60 km to (4.6 ± 0.14) at 51.6 km, to (3.54 ± 0.04) at 41.7 km to (3.41 ± 0.01) at 21.6 km altitude (**Figure 3.1-2**). This result contradicts the expectation that the atmosphere is well mixed and therefore constant with altitude in the lower thermosphere and troposphere. Inferences of the CO_2 concentrations also obtained by Pioneer Venus show that the CO_2 gas concentration varies with altitude, but in this case the gas density increases with altitude (Oyama et al. 1980). This result is also in conflict with the expected atmospheric profile. The question arises, is this a real variation in the vertical profiles or is the use of the hydrostatic law used to infer the thermal structure no longer applicable (e.g., could the gases be behaving as super critical fluids)? To further verify and interpret the available atmospheric structure results, high vertical resolution and high precision measurements of both the bulk and trace species are needed. These types of measurements can be derived from a well-designed Venera-D lander and probe that may be included on the lander. Additionally, should a mobile aerial platform be added to the mission architecture, with the proper design, such a vehicle might operate from the top of the atmosphere to the altitude of float/fly of the UAV and could provide critical measurements on the bulk atmosphere state between 50 and 60 km altitude

The outstanding questions are:

- What are the noble gas isotopic ratios that can provide clues to the origin and evolution of the Venus atmosphere?
- What are the isotopic ratios of the light elements, crucial to understand the origin of the atmosphere?
- What is the N_2 mixing ratio profile from surface to the homopause level? What causes the observed vertical gradient of N_2?
- What are the vertical profiles of trace species in the Venus atmosphere that play a role in the vertical cloud structure globally? The abundances of SO_3, SO and elemental sulfur in the cloud layer are needed to understand the sulfur cycle and chemistry, particularly near the base of the cloud layer. Below this layer, CO and different sulfur species (COS, SO_2, S_2, H_2S) are needed down to the surface

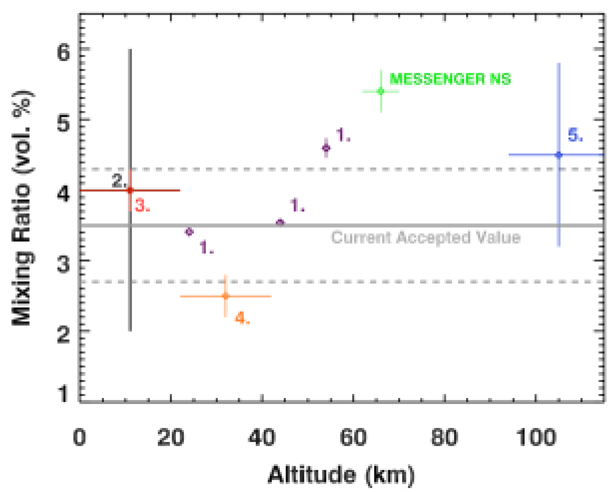

Figure 3.1-2. Peplowski and Lawrence (2016) present this figure comparing the MESSENGER Neutron Spectrometer (green) results to previous N_2 measurements and the accepted VIRA value which is an average of all in-situ measurements made prior to 1980. The measurements presented for comparison are: 1. Pioneer Venus Large Probe Gas Chromatograph, 2. Pioneer Venus Large Probe Mass Spectrometer, 3. Venera 11 and 12 Mass Spectrometer, 4. Venera 12 Gas Chromatograph, and 5. Pioneer Venus Multiprobe Bus Mass Spectrometer, from von Zahn et al. 1983.

to constrain the oxidation state of the lower atmosphere and surface, and determine the stability of various minerals. (Bezard and de Bergh 2007).

3.1.1.4 Clouds

The clouds play an important role in the thermal balance through the absorption of incident solar energy on the dayside and emission to space on the night side. They participate in chemistry of the atmosphere, trace the circulation of the atmosphere through contrast features, and reveal the presence of gravity waves and thermal tides.

For the detailed characterization of the thermal balance it is necessary to know the cloud structure, composition and microphysics. The measurements should allow for an adequate analysis of the cloud opacity which is an input component to the greenhouse effect, and the cloud albedo levels which directly impacts the thermal balance. The fact that the upper clouds of Venus are composed mainly of ~1 µm radius particles has been known since the last century from polarization measurements (Lyot 1929), but the composition of the particles with a high concentration of sulfuric acid was not identified until nearly 50 years later (Hansen and Hovenier 1974). Vertical profiles of aerosol distribution were successfully obtained during the descent of the Venera 9 and 10 landers (Marov et al. 1980), Pioneer Venus Large Probe (Knollenberg and Hunten 1980), and the VEGA 1 and VEGA 2 lander descents (Moshkin et al. 1986). Clearly, the measurements are sparse, and information about aerosol profiles below 30 km is somewhat contradictory between these measurements.

The clouds of Venus have a vertical depth of ~20 km (τ ~ 20 - 40). There are three separate layers of clouds with each layer showing its own peculiarity. Surprisingly, the upper cloud properties are similar over the entire planet except in high latitudes poleward of ~70º. In general, the clouds are composed of sulfuric acid aerosols but other species are present depending on the altitude. Spectral observations from Venera-15 (Zasova et al. 2007) indicate that sulfuric acid is the main compound of cloud particles at all latitudes, from the equator to the poles. In the diffuse upper cloud layer, sulfuric acid droplets are formed, the middle clouds containing sulfuric acid are convective, the low cloud layers are patchy, and the abundance of sulfuric acid in gaseous phase admit that low clouds are condensing. Other aerosol and/or particle species may also be present. For example, in the low cloud, the VEGA 2 Lander found sulfur, phosphorus, and chlorine particles (Surkov et al. 1987). The size of the cloud particles are distributed in three modes: the Mode 1 particle radius, r, is 0.2–0.3 µm, these particles exist from 30 to 90 km; the Mode 2 with radius 1 µm in the upper clouds and Mode 2′ with radius of 1.4 µm in the middle clouds; and Mode 3, with radius of 3.65 µm in the middle and low clouds, below 57 km (Pollack et al. 1980).

The outstanding issues are:

- Rigorous identification of the composition of the Modes 1 and 3 particles
- Rigorous proof of the existence and composition of crystals in the low clouds
- Characterization of the structure of the aerosol layers and their composition below the clouds; Is it possible for these layers to exist down to the near surface layer (indications were found by VEGA-2)?
- Characterization of the vertical and horizontal structure of the clouds, their local time variations, and solar related structure.
- Insights regarding the influence of the surface-atmosphere interaction on the cloud formation/dissipation and cloud circulation.

3.1.1.5 Dynamics Tracers and the Cloud Contrasts

The Role of the Unknown UV Absorber. Venus' disk is practically featureless in the VIS and NIR spectral ranges (contrasts maximum of 2–3 %), but in the UV they reach 30% at 365nm (**Figure 3.1-3**). The albedo of Venus decreases from a value of ~0.8 at longer than 550 nm to as low as 0.3 at UV wavelengths. The cloud contrast peak is observed at 365 nm. The UV contrasts, even though we do not know their origin, enable the global circulation to be measured by using them as circulation tracers for Venus' cloud top dynamics. In fact, it was by tracking UV features that Venus' cloud top superrotation was first discovered. Providing a way to derive wind speeds and cloud motions, the UV absorber is responsible for 50% of the energy deposit on Venus. Notably, UV-absorption at 0.32–0.5 µm was observed to disappear below 58–60 km by the PV-probes (Tomasko et al. 1985) and VEGA (Bertaux et al. 1987). Thus, absorption by Venus' UV absorbing species has primarily been associated with the cloud tops. Since the atmospheric circulation is directly linked to the solar ultraviolet radiation, absorbed in the cloud layer of Venus, absorption by these species results in the generation of the thermal tides and consequently provides the energy to drive the superrotation (Gierasch et al. 1997). At $\lambda <$ 0.32 µm the main absorbers are SO_2 and SO and this absorption continues in the clouds and below (Bertaux at al. 1996).

Currently, the distribution and the composition of the UV absorbing species are also poorly known, although SO_2 is certainly a contributor. As described above, there are a few available profiles of UV flux in the atmosphere that suggest that the UV absorber is present at and below the cloud tops in the upper clouds. However, it is a long-term debate as to whether the cloud level abundance of the absorber is a result of material upwelled from below, or results from chemical reactions of upwelling and downwelling species. In terms of composition, currently the strongest candidates for 'unknown UV absorber' are allotropes of sulfur (Carlson et al. 2016) and 0.7% $FeCl_3$ in sulfuric acid (Zasova et al. 1981). Both species fit well the UV Venus spectrum (0.32–0.50 µm), but face some difficulties. Zasova et al. (1981) pointed out that the lifetime of a solution of $FeCl_3$ in H_2SO_4 is of 2 weeks at room temperature (~ temperature in the middle and low clouds) and the conversion of $FeCl_3$ to $FeSO_4$ results in a white color that may explain the disappearance of the UV absorption. For this hypothesis to be supported there must be a resupply of $FeCl_3$ chemically or through transport from the surface. However, Krasnopolsky (2016) concludes that sulfur abundance measured is insufficient and only $FeCl_3$ is the likely absorber.

There may be another possible source of the UV contrasts. Recent information about properties of acid resistant bacteria such as *Thiobacillus Ferrooxidans* indicates that these species have absorptive signatures in UV and NIR spectral ranges. These data allow us to speculate about possibility of a biogenic origin of the UV absorber.

New observations providing extensive and temporally continuous observations of the cloud layers from in situ could significantly improve our ability to sort out the viability of the most likely potential candidates for the UV absorber.

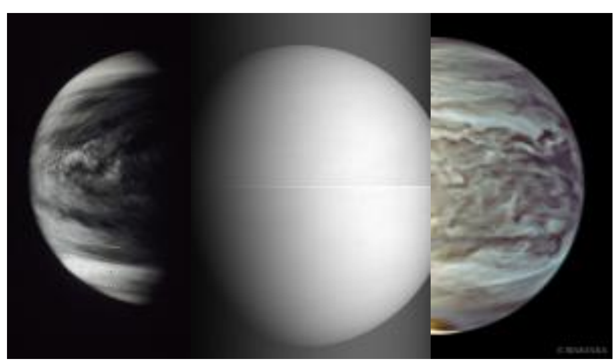

Figure 3.1-3. Images of Venus in reflected sunlight in the UV (left) and at 1.0 µ (middle). Composite image of Venus' nightside atmosphere in the emitted near IR (1.74, 2.26 and 2.32 µ). Credit-NASA, JAXA, JAXA

The Role of NIR Imaging. Night side IR imaging of Venus' disk between 1–3 µm (**Figure 3.1-3**) reveals contrasts (~2–3%). Images, obtained by VMC VEX at 1 µm enable the tracking of contrasts to calculate the wind at the cloud tops related to the middle cloud (55 ± 4 km), the effective level from which the 1 µm NIR radiation originate (Khatuntsev et al. 2017). The origin of the contrasts is not certain and they may possibly be related to variations in the clouds opacity. These NIR contrasts do not correlate with those observed in UV images on the dayside

Tracking the cloud structures in the low clouds on the night side allows for the winds at lower altitude to be calculated. To accomplish this, there are several windows in the CO_2 bands in the NIR (1, 1.18, 1.74, 2.3 µm). The structure of the low clouds evident in the images in this wavelength range is similar, but with different contrasts. The highest contrasts are in the 2.3 µm window, making it the most reliable for tracking. The low clouds are patchy, so, possibly, the contrasts are connected to different cloud opacities.

Barstow et al. (2012) use 2.3 µm VIRTIS images to retrieve data about the microphysical and chemical composition of Venus' clouds, suggesting that variations in the acid concentration and H_2O and CO abundance are recorded in the images—specific conclusions regarding the relative importance of dynamics and chemistry in maintaining the observed variability is deferred until in situ observations can provide definitive insight into the vertical motions and thermal structure of the atmosphere.

The Path Forward. Until observations are obtained that can characterize the distribution, vertical profile and lifetime of the Venus UV absorber and NIR contrasts, as well as the thermal structure and vertical motions of the atmosphere, the open questions about Venus' dynamic tracers will remain:

- What is a nature of the UV absorber (organic, inorganic, aerosol, gas, etc.) and what controls its distribution?
- What causes the UV and NIR contrasts?
- What are the impacts of the UV contrasts on the radiative balance?

Venera-D would use instruments on the orbiter, lander, and any other available in situ element to help resolve these questions. For example, detailed long-term UV spectroscopy in combination with Raman LIDAR observations of the cloud layers would be an invaluable way to thoroughly document the spectral properties of Venus' atmosphere at the altitude level where the UV absorber is anticipated to be present. The long-term observations could be used to uniquely identify the composition (and better document the lifetime) of the UV absorbing source based on a comparison to the measured optical properties of the candidate species in the 0.27–0.5 µm range.

3.1.1.6 Solar Wind-Venus Interaction and Venus Magnetosphere

As Venus does not have intrinsic magnetic field, the solar wind interacts directly with Venus atmosphere (**Figure 3.1-4**). As a result, Venus' upper atmosphere has a cometary type interaction with the solar wind flow. That is, the flow past Venus is loaded by planetary ions formed in the solar wind flow due to solar UV ionization. This pick-up of planetary ions leads to the development of an accretion magnetosphere and bow shock. The solar wind induced mass-loss is an important component of Venus' atmospheric loss processes.

Plasma and magnetic field experiments on Venera-9 and Venera-10 in the 1970s provided the initial data on Venus' solar wind interaction and magnetosphere formation. (Vaisberg et al. 1976). Important follow-on investigations of the magnetic barrier and magnetic tail were performed by the Pioneer-Venus Orbiter (Russell and Vaisberg 1983). A Model of the induced magnetosphere (Vaisberg and Zelenyi 1984; Zelenyi and Vaisberg 1985) was developed based on these experimental data. To further advance the field, Venus Express also performed investigations of the solar wind interaction with Venus (Barabash et al. 2007).

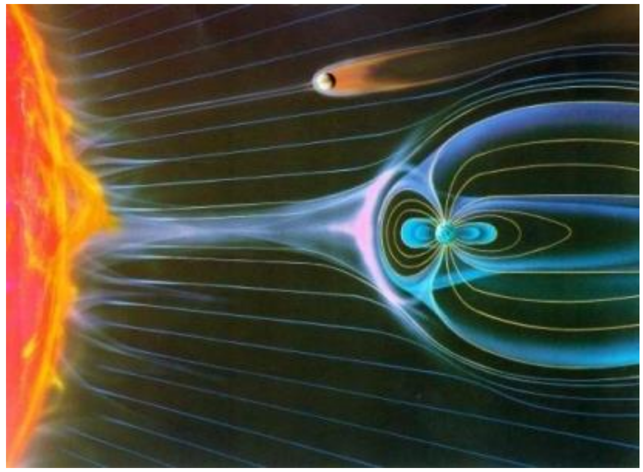

Figure 3.1-4. Artist's impression showing how the solar wind shapes the magnetospheres of Venus (shown with a brown tail, closer to the Sun) and Earth (shown in blue). Both planets are roughly the same size. Venus is closer to the Sun, at roughly 0.7 AU (Astronomical Unit) while Earth is located at 1 AU. Unlike Venus, Earth has an internal magnetic field which makes its magnetosphere bigger. The lines coming out of the Sun symbolize the propagation direction of the solar wind. Credit: ESA - http://www.astrobio.net/also-in-news/a-magnetic-surprise-from-venus/#sthash.emLmRyIQ.dpuf

Even with the work completed by Venus Express, there are outstanding problems in the study of the solar wind-Venus interaction. They include:

- Determination of the mass-composition of planetary ion outflow, besides H+, He+, O+, and its variations under varying conditions and in different regions of Venusian magnetosphere
- The measurements of the velocity distribution of escaping ions to investigate loss and acceleration processes
- Investigation of the structure of the thin magnetospheric boundary with high temporal plasma and magnetic field measurements in order to understand the origin of this boundary
- Investigation of mass-loading processes at an atmospheric obstacle
- Investigation of acceleration processes at current layers

3.1.2 Needed Measurements

To advance our understanding of the dynamics, structure, and composition of the Venus atmosphere and plasma, the following measurements are required:

1. Mapping of the vector wind fields at the different levels in the atmosphere from the surface, low atmosphere, to the thermosphere. These measurements are needed to assess the atmospheric thermal structure, dynamics, convective behaviors, and thermal balance as a function of altitude and horizontal distribution. The required measurements could be obtained from the orbiter, lander and a supplemental aerial platform combined with a long-lived surface-station. These measurements are also critical for the study of the superrotation source mechanism, and, in this case, it is required that the measurements be obtained near continuously over one full Venus day.
2. Measurements that map thermal tides, gravity waves, and planetary waves, which includes mapping information regarding the thermal structure, solar-related behavior of

the clouds, and wind from UV and NIR spectroscopy and imaging. Measurement of temperature profiles from the surface to 140 km altitude (from lander, orbiter, atmospheric platform and long-lived station on the surface).

3. Measurements that map the thermal balance—this includes mapping of the wind, pressure, and temperature fields as well as detailed measurements of the composition of the atmosphere and associated aerosols as a function of altitude, local time, latitude and longitude.
4. Measurements to help understand the processes associated with the greenhouse effect. This includes mapping of the composition and abundance of the atmosphere and associated aerosols as a function of altitude at all latitudes, as a function of local time, and as a function of latitude/longitude. Spectroscopic imaging of the clouds remotely and in situ in order to identify the location and composition of the UV absorber.
5. Measurements to help infer the origin and evolution of the atmosphere. This requires accurate measurement of the composition of the atmosphere, including the noble and light elements and their isotopes as a function of altitude and horizontal distribution. The required measurements could be obtained by using in concert instruments proposed for the orbiter, lander, and aerial platform (from the lander—vertical profile, aerial platform — horizontal distributions), including vertical profiles of the main components N_2 and CO_2.
6. Measurements to help constrain microphysical processes within the atmosphere. This requires measurements that map the chemical composition of the clouds and aerosols and the acquisition of measurements that can assess the size and shape of the aerosols. This latter measurement may help to identify the unique distribution of the UV-absorber and the H_2SO_4 aerosol, which help to segregate the role of the UV-absorber and the H_2SO_4 condensate in microphysical processing. These types of measurements are best accomplished using remote and direct measurement of the aerosol properties from payloads aboard the lander and aerial platform with the capability to map both the vertical and horizontal distribution of the aerosol and UV absorber species from orbiter.
7. Measurements of the magnetic field, ion, and electron characteristics, including energetic ions and electrons, ion composition, and plasma waves. The outstanding problems in the study of the solar wind-Venus interaction will be solved by the plasma-suite located on the orbiter and sub-satellite.

Previous missions have provided significant insight into many aspects of Venus atmospheric studies. The new knowledge that has been gained from these missions define the next Venus atmospheric investigations. Venera-D's baseline mission, which consists of an orbiter and a lander, could fulfill these investigations by using instruments with improved capability. In particular, instruments on the orbiter would have higher spatial and spectral resolution, greater mapping capability at UV and IR wavelengths than previously flown. The orbiter would have instruments with the capability to obtain critical measurements from the surface (at night side) to the thermosphere. The lander instruments would have higher spectral resolution and sensitivity and improved capabilities relative to those flown on the Venera and VEGA landers, allowing for high accuracy meteorological and compositional measurements during descent.

The JSDT emphasizes that to fully study the superrotation of the atmosphere, the atmosphere must be monitored both remotely, in situ, and on the surface on a long-term basis (months). The single-trajectory measurements that would be obtained from the lander (during descent) would be extremely valuable because of their high accuracy, but insufficient to meet the need of long-term monitoring of the atmosphere over a full Venus day. The VEGA balloons have illustrate the possibilities and importance of long-duration measurements in the atmosphere, particularly within the cloud layer. The JSDT considered potential platforms such as variants of the constant level VEGA type balloons as well as the Pathfinder prototype of the solar powered Venus Atmosphere Mobile Platform (VAMP) currently under development by the Northrop-Grumman Corp. The VAMP/Pathfinder platform would be capable of flying within a range of altitudes within the cloud layer (~50–62 km) and is being developed to operate over the 117 Earth days needed for complete monitoring over one full Venus day. With the appropriate payload, the VAMP/Pathfinder mobile aerial platform could acquire crucial observations of the atmospheric structure, circulation, radiation, composition (light and noble gases as well as the isotopologues of both the bulk (CO_2, N_2) and trace gas species such as S, O, etc. along with cloud particles/aerosols and the unknown ultraviolet absorber(s).

Another set of important measurements that could have a significant impact on our understanding of the superrotation are long-term meteorological measurements on the surface. These measurements could be obtained from a proposed long-live station—and multiple stations could provide enhanced surface coverage by extending the capability of the Venera-D mission to several points. Such a station could provide sporadic monitoring of meteorological parameters at the surface over a long period of time (months), possibly identifying the origin of gravity waves, which surprisingly have been evident in the atmosphere over a broad altitude range extending up to at least 100 km. Additionally, the long-lived surface stations could help to track planetary waves, tides, turbulence, and momentum transfer from the surface to atmosphere. Currently, a long-lived wind-powered station is being developed by NASA/GRC that could be included as an instrument within the anticipated mass constraints for the payload of the lander. The successful development of this station would represent a significant advance in the capabilities from available technology and could result in significant advancement in our ability to explore Venus.

3.2 Science at the Surface of Venus

3.2.1 Venus Geology

The strong greenhouse effect on Venus limits the range of possible geological processes operating on this planet. The surface temperature, ~500°C, and apparently low temperature/pressure gradients in the lower atmosphere cause the hyper-dry, almost stagnant near-surface environment. They preclude the water- and wind-driven geological processes and, thus, the common Earth-like geological record of sedimentary materials cannot form in the current Venus environment. Only three geological processes are important on the planet: volcanism, tectonism, and impact cratering.

There are only about a thousand impact craters on Venus. This means that: 1) the surface of the planet is relatively young (the mean age estimates vary from ~750 to ~300 Ma (Schaber et al. 1992; Phillips et al. 1992; McKinnon et al. 1997) and 2) the contribution of impact craters to resurfacing is minor. Only volcanism and tectonics were the principal geological processes during the observable geologic history of Venus (**Figure 3.2-1**).

Regardless of the volcanic and/or tectonic nature, there are two classes of Venusian landforms: simple and complex. The morphologically homogenous terrains represent the simple landforms; their homogeneity suggests that they formed under the dominance of a specific process. Examples of the simple terrains/landforms are lava plains with a specific morphology or

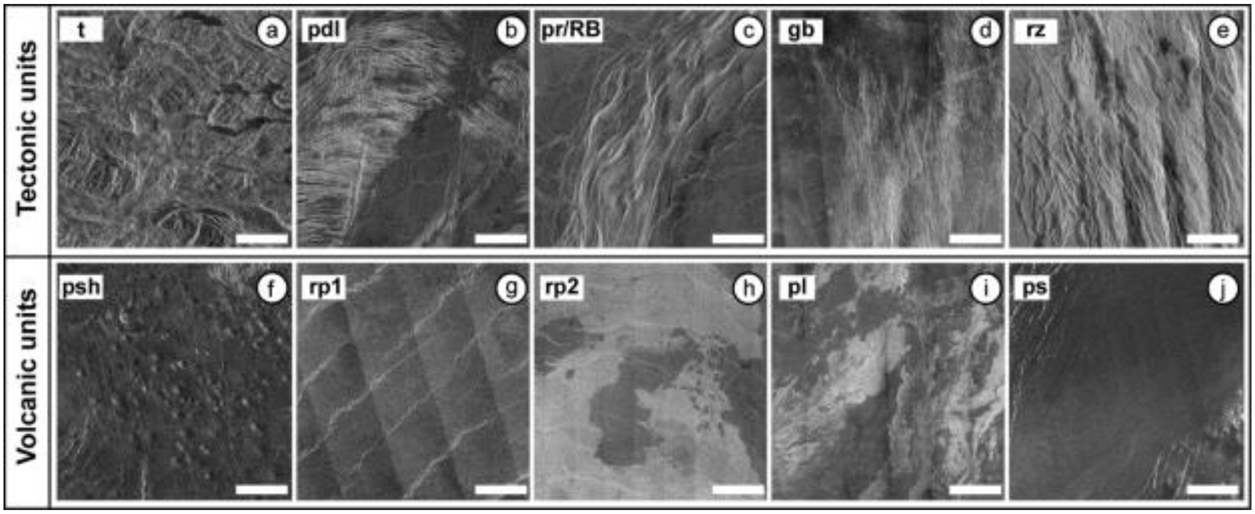

Figure 3.2-1. The major tectonic and volcanic units that make up the surface of Venus. Each scale bar is 25 km, North is up.

graben swarms. When the simple terrains are tied by common evolution and aggregated, they produce complexes. Coronae represent classic examples of the complex terrains.

The simple terrains constitute morphologically homogenous units that establish the base for the unfolding of the geologic histories of planets (Wilhelms 1990). Inspection and comparison of units mapped by many geologists on Venus have shown that a restricted number of units adequately describes the geology in different and remote regions of the planet (Basilevsky and Head 2000). The repeatability of these units over the surface of Venus allows compiling of a global geological map of the planet that shows the distribution of units in space and time. Since the morphologically distinct units are related to specific geological processes, the geological map allows tracing the changes of the rate and style of geological activity, expressed in resurfacing, as a function of time (Ivanov and Head 2011).

Analysis of the global geological map reveals that the observable geologic history of Venus consists of three different regimes of resurfacing: 1) the global tectonic regime, 2) the global volcanic regime, and 3) network rifting-volcanism regime (**Figure 3.2-2**) (Ivanov and Head 2015).

The Global Tectonic Regime. The tectonic resurfacing dominated during the earlier stages of the observable geologic history of Venus resulted in the formation of strongly tectonized terrains (**Figure 3.2-1**) such as tessera (t), densely lineated plains (pdl), ridged plains/ridge belts (pr/RB), and groove belts (gb). Exposures (minimum area) of these units comprise ~20% of the surface of Venus (**Table 3.2-1**). The apparent beginning of the global tectonic regime is related to the formation of tessera, which is among the oldest material units on the planet and may represent the only "window" into its far geological past. The age relationships of tectonic structures within tesserae indicate that this terrain is the result of crustal shortening and may a mosaic of crustal blocks (Senske 2010). The shortening of the crust suggests that the global tectonic style during the tessera formation included elements similar to plate tectonics such as large-scale underthrusting. No morphologic evidence for plate tectonics was found on Venus among the landforms that postdate tessera. Densely lineated and ridged plains are partly overlapping in time with tessera. Formation of groove belts manifest the later phases of the global tectonic regime. and the majority of coronae formed synchronously with the development of groove belts (**Figure 3.2-2**).

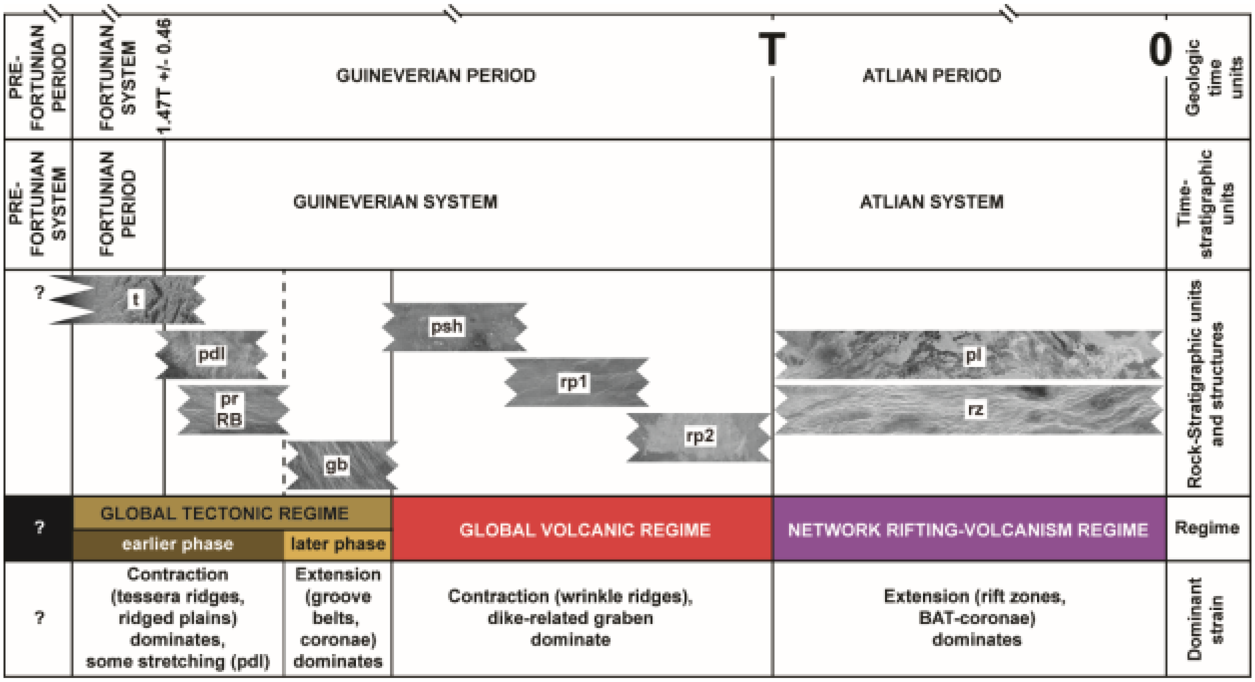

Figure 3.2-2. Regimes of resurfacing that operated throughout the visible portion of the geologic history of Venus. T is the mean age of the surface (based on the density of all craters).

The Global Volcanic Regime. During this time, volcanism overwhelmed tectonic activity and caused formation of vast volcanic plains mildly deformed by tectonic structures (**Figure 3.2-1**). Three types of plains manifest the global volcanic regime (**Figure 3.2-2**): 1) shield plains (psh), 2) regional plains, lower unit (rp1), and 3) regional plains, upper unit (rp2). These plains compose ~60% of the surface of Venus (**Table 3.2-1**) and show a clear stratigraphic sequence from the older shield plains to the younger upper unit of regional plains (Ivanov and Head 2004). The distinctly different morphologies of the plains (**Figure 3.2-1**) indicate different volcanic styles of their formation. Shield plains have numerous small volcanic constructs that were the sources of the plains material. In contrast, the lower unit of regional plains shows no evidence for the sources and the style of its formation resemble volcanic flooding.

The upper unit of regional plains formed by the emplacement of individual extensive lava flows often erupted from large distinct sources such as coronae or large volcanoes.

The density of impact craters on units of the tectonic and volcanic regimes suggests that these regimes characterized about first one third of the visible geologic history of Venus. During this time, ~80–85% of the surface of the planet was renovated.

Table 3.2-1. Areas of the most important units from different regimes of resurfacing on Venus.

Unit	Unit area, 10^6 km^2	Unit Area, %
Global tectonic regime		
t	35.7	7.8
pdl	7.8	1.7
pr	10.3	2.2
gb	39.9	8.7
SUM	**93.6**	**20.3**
Global volcanic regime		
psh	85.2	18.5
rp1	152.0	33.0
rp2	45.2	9.8
SUM	**282.4**	**61.4**
Network rifting-volcanism regime		
rz	24.3	5.3
pl	40.7	8.8
ps	10.3	2.3
SUM	**75.3**	**16.4**

The Network Rifting-Volcanism Regime. This regime characterized the last two thirds of the visible geologic history of Venus (**Figure 3.2-2**). Three units represent the major components of the regime (**Figure 3.2-1**): lobate plains (pl), rift zones (rz) and smooth plains (ps). These units are broadly synchronous to each other and units of the volcanic nature (pl and ps) are about twice as abundant (**Table 3.2-1**). Although the volcano-tectonic regime characterized ~2/3 of the visible geologic history of Venus, only 15–20% of the surface was renovated during this time. This means that the level of endogenous activity during the volcano-tectonic regime (**Figure 3.2-2**) has dropped by about an order of magnitude comparing with the earlier regimes.

3.2.1.1 Open Questions and the Venera-D Concept

Despite the detailed view of the surface provided by the Magellan and Venera data, there are a range of questions about the nature of the surface, its evolution, and its implications for volatile history and interior evolution. For the surface: What is the geochemistry and mineralogy of the different units we see in the Venera and Magellan data? What is the origin of layered rocks seen in Venera panoramas? What formed the mountain belts of Ishtar Terra, which rise up to 11 km above the mean planetary radius? Are the coronae the surface manifestation of mantle plumes, are they still active, and what are the implications of their morphologic and size diversity? Has resurfacing occurred in brief, global catastrophes, at a steady uniform rate, or by some mixture of these two styles?

Many questions directly relate to the tessera, including whether all tessera formed by the same mechanism(s), how widespread the terrain is, whether tessera form from upwelling or downwelling and their relationship to volcanic rises, and whether the tessera are composed of thickened basaltic crust or a different low density composition. The current and past rates of volcanic outgassing are unknown, as is an understanding of how volcanoes affected the atmosphere and climate. Even more fundamentally, the role of water in geodynamics and petrogenesis needs to be constrained.

Just as on Earth, or perhaps more so, Venus' geology and climate are interconnected (Bullock and Grinspoon 2001). The causes and effects of rapid changes in geologic expression can be investigated in detail by a capable surface payload and remote surveying techniques (Helbert et al., 2008). The surface and climate systems may be so coupled (Phillips et al. 2001; Solomon et al. 1999) that records of climate change, either in atmospheric or surface isotopes and chemistry, may ultimately elucidate the geologic history of Venus.

To resolve the key geologic questions, it is necessary to characterize the geochemistry, mineralogy, and petrology of surface features/terrains, especially tessera. These data, which are the clues to the first 80% of Venus history now obscured by volcanic and tectonic resurfacing, will allow us to constrain the history of volatiles, especially water, on Venus, and provide a basis for direct comparison of crustal evolution on Earth and Mars. In addition, isotopic measurements of the composition of the Venus atmosphere and an improved understanding of atmosphere-surface interactions will aid in constraining the outgassing history, in particular current and past volcanic outgassing rates.

3.2.1.2 Needed Investigations

The geologic objective of Venera-D is to understand the geologic processes and history of Venus. Within the context of this objective, a number of specific questions are put forward:

1. What are the geologic processes that have shaped the surface of Venus from the regional scale to that of a landed element and what does this imply about the resurfacing history of Venus?
2. What is the composition of surface material units and how might they vary across Venus?
3. Are there significant volumes of silicic volcanic deposits?

Landing Site Selection and Rationale Science

Although the results from the Soviet Venera landers suggest that the surfaces that they sampled are primarily basaltic in composition, there is morphologic evidence that suggests a range of rock types may be present. Based on geologic setting, rock types may range from continental-like in nature to those associated with subduction. As such, future measurements should focus on understanding the diversity of rock types on Venus, with implications for crustal recycling. A number of target areas for landed measurements that would most likely provide opportunities to improve understanding of geologic process on Venus include:

Tessera (e.g., Alpha Regio): It has been suggested that some occurrences of tessera may be composed of low-density continental-like crust. To investigate this hypothesis, geochemical sampling and optical imaging of a region of tessera is a high priority.

Lava flow fields: Rocks sampled by the Venera landers show compositions that are similar to terrestrial basalts. Although basaltic plains may generally be representative of Venus, morphologic evidence suggests the presence of more exotic compositions. In areas where lava channels have mechanically eroded the substrate, compositions analogous to carbonatites have been proposed (Kargel et al. 1994). It has also been suggested that broad homogeneous lava flow fields may be analogous to Deccan trap or Snake river plains volcanism and composed of high Fe/Mg high temperature basalts. To provide greater insight into materials that may represent a large part of the Venus crust it is necessary to determine the chemistry of at least one of these regions.

Regional plains: Although the regional plains have previously been sampled, the uncertainties of the measurements are typically large. To provide greater insight into the makeup of "non-exotic" (i.e., typical) surface materials, it would be useful to investigate the chemistry of the rocks that may represent a large part of the Venus crust.

3.2.2 Venus Geochemistry

In contrast to the geological models, our knowledge of geochemistry of solid Venus is limited. This is primarily because the dense layer of clouds prevents optical and, thus, spectral studies of Venus. The only means by which the geochemical data from Venus' surface can be obtained are landers. Several of them have visited the planet in a period from 1972 (Venera-8) to 1985 (VEGA-1 and 2) and reported the first and only data on the chemical composition of soils on the surface of Venus. Chemical measurements were made in seven points that are concentrated in the Beta-Phoebe region and in Rusalka Planitia to the north of Aphrodite Terra (**Figure 3.2-3**). Selection of the landing sites were based purely on the interplanetary ballistic constraints because no knowledge on the surface geology existed when the Venera-VEGA missions were planned and implemented.

In four landing points (Venera-8, -9, -10, and VEGA-1), concentrations of the three major thermal-generating components, K, Th, U, were determined by gamma spectrometry (**Table 3.2-1**) (Surkov 1997). The mean values of their concentrations on Venus are well within the range that is typical of the terrestrial basalts (Kargel et al. 1993; Nikolaeva 1995, 1997). However, the

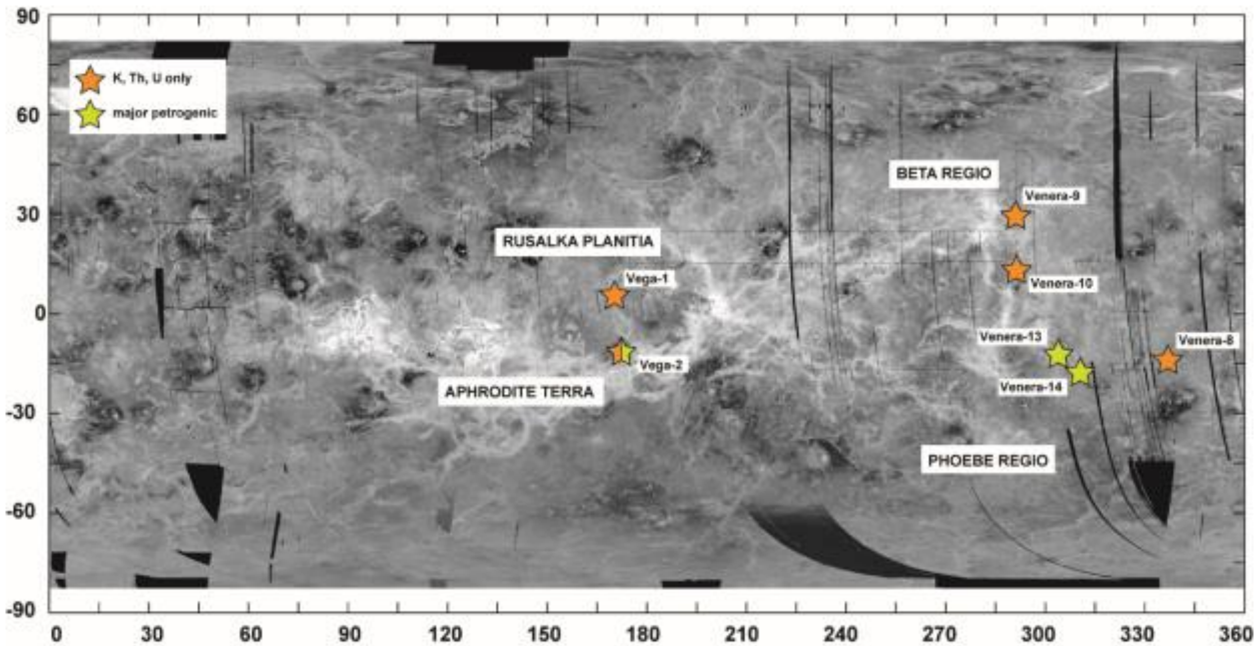

Figure 3.2-3. Landing sites of the Soviet stations of the Venera-VEGA series.

enhanced concentrations of K, Th, and U in soils at the Venera-8 landing site gave the possibility to interpret the results of this station as evidence for the presence of a non-basaltic material on Venus (Nikolaeva 1990).

In two landing sites (Venera-13, and -14), the concentrations of the major petrogenic oxides (without Na_2O) were measured by the X-ray fluorescence (XRF) method (**Table 3.2-2**) (Surkov 1997). In one point (VEGA-2), both methods (gamma spectrometry and XRF) were used separately and the concentrations of the thermal-generating elements and the major oxides were measured (**Table 3.2-2**) (Surkov 1997). The XRF data also suggested that rocks of basaltic composition make up the surface in the landing sites (Surkov et al. 1984, 1986; Kargel et al. 1993).

Two important factors, unfortunately, strongly limit the value of the Venera/VEGA data and prevent their robust interpretation.

Table 3.2-2. Results of chemical analyses conducted by the Venera (V) and VEGA (Vg) landers.

Lander	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	K_2O	S*	Cl*	K	Th	U
V-8											4.0 ±1.2	6.5 ±0.2	2.2 ±0.7
V-9											0.5 ±0.1	3.7 ±0.4	0.6 ±0.2
V-10											0.3 ±0.2	0.7 ±0.3	0.5 ±0.3
V-13	45.1 ±3.0	1.59 ±0.45	15.8 ±3.0	9.3 ±2.2	0.2 ±0.1	11.4 ±6.2	7.1 ±0.96	4.0 ±0.63	0.65 ±0.4	<0.3			
V-14	48.7 ±3.6	1.25 ±0.41	17.9 ±2.6	8.8 ±1.8	0.16 ±0.08	8.1 ±3.3	10.3 ±1.2	0.2 ±0.07	0.35 ±0.31	<0.4			
Vg-1											0.45 ±0.22	1.5 ±1.2	0.64 ±0.47
Vg-2	45.6 ±3.2	0.2 ±0.1	16. 0±1.8	7.74 ±1.1	0.14 ±0.12	11.5 ±3.7	7.5 ±0.7	0.1 ±0.08	1.9 ±0.6	<0.3	0.40 ±0.20	2.0 ±1.0	0.68 ±0.38

1) The first major problem is that we do not know the exact position of the landers. This situation makes impossible the clear understanding of the type of materials that the landers investigated. All stations landed somewhere within their own landing circle, which is ~300 km in diameter and usually embrace terrains of different origin and age. For example, the landing circle of Venera-10 includes six various and extensive units related to tectonics and volcanism. According to the Venera-10 panorama (**Figure 3.2-4**) and the inclinometer data, the station is on a flat, sub-horizontal surface. This type of surface favors vast volcanic plains (shield plains and/or regional plains) as the hosting units for the lander and disfavors the tectonized units such as tessera, densely lineated plains, and groove belt, although these later units cannot be ruled out confidently.

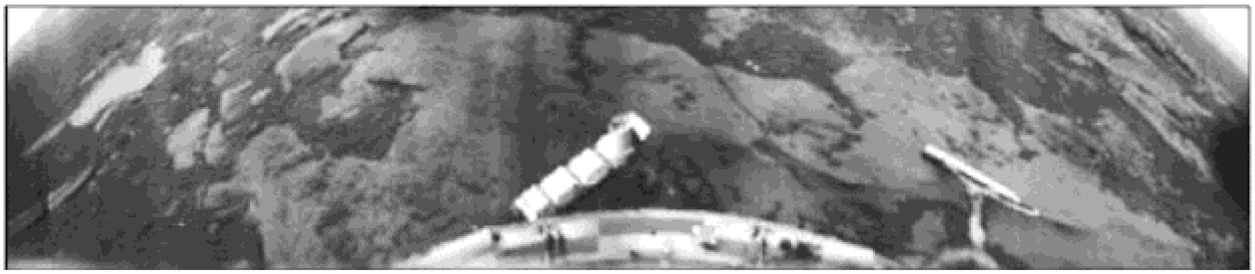

Figure 3.2-4. Panorama taken by the TV-system on the Venera -10 lander.

Thus, in the Venera-10 landing circle and in all other landing sites as well, association of the chemical data with the specific terrains can be made on a probabilistic basis only (Abdrakhimov 2005). From the morphology of the surface, it is obvious that different volcanic units on Venus are related to different volcanic styles, each of which could have its own geochemical signature. The lack of knowledge on the exact location of the landers prevents understanding of the geochemical aspects of nature of the units and, thus, prevents formulation of reasonable petrogenic models.

2) The second and most important limitation of the Venera/VEGA geochemical data is the low precision of the measurements made on the surface (**Table 3.2-2**). The large error bars keep the data collected by the landers at a low level of possible interpretation. For example, on a ternary plot that shows relationships of the major thermal-generating elements (**Figure 3.2-5**) points of terrestrial magmatic rocks form a prominent trend that reflects broad variations of Th/K

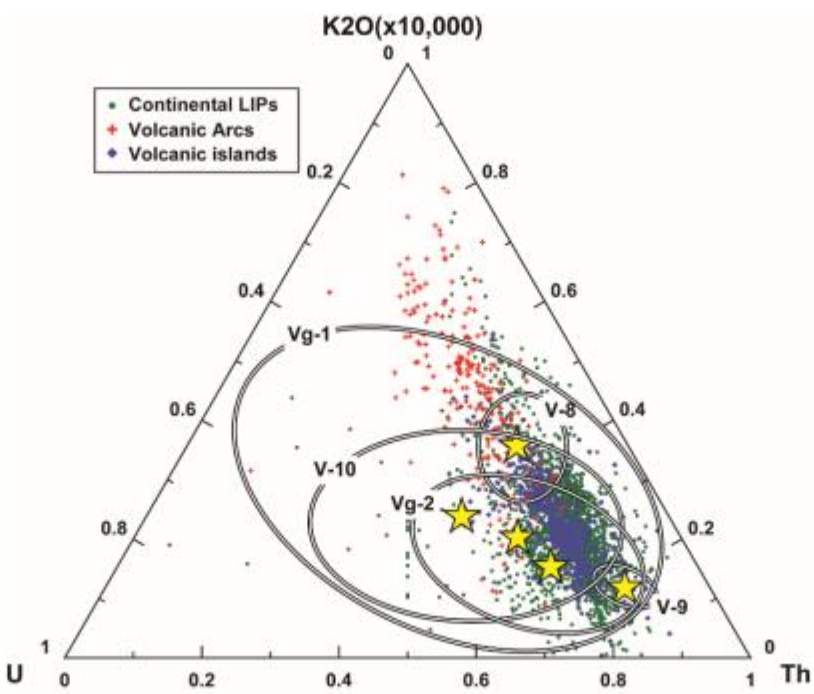

Figure 3.2-5. Ternary plot that shows relationships of the major thermal-generating elements for volcanic rocks from different geodynamic settings on Earth. Yellow stars correspond to the mean values of the measurements by the Venera-VEGA landers. Ellipses around the stars correspond to the measurement errors.

ratio in the rocks. The points of the Venera-8 and Venera-9 landers, which have the smallest errors, fall onto the terrestrial trend. The mean value of Venera-9 lies at the lower (Th-richer) end of the trend and the Venera-9 error ellipse overlays rocks from continental magmatic provinces and ocean volcanic islands, the sites presumably related to the mantle plume activity. The mean value of Venera-8 lies in the middle of the trend and its error ellipse overlays the transition from the plume-related geodynamic environments to the subduction zones (i.e., oceanic arcs). The mean values of Venera-10 and VEGA-1 and 2 seem to be shifted from the main terrestrial trend toward the U-side of the diagram (**Figure 3.2-5**). However, the error ellipses of these measurements are so large that make them to be almost completely unconstrained.

All these interpretations are based on the assumption that the chemical weathering did not significantly change the surface material on Venus. Such an assumption is potentially consistent with the lack of free water on the surface, but cannot be reasonably constrained by the available chemical data, particularly because of the large error bars for the sulfur measurements (**Table 3.2-2**).

So far, Venus remains to be the less geochemically studied terrestrial planet and the Venera-D mission is called to partly close this gap in our knowledge.

3.2.2.1 Open Questions

Questions related to the geochemistry of Venus include:

1. Was there ever an ocean on Venus, and if so, when did it exist and how did it disappear? This question requires a search for rock compositions affected by abundant water. At the broadest scale, oceans of water should affect magma genesis as they have done on Earth: “No water, no granite; no oceans, no continents” (Campbell and Taylor 1983).
2. What caused resurfacing of Venus during the last billion years? Are resurfacing and climate change related? Is Venus still an active planet? Most models of Venus’ recent past point to a relatively young surface, completely reworked and resurfaced within the last hundreds of millions of years. This absence of obvious ancient crust has led to geophysical models of periodic catastrophic mantle overturn and crustal disruption (e.g., Parmentier and Hess 1992). Measurement of abundances of heat-producing elements (K, Th, U) at the surface would help constrain models of their abundances in Venus’ mantle, and thus the heat production responsible for mantle overturn.
3. What are the nature and extent of present-day chemical reactions between Venus’ atmosphere and its surface? Is the composition of the atmosphere buffered by the surface? Because of Venus’ high surface temperature, chemical reactions between surface rocks and atmosphere may be so fast and extensive as to partially buffer the atmosphere’s composition. (Fegley and Treiman 1992; Lewis 1970; Urey 1952). Current models disfavor CO_2-buffering, but favor buffering of sulfur gases and oxidation state (Hashimoto and Abe 1998). Even the simplest mineralogical probe at Venus’ surface could resolve these questions immediately. Measurement of volatile abundances in fresh basalt at the surface could constrain their pre-eruptive volatile contents, and thus the atmospheric/climate input from weathering. The age of Venus’ volcanism could be estimated through investigation of the thicknesses and patterns of weathering ‘rinds’ on rocks, calibrated by laboratory experiments and theoretical studies.
4. What are the geodynamic settings of Venus’ volcanism? Can one correlate tectonic environments with magma compositions? Based on geomorphologic interpretation,

Venus volcanism is primarily basaltic. On Earth, basalts in different tectonic settings can commonly be distinguished by their geochemistry (e.g., Pearce 1976, 2008; Verma et al. 2006; Vermeesh 2006; Winchester and Floyd 1977). By analogy with Earth, one might expect that in different geodynamic position on Venus the volcanic products will be different. For example, the 'hot-spot-like' basalts may associate with Venus' shield volcanoes, basalts within rift zones might be alkaline, and the extensive plains volcanism might be comparable to that of the large igneous provinces on Earth.

3.2.2.2 Needed Investigations

For the geochemical aspects of Venus exploration, two types of measurements are paramount: (1) elemental chemical analyses of rocks/soils and (2) mineralogical analyses, determining the crystalline compounds that contain those elements. Measurements of these categories would allow understanding rock compositions and inferring on this basis mantle processes that produced surface rocks and atmospheric processes that modified surface rocks. Of the many analytic techniques available, gamma-ray spectroscopy has the potential for measuring the bulk elemental composition in the region within 1 m^3 of a lander. X-ray fluorescence spectroscopy is a precise way of quantifying the elemental composition of the rocks and soils of Venus.

Definitive mineral identification can be achieved by X-ray diffraction, similar to the Chemin instrument on Mars Science Laboratory rover. Raman spectroscopy on acquired samples holds promise for identifying minerals and weathering layers at the surface.

3.3 Traceability of Venera-D Goals and Objectives to the Decadal Survey and VEXAG

Traceability to Decadal Survey and VEXAG Objectives. The development of the Venera-D concept was underway with its own science goals and objectives prior to the most recent NASA Planetary Decadal Survey (SSB, 2011). To determine how this science would correlate with that defined in *Visons and Voyages* (SSB, 2011) along with mapping to the goals, objectives, and investigations identified by VEXAG (*Venus Exploration Goals, Objectives, Investigations, and Priorities: 2007* (Herrick et al. 2014), the JSDT compiled a traceability that links the goals of IKI/Roscosmos to those of the NASA Planetary Science Division for the scientific exploration of Venus. As the science goals discussed in the NASA Decadal Survey are for the study of Mercury, Venus, and the Moon, their corresponding objectives, questions, and future directions for investigations are presented at a high-level. The results here show the overall relevance of Venera-D to the NASA desires for Venus exploration (**Table 3.3-1**). As conceived, Venera-D would address each key objective identified in the Decadal Survey.

Table 3.3-1. Mapping of the science capability of Venera-D to the NASA Planetary Decadal Survey.

Decadal Survey Goals for the Study of Mercury, Venus, and the Moon	Objectives	Important Questions	Future Directions for Investigations and Measurements Relevant to Venus	Venera-D Contribution to Future Investigations and Measurements
Understand the origin and diversity of terrestrial planets	Constrain the bulk composition of the terrestrial planets to understand their formation from the solar nebula and controls on their subsequent evolution	What are the proportions and compositions of the major components (e.g., crust, mantle, core, atmosphere/ exosphere) of the inner planets?	• • In situ investigation of Venus's crust	• Lander chemical and mineral analysis of crustal rocks; • Orbiter measurement of 1 micron emissivity
		What are the volatile budgets in the interiors, surfaces, and atmospheres of the inner planets?	• Venus's bulk composition and interior evolution awaits the critical characterization of the noble gas molecular and isotopic composition of the Venus atmosphere	• Lander atmospheric compositions, isotopic ratios and reactive gas measurements; effect of super-critical state of the two primary constituents
		How did nebular and accretionary processes affect the bulk compositions of the inner planets?		
	Characterize planetary interiors to understand how they differentiate and dynamically evolve from their initial state	How do the structure and composition of each planetary body vary with respect to location, depth, and time?	• Obtaining higher resolution topography of Venus would provide new insights into the emplacement mechanisms of features such as mountains and lava flows	• Lander stereo imaging on descent
		What are the major heat-loss mechanisms and associated dynamics of their cores and mantles?		
		How does differentiation occur (initiation and mechanisms) and over what timescales?		
	Characterize planetary surfaces to understand how they are modified by geologic processes	What are the major surface features and modification processes on each of the inner planets?	• Major advances in our understanding of the geologic history of the inner planets will be achieved in the coming decade through the orbital remote sensing of Venus...as well as from in situ data from Venus	• Both orbiter and lander observations will advance the understanding of Venus; measure vertical profile of reactive constituents to characterize surface atmosphere interactions
		What were the sources and timing of the early and recent impact flux of the inner solar system?		
		What are the distribution and timescale of volcanism on the inner planets?		
		What are the compositions, distributions, and sources of planetary polar deposits?		
Understand how the evolution of terrestrial planets enables and limits the origin and evolution of life	Understand the composition and distribution of volatile chemical compounds;	How are volatile elements and compounds distributed, transported, and sequestered in near-surface environments on the surfaces of the Moon and Mercury? What fractions of volatiles were outgassed from those planets' interiors, and what fractions represent late meteoritic and cometary infall?	• Determine the inventories and isotopic compositions of volatiles in the mantle and crust of all of the terrestrial planets	• Both lander and orbiter compositional measurements of volatiles. Chemical measurements may indicate dis-equilibrium, e.g., COS, nitriles. Isotopic ratios may indicate life or other processes.

Decadal Survey Goals for the Study of Mercury, Venus, and the Moon	Objectives	Important Questions	Future Directions for Investigations and Measurements Relevant to Venus	Venera-D Contribution to Future Investigations and Measurements
		What are the chemical and isotopic compositions of hydrogen-rich (possibly water ice) deposits near the Moon's surface?	• Of high importance for Venus is to obtain high-precision analyses of the light stable isotopes (especially carbon, hydrogen, oxygen, nitrogen, and sulfur) in the lower atmosphere and noble gas concentrations and isotopic ratios throughout its atmosphere.	• Both the lander and orbiter will make measurements of the light stable isotopes
		What are the inventories and distributions of volatile elements and compounds (species abundances and isotopic compositions) in the mantles and crusts of the inner planets?		
		What are the elemental and isotopic compositions of species in Venus's atmosphere, especially the noble gases and nitrogen-, hydrogen-, carbon-, and sulfur-bearing species? What was Venus's original volatile inventory, and how has this inventory been modified during Venus's evolution? How and to what degree are volatiles exchanged between Venus's atmosphere and its solid surface?		
		Are Venus's highlands and tesserae made of materials suggestive of abundant magmatic water (and possibly liquid water on the surface)?		
	Understand the effects of internal planetary processes on life and habitability	What are the timescales of volcanism and tectonism on the inner planets?	• Determining the transport rates and fluxes of volatile compounds between the interiors and atmospheres of the inner planets, specifically Venus	• Both the lander and orbiter will make measurements of atmospheric volatile compounds
		Is there evidence of environments that once were habitable on Venus?	• Determining the composition of the Venus highlands	• Orbiter 1 micron emissivity observations should provide insight into the composition of highlands material; • If the lander is sent to the highlands, direct, in situ measurements will be made
		How are planetary magnetic fields initiated and maintained?	• Constraining the styles, timescales, and rates of volcanism and tectonism on Venus	• Lander descent, surface imaging, and chemical analysis of surface samples will provide insight into the styles of volcanism

Decadal Survey Goals for the Study of Mercury, Venus, and the Moon	Objectives	Important Questions	Future Directions for Investigations and Measurements Relevant to Venus	Venera-D Contribution to Future Investigations and Measurements
	Understand the effects of processes external to a planet on life and habitability.	What are the mechanisms by which volatile species are lost from terrestrial planets, with and without substantial atmospheres (i.e., Venus versus the Moon), and with and without significant magnetic fields (i.e., Mercury versus the Moon)? Do other mechanisms of loss or physics become important in periods of high solar activity?	• Investigation of the rates of loss of volatiles from planets to interplanetary space, in terms of solar intensity, gravity, magnetic-field environment, and atmospheric composition.	• Both the lander and orbiter will make atmospheric compositional measurements; potential sub-satellite simultaneous measurements could constrain atmospheric escape
		What are the proportions of impactors of different chemical compositions (including volatile contents) as functions of time and place in the solar system?		
		What causes changes in the flux and intensities of meteoroid impacts onto terrestrial planets, and how do these changes affect the origin and evolution of life? What are the environmental effects of large impacts onto terrestrial planets?		
Understand the processes that control climate on Earth-like planets	Determine how solar energy drives atmospheric circulation, cloud formation, and chemical cycles that define the current climate on terrestrial planets	What are the influences of clouds on radiative balances of planetary atmospheres, including cloud properties: microphysics, morphology, dynamics, and coverage?	• Measurement of the influence of clouds on radiative balances at Venus with both in situ and orbital investigations, including cloud microphysics, morphology, dynamics, and coverage, and an elucidation of the role of volcano-climate interactions.	• Both the lander and orbiter will focus on characterizing the Venus atmosphere; on descent will obtain single vertical profile of clouds, composition, absorbers, winds, waves, vertical transport. Remote sensing of cloud structure and motions.
		How does the current rate of volcanic outgassing affect climate?	• Explain Venus's global circulation better within the theoretical framework of modeling techniques developed for terrestrial GCMs and to understand the chemistry and dynamics of Venus's middle atmosphere.	• Look for volcanic gases on descent and anomalies relative to prior observations.
		How do the global atmospheric circulation patterns of Venus differ from those of Earth and Mars?	• Characterize the photochemistry of chlorine, oxygen, and sulfur on Venus and measuring current	• Potential sub-satellite simultaneous measurements would constrain atmospheric escape
		What are the key processes, reactions, and chemical cycles controlling the chemistry of the		

Decadal Survey Goals for the Study of Mercury, Venus, and the Moon	Objectives	Important Questions	Future Directions for Investigations and Measurements Relevant to Venus	Venera-D Contribution to Future Investigations and Measurements
		middle, upper, and lower atmosphere of Venus?	atmospheric escape processes at Venus with orbital and in situ investigations.	
		How does the atmosphere of Venus respond to solar-cycle variations?		• Measure solar wind properties and interactions from orbiter and possible sub-satellite over part of a solar cycle. Observe ionospheric response and mass loss from the Venus atmosphere.
	Characterize the record of and mechanisms for climate evolution on Venus, with the goal of understanding climate change on terrestrial planets, including anthropogenic forcings on Earth	What is the history of the runaway greenhouse on Venus, and is this a possible future for Earth's climate?	• Quantifying surface/atmosphere interactions on Venus, including the composition of the lower atmosphere, the bulk composition and mineralogy of Venus's surface rocks, and effects of that interaction at depth in Venus's crust	• The lander chemical analysis would identify weathering crusts and focus on surface-atmosphere interactions
		What is the relative role of water on the terrestrial planets in determining climate, surface geology, chemistry, tectonics, interior dynamics, structure, and habitability?	• Quantifying the effects of outgassing (volcanic and other) fluxes (e.g., biogenic methane) on the climate balances of terrestrial planets, with emphasis on Venus	• Venera-D would focus extensively on understanding the atmospheric chemistry and dynamic processes
		What is the history of volcanism and its relationship to interior composition, structure, and evolution (e.g., outgassing history and composition, volcanic aerosols, and climate forcing)?	• Studying complex nonlinear global systems theory through an analysis of Venus climate feedback	• Venera-D data would allow the analysis of climate feedback processes.
		How has the impact history of the inner solar system influenced the climates of the terrestrial planets?	• Measure the stable isotopes of the light elements (e.g., carbon, hydrogen, oxygen, nitrogen, and sulfur) on Venus for comparison with terrestrial and martian values	
		What are the critical processes involved in atmospheric escape of volatiles from the inner planets?	• Identify mechanisms of gas escape from terrestrial planet atmospheres, and to quantify the rates of these mechanisms as	

Decadal Survey Goals for the Study of Mercury, Venus, and the Moon	Objectives	Important Questions	Future Directions for Investigations and Measurements Relevant to Venus	Venera-D Contribution to Future Investigations and Measurements
			functions of time, magnetic-field strength, distance from the Sun, and solar activity	
	Constrain ancient climates on Venus and search for clues into early terrestrial planet environments so as to understand the initial conditions and long-term fate of Earth's climate	Do volatiles on Mercury and the Moon constrain ancient atmospheric origins, sources, and loss processes?	• Measuring and modeling the abundances and isotopic ratios of noble gases on Venus to understand how similar its original state was to those of Earth and Mars and to understand the similarities and differences between the coupled evolution of interiors and atmospheres for these planets	• The lander would make noble gas and isotopic ratio measurements
		How similar or diverse were the original states of the atmospheres and the coupled evolution of interiors and atmospheres on Venus, Earth, and Mars?	• Characterizing ancient climates on the terrestrial planets, including searching for isotopic or mineral evidence of ancient climates on Venus	
		How did early extreme ultraviolet flux and solar wind influence atmospheric escape in the early solar system?	• Examining the geology and mineralogy of the tesserae on Venus to search for clues to ancient environments.	

Flowing from the broad Decadal Survey science goals are specific VEXAG goals, objectives and investigations from which that science for a mission could be formulated. To show the relation to the Venera-D concept, the JSDT first generated a mapping of the three Decadal Survey goals: (1) Understand the origin and diversity of terrestrial planets, (2) Understand how the evolution of terrestrial planets enables and limits the origin and evolution of life, and (3) Understand the processes that control climate on Earth-like planets to the VEXAG investigations. This was done separately for atmospheric, surface, and surface-atmosphere interaction science (**Tables 3.3-2**, **3.3-3**, and **3.3-4**). Secondly, the VEXAG investigations were prioritized as high (green), medium (yellow), or low (red). Finally, the appropriate individual or set of Venera-D objectives from **Tables 2.3-1** and **2.3-2** (captured as short title names) were mapped to each VEXAG investigation. In addition, the JSDT provided a high-level assessment of potential technology needs and requirements and designated if there were any perceived missing measurements. The detailed assessment of technology needs is provided in Section 5.

Table 3.3-2. Mapping of science capability of Venera-D to the VEXAG Objectives and Investigations for Atmospheric Science.

Venus Atmosphere				VEXAG Goals, Objectives and Investigations Goals are not prioritized; Objectives and Investigations are in priority order		Venera-D as Currently Defined				
Decadal Survey										
Understand the origin and diversity of terrestrial planets	Understand how the evolution of terrestrial planets enables and limits the origin and evolution of life	Understand the processes that control climate on Earth-like planets	VEXAG Goal	Objective	Investigation (items listed in red cannot be achieved by the baseline orbiter/lander)	Venera-D Objective	Venera-D Flight Element (s)	Applicable Venera-D Instrument (s)	Technology Needs & Requirements	Missing Measurements (orbiter/lander inadequacy described in red; other colors highlight capabilities of alternative measurement platforms)
X	X		I. Understand atmospheric formation, evolution, and climate history on Venus	A. How did the atmosphere of Venus form and evolve?	1. Measure the relative abundances of Ne, O isotopes, bulk Xe, Kr and other noble gases to determine if Venus and Earth formed from the same mix of solar nebular ingredients, and to determine if large, cold comets played a substantial role in delivering volatiles.	L1. Atmosphere composition during descent	Lander	1. Chemical analyses package (CAP); 2. Multi-channel tunable diode laser spectrometer ISKRA-V	Delivery of the atmospheric probes, rarefying for MTDL	N/A
X	X				2a. Measure the isotopes of noble gases (especially Xe and Kr), D/H, 15 N/14 N	L1. Atmosphere composition during descent	Lander	1. Chemical analyses package (CAP); 2. Multi-channel tunable diode laser spectrometer ISKRA-V	Delivery of the atmospheric probes, rarefying for MTDL	N/A
X	X	X			2b. Measure current O and H escape rates to determine the amount and timeline of the loss of the original atmosphere during the last stage of formation and the current loss to space.	O4. Vertical Structure and composition of the atmosphere; O10. Solar wind ionosphere interactions	Orbiter [Subsatellite]	1. UV & IR solar and stellar occultation spectrometer; 2. Plasma package	N/A	**Sub-Satellite:** Has best capability to measure neutrals, ions and their escape rates
X		X		B. What is the nature of the radiative and dynamical energy balance on Venus that defines the current climate? Specifically, what processes control the atmospheric super-rotation and the atmospheric greenhouse?	1. Characterize and understand the atmospheric super-rotation and global circulation, **including solar-anti-solar circulation above ~90 km** and planetary-scale waves, by measuring the zonal and meridional wind structure and energy transport from the equator to polar latitudes and **over time-of-day from the surface to ~120** km altitude. Use global circulation models to comprehensively connect observations acquired over different epochs, altitudes, and latitudinal regions.	O1. Vertical structure of mesosphere and cloud born gases; O3. Structure, composition, and dynamics of clouds, hazes and surface thermal emissivity; O4. Vertical Structure and composition of the atmosphere; O5. Dynamics of UV and UV-absorbers. O6. Ionosphere and atmosphere; O7. Structure composition and dynamics of the atmosphere (20 to 60 km altitude); O8. Atmospheric density, temperature, wind velocity, mesospheric minor constituents, and CO_2 dayglow	Orbiter [Aerial Platform] [Subsatellite] [Small Long-lived Station]	1. Fourier transform spectrometer PFS-VD; 2. Monitoring camera CMV; 3. UV-IR imaging spectrometer VENIS; 4. UV imaging spectrometer; 5. UVMAS; 6. Radio occultations; 7. Heterodyne hi-res IR spectrometer	N/A	**Aerial Platform**: Measurement of P,T over range of altitudes (50–65 km) that varies as function of local time; floating platform can measure P,T and winds at the same level on the day and night side and their variation with local time-- at ~55 km altitude range; **Sub-Satellite:** Simultaneous remote observing would help for higher altitudes--best from sub-satellite orbiter **Small Long-lived Station**: would provide measurements for lower altitude
X		X			2a. Define the atmospheric radiative balance needed to support the atmospheric temperature profile observed as a function of **latitude and time-of-day, from the surface to ~140 km altitude**	O1. Vertical structure of mesosphere and cloud born gases; O3. Structure, composition, and dynamics of clouds, hazes and surface thermal emissivity; O4. Vertical Structure and composition of the atmosphere; O6. Ionosphere and atmosphere; O7. Structure composition and dynamics of the atmosphere (20 to 60 km altitude); O8. Atmospheric density, temperature, wind velocity, mesospheric minor constituents and CO_2 dayglow; L3. Atmospheric Structure and Dynamics.	Orbiter, Lander [Aerial Platform] [Subsatellite] [Small Long-lived Station]	1. Fourier transform spectrometer PFS-VD; 2. Radio occultations, 3. MM-radiometer; 4. IR solar and stellar occultation spectrometer; 5. T,P,W meteo package; 6. Optical package	N/A	**A measurement of the horizontal variation of cloud structure is needed** **Aerial Platform**: flying aerial platform can provide details 50–65 km; **Sub-Satellite**: remote sensing from sub-satellite orbiter for additional altitudes; **Small Long-lived Station**: drop sondes/probes needed for lower altitude measurements;

Venus Atmosphere				VEXAG Goals, Objectives and Investigations Goals are not prioritized; Objectives and Investigations are in priority order		Venera-D as Currently Defined				
Decadal Survey										
Understand the origin and diversity of terrestrial planets	Understand how the evolution of terrestrial planets enables and limits the origin and evolution of life	Understand the processes that control climate on Earth-like planets	VEXAG Goal	Objective	Investigation (items listed in red cannot be achieved by the baseline orbiter/lander)	Venera-D Objective	Venera-D Flight Element (s)	Applicable Venera-D Instrument (s)	Technology Needs & Requirements	Missing Measurements (orbiter/lander inadequacy described in red; other colors highlight capabilities of alternative measurement platforms)
		X			2b. Determine the atmospheric radiative balance based on characterization of the deposition of solar energy in the cloud layers and re-radiation from below, including the role of the widespread UV absorber(s).	O1. Vertical structure of mesosphere and cloud born gases; O2. Atmospheric dynamics and airglow; O3. Structure, composition and dynamics of clouds, hazes and surface thermal emissivity; O4. Vertical structure and composition of the atmosphere; O5. Dynamics of UV and UV-absorbers; O6. Ionosphere and atmosphere; O7. Structure composition and dynamics of the atmosphere (20 to 60 km altitude); O8. Atmospheric density, temperature, wind velocity, mesospheric minor constituents, and CO_2 dayglow; L1. Atmospheric composition during descent; L3. Atmospheric structure and dynamics; L4. Physical properties of atmospheric aerosols.	Orbiter, Lander [Aerial Platform] [Subsatellite] [Small Long-lived Station]	1. Fourier transform spectrometer PFS-VD; 2. Radio occultations; 3. MM-radiometer; 4. UV imaging spectrometer UVMAS; 5. UV & IR solar and stellar occultation spectrometer; 6. T,P,W meteo package; 7. Optical package	N/A	A measurement of the horizontal variation of cloud structure, composition and microphysics is needed to meet this goal; Aerial platform: aerial platform can provide details 50–65 km (flying) or 50–55 km (floating); Small Long-lived Station: drop sondes/probes needed for lower altitude measurements; Sub-Satellite: remote sensing from sub-satellite orbiter for additional altitudes
		X			3. Characterize small-scale vertical motions in order to determine the roles of convection and local (e.g., gravity) waves in the vertical transport of heat and mass and their role in global circulation.	O3. Structure, composition, and dynamics of clouds, hazes and surface thermal emissivity; O5. Dynamics of UV and UV-absorbers; O8. Atmospheric density, temperature, wind velocity, mesospheric minor constituents, and CO_2 dayglow	Orbiter [Aerial Platform]	1. IVOLGA-V Infrared heterodyne spectrometer; 2. Monitoring camera CMV; 3. UV-IR imaging spectrometer	N/A	Aerial Platform: Small-scale motions and turbulence require direct measurements from a flying/floating platform.
X		X		C. What are the morphology, chemical makeup and variability of the Venus clouds, what are their roles in the atmospheric dynamical and radiative energy balance, and what is their impact on the Venus climate? Does the habitable zone in the clouds harbor life?	1. Characterize the dynamic meteorology and chemistry of the cloud layer through correlated measurements of formation and dissipation processes over all times-of-day and a range of latitudes. Analyze cloud aerosols, including their particle sizes, number/mass densities, bulk composition, and vertical motions. Study the abundances of their primary parent gaseous species, such as SO_2, H_2O, and H_2SO_4, as well as minor cloud constituents, such as Sn and aqueous cloud chemical products.	O2. Atmospheric dynamics and airglow; O4. Vertical structure and composition of the atmosphere; O5. Dynamics of UV and UV-absorbers; O6. Ionosphere and atmosphere; O7. Structure dynamics of the atmosphere (20 to 60 km altitude); L1. Atmospheric composition during descent; L3. Atmospheric structure and dynamics; L4. Physical properties of atmospheric aerosols.	Orbiter, Lander [Aerial Platform]	1. UV imaging spectrometer; 2. UVMAS; 3. UV & IR solar and stellar occultation spectrometer; 4. Radio occultations; 5. Nephelometer – particle counter (NEFAS)	N/A	Numerous remote spectroscopic measurements have not uniquely resolved the questions regarding the composition/characteristics of the cloud particles and the nature of the UV absorber, strongly indicating that in situ measurements are needed. Aerial Platform: Measurements of the cloud particles, their microphysics and chemistry from the flying/floating platform should be able to advance this objective
X		X			2. Determine the composition, and the production and loss mechanisms, of "Greenhouse" aerosols and gases, including sulfur cycle-generated species and UV absorbers, and their roles in the cloud-level radiative balance.	O1. Vertical structure of mesosphere and cloud born gases; O2. Atmospheric dynamics and airglow; O3. Structure, composition, and dynamics of clouds, hazes and surface thermal emissivity; O4. Vertical structure and composition of the atmosphere; O5. Dynamics of UV and UV-absorbers; O6. Ionosphere and atmosphere;	Orbiter, Lander [Aerial Platform]	1. UV & IR solar and stellar occultation spectrometer; 2. Radio occultations; 3. UV-IR imaging spectrometer VENIS; 4. UV imaging spectrometer UVMAS; 5. Fourier transform	Delivery of the atmospheric probes, rarefying for MTDLS	Aerial Platform: Diurnal variations in the thermal structure and thermal balance needed to properly assess radiative balance process are best determined from a floating/flying in-situ platform.

Venus Atmosphere				VEXAG Goals, Objectives and Investigations Goals are not prioritized; Objectives and Investigations are in priority order		Venera-D as Currently Defined				
Decadal Survey										
Understand the origin and diversity of terrestrial planets	Understand how the evolution of terrestrial planets enables and limits the origin and evolution of life	Understand the processes that control climate on Earth-like planets	VEXAG Goal	Objective	Investigation (**items listed in red cannot be achieved by the baseline orbiter/lander)**	Venera-D Objective	Venera-D Flight Element (s)	Applicable Venera-D Instrument (s)	Technology Needs & Requirements	Missing Measurements (**orbiter/lander inadequacy described in red**; other colors highlight capabilities of alternative measurement platforms)
						L1. Atmosphere composition during descent; L3. Atmospheric structure and dynamics; L4. Physical properties of atmospheric aerosols		spectrometer PFS-VD; 6. Multi-channel tunable diode laser spectrometer ISKRA-V		
X		X			3. Characterize lightning/electrical discharge strength, frequency, and variation **with time of day** and latitude. Determine the role of lightning in creating trace gas species and aerosols.	L9. Electric magnetic fields; O13. Electromagnetic fields	Lander Orbiter [**Aerial Platform**]	1. GROZA-SAS2-D	N/A	**Aerial Platform**: Diurnal variations in lightning are best determined from an in-situ flying/floating platform.
X		X			4. Determine the atmospheric/surface sulfur cycle by measurements of the isotopic ratios of D/H, 15 N/14 N, 17 O/16 O 18 O/16 O, 34 S/32 S 13 C/12 C in solid samples and atmospheric measurements of SO_2, H_2 O_2, OCS, CO, 34 S/32 S and sulfuric acid aerosols (H_2SO_4), to determine, in particular, the current rate of sulfur outgassing from the surface.	L2. Atmosphere Composition at the surface; L6. Surface elemental composition; O4. Vertical Structure and composition of the atmosphere	Lander, Orbiter [Aerial Platform]	1. Chemical analyses package (CAP); 2. Multi-channel tunable diode laser spectrometer ISKRA-V; 3. UV & IR solar and stellar occultation spectrometer	Delivery of the atmospheric probes, rarefying for MTDLS	**Aerial Platform**: Chemical analyses package (CAP)-for aerosol; Multi-channel tunable diode laser spectrometer ISKRA-V - may be installed on flying platform

Priority

(green)	High
(yellow)	Medium
(red)	Low

Decadal Survey Future directions for investigations and measurements

(blue)	Understand the origin and diversity of terrestrial planets
(purple)	Understand how the evolution of terrestrial planets enables and limits the origin and evolution of life.
(grey)	Understand the processes that control climate on Earth-like planets.

Table 3.3-3. Mapping of science capability of Venera-D to the VEXAG Objectives and Investigations for Surface Science.

Venus Surface and Interior / Decadal Survey: Understand the origin and diversity of terrestrial planets	Understand how the evolution of terrestrial planets enables and limits the origin and evolution of life	Understand the processes that control climate on Earth-like planets	VEXAG Goal	VEXAG Goals, Objectives and Investigations (Goals are not prioritized; Objectives and Investigations are in priority order): Objective	Investigation	Venera-D as Currently Defined: Venera-D Objective	Venera-D Flight Element (s)	Applicable Venera-D Instrument (s)	Technology Needs & Requirements	Missing Measurements
X			II. Determine the evolution of the surface and interior of Venus	A. How is Venus releasing its heat now and how is this related to resurfacing and outgassing? Has the style of tectonism or resurfacing varied with time? Specifically, did Venus ever experience a transition in tectonic style from mobile lid tectonics to stagnant lid tectonics?	1. Through high-resolution imaging and topography, characterize the stratigraphy and deformation of surface units in order to learn the sequence of events in Venusian geologic history. This includes assessing any evolution in volcanic and tectonic styles and analyzing any evidence of significant past horizontal surface displacement.	L5. Surface structure and morphology	Lander (regionally to locally)	1. Imaging during descent and while on the surface	Correlation of descent imaging with landforms in Magellan radar images; Data volume will be an issue	N/A
X	X	X			2. Characterize radiogenic 4 He, 40 Ar and Xe isotopic mixing ratios generated through radioactive decay to determine the mean rate of interior outgassing over Venus's history.	L1. Atmosphere composition during descent	Lander	1. Chemical analyses package (CAP)--Gas Chromatograph Mass Spectrometer (GCMS)	1. Challenge of taking atmospheric samples at different levels in the atmosphere.	N/A
X					3. Combine geophysical measurements with surface observations to characterize the structure, dynamics, and history of the interior of Venus and its effects on surface geology. Relevant geophysical approaches include, but are not limited to, gravity, electromagnetics, heat flow, rotational dynamics, remnant magnetization, and seismology.	L8. Global and regional seismic activity; L5. Surface structure and morphology	Lander (possibly, but low priority for Venera-D)	1. Seismometer (S-VD); 2. High-resolution imaging	1. Provide strong coupling between the ground and the instrument; 2. Very high resolution imaging to identify features at the sub-millimeter scale	N/A
X	X				4. Determine contemporary rates of volcanic and tectonic activity through observations of current and recent activity, such as evaluating thermal and chemical signatures, repeat-image analysis, ground deformation studies, and observations of outgassing.	O3. Structure, composition, and dynamics of atmosphere and clouds, hazes, and surface thermal emissivity, O_2, OH airglows	Orbiter	1. VENIS,UV-IR imaging spectrometer	1. High signal to noise Imaging on the night side at 1 µm spectral widow	N/A
X	X				5. Determine absolute ages for rocks at locations that are key to understanding the planet's geologic history.	N/A	N/A	N/A	N/A	N/A
X	X			B. How did Venus differentiate and evolve over time? Is the crust nearly all basalt, or are there significant volumes of more differentiated (silica-rich) crust?	1. Determine elemental composition, mineralogy, and petrography of surface samples at key geologic sites, such as the highlands tesserae, in order to understand the compositional diversity and origin of the crust.	L6. Surface elemental composition	Lander (measure major and trace elements)	1. Active Gamma-spectrometer (e.g., AGNESSA); 2. XRF mode of Mössbauer spectrometer; 3. Chemical Analyses Package (CAP)	Raman Spectroscopy is desirable for mineralogy	N/A
						L7. Mineral phases	Lander	Miniaturized Mössbauer spectrometer (MIMOS2A	1. Delivery of rocky sample inside the lander. Delivery of at least 1 g (min) of rocky sample inside the lander; Rock Sample by drilling, brushing, grinding, etc.; sample distribution system; human in the loop for sample site selection would require a longer-lived lander; need to establish context for the sample	N/A
X	X				2. Determine compositional information for rocks at large scales using remote sensing to gain a regional picture of geochemical processes.	O3. Structure, composition, and dynamics of atmosphere and clouds, hazes, and surface thermal emissivity, O_2, OH airglows		1. VENIS,UV-IR imaging spectrometer	N/A	N/A

Venus Surface and Interior				VEXAG Goals, Objectives and Investigations Goals are not prioritized; Objectives and Investigations are in priority order		Venera-D as Currently Defined				
Decadal Survey										
Understand the origin and diversity of terrestrial planets	Understand how the evolution of terrestrial planets enables and limits the origin and evolution of life	Understand the processes that control climate on Earth-like planets	VEXAG Goal	Objective	Investigation	Venera-D Objective	Venera-D Flight Element (s)	Applicable Venera-D Instrument (s)	Technology Needs & Requirements	Missing Measurements
X					3. Determine the structure of the crust, as it varies both spatially and with depth, through high-resolution geophysical measurements (e.g., topography and gravity, seismology), in order to constrain estimates of crustal volume and lithospheric structure and processes.	L8. Global and regional seismic activity	Lander	1. Seismometer (very limited and low priority for Venera-D)	1. Provide strong coupling between the ground and the instrument;	N/A
X					4. Determine the size and state of the core and mantle structure (e.g., via geodesy or seismology) to place constraints on early differentiation processes and thermal evolution history.	L8. Global and regional seismic activity	Lander	1. Seismometer (very limited and low priority for Venera-D)	1. Provide strong coupling between the ground and the instrument;	N/A
X	X				5. Evaluate the radiogenic heat-producing element content of the crust to better constrain bulk composition, differentiation and thermal evolution.	L6. Surface elemental composition	Lander	1. Gamma-spectrometer (AGNESSA)	N/A	N/A
X					6. Characterize subsurface layering and geologic contacts to depths up to several km to enhance understanding of crustal processes.	N/A	N/A	N/A	N/A	N/A

Priority

- High
- Medium
- Low

Decadal Survey Future directions for investigations and measurements

- Understand the origin and diversity of terrestrial planets
- Understand how the evolution of terrestrial planets enables and limits the origin and evolution of life.
- Understand the processes that control climate on Earth-like planets.

Table 3.3-4. Mapping of science capability of Venera-D to the VEXAG Objectives and Investigations for Surface-Atmosphere interaction.

Venus Surface-Atmosphere Interaction			VEXAG Goals, Objectives and Investigations Goals are not prioritized; Objectives and Investigations are in priority order			Venera-D as Currently Defined				
Decadal Survey										
Understand the origin and diversity of terrestrial planets	Understand how the evolution of terrestrial planets enables and limits the origin and evolution of life	Understand the processes that control climate on Earth-like planets	VEXAG Goal	Objective	Investigation	Venera-D Objective	Venera-D Flight Element (s)	Applicable Venera-D Instrument (s)	Technology Needs & Requirements	Missing Measurements
X	X	X	III. Understand the nature of interior-surface-atmosphere interactions over time, including whether liquid water was ever present.	A. Did Venus ever have surface or interior liquid water, and what role has the greenhouse effect had on climate through Venus' history?	1. Determine the isotopic ratio of D/H in the atmosphere to place constraints on the history of water. Determine isotopic ratios of $^{15}N/^{14}N$, $^{17}O/^{16}O$, $^{18}O/^{16}O$, $^{34}S/^{32}S$, and $^{13}C/^{12}C$ in the atmosphere to constrain evaluation of paleochemical disequilibria.	O4. Vertical structure and composition of the atmosphere (90–140 km) of the atmosphere	Orbiter	1. UV & IR solar and stellar occultation spectrometer	N/A	N/A
						L1. Atmosphere composition during descent	Lander	1. Chemical analyses package (CAP); 2. "ISKRA-V": Diode Laser Spectrometer (DLS) with multiple channels and Atmosphere Gas Sampling (AGS) system	1. Challenge of taking atmospheric samples at different levels in the atmosphere. 2. Rarified atmosphere sampling during descent and after landing; QCL-laser technique and optical fibers for longer wavelengths ($\lambda>5$ μm); ICOS spectrometry for long optical paths (1 m–1 km); Challenge of taking atmospheric samples at different levels in the atmosphere	N/A
	X	X			2. Identify and characterize any areas that reflect formation in a geological or climatological environment significantly different from present day. Determine the role, if any, of water in the formation of highlands tesserae.	N/A	N/A	N/A	N/A	Raman Spec.
	X	X			3. Search for evidence of hydrous minerals, of water-deposited sediments, and of greenhouse gases trapped in surface rocks in order to understand changes in planetary water budget and atmospheric composition over time.	N/A	N/A	N/A	N/A	Atmospheric platform.
X		X		B. How have the interior, surface, and atmosphere interacted as a coupled climate system over time?	1. Characterize elemental composition and isotopic ratios of noble gases in the Venus atmosphere and in solid samples, especially Xe, Kr, ^{40}Ar, ^{36}Ar, Ne, ^{4}He, and ^{3}He, to constrain the sources and sinks that are driving evolution of the atmosphere, including outgassing from surface/interior.	L1. Atmosphere composition during descent	Lander	1. Chemical analyses package (CAP); 2. "ISKRA-V": Diode Laser Spectrometer (DLS) with multiple channels and Atmosphere Gas Sampling (AGS) system	1. Challenge of taking atmospheric samples at different levels in the atmosphere. 2. Rarified atmosphere sampling during descent and after landing; QCL-laser technique and optical fibers for longer wavelengths ($\lambda>5$ μm); ICOS spectrometry for long optical paths (1 m–1 km); Challenge of taking atmospheric samples at different levels in the atmosphere	N/A
		X			2. Understand chemical and physical processes that influence rock weathering on Venus in order to determine contemporary rates and identify products from past climate conditions. At large scales, determine the causes and spatial extent (horizontal and vertical) of weathering regimes such as the high-elevation lowering of microwave emissivity. At local scales, evaluate the characteristics of weathering rinds and compare to unweathered rocks.	L7. Mineral phases	Lander	1. Miniaturized Mössbauer spectrometer (MIMOS2A) + APXS	Delivery of rocky sample inside the lander. Delivery of at least 1 g (min) of rocky sample inside the lander; Rock Sample by drilling, brushing, grinding, etc.; sample distribution system; human in the loop for sample site selection would require a longer-lived lander; need to establish context for the sample	N/A
						L1. Atmosphere composition during descent	Lander	1. Chemical analyses package (CAP); 2. "ISKRA-V": Diode Laser Spectrometer (DLS) with multiple channels and Atmosphere Gas Sampling (AGS) system	L1: 1. Challenge of taking atmospheric samples at different levels in the atmosphere. 2. Rarified atmosphere sampling during descent and after landing; QCL-laser technique and optical fibers for longer wavelengths ($\lambda>5$ μm); ICOS spectrometry for long optical paths (1 m–1 km); Challenge of taking atmospheric samples at different levels in the atmosphere	Raman Spec.

Venus Surface-Atmosphere Interaction				VEXAG Goals, Objectives and Investigations Goals are not prioritized; Objectives and Investigations are in priority order		Venera-D as Currently Defined				
Decadal Survey										
Understand the origin and diversity of terrestrial planets	Understand how the evolution of terrestrial planets enables and limits the origin and evolution of life	Understand the processes that control climate on Earth-like planets	VEXAG Goal	Objective	Investigation	Venera-D Objective	Venera-D Flight Element (s)	Applicable Venera-D Instrument (s)	Technology Needs & Requirements	Missing Measurements
		X			3. Determine the abundances and altitude profiles of reactive atmospheric species (OCS, H_2S, SO_2, SO_3, H_2SO_4, Sn, HCl, HF, ClO_2 and Cl_2), greenhouse gases, H2 O, and other condensables, in order to characterize sources of chemical disequilibrium in the atmosphere and to understand influences on the current climate.	L1. Atmosphere composition during descent	Lander	1. Chemical analyses package (CAP); 2. "ISKRA-V": Diode Laser Spectrometer (DLS) with multiple channels and Atmosphere Gas Sampling (AGS) system	1. Challenge of taking atmospheric samples at different levels in the atmosphere. 2. Rarified atmosphere sampling during descent and after landing; QCL-laser technique and optical fibers for longer wavelengths (λ>5 µm); ICOS spectrometry for long optical paths (1 m–1 km); Challenge of taking atmospheric samples at different levels in the atmosphere	N/A
	X	X			4. Determine the atmospheric/surface sulfur cycle by measurements of the isotopic ratios of D/H, 15 N/14 N, 17 O/16 O 18 O/16 O, 34 S/32 S 13 C/12 C in solid samples and atmospheric measurements of SO_2, H_2O_2, OCS, CO, 34 S/32 S and sulfuric acid aerosols (H_2SO_4), to determine, in particular, the current rate of sulfur outgassing from the surface.	L1. Atmosphere composition during descent	Lander	1. Chemical analyses package (CAP); 2. "ISKRA-V": Diode Laser Spectrometer (DLS) with multiple channels and Atmosphere Gas Sampling (AGS) system	1. Challenge of taking atmospheric samples at different levels in the atmosphere. 2. Rarified atmosphere sampling during descent and after landing; QCL-laser technique and optical fibers for longer wavelengths (λ>5 µm); ICOS spectrometry for long optical paths (1 m–1 km); Challenge of taking atmospheric samples at different levels in the atmosphere	N/A

Priority
- High
- Medium
- Low

Decadal Survey Future directions for investigations and measurements
- Understand the origin and diversity of terrestrial planets
- Understand how the evolution of terrestrial planets enables and limits the origin and evolution of life.
- Understand the processes that control climate on Earth-like planets.

3.4 Venera-D Science Relative to Ongoing and Potential Other Future Missions

The science that could be achieved by Venera-D would build upon and be synergistic with that from past and current missions. To demonstrate this, **Table 3.4-1** provides a comparison between the notional Venera-D payload and the instruments carried on Venus Express and Akatsuki.

The primary goals of Venera-D—atmospheric superrotation and improved knowledge of Venus surface—would be achieved by improved and augmented instruments compared to Venus Express and Akatsuki through an IR Fourier Transform Spectrometer, better IR imaging from orbit, high-resolution surface imaging from the lander, Raman LIDAR, and other instruments.

Table 3.4.1. Baseline Venera-D Unique Science relative to recent missions.

Venera-D Baseline	Venus Express	Akatsuki
PFS-VD Fourier transform spectrometer, 250–2000 cm^{-1} λ=5-45 μm, Δv = 1 cm^{-1}	**PFS** didn't function	**Longwave infrared camera (LIR)** structure of upper clouds at altitude of τ = 1 at 10 μm (8–12 μm).
UVmapping spectrometer,190–490 nm, Δλ=0.3 nm,		**Ultraviolet imager (UVI)** (293–365 nm).
MM-radiometer, Millimeter Wave Radiometer; Ka, V and W bands		
UV-IR Imaging Spectrometer, **VENIS**	**VIRTIS** Visible and Infrared Thermal Imaging Spectrometer	**2 μm camera (IR2)** (1.65–2.32 μm) radiation coming from low clouds and below the clouds
Monitoring camera	**VMC** Venus Monitoring Camera	**1 μm camera (IR1)** would image heat radiation emitted from (0.90–1.01 μm)
SSOE Solar and star occultation spectrometer	Solar and star occultation spectrometer **SPICAV/ SOIR**	
IVOLGA, Infrared heterodyne spectrometer		
Radio-science 1 Orbiter to ground, two-frequency occultation in (L?) S- and X-bands	**VeRa** Venus Radio Science	**Ultra-Stable Oscillator (USO)** for high precision measurement of distance and communication
Radio-science 2 Ground to orbiter two-frequency occultation in (L?), S-and X-bands		
GROZA-SAS2-DFM-D, Electromagnetic waves generated by lightning and other electric phenomena		**Lightning and Airglow Camera (LAC)** lightning in the visible wavelengths of 552 to 777 nm
Plasma instruments – Suite of 3 Panoramic energy mass-analyzer of ions CAMERA-O, electron spectrometer ELSPEC, fast neutrals analyzer FNA **Energetic particle spectrometer**	**ASPERA-4** Analyzer of Space Plasmas and Energetic Atoms	

3.5 Science Gaps

The JSDT has identified several areas where important VEXAG science may not be addressed by the baseline Venera-D concept and has suggested options to resolve these "science gaps." For surface science, Mossbauer spectroscopy (current Venera-D notional instrument) is limited to iron-bearing minerals of a sample brought inside the lander. It has been suggested that inclusion of a Raman spectrometer would provide greater molecular compositional measurements of surface materials inside or outside the lander.

To better address the drivers of atmospheric superrotation and characterize of the chemical composition and dynamics in situ in the atmosphere, The JSDT concluded that the addition of a capable/semi-autonomous long-lived atmospheric platform operating at 55–60 km to perform in situ analysis would enhance the science return by providing the first opportunity to complete long-term cloud layer measurements of dynamic and microphysical cloud properties using meteorological instrumentation, Raman LIDAR and a UV spectrometer over a time period ~1 Venus day. In-situ measurements obtained using these instruments would also greatly advance the investigation of the nature of the enigmatic ultraviolet absorber. In addition, inclusion of a simple long-lived (months) small surface station could provide measurements of atmospheric motion (pressure, temperature, wind direction) over a range of latitudes and longitudes and could provide needed data to better constrain models of atmospheric superrotation.

4 Mission Architecture

As the supplier of the flight system and mission design, the Lavochkin Association has provided a general assessment of the mission architecture. This includes, an evaluation of launch opportunities, general configuration of the spacecraft, accommodation of potential “contributed” payload elements, cruise to Venus and orbit insertion, and telecommunication for data return.

4.1 General Architecture

Successful Venus exploration commenced in 1967 with Venera-4, which was the first mission designed at Lavochkin Association. From 1970 to 1984, 10 successful landings on the surface of Venus were accomplished with the landers surviving up to 2 hours. The current Venera-D concept is based on the reliable prototypes from previous mission architectures. The overall mission concept is to use a carrier spacecraft to deliver a lander to the vicinity of Venus. After separation of the lander, the carrier would be inserted into orbit to serve as a relay orbiter and the means to downlink data to the earth. For Venera-D, the orbiting element would also serve as a platform to make high-priority atmospheric science observations.

4.1.1 Launch, Cruise, and Orbit Insertion at Venus

The trajectory analysis presented here assumes launch opportunities in 2026 and 2027 (**Figures 4.1-1** and **4.1-2**). The key components and events in the launch, cruise, and orbit insertion at Venus phases include:

1. Launch from Earth using and Angara-A5 launch vehicle for the Vostochny launch facility in 2026. The backup dates would be in 2027 and 2029;
2. Transition to the Earth-Venus flight trajectory using (hydrogen) KVTK («КВТК») or Briz («Бриз») upper stage vehicle;
3. Flight along the Earth-Venus trajectory with necessary corrections (practically, two corrections);
4. Separation of the descent module (lander, and any other component that would enter the atmosphere, e.g., small surface stations or balloon) and VAMP (two days before arrival at Venus);
5. Maneuver to transfer the orbiter to the nominal approaching orbit;
6. Entry into the atmosphere: lander, small surface station, and balloon may enter inside the descent module. VAMP enters separately;
7. Transfer of the orbital module onto a high elliptical orbit by the use of the rocket engine;
8. Separation of a sub-satellite (if provided);
9. Nominal scientific operations assuming data transmission from the Venus surface, VAMP and sub-satellite to the Earth through the orbiter

For this analysis, the flight system includes the following main constituents:

1. Orbiter and subsatellite and their scientific payload;
2. Descent module and its scientific payload (including small-surface station(s) and balloon);
3. VAMP (see below for discussion of the VAMP concept)

It should be mentioned that an alternative to the architecture described above has not been assessed. It assumes the transfer of the composite spacecraft into a high elliptical orbit. The current assessed configuration demands a high expenditure of propellant. Additional work is required to optimize the mission.

The key parameters for a mission launch in 2026 are provided in **Table 4.1-1**. For a backup launch in 2027, the parameters are given in **Table 4.1-2**. Trajectory plots are shown in **Figures 4.1-1** and **4.1-2**. The following notations are used:

ΔV_1	delta-V to start from Earth satellite initial circular low orbit with altitude 200 km;
V_1^∞	modulus of departing velocity vector (at infinity), km/s;
$C_{31} = (V^\infty)^2$	energy of departing from the Earth trajectory, km^2/s^2;
δ_1^∞	declination of the departing asymptotic velocity vector (at infinity), degrees;
α_1^∞	right ascension of the same vector at J2000 equatorial coordinate system, degrees;
ΔV_2	delta-V to transfer onto Venus satellite high elliptic orbit with pericenter altitude 500 km and period of orbit equal 24 hours;
V_2^∞	modulus of arriving to Venus relative velocity at infinity (i.e. asymptotic), km/s;
$C_{32} = (V^\infty)^2$	energy of arriving relative to the Venus trajectory, km^2/s^2;
δ_2^∞	declination of the vector of arriving asymptotic velocity, degrees, degrees;
α_2^∞	right ascension of the arriving relative vector of asymptotic velocity in coordinate J2000, degrees.

Table 4.1-1. Key trajectory parameters for 2026 date of launch.

Parameter	First Date for Launch Period	Middle Date for Launch Period	Last Date for Launch Period
Date of launch	30.05.2026	09.06.2026	20.06.2026
ΔV_1, km/s	3.905	3.881	3.896
V_1^∞ (C_{31}), km/s	3.930 (15.4)	3.858	3.904
δ_1^∞, ° - J2000 - ecliptic	 -28.44 -17.64	 -38.33 -26.50	 -46.17 -33.46
α_1^∞, °	202.50	203.15	203.65
Duration of transfer trajectory days	189	182	180
Angular distance of transfer, degrees	210.04	206.57	209.05
Date of arrival	05.12.2026	09.12.2026	17.12.2026
ΔV_2, km/s	0.899	0.859	0.899
V_2^∞ (C_{32}), m/s	3.117 (9.7)	2.982	3.118
δ_2^∞, ° - J2000 - ecliptic - Venus equator	 -12.71 -9.00 -10.17	 -0.12 6.66 5.46	 13.14 20.76 19.56
α_2^∞, °	186.73	197.25	202.11

Initial mass of spacecraft after separation from upper stage (Hydrogen block «КВТК»): 6500 kg.
Mass of the orbital module after putting it onto Venus satellite orbit with 24 hours period and 500 km pericenter altitude: more than 3100 kg.

Table 4.1-2. Key trajectory parameters for 2027 date of launch.

Parameter	First Date for Launch Period	Middle Date for Launch Period	Last Date for Launch Period
Date of launch	25.12.2027	06.01.2028	16.01.2028
ΔV_1, km/sкм/c	4.302	4.198	4.112
V_1^∞ (C_{31}), км/с	4.989	4.732	4.510
δ_1^∞, ° - J2000 - ecliptic	 44.22 24.43	 49.78 28.37	 52.98 30.64
α_1^∞, °	52.56	61.36	68.57
Duration of transfer trajectory days	200	197	193
Angular distance of transfer, degrees	224.29	224.76	225.55
Date of arrival	12.07.2028	20.07.2028	27.07.2028
ΔV_2, км/с	0.917	0.975	1.058
V_2^∞ (C_{32}), km/s	3.178	3.365	3.613
δ_2^∞, ° - J2000 - ecliptic - Venus equator	 -1.33 -18.04 -16.83	 -10.09 -28.31 -27.13	 -15.07 -34.08 -32.92
α_2^∞, °	46.48	53.18	56.91

Initial mass of spacecraft after separation from upper stage (Hydrogen block «КВТК»): 6400 кг.
Mass of the orbital module after putting it onto Venus satellite orbit with 24 hours period and 500 km pericenter altitude: more than 2900 кг.

As an example, **Figure 4.1-1** illustrates the descent of module (lander), which enters the atmosphere of Venus on a ballistic trajectory with a speed of *v = 11.0 km/s*. The descent module would make an adjusted entry at the formal altitude of the border of Venus' atmosphere, 120 km, with the entry angle being θ_{in} = *-15°*. This means that the maximum load during entry into atmosphere would not exceed 100g.

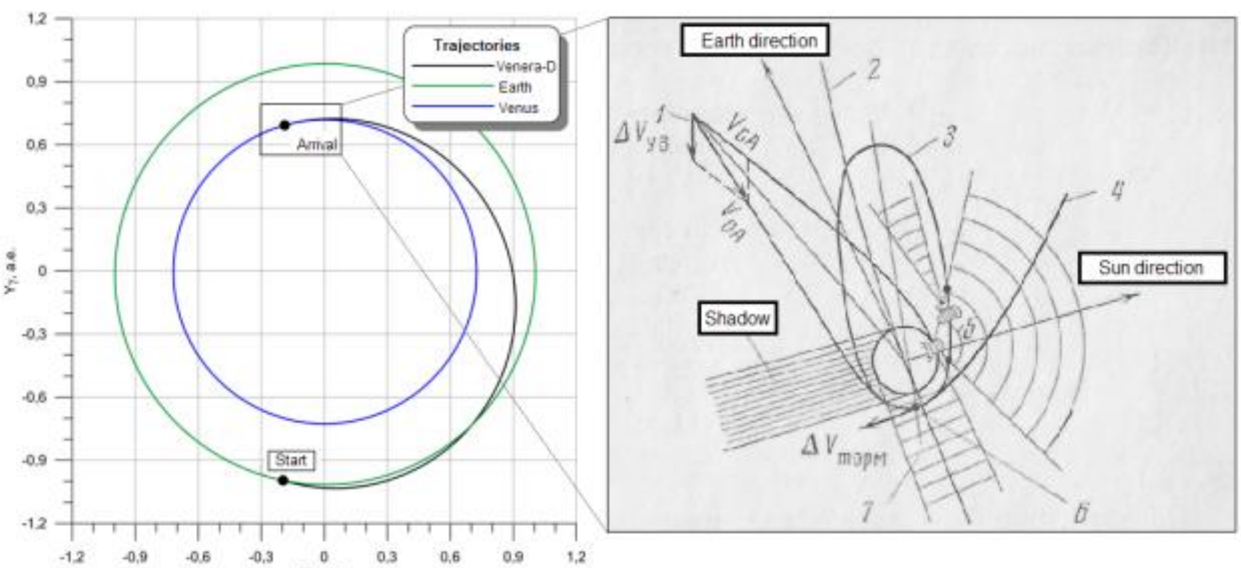

Figure 4.1-1. ***(Left)*** Trajectory of transfer Earth-Venus with start in June 2026. ***(Right)*** Arrival in detail. Notes: 1: Separation and trajectory offset, 2: Venus orbit, 3: Orbiter's orbit, 4: Flyby trajectory, 5: Area of orbiter-lander communication, 6: Braking and transferring the orbiter onto the orbit around Venus, 7: Radio shadow of Venus.

It is important to note that for planning the operations in vicinity of the Venus at least four factors must be taken into account. The first is the entry angle (or what is directly connected with the so called virtual pericenter height), second is position of the entry point (or the height of virtual pericenter). This means that the position of the entry point on the circle which presents points set on the surface of entry. We can choose any point on this circle when we perform the final maneuver before entry and before separation of the lander. Furthermore, the lander would fly uncontrolled (the orbit cannot be changed). The other two factors are the orbiter pericenter coordinates with respect to the Venus surface. On **Figure 4.1-1**, the case is presented (the case for Venera-12) when the two points (entry point and orbiter pericenter point) were chosen to be in the same plane but with the opposite direction of motion; the orbiter has a retrograde motion as observed from the Earth. This was done in order to reach the most favorable conditions for relay of the lander signal to the Earth from the lander.

The conditions of the VAMP separation are different from that mentioned above and should be specified by Northrop-Grumman. The entry angle is expected to be much lower, about 5°. To achieve this configuration. The VAMP separation would need to be earlier than that of the lander.

4.1.2 The Composite Venera-D Spacecraft

For the composite Venera-D spacecraft, it is suggested to use a spacecraft similar to the Expedition-M («Экспедиция-М»), which is currently under development. The composite spacecraft is a truss structure with 4 fuel tanks and rocket engines mounted onto it, shaped as a 4- or 8-face structure with solar panels and all the necessary service systems that facilitate the spacecraft during the mission. The systems and the scientific payload, depending on their requirements, could be mounted at the side faces, top or bottom faces, structure elements of solar panels, outer beams or other design elements.

In regard to the choice of launch vehicle fairing, it is suggested for the Venera-D mission to use a KVTK fairing (currently under development). It consists of 3 conical parts. The lowest part

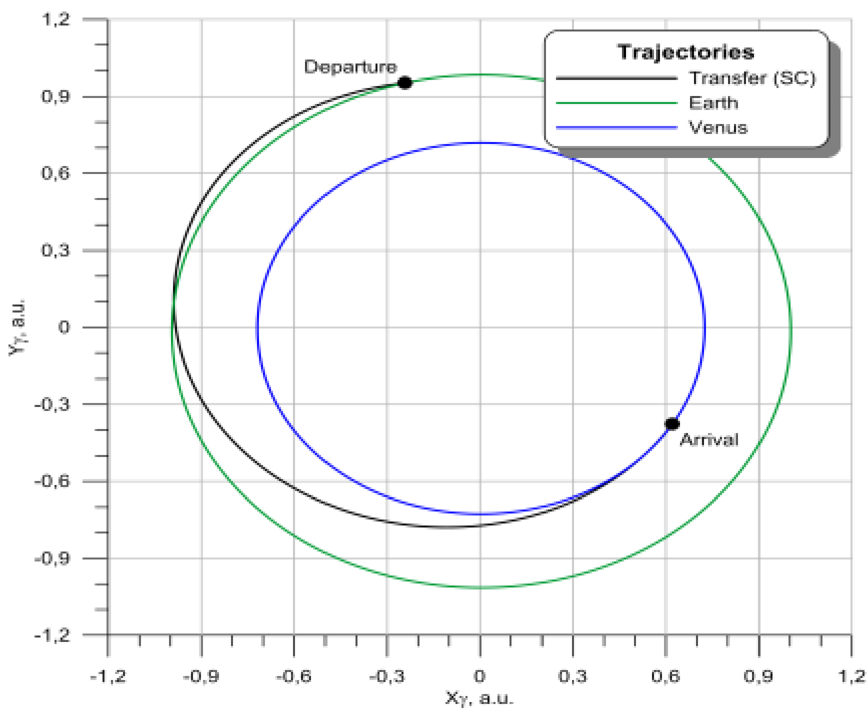

Figure 4.1-2. Trajectory of transfer from Earth to Venus with a launch in December 2027.

has an almost cylindrical shape with a height of 6,635 mm. Its inner lower diameter is 4,600 mm and inner upper diameter is 4,480 mm.

Two crucial payload elements are considered below: (1) the lander, because of its mass (1,600 kg) and (2) the VAMP, because of its size (3×6 m).

There are two options for accommodating the lander and the VAMP inside the composite spacecraft (**Figure 4.1-3**):

Option 1. Lander along the +X axis, VAMP along the –X axis. This combination has a height of ~10 m, and the center of mass is at ~7 m height. With such a large height of the center of mass, an additional assessment of the KVTK and Angara-A5 capabilities is required.

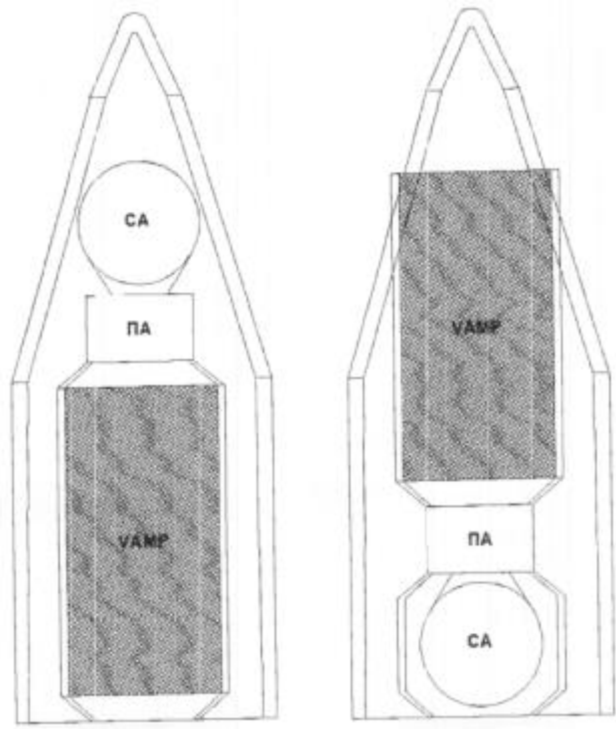

Figure 4.1-3. Notional concept of the composite spacecraft and the 2 accommodation options described above.

Option 2. Lander along the –X axis, VAMP along the +X axis. This combination has a height of ~10 m as well, and the center of mass is at ~3 m height. This option needs special requirements for the spacecraft design and use of a fairing with a taller cylinder part. It is recommended to reduce the height and the geometry of the VAMP in its folded form while preserving its volume.

4.1.3 Communication and Data Transmission

To transmit the scientific data from the lander and other surface or atmosphere mission elements to the orbiter it is suggested to use medium-gain antennas and transmitters that could meet all the requirements. It is planned to use the UHF frequency band for this communication.

To transmit the scientific information from the orbiter to the Earth several communication options are suggested, using high-gain antennas and ground-based stations:

1. X-band at 8 Mbit/s data rate. This is a traditional option—the data would be received by already existing ground-based stations. The average data volume per 24 hours would be ~20 Gbyte in this case;
2. X-band, 12–17 Mbit/s data rate. This option is currently under development within projects that are expected to be launched by 2020–2022. The data would be received by already existing ground-based stations with some level of augmentation necessary. The average data volume per 24 hours would be from 35 to 50 Gbyte in this case;
3. Ka-band, 100 Mbit/s data rate. This option is the most difficult because the construction of Ka-band receivable ground stations is required. The average data volume per 24 hours would be from 100 to 200 Gbyte in this case.

4.1.4 Spacecraft Mass

Table 4.1-3 provides a preliminary estimate of spacecraft mass distribution, including the VAMP. Not included is the mass of design elements that attach the VAMP itself, and the upper stage–spacecraft adapter.

Table 4.1-3. Estimated mass breakdown for Venera-D.

Name	Mass, kg
Orbiter (w/o scientific payload) • Structure • Fuel • Reserve	3,250 • 1,000 • 2,100 • 150
Lander • Structure • Scientific instruments	1,600 • 1,500 • 100
Scientific payload which includes: • VAMP, drop sondes, subsatellite, orbiter scientific instruments and all subsystems • Reserve	1,650 • 1,550 • 100
Total	**6,500**

Notes:

1. The 6,500 kg mass is for the spacecraft fully filled with propellant after separating from the upper stage, without the adapter.
2. This is the maximum spacecraft mass for the worst launch conditions.
3. The mass of the spacecraft and its elements will be clarified during future stages of development.
4. The scientific payload includes all the instruments, all of their subsystems, and other necessary structural parts.

4.1.5 Architecture Summary

1. Launch of the Venera-D mission is possible in the years of 2026, 2027 and beyond, with intervals between launch opportunities of approximately 1.6 years (583.9 days), using the Angara-A5 launcher and KVTK or Briz upper stage.
2. The spacecraft mass after separation from upper stage after insertion into a transfer trajectory to Venus is 6,500 kg for the entire period of launch cycles for 8 years starting in 2026.
3. The scientific payload mass, including subsystems and structural elements, is 1,650 kg, plus 100 kg for the lander.
4. The Lander-Orbiter, small surface station-Orbiter, VAMP-Orbiter, as well as Orbiter-Earth communication options are shown to be feasible.
5. If the VAMP is implemented and its folded size is 3×6 m, it will require further development of the launcher, upper stage, and the fairing.

5 Technology, Challenges (CH) and Enablers (EN)

5.1 Baseline Mission

As discussed in previous sections, the baseline missions consist of a long-lived orbiter and a short-lived lander. Recent mission experience such as Venus Express and Akatsuki, as well as a number of critically reviewed orbital mission proposals submitted to NASA and other agencies, suggest that all needed instrumentation is at a technology readiness level of 6 or higher, and in many cases, there is no technology development required to implement a remote-sensing-orbital mission around Venus. This proves true for the Venera-D mission concept developed by the JSDT. The only instrumentation with an identified technology readiness level less than 6 relates to development of L and W band systems for atmosphere probing. A top-level summary of overall technology readiness for the main mission elements is provided in **Table 5.1-1**. The colors used in the Assessment Tables in this chapter represent relative readiness, or consequently relative risk levels. A green box represents high level of readiness / relatively low risk, essentially an expectation that little new development is required and that standard practices and processes are expected to lead to successfully meeting requirements. A red box indicates there are known areas where significant development, test, and demonstration will be required to be confident in success, and a yellow box indicates a moderate level of readiness / risk. The detailed technology assessment is provided in Appendix A.

Implementation of the main lander is technically more challenging, but there have been numerous examples of successfully landing and operating missions very similar to what is planned for Venera-D. While several successful landers have been implemented, it has been several decades since a lander has been put on the Venus surface; therefore, work in analysis, testing, and qualifying of materials and systems for entry, the descent through the sulfuric acid clouds, and hours-scale tolerance for the high surface temperatures and pressures will be required. Test facilities to replicate surface pressures and temperatures in a CO_2 environment will be required, and at least one facility will be needed that is large enough to accommodate the main lander (CH). There are facilities in the United States that can perform some of these tests including the Glenn Extreme Environments Rig (GEER) facility at NASA Glenn Research Center, which can replicate precise chemistry in addition to surface temperature and pressure. The current GEER vessel however, is not large enough to accommodate the planned lander.

The bulk of the technology-related efforts for the lander; however, will be in 1) development of the sample acquisition and processing system (CH), 2) updating components or elements of instruments with recent heritage in other environments and then testing and qualifying them for use inside the Venera-D landing vessel, 3) developing and testing the sensors and systems exposed to the Venus environment (CH), and 4) maximizing data recovered from the lander instrument suite (EN).

(CH): The sample handling system will need to collect 5 cm^3 of sample through a pressure lock and process/distribute portions of the sample to several potential instruments (e.g., Gas Chromatograph Mass Spectrometer [GCMS], possible Mossbauer Spectrometer/Alpha Particle X-ray Spectrometer [APXS], possible Raman spectrometer, and possible X-ray Fluorescence Spectrometer [XRF]), which would be inside the landed vessel. The acquisition and distribution system must minimize heat transfer during the acquisition process in order to maximize lander life. A system that ingests the required volume of sample and minimizes heat transfer has been proven on previous Venera missions. However, the sample processing and distribution system inside the vessel would be new, and need complete development and testing. Sample handling and processing is a critical element of the lander, and needs significant development and testing and should begin as soon as possible.

(CH): Most instruments planned for the lander have some heritage related to an instrument flown on another mission. However, none of the instruments have been used at Venus or from a pressure vessel as planned for Venera-D. The instruments would need to be tested for the

Table 5.1-1. Overall Technology Readiness.

Platform	Instrument/Subsystem	Development Required	Overall Assessment
Orbiter and/or Sub-satellite	Given prior successful orbiting missions including the recent Venus Express and current Akatsuki orbiters, the overall risk to a successful orbit and remote sensing mission element is deemed **Low**.	Specific science objectives may require enhancing remote sensing capability previously applied in this environment (Higher resolutions, probing with expanded or new frequencies, updated detectors and electronics are examples).	
Lander	Several Soviet lander missions have been successfully implemented in the past and the basic approach of a pressurized vessel has proven successful. Priority science measurements that can be completed and data transferred to the orbiter at time scales of 1–2 hours have been identified and are viable. However, it has been several decades since the last landed mission. The people, instruments and lander subsystems, facilities, and procedures would be new. Some subsystems, like the sample handling system, are a new design and involve complex integration to support up to four internal instruments. Overall risk is deemed **Medium** although some subsystems and potential instruments have low maturity or long development time and therefore will require early attention and resources.	Essentially all the instruments, while having heritage in other applications, would need to be adapted and tested to ensure proper operation and results—whether they are exposed to the Venus environment or inside the vessel. The highest risk is expected to be the sample handling system, the capture and manipulation of the sample(s) from the sample acquisition mechanism to the various instruments within the vessel. Other higher risk items / more development include instruments such as Mossbauer spec / APSX and the integrated GC mass spec. Facilities will need to be established to test and qualify systems, particularly notable is the ability to test the full scale lander.	
Aerial Platforms	Soviet missions have also successfully deployed and implemented balloon-based science platforms over periods of days and proved the basic concept. Depending on the mobile platform itself, the overall risk may be **Medium** to **High**. Conventional balloons have been proven, but long-lived balloons are desired as is mobility. Both vertically and horizontally mobile platforms will require significant development and testing. As with landers, all instruments would require adaptation to the Venus environment, including sulfuric acid clouds at certain altitudes.	Essentially all the instruments, while having heritage in other applications, would need to be adapted and tested to ensure proper operation and results in the Venus atmosphere at the specific altitudes the platform will operate in. Conventional balloons will require some development to realize longer life and more power than earlier missions. Mobile platforms like VAMP or a vertically cycling balloon will require significant development and testing.	**Conventional** **Mobile**
Long-Lived Station	This element will rely on latest development in high temperature sensors, electronics, power and mechanisms. When successfully demonstrated, these capabilities may create a new paradigm for Venus surface exploration. This system has low system level maturity although many of the components have been successfully tested in Venus surface environments. Overall relative risk is deemed **High**.	Power and communication systems are the driving capabilities. The sensors and electronics need scaling to for specific lander needs and integration/ testing at a system level. A project to develop and test the long-lived station is currently underway at NASA.	

environmental conditions, and calibrated to understand the effects of the vessel and Venus surface conditions on the measurements (e.g., optical effects of looking through windows and the effects of the high pressure/temperatures gases and supercritical fluids on remote sensing measurements). Given the short mission life and limited power, careful planning and management of power utilization, instrument operations, and data transmission will be required.

(EN): Lander science would benefit from instruments that precisely determine mineralogy/composition. Raman-based spectroscopy may serve such needs, and a couple systems are nearing maturation and may be considered for inclusion in the lander instrument suite.

(EN): Long term study of the Venus surface is currently not possible due to the harsh conditions. This severely limits our ability for temporal studies of near surface winds, dynamics during transitions, seismology and other important investigations that would allow better understanding of superrotation, surfacing history, and other important science questions. Recent advances in high temperature electronics and other subsystems may enable a paradigm shift in Venus exploration concepts, and Venera-D may have the opportunity to demonstrate that capability while producing new long-term measurements of surface temperature, pressure, winds, and basic chemistry. If the technology currently in development meets its goals, it will be feasible to incorporate a long-lived element/instrument onto the exterior of the lander that would make, take, and transmit these measurements long after the lander ceases to function. This element would be based on the capability planned for the long-lived station described below.

(EN): Given that opportunities to explore the Venus surface are rare, every effort needs to be made to maximize the science data returned. The amount of data returned is a function of lander life and the data-transfer rates to the orbiter, which must be within view for the short life of the lander. Analysis indicates that approximately 200 Mbytes of data can be transmitted to the orbiter, assuming one hour of operations once the lander reaches the surface. This will be accomplished by selecting a transmission frequency (50 Mhz) that is optimized for the Venus atmosphere, and using lossless compression coding techniques.

Other obvious opportunities to maximize lander life exist and should be considered. Some of these include minimizing power consumed within the vessel, utilizing high efficiency electronics/designs, minimizing heat sources in the vessel and heat transfer into the vessel.

5.2 Other Potential Mission Components

The baseline mission can be significantly enhanced by adding other elements to the mission such as mobile aerial platform(s), long-lived station(s) and a smaller orbiting sub–satellite.

Previous missions (e.g., VEGA) have demonstrated successful deployment and operation of free-floating balloons in the Venus atmosphere. Such a platform with new instruments is of high science value and deemed relatively low risk. Some material testing work is required, however, particularly since longer float periods are desired than what was achieved on previous missions. Mass on such platforms is highly constrained so ultra-low mass (and low power) versions of instruments would be sought.

(EN and CH): An increase in science, above what can be achieved by a standard balloon, could be realized with an aerial platform that has propulsive capability to control altitude and position. VAMP is such a concept, and has been looked at by this SDT. Analysis and work to date offers promise of feasibility, but there is significant development required to mature the VAMP or another mobile aerial platform concept (e.g., materials qualification, deployment demonstration, flight demonstration, controlled entry, and more). To get a large enough payload to accommodate instruments that take advantage of the enhanced capability, requires a VAMP of the “Pathfinder” class. There is a challenge in that a vehicle of that class requires a very large amount of volume on the launch vehicle and about 500 kg of added mission mass. These may prove difficult to accommodate but the VAMP technology is robust in that it can trade parameters to meet particular constrains. For example, to meet mass of volume constraints, float altitude, science payload or life can all be adjusted.

(EN and CH): A long-lived station is another platform that could provide a significant science return (e.g., temporal atmospheric data from Venus surface), but it needs development. Such a platform would need to rely on components and electronics that not only survive but function at 460°C and 92 bar in harsh chemistry. Recent advances in high temperature electronics offer such promise. A long-lived station that would operate through two Venus day/night transitions and the period in between is desired (~60 Earth days). In addition to the immediate and significant science return, such capability could open the door for future Venus mission concepts, and could be a powerful technology demonstration option. Prime technology challenges are storing or harnessing enough energy and the operations of the electronics, especially the communication system, in Venus ambient conditions.

There are solution options being developed and plans to demonstrate such capability. For example, high temperature batteries exist, and some have been demonstrated to work at Venus temperatures. Scaling and packaging work is required for a rechargeable system and ultimately a demonstration of operation in Venus conditions.

For long-term Venus surface investigations, such as taking seismic measurements or mobile platform operations, long-term power solutions would be required. Techniques that help solve that challenge include harnessing power in situ or use of radioisotope based power systems. Both have challenges, but a non-nuclear system is expected to have fewer integration and materials challenges, and lower cost. This is the preferred power system option at this time. Given the dense and dynamic atmosphere, a system that captures energy from that atmosphere may be feasible. This idea is being investigated by NASA Glenn Research Center and considered by the JSDT. Power from such a system is envisioned to support a long-lived station that would function as a simple weather and chemical sensing probe for a minimum of 60 days and perhaps for years.

The other critical component, high temperature electronics, also exist. These have been demonstrated to function long term in Venus surface conditions, but these circuits still need to scale up in complexity. Another challenge at this time is to develop very low power circuits to acquire and transmit science data in very efficient ways. Development should continue for the electronics and a power system that will enable long-term Venus-surface exploration, and for Venera-D, a long-lived weather and chemical sensing probe.

(EN): The SDT also explored a sub-satellite platform to enhance science return focused on better understanding Sun–Venus interactions and upper atmosphere/ionosphere composition and loss. Because this would be a small orbiter, technical risk is deemed low. Key technology considerations would be the ability to transmit/receive the desired frequencies and the ability to move or control the relative position between the sub-satellite and the main orbiter. Both of these are seen as engineering efforts versus technology development efforts. A summary of technology readiness for the main mission elements and major instruments is provided in **Tables 5.2-1** and **5.2-2**.

Table 5-2-1. Technology readiness for main mission elements. Relatively High Risk Instruments (High Priority Science but low maturity and / or long development time expected).

Platform	Instrument/Subsystem	Development Required	Overall Assessment
Orbiter	Millimeter Wave Radiometer	Development of W channel, scanning antenna	
Orbiter	Radio-science two-frequency duplex occultation in S and X- and possible L-bands.	L band detector development - but prototype is available	
Orbiter/Sub-Satellite	Suite of 3 plasma instruments Panoramic energy mass-analyzer of ions CAMERA-O, electron spectrometer ELSPEC, fast neutrals analyzer FNA	ELSPEC and NPD need developing but relies on existing technology. Prototypes are under development.	
Orbiter	IR Imager	Adapt Akatsuki - like cameras for Venera-D needs	
Main Lander	Mossbauer Spectrometer / APXS	Demonstrate feasibility to make the measurements at the temperatures and within the available time	
Main Lander	Chemical analyses package (CAP)--Gas Chromatograph Mass Spectrometer	Sampling System for atmospheric gases/aerosols, Coupling of MS with LIMS	
Main Lander	METEO	Requires design and constructive integration to the lander	
Main Lander	Sample acquisition	Based on heritage system but will need updating / testing with new vessel and to minimize thermal transfer	
Main Lander	Sample handling / processing	Handling system must pull sample from acquisition system, separate sample, process if needed and delivery to up to four instruments in vessel interior	

Table 5.2-2. Technology Readiness for Potential Sub Elements and Infrastructure. Relatively High Risk Instruments (High Priority Science but low maturity and / or long development time expected).

Platform	Instrument/Subsystem	Development Required	Overall Assessment
Mobile Aerial	US Balloon(s)	Confirm performance with prototype testing, demonstrate aerial deployment and inflation technology, integration. Need approach to track position and orientation	
Mobile Aerial	VEGA based long-lived balloon	Requires materials qualification, solar power development, and integration. Need approach to track position and orientation	
Mobile Aerial	For VAMP or vertically mobile balloon	Need proof of concept demonstration at relevant environments, significant development and testing, and integration work with entry systems	
Long-Lived Station	Temp, pressure and winds	Validate life at conditions, develop wind sensor for battery version, demonstrate orientation determination capability	
Long-Lived Station	MEMS chemical sensors	Validate life at conditions and performance with complex chemistries	
Long-Lived Station Platform	Long-lived station life platform	Demonstrate power solutions, develop 50M Hz comm system, complete development of low power circuits	
Entry System		If using VAMP or second entry for long-lived stations, additional deployment / entry work may be needed.	
Test Facilities	Facilities for experiments, testing and calibration and qualification	Some facilities exist, (e.g., GEER) but more will need to be built, especially to qualify full scale lander	

5.3 Potential Technology Demonstrations

As new Venus mission concepts begin to migrate from orbiters to in situ systems, either in the atmosphere or on the surface, there will be a need to address the technical challenges posed by the hostile environments. Consequently, in situ Venus exploration is ripe for potential technology demonstrations, especially those that open up opportunities to increase the survival/mission life.

The greatest technical impacts for exploring Venus' harsh environments are in the areas of 1) high temperature systems such as electronics, 2) surface power generation and storage, and 3) mobility, with aerial mobility being the easier challenge to work given the prior successes with balloons.

Two potential technology demonstrations stand out for the Venera-D mission that have been considered and assessed from science impact and architecture feasibility perspectives.

One potential technology demonstration that addresses the mobility challenge is a long-lived mobile aerial platform. The Venera-D JSDT has looked at a concept in development by the Northrop Grumman Corporation that is being designed to offer vertical and horizontal mobility in the 50–62 km range (**Figure 5.3-1**). Vertical mobility however is heavily depended on the scale of the vehicle. A mid-size version, one that could potentially launch with Venera-D, is expected to have a vertical range of approximately 55–60 km. The platform has a number of other significant advantages including the ability to cover a target multiple times as it traverses the planet. It is expected to stay at float altitudes for up to three months, and provide approximately 25 kg of payload for science instruments. Such a platform could provide science return related to the long-standing UV absorption questions.

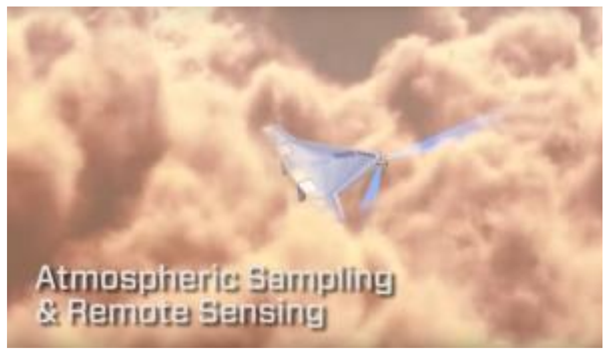

Figure 5.3-1. Concept for the Venus Atmospheric Maneuverable Platform (VAMP) being developed by the Northrop-Grumman Corporation.

The potential technology demonstration in the Venera-D architecture that would target the problems of surface power and long-term survivability via high temperature systems is the long-lived station. The element is designed to be stand-alone, would communicate directly to an orbiter, be self-powered, and operate in Venus surface conditions for thousands of hours. It could be incorporated directly onto the lander as an instrument, if needed. If the capability to survive long term in Venus conditions is demonstrated, it would allow for exciting new concepts to be considered for future missions, even the idea of directly measuring seismic activity over long time periods. The long-lived station would provide science return as well, functioning as a long-term weather station to help better understand weather and superrotation, and will provide deep atmosphere chemistry measurements over long time periods including across day/night terminators.

Both demonstrations would offer major technical advances and high-value science return, and both require development before they are ready for flight (as discussed in previous sections). However, the science and technology benefits are significant, and therefore, these should be considered for inclusion into the final mission design.

6 Opportunities for Lab Work

6.1 Baseline Mission

Laboratory experiments could significantly improve preparing for implementing and interpreting results of the Venera-D mission concept. For the orbiter, experiments on emissivity of expected Venus surface materials at the one micron window would be valuable. Experiments to quantify propagation parameters for the intended communication and sounding frequencies, and correlate that to atmosphere composition and properties, is also desired. Other experiments can be considered such as optical properties / spectral profiles at various wavelengths again correlating that with atmosphere characteristics. Modeling and experiments would also be invaluable to better understand and constrain our understanding of the Venus atmosphere. This could confirm some basic assumptions such as mixing particularly in high temperature/pressure conditions.

Similar types of experiments are needed in support of lander science. Optical properties of the near-surface atmosphere are needed at wavelengths corresponding to what the remote sensing instruments would be using. For composition and mineralogy science experiments, weathering experiments (exposing potential Venus minerals to expected Venus near surface atmosphere conditions) are needed to help determine and refine sampling and sample processing objectives. Other lab work / experiments should include trace and noble gas enrichment procedures, supercritical fluid properties, and trace gas composition changes due to temperature and pressure drop during sampling. This will help interpret measurement results and science implications.

There is also a class of experiments that is required simply to verify and validate instrument performance and support calibration. Many instruments for the lander will require these types of tests/experiments.

6.2 Other Potential Mission Components

Laboratory experiments are required in support of potential science from an aerial platform. The in situ instruments will need to be tested and calibrated for expected chemistry, optical and infrasound properties, particulates/aerosols, and of the local environmental conditions including corrosive compounds. Experiments on the potential make-up of the UV absorber, even perhaps biologically connected processes, are recommended to better predict mission scenarios and test intended platform instruments.

Laboratory experiments are also needed for testing the long-lived station and its sensors and systems. As mentioned previously, environmental tests are needed for all systems to demonstrate performance and function in the anticipated environment. Specific for the station, more tests will need to be conducted to verify performance of the chemical sensors and their ability to uniquely identify and quantify target species from a complex and unknown set of species. Engineering oriented experiments will be required to understand power generation capability in various wind conditions should a wind powered version be flown.

The sub-satellite will require focused test and experiments. Like all elements, tests will be required to demonstrate performance and to calibrate the planned instruments. However, there are unique tests/experiments required to support the sub-satellite. These include propagation experiments, especially in the L band, to allow interpretation of future data and perhaps fine-tune instrument parameters.

7 Potential Contributions to the Baseline Venera-D Concept

As part of its science assessment, and based on the areas of "science gaps" discussed previously, the JSDT identified a range of specific items that could be candidates for potential contribution or collaboration. Depending on the final architecture of the Venera-D mission, these items could range from individual instruments to flight elements. **Table 7-1** summarizes, in priority order, areas for potential contribution or collaboration. In this list, the JSDT emphasized that the first priority would be to accommodate the baseline Venera-D mission consisting of an orbiter and lander. The remainder of this section provides a general discussion of the science enabled by the aerial platform and small long-lived surface station(s).

Table 7-1. Priority list of potential contributions, augmenting the baseline mission.

First Priority: Accommodation of Baseline Venera-D (orbiter and lander)		
Element	**Mass Estimate**	**Description**
Instrument(s)--lander	Variable	Raman Spectrometer; X-ray Fluorescence Spectrometer (XRFS); Alpha-Proton X-ray Spectrometer (APXS) to baseline lander
Venus simulation and Test Facilities		
Aerial platform	450 kg	Lifetime of 1 to 3 months; approximately 25 kg of payload to address atmospheric superrotation, chemistry, and trace species in the middle cloud layer; mobility to different altitudes in the atmosphere
Small long-lived station(s)	8 to 10 kg per station—5 stations ~50 kg	Potential for long-lived (60 days to a year) presence on the surface; For studying superrotation, meteorology and chemistry (temperature/pressure/winds/atmospheric composition) measurements in the near surface layer; limited to data taken when the relay asset is in view—restricted to real time measurements
Free-floating balloon	Up to 450 kg	Lifetime of up to 1 month; approximately 15 kg of payload for studying the atmosphere; moves by winds, no directed mobility; would need tracking from the Earth
Small satellite (Roscosmos contribution)	~40 kg	Magnetospheric and atmospheric science
Small aerial platform	~90 kg	Lifetime of 1 to 4 weeks; server as a technology demonstration for pathway to larger vehicle; very limited mass for science payload

7.1 Aerial Platform

Advancement in addressing science questions focused on understanding the mechanisms that drive and maintain atmospheric superrotation along with the identification of the unknown UV absorber, could be enabled by in situ measurements over an extended period of time (months). In its proceedings, the JSDT received a briefing from the Northrup-Grumman corp. on a concept for a Venus Atmospheric Maneuverable Platform (VAMP) with the capability to navigate and operate over a range of altitudes (**Table 7.1-1**). In comparison with most balloon systems that are restricted to a single altitude, this type of vehicle would potentially enable the assessment of vertical variations in atmospheric composition and properties. Examples of the type of scientific measurements that could be made are provided in **Table 7.1-2**. In the context of Venera-D, the JSDT discussed the accommodation the Pathfinder VAMP. Preliminary assessment by the Lavochin Association suggests that the estimated mass of 450 kg could be accommodated, but accommodation of the vehicle and is support structure would be challenging and additional work would be needed.

Table 7.1-1. General specifications for Venus Atmospheric Maneuverable Platform (VAMP) (provided by Northrup-Grumman Corp.).

	Baseline VAMP	Pathfinder VAMP	Tech Demo VAMP
Objectives	Powered flight Full climb ability to 68 km altitude Greatly expanded science	Powered flight Limited climbing ability Nighttime science operations Expanded science	Lifting entry Operation in H_2SO_4 environment Basic science (temperature, pressure, wind speed)
Nominal Science Ops Duration	Up to 1 year	1 – 3 Months	1 – 4 Weeks
Nominal Altitude Range	50 – 65 km	~55 – 60 km	Fixed (~50 km)
Science Instruments & Capabilities	> 50 kg	> 25 kg	> 10 kg
Minimum Power	8,000 w (day); 100 w (night)	300 w (day); 100 w (night)	100 w (day); 20 w (night)
Notional Wing Span	59 m	30 m	6 m
Vehicle Mass	880 kg including instruments	450 kg including instruments	90 kg including instruments
Launch Vehicle	Atlas V 551 or Equivalent	Atlas V 401 or Equivalent	Piggy-back on Venus flyby spacecraft

Table 7.1-2. Key science investigations that could be achieved by an aerial platform.

Area of Investigation	Science to be Achieved	Example Payload
Origin & evolution of reactive species	Trace gas composition and profiles; isotopic ratios; temporal/spatial variability of chemical species	Tunable Laser Spectrometer (TLS); GCMS
Clouds	Composition; particle microphysics; cloud chemistry; identification of UV adsorber	Nephelometer; microscopy; TLS; Raman-lidar; UV-VIS-NIR imager
Dynamics	Winds (u, v, w); turbulence; planetary waves; atmospheric momentum; net-flux	Doppler radar; accelerometer; UV-VIS-NIR imager; radiometer
Meteorology	Pressure and temperature profiles; dT/dz stability; thermal structure & gradients	Meteorology package
Surface science	Surface geology; topography; search for active volcanism	Navigation radar; NIR spectrometer (or camera with several channels)
Electromagnetic environment	Lightning intensity & location; atmosphere conductivity	Lightning probes; microphones

7.2 Small Long-Lived-Stations

In situ measurements to serve as input to constrain parameters in models of atmospheric circulation have been limited in location and single instances in time. To clearly understand the dynamic nature of atmospheric phenomena, measurements over a relatively long temporal baseline are required (see discussion in Section 3.1). As little is known about how the atmosphere behaves at or near the surface, meteorological observations in this harsh part of the Venus environment are needed. Recent advancements in high temperature components, along with the development of chambers to test these components (see Section 5) have led to the concept of the small long-lived meteorological station discussed in Section 5.2 (**Figure 7.2-1**). The goal would be to make observations of pressure, temperature, wind speed and direction, and near-surface atmosphere composition over a period from 60 days to a year. Due to power constraints, the station would be limited to collecting and transmitting measurements when the orbiter is in view. It is anticipated that each station would have a mass of 10 kg. For a set of stations, possibly up to five, distributed across planet, the scientific goals would be as follows:

Figure 7.2-1. Concept for a small long-lived station that would operate on the surface of Venus for up to at least 60 days to make measurements of pressure, temperature, wind, and atmosphere composition.

- Monitor the amplitude and phase of diurnal tides, other planetary scale waves, and mesoscale turbulence;
- Characterize the exchange of the planet's solid body and air mass, which may be a source of angular momentum to address processes associated with superrotation;
- Simultaneous monitoring of air mass flow with variations in composition to give insight into the role that atmospheric transport plays in the maintenance of the current chemical balance in the lower Venus troposphere;
- Development of a new three-dimensional Global Circulation Model (GCM), as well as providing data to validate and tune existing models

8 JSDT Findings and Recommendations

This section provides a summary of the findings and recommendations of the Venera-D JSDT. Based on the tasks set forth in the JSDT charter and from additional direction received from both IKI and NASA, findings and recommendations are put forward in regard to (1) the science that could be achieved by a Venera-D mission, (2) strategic needs that would enable successful implementation of Venera-D, (3) architectural options to consider when scoping the mission, and (4) a summary and assessment of completeness of the tasks defined in the JSDT charter.

8.1 Science that Could Be Achieved by Venera-D

In its deliberations, the JSDT set priorities on the overall science goals and objectives. Based on these priorities, a baseline mission would consist of a single highly capable orbiter and a single highly capable lander. Each would address science questions regarding the composition and dynamics of the atmosphere. In terms of surface and surface-atmosphere interactions, the lander would be the primary mission element to address these objectives while the orbiter, making surface observations in the near-infrared would provide global-scale data to address questions related to recent volcanic activity and compositional variability of terrains. The anticipated science that could be achieved is summarized in **Table 8.1-1**.

Table 8.1-1. Baseline Venera-D Mission.

Mission Element	Science Goal	Anticipated Science
Orbiter (High eccentricity polar orbit with periapsis ~300 km, 24-hour period)	Understanding atmospheric superrotation and global circulation	Validate different processes that maintain superrotation
	Radiative balance and driver for super rotation	Structure and relationship of solar thermal tides to energy deposition and their role in superrotation
	Origin and evolution	Noble gas isotopes from descending lander, global distribution of trace species from UV and IR spectra from orbit
		Source and processes of electrical activity
	Solar wind and magnetosphere and ionosphere interaction	Structure and response of the magnetosphere/ionosphere to solar wind and activity, solar wind induced atmospheric mass losses
	Volcanism	Possible detection of recent volcanism
Lander (1 hour descent to the surface, 1 hour of surface measurements and 1 hour of margin for additional measurements)	Composition of the Venus surface	Elemental and mineralogical composition for detailed geochemical characterization of soils/rocks and assessment of local geology
	Geology of the Venus surface	Geological context if the landing site, characterization of the surface morphology at visible wavelengths and "ground truth" at regional to local scales
	Surface/Atmosphere interaction	High-precision composition of both the atmosphere and surface materials to constrain models of alteration processes
	Origin and evolution	Clues to the origin and evolution of Venus from differences in Noble gas isotopic ratios compared to the Earth and Mars

As part of its evaluation of the Venera-D concept, the JSDT identified areas in which the science could be enhanced or new science, above that to be accomplished by the baseline mission, could be achieved (**Table 8.1-2**). It was clear that in situ measurements, both at the surface and aloft made over an extended period of time are of great importance, especially for understanding the processes that drive the atmosphere. Mobility within the atmosphere was also deemed of high priority in terms of understanding the location of the UV absorber and identifying its composition. Although science objectives to understand atmospheric and geologic processes were deemed of highest priority, the JSDT also assessed advancements that could be made in magnetospheric and space environment science, which was ranked as a medium priority. The inclusion of a sub-satellite with a focus on solar wind and ionospheric processes was examined and found to provide an incremental advancement in the state of knowledge.

Table 8.1-2. Potential Enhancements to the Venera-D Mission.

Mission Element	Science Goal	Anticipated Science
Variable altitude maneuverable aerial platform (>3 months lifetime, ~25 kg payload, ~5 km altitude excursions between 50 to 62 km)	Understanding atmospheric superrotation	First ever continuous measurements of turbulence on day and night side at multiple altitudes, small-scale and planetary waves, solar thermal tides
	Nature of the ultraviolet absorber	Identity of the unknown ultraviolet absorber(s) from chemical disequilibrium
	Radiative balance and driver for superrotation	Differences in the energy deposition in the atmosphere that drives the atmospheric circulation
	Clouds and composition	Correlation between ultraviolet contrasts and near-infrared opacity and cloud chemistry/composition
	Atmospheric composition variation in the major constituent vertical profile	Confirm vertical gradient measured by Pioneer Venus in abundances of carbon dioxide and nitrogen
Balloon (~7 to 30 days lifetime, ~15 kg payload, ~54 ± 0.5 km altitude	Understand atmospheric superrotation	Better knowledge of the ambient wind at almost constant altitude enabling determination of thermal tide amplitude and phase
	Radiative balance and driver for superrotation	Energy deposition differences between day and night and whether correlated with ultraviolet contrasts
	Electrical activity/lightning and other significant atmospheric processes	Connection between surface topography and standing waves, whether electrical activity is related to topography or dynamics
	Clouds and composition	Correlation between ultraviolet contrasts and near-infrared opacity and cloud chemistry/composition
Long-lived station on the surface (~month to 1 year, wind powered, data sent to orbiter)	Surface/Atmosphere angular momentum exchange	Sign of the transfer of angular momentum between the atmosphere and the planet, temporal variations in temperature and pressure that may be related to different waves
	Near-surface composition changes	Whether there is any temporal variations in bulk chemistry of the atmosphere due to venting from the surface or waves
	Technology development	First demonstration of long-lived station on the surface of Venus
Sub-satellite	Solar wind and magnetosphere and ionosphere interaction	Solar wind control, separation of spatial from temporal variations, ionospheric/atmospheric radio occultations

8.2 Strategic Needs for Future Development

In planning for the implementation of Venera-D, the JSDT identified areas in which strategic (within the next 5 to 7 years) investments would need to be made to bring the mission concept to fruition. For an anticipated launch in the post 2025 timeframe, activities of the following nature would be needed to ensure mission success:

- The types of instruments to achieve the Venera-D science require various levels of validation and maturation to ensure robust and successful operation in the Venus environment;
- Laboratory work to characterize the chemistry of the Venus atmosphere at high temperatures and pressures;
- Development of capable facilities to test mission enabling instruments and the spacecraft at the component and system level in a simulated Venus environment;
- Continued development regarding all potential contributions

8.3 Architectural Options

The JSDT realizes that with additional study the Venera-D concept will evolve. As resources (mass, power, volume, and funding to name a few) are better defined, trades will need to be made that impact science. In anticipation of this, a set of potential architectural options (**Table 8.3-1**), ranked as Ambitious, Adequate, and Minimal, were identified that achieve no less than the core baseline science. The most ambitious option contains the most flight elements, the highest potential science return, and offers the greatest range of potential contributions. Its complexity due to the large number of elements results in a high level of technical and scientific risk. The Adequate mission option, composed of three flight elements, would be a challenge from the standpoint of complexity, interfaces, testing, validation, and operation. Like the Ambitious option, the opportunity for potential contribution is very high. The Minimal concept would produce significant science results focusing on the core objectives, but the set of potential contributions would be reduced relative to the Ambitious and Adequate architectures. For future work, the overall set of architectural options could provide a basis for additional study as the Venera-D concept matures.

Table 8.3-1. Venera-D architectural options.

	Ambitious Mission	Adequate Mission	Minimal Mission
Flight Elements	Baseline orbiter and lander; Aerial platform; Small long-lived station	Baseline orbiter and lander; Aerial Platform	Baseline orbiter and lander
Science Enabled	Comprehensive atmosphere and surface science	Core science objectives with enhanced atmospheric science	Core science objectives (High and medium priority)
Challenges	• Large number of flight elements and deployments resulting in potentially high technical and scientific risk; • Integration, validation, testing, and operation of multiple flight elements	Integration, validation, testing, and operation of multiple flight elements	Integration, validation, testing, and operation of flight system
Potential Contribution Options	DSN Support; Instrument(s); Flight element; Test facilities	DSN support; Instrument(s); Flight element; Test facilities	DSN support; Instrument(s); Test facilities

8.4 Assessment of JSDT–Chartered Tasks

As discussed in Section 2.4, the Venera-D JSDT was provided with five tasks to address as it carried out its work. Below we provide a brief summary as to how each task has been completed.

1. Identify, prioritize and develop science goals, investigations, and measurements consistent with the current Venera-D concept

Based on the initial concept, the JSDT prioritized the science goals and objectives of the baseline Venera-D mission. The science that would be achieved addresses aspects of all NASA Planetary Decadal Survey goals for the study of Mercury, Venus, and the Moon. In addition, for all types of objectives (atmosphere, surface, surface/atmosphere interaction), the baseline Venera-D concept would address 16 out of 17 high priority and 8 out of 8 medium priority VEXAG investigations. (Section 3.3)

2. Assess the Venera-D mission architecture including possible modular options (e.g., subsystems) for collaboration opportunities and required instrumentation capabilities. Assess technology readiness level to implement the mission concept and identify areas for which development is required

The JSDT technology subgroup performed a comprehensive survey of the identified notional instrument and potential alternatives. Capabilities and technology readiness for each was evaluated and a rating of level of needed development was established to quantify the time to needed to reach flight readiness TRL. (Section 5)

3. Identify mission components (mission elements/subsystems/instruments) that best lend themselves to potential collaboration. Outline a general maturation schedule needed to support a Venera-D mission for launches in the post-2025 time frame;

Potential contributions identified could range from standalone instruments to flight elements (aerial platform or small stations). The JSDT technology subgroup assessed the TRL level of each and the time to reach flight readiness has been identified. (Section 5)

4. Assess the precursor observations and instrumentation validation experiments needed to enable or enhance the Venera-D mission (e.g., instrument testing in a chamber that emulates the chemistry, pressures and temperatures found in the atmosphere or at the surface of Venus);

Areas of critical testing and advance development have been identified. Validation of compatibility with the Venus environment is a top driver. (Section 6)

5. Evaluate how Venera-D would advance the scientific understanding of Venus and feed forward to future missions with the ultimate goal of sample return.

Long-term observations and direct, in situ, sampling and chemical analysis of the atmosphere would form the basis to understand the process of atmospheric superrotation. Feeding forward to future missions, the resulting high-fidelity Global Circulation Models (GCMs) would form the basis for devising engineering techniques to successfully launch samples from the surface for retrieval in space. In situ atmospheric sampling and analysis would constrain and optimize where samples of atmospheric gases should be collected for return. Similarly, precise and accurate in situ analysis of surface materials would provide the basis to understand where best to collect rock samples for return to Earth. The techniques by which the Venera-D science would be achieved would validate critical technologies for potential follow-on missions.

9 Framework for Future Work

Relative to the development life-cycle process provided by the Central Research Institute of Machine Building (Центральный научно-исследовательский институт машиностроения--TSNIIMASH), the JSDT activity has completed the activities of defining the science goals, identifying a notional scientific payload, and has participated in the preliminary assessment of the mission feasibility (**Figure 9-1**). The next phase of development would focus on a deeper examination of the science and instruments along with the definition of spacecraft requirements. Within this context, the JSDT has identified specific areas that deserve immediate attention. These include the following:

1. Definition of a focused mission concept
2. Definition of a concept of operations for the lander including a timeline of science observations, strategy for sample acquisition, handling, and analysis, data flow and downlink
3. Refinement of instrument capability relative to the ability to achieve the science goals
4. Refinement of the envelope (mass, power, volume) for a potentially contributed element
5. Maturation of the small station concept; instrumentation and concept for targeting and deployment—if provided as a contribution
6. Aerial Platform accommodation and deployment optimization along with science priorities and instrumentation—If provided as a contribution

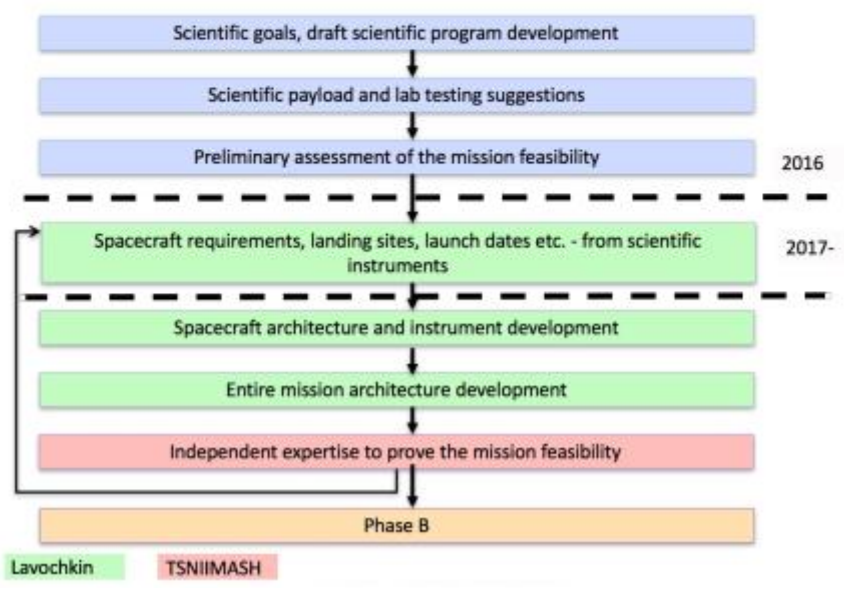

Figure 9-1. Mission development cycle provided by TSNIIMASH.

To achieve a number of these items, a greater engagement of the broader Venus science community is recommended. Current discussion has focused on holding workshops in both the United States and Russia to understand the limitation and needs of current models (e.g., GCMs) and the types of measurements needed to more adequately constrain parameters in the models. This would in-turn form a basis to better identify the types of instruments needed to achieve the science of Venera-D.

10 References

Abdrakhimov, A.M., 2005, Geochemical comparison of volcanic rocks from terrestrial intraplate oceanic hot spots with Venusian surface material, *Geochem. Int*., v. 43, No. 8, 2005, pp. 732–747.

Avduevskii et al., 1977, Measurement of wind velocity on the surface of Venus during the operation of stations Venera 9 and Venera 10, *Cosmic Res*., 14 (5), 622-625.

Barabash, S., Fedorov, A., Lundin,R., Sauvaud, J.A., 2007, Martian atmospheric erosion rates, *Science,* 315, 501–503.

Barstow, J.K., Tsang, C. C. C., Wilson, C. F., Irwin, P. G. J., Taylor, F. W., McGouldrick, K., Drossart, P., Piccioni, G. Tellmann, S., 2012, Models of the global cloud structure on Venus derived from Venus Express observations, *Icarus*, 217, 542-560.

Barsukov, V.L. et al., 1982, Geochemical studies of Venus surface by Venera 13 and Venera 14 spacecrafts (in Russian), Geokhimia, 7, 899-919.

Barsukov, V.L. et al., 1986, The geology and geomorphology of the Venus surface as revealed by radar images obtained by Veneras 15 and 16, *J. Geophys. Res*., 378–398.

Basilevsky, A.T. and J.W. Head, 2000, Geologic units on Venus: Evidence for their global correlation *Planet. Space Sci*., v. 48, p. 75–111.

Bertaux, J-L.; Ekonomov, A. P.; Mezh, B.; Moroz, V. I.; Aberzhal, A.; Gnedykh, V. I.; Grigoryev, A. V.; Moshkin, B. Ye.; Oshkorn, A.; Pommero, J. P, 1987, Research on absorption of UV radiation in Venusian atmosphere from Vega-1 and Vega-2 landing module, *Kosmich. Issled*., v. 25, no. 5, p 691-706

Bertaux, J-L. et al., 1996, Vega-1,2 entry probes: An investigation of local UV absorption (220-400 nm) in the atmosphere of Venus (SO2, aerosols, cloud structure), *J. Geophys. Res.,* 101, 12,709–12,745, doi:10.1029/96JE00466.

Bertaux, J-L., I.V. Khatuntsev, A. Hauchecorne, W.J. Markiewicz, E. Marcq, S. Lebonnois, M. Patsaeva, A. Turin, A. Fedorova, 2016, Influence of Venus topography on the zonal wind and UV albedo at cloud top level: The role of stationary gravity waves, *J. Geophys. Res.*, Volume 121, Issue 6, June 2016, Pages 1087–1101, DOI: 10.1002/2015JE004958.

Bézard, B.; de Bergh, C., 2007, Composition of the atmosphere of Venus below the clouds, *J. Geophys. Res.*, 112, E04S07, doi:10.1029/2006JE002794.

Blamont, J. E. et al., 1986, Implications of the VEGA balloon results for Venus atmospheric dynamics; *Science*, 231, 1422–1425.

Bullock, M. A., Grinspoon, D. H., 2001. The recent evolution of climate on Venus. Icarus. 150**,** 19-37.

Bullock, M.A. and D.H. Grinspoon, 2013, The atmosphere of climate of Venus, In *Comparative Climatology of Terrestrial Planets*, S.J. Mackwell et al., eds. pp 19–54. Univ. of Arizona, Tucson, AZ, DOI:10.2458/azu_uapress_9780816530595-ch002.

Campbell, I. H., Taylor, S. R., 1983. No water, no granites - No oceans, no continents. Geophysical Research Letters. 10**,** 1061-1064.

Carlson et al., 2016, Venus's ultraviolet absorber: Cyclo-octal (S_8) and polymeric sulfur (S_X) and their Latitudinal behavior; In International Venus Conference 2016. Held 4–8 April 2016, in Oxford, UK.

Chaufray J.-Y. et al., 2012, Hydrogen density in the dayside venusian exosphere derived from Lyman-α observations by SPICAV on Venus Express, *Icarus*, 217, 767–778.

Clancy R.T. et al., 2012, Circulation of the Venus upper mesosphere/lower thermosphere: Doppler wind measurements from 2001-2009 inferior conjunction, sub-millimeter CO absorption line observations, *Icarus*, 217, 794–812.

Drossart, P. et al., 2007, A dynamic upper atmosphere of Venus as revealed by VIRTIS on Venus Express, *Nature*, 450, 641–645.

Fegley, B., Treiman, A. H., Chemistry of atmosphere-surface interactions on Venus and Mars. In: J. G. Luhmann, et al., Eds.), Venus and Mars: Atmospheres, Ionospheres and Solar Wind Interactions. American Geophysical Union, Washington, DC, 1992, pp. 7-71.

Florensky, K. P. et al., 1977, The Surface of Venus as revealed by Soviet Venera 9 and 10, *Geol. Soc. Am. Bull.*, 88, 1537–1545.

Fukuhara et al., 2017, Large stationary gravity wave in the atmosphere of Venus, *Nature Geoscience*, doi:10.1038/ngeo2873.

Gierasch, P.J. et al., 1997, The general circulation of the Venus atmosphere: An assessment; In: Bougher, S.W., Hunten, D.M., Philips, R.J. (Eds.), *Venus*, vol. II. Univ. Arizona Press, Tucson, pp. 459–500.

Hansen, J.E., Hovenier, J.W., 1974, Interpretation of the polarization of Venus, *J. Atmos. Sci.*, 31, 1137–1160.

Hashimoto, G. L., Abe, Y., Venus' surface temperature controlled by a chemical-albedo feedback. LPSC XXIX. Abstract 1593, 1998.

Helbert, J., Muller, N., Kostama, P., Marinangeli, L., Piccioni, G., Drossart, P., 2008. Surface brightness variations seen by VIRTIS on Venus Express and implication for the evolution of the Lada Terra region, Venus. Geophysical Research Letters. 35**,** L11201, doi:10.1029/2008GL033609.

Herrick, R., K. Baines, M. Bullock, G. Chin, B. Grim, W. Kiefer, S. Mackwell, K. McGouldrick, B. Sharpton, S. Smrekar, C. Tsang, 2014, Goals, Objectives and Investigations for Venus Exploration, 1–15.

Hodges, R. R., Jr., Tinsley, B. A., 1982, The influence of thermospheric winds on exospheric hydrogen on Venus, *Icarus*, 51, 440–447.

Hueso, R., Peralta, J., Sanchez-Lavega, A., 2012. Assessing the long term variability of Venus winds at cloud level from VIRTIS-Venus Express, *Icarus*, 217, 585–598.

Ivanov, M.A. and J.W. Head, 2004, Stratigraphy of small shield volcanoes on Venus: Criteria for determining stratigraphic relationships and assessment of relative age and temporal abundance, *J. Geophys. Res.*, v.109, NE10001, doi:10.1029/2004JE002252.

Ivanov, M.A., and J.W. Head, 2011, Global geological map of Venus, *Planet. Space Sci.*, v. 59, p. 1559–1600, doi:10.1016/j.pss.2011.07.008.

Ivanov, M.A. and J.W. Head, 2015, The history of tectonism on Venus: A stratigraphic analysis, *Planet. Space Sci.*, v. 113–114, p. 10–32.

Kargel, J.S., G. Komatsu, V.R. Baker, and R.G. Strom, 1993, The volcanology of Venera and VEGS landing sites and the geochemistry of Venus, *Icarus*, v. 103, p. 253–275.

Kargel, J.S., Kirk, R. L., Fegley, B., 1994, Carbonate-sulfate volcanism on Venus?, Icarus, 112, 219-252.

Kerzhanovich, V.V., Limaye, S.S., 1985, Circulation of the atmosphere from the surface to 100 km, *Adv. Space Res*. 5, 59–83.

Khatuntsev, I.V. et al., 2013, Cloud level winds from the Venus Express Monitoring Camera imaging, *Icarus*, 226, 140–158.

Khatuntsev, I.V. et al., 2017, Winds in the middle cloud deck from the near-IR imaging by the Venus Monitoring Camera onboard Venus Express, *in press*.

Knollenberg, R.G.; Hunten, D.M., 1980, The microphysics of the clouds of Venus – Results of the Pioneer Venus particle size spectrometer experiment, *J. Geophys. Res*., 85, 8039–8058.

Krasnopolsky, V.A. (2016) On the iron chloride aerosol in the clouds of Venus. Icarus (2016), http://dx.doi.org/10.1016/j.icarus.10.003

Kouyama, T, T. Imamura, M. Nakamura, T. Satoh, Y. Futaana, 2013, Long-term variation in the cloud-tracked zonal velocities at the cloud top of Venus deduced from Venus Express VMC images, *J. Geophys. Res*., 118, 1, p. 37–46.

Lee, Y.J., T. Imamura, S.E. Schröder, et al., 2015, Long-term variations of the UV contrast on Venus observed by the Venus monitoring camera on board Venus express, *Icarus*, 253, pp. 1–15, doi: 10.1016/j.icarus.2015.02.015.

Lewis, J. S., 1970. Venus: Atmospheric and lithospheric composition. Earth and Planetary Science Letters. 10**,** 73-80.

Limaye, S.S., 1988, Venus: Cloud level circulation during 1982 as determined from Pioneer Cloud Photopolarimeter images. II. Solar longitude dependent circulation, *Icarus*, 73, 212–226.

Limaye, S.S., 2007, Venus atmospheric circulation: Known and unknown, *J. Geophys. Res*., 112, E04S09, doi:10.1029/2006JE002814.

Limaye, S.S., Grund, C.J., and Burre, S.P., 1982, Zonal Mean Circulation at the Cloud Level on Venus: Spring and Fall 1979 OCPP Observations, *Icarus*, vol. 51, pp. 416–439.

Limaye, S.S., Suomi, V.E., 1981, Cloud motions on Venus: Global structure and organization, *J. Atmos. Sci*. 38, 1220–1235.

Limaye, S.S., C. Grassotti, and M.J. Kuetemeyer, 1988, Venus: Cloud level circula¬tion during 1982 as determined from Pioneer Cloud Photopolarimeter images. I. Time and zonally averaged circulation, *Icarus*, 73, 193–211.

Limaye, S.S., Kossin, J.P., Rozoff, C., Piccioni, G., Titov, D.V., Markiewicz, W.J., 2009, Vortex circulation on Venus: Dynamical similarities with terrestrial hurricanes, *Geophysical Research Letters*, 36, 4, L04204, http://dx.doi.org/10.1029/2008GL036093.

Linkin, V.M. et al., 1987, Thermal structure of the Venus atmosphere according to measurements with the VEGA-2 lander; Kosmicheskie Issledovaniia (ISSN 0023-4206), 25, 659–672. In Russian.

Luz, D., Berry, D.L., Piccioni, G., Drossart, P., Politi, R., Wilson, C.F., Erard, S., Nuccilli, F., 2011, Venus's southern polar vortex reveals precessing circulation, *Science* 332, 577.

Lyot, B., 1929, Recherches sur la polarisation de la lumiere des planetes et de quelques substances terrestres. Ann. Observ. Paris (Meudon), 8, 161 pp. [available in English as NASA TT F-187, 1964].

Marov, M., Ia. et al., 1973, Venera 8: measurements of the temperature, pressure and wind velocity on the illuminated side of Venus., *J. Atmos. Sci.*, 30, 1210 – 1214.

Marov, M., I., 1978, Results of Venus missions, *Ann. Rev. Astron. Astrophys.*, 16, 141-169, doi: 10.1146/annurev.aa.16.090178.001041

Marov, M., Ya. et al., 1980, The structure and microphysical properties of the Venus clouds – Venera 9, 10, and 11 data, *Icarus*, 44, 608–639.

McKinnon, W.B., K.J. Zahnle, B.A. Ivanov, and H.J. Melosh, 1997, Cratering on Venus: Models and observations in: *Venus II Geology, Geophysics, Atmosphere, and Solar wind environment*, S.W.Bougher, D.M. Hunten, and R.J. Phillips eds., Univ. Arizona Press Tucson, p. 969–1014.

Migliorini, A. et al., 2012, Investigation of air temperature in the night side of Venus derived from VIRTISH onboard Venus Express, *Icarus*, 217, 640–647.

Moissl, R. et al., 2009, Cloud top winds from tracking UV features in Venus Monitoring Camera images, *J. Geophys. Res*., 114. 2008JE003117.

Moroz, V., 1983, Stellar magnitude and albedo data of Venus, D.M. Hunten, L. Colin, T.M. Donahue, V.I. Moroz (Eds.), *Venus*, University of Arizona Press, Tucson, pp. 27–35.

Moroz, V.I. et al., 1985, Solar and thermal radiation in the Venus atmosphere, *Adv. Space Res*. 5, 197–232.

Moroz V.I., 1990, Atmospheric Structure of Venus According to Optical Measurements by VENERA-11 VENERA-13 and VENERA-14, *Solar System Research*, Vol. 23, Issue 4, p. 206

Moroz, V.I., Zasova, L.V., and Linkin, V.M., 1996, Venera-15,16 and Vega Mission Results as Sources for Improvements of the Venus Reference Atmosphere, *Adv. Space Res*., vol. 17, no. 11, pp. 171–180.

Moshkin, B.E. et al., 1986, VEGA-1 and VEGA-2 Optical Spectrometry of Venus Atmospheric Aerosols at the 60-30-KM Levels – Preliminary Results; Soviet Astronomy Letters, vol. 12, Jan.–Feb. 1986, p. 36–39. Translation Pisma v *Astronomicheskii Zhurnal*, vol. 12, Jan. 1986, p. 85–93.

Murray, B.C. et al., 1974, Venus: Atmospheric motion and structure from Mariner 10 pictures, *Science*, 183, 1307–1315.

Newman, M. et al., 1984, Zonal winds in the middle atmosphere of Venus from Pioneer Venus Radio Occultation Data, *J. Atmos. Sci.*, 41, 1901–1913.

Nakamura, M. et al., 2011, Overview of Venus orbiter, Akatsuki, *Earth, Planets and Space*, 63 (5), 443-457.

Nikolaeva, O.V., 1990, Geochemistry of the Venera 8 Material demonstrates the presence of continental crust on Venus, Earth, *Moon, and Planets*, v.50/51, p.329–341.

Nikolaeva, O.V., 1995, K-U-Th systematics of terrestrial magmatic rocks for planetary comparisons: Terrestrial N-MORBs and venusian basaltic material, *Geochem. Int.*, v. 33, p. 1–11.

Nikolaeva, O.V., 1997, K-U-Th Systematics of igneous rocks for planetological comparisons: Oceanic island-arc volcanics on Earth versus rocks on the surface of Venus, *Geochem. Int.*, v. 35, p. 424–447.

Oyama, V. I., Carle, G. C., Woeller, F., Pollack, J. B., Reynolds, R. T., Craig, R. A., 1980, Pioneer Venus gas chromatograph of the lower atmosphere of Venus, J. Geophys. Res., 85, 7891-7902.

Parmentier, E.M. and P.C. Hess, 1992, Chemical differentiation of a convecting planetary interior: Consequences for a one plate planet such as Venus, *Geophys. Res. Lett.*, v.19, p.2015–2018.

Pearce, J. A., 1976. Statistical analysis of major element patterns in basalts. Journal of Petrology. 17**,** 15-43.

Pearce, J. A., 2008. Geochemical fingerprinting of oceanic basalts with applications to ophiolite

Pechmann, J.B., and A.P. Ingersoll, 1984, Thermal tides in the atmosphere of Venus – Comparison of model results with observations, *J. Atmos. Sci*., 41, pp. 3290–3313.

Peplowski, P. N., and Lawrence, D. J., 2016, Nitrogen Content of Venus' Upper Atmopshere from the MESSENGER Neutron Spectrometer, 47th LPSC, LPI Contribution No. 1903, p. 1177.

Peralta, J., Hueso, R., Sanches-Lavega, A., 2007, A reanalysis of Venus winds at two cloud levels from Galileo SSI images, *Icarus*, 190, 469–477.

Phillips, R.J., R.F. Raubertas, R.E. Arvidson, I.C. Sarkar, R.R. Herrick, N. Izenberg, and R.E. Grimm, 1992, Impact craters and Venus resurfacing history *J. Geophys. Res*., v.97, p.15923–15948.

Phillips, R. J., Bullock, M. A., Hauck, S. A., 2001. Climate and interior coupled evolution on Venus. Geophysical Research Letters. 28**,** 1779-1782.

Piccialli, A. et al., 2008, Cyclostrophic winds from the visible and infrared thermal imaging spectrometer temperature sounding: A preliminary analysis, *J. Geophys. Res.* 113 (E00B11), 147–155.

Piccialli, A., S. Tellmann, D.V. Titov, S.S. Limaye, I.V. Khatuntsev, M. Pätzold, B. Häusler, Titov, D.V., 2012, Dynamical properties of the Venus mesosphere from the radio-occultation experiment VeRa onboard Venus Express, *Icarus*, Volume 217, Issue 2, Advances in Venus Science, February 2012, pp. 669–681, http://dx.doi.org/10.1016/j.icarus.2011.07.016.

Piccioni, G. et al., 2007, South-polar features on Venus similar to those near the north pole, *Nature*, 450, 637–640.

Piccioni, G. et al., 2009, Near-IR oxygen nightglow observed by VIRTIS in the Venus upper atmosphere, *J. Geophys. Res.*, 114, E00B38, doi: 10.1029/2008JE003133.

Pollack, J.B. et al., 1980, Distribution and source of the UV absorption in Venus' atmosphere, *J. Geophys. Res.*, 85, 8141–8150.

Rossow, W.B., Del Genio, A.D., Limaye, S.S., et al., 1980, Cloud Morphology and Motions from Pioneer Venus Images, *J. Geophys. Res*. 85, pp. 8107–8128.

Rossow, W.B., Del Genio, A.T., Eichler, T., 1990, Cloud-tracked winds from Pioneer Venus OCPP images; *J. Atmos. Sci.*, 47, 2053–2084.

Russell, C.T, O.L.Vaisberg, 1983, The Interaction of the Solar Wind with Venus, In: VENUS, Ed. by D.M. Hunten, L. Colin, T.M. Donahue, V.I. Moroz, Univ. of Arizona Press, pp. 873–940.

Sagdeev, R. Z. et al., 1986, Overview of VEGA Venus balloon in situ meteorological measurements, *Science*, 231, 1411.

Sagdeev, R.Z. et al., 1992, Differential VLBI measurements of the Venus atmosphere dynamics by balloons: VEGA project, *Astron. Astrophys.*, 254, 387–392.

Sanchez-Lavega, A. et al., 2008, Variable winds on Venus mapped in three dimensions, *Geophys. Res. Let.*, 35 (13), L13204.

Saunders, R.S., et al., 1992, Magellan Mission Summary, *J. Geophys. Res.*, 97, 13, 067–13090.

Schaber, G.G., R.G. Strom, H.J. Moore, L.A. Soderblom, R.L. Kirk, D.J. Chadwick, D.D. Dawson, L.R. Gaddis, J.M. Boyce, and J. Russel, 1992, Geology and distribution of impact craters on Venus: What are they telling us? *J. Geophys. Res.*, .97, 13257–13301.

Schofield, J.T., Taylor, F.W., 1983. Measurements of the mean, solar-fixed temperature and cloud structure of the middle atmosphere of Venus, *Q. J. R. Meteorol. Soc.*, 109, 57–80.

Seiff, A. et al., 1980, Measurements of thermal structure and thermal contrasts in the atmosphere of Venus and related dynamical observations - Results from the four Pioneer Venus probes, *J. Geophys. Res.*, 85, 7903-7933.

Seiff, A. et al., 1985, Models of the structure of the atmosphere of Venus from the surface to 100 kilometers altitude, *Adv. Space Res*., 5(11), 3-58

Senske, D.A., 2010, Tessera terrain on Venus: Comparing Phoebe Regio and Tellus Tessera, LPSC-41 #1256.

Solomon, S. C., Bullock, M. A., Grinspoon, D. H., 1999. Climate change as a regulator of tectonics on Venus. Science. 286**,** 87-89.

SSB, 2011, *Vision and Voyages for Planetary Science in the Decade 2013–2022*, Space Studies Board, National Research Council, National Academies Press, Washington, D.C.

Stiepen, A., Gérard, J.-C., Dumont, M., Cox, C., Bertaux, J.-L, 2013, Venus nitric oxide nightglow mapping from SPICAV nadir observations, *Icarus*, 226, 428–436.

Surkov, Yu.A., V.L. Barsukov, V.P. Moskalyova, A.D. Kharyukova, and A.L. Kemurdzhian, 1984, New data on the composition, structure, and properties of Venus rock obtained by Venera 13 and 14 Proc. Lunar Planet. Sci. Conf. 14th, Part 2, J. *Geophys. Res.*, 896 suppl., p. B393–B402.

Surkov, Yu.A., V.P. Moskalyova, A.D. Kharyukova, A.D. Dudin, G.G. Smirnov, and S.E. Zaitseva, 1986, Venus rock composition at the VEGA 2 landing site Proc. Lunar Planet. Sci. Conf. 17, Part 1, *J. Geophys. Res*., v.91, suppl., p. E215–E218.

Surkov, Yu. A., V. F. Ivanova, A. N. Pudov, and D. Caramel, 1987, Determination of the aerosols chamical composition in the Venusian clouds by means of the mass-spectrometer MALAHIT on the VEGA-1 probe, Kosmich. Issled., 15, 744–750 (in Russian).

Surkov, Y.A., 1997, *Exploration of Terrestrial Planets from Spacecraft: Instrumentation, Investigation, Interpretation*, 2nd ed., Chichester; New York, Chichester, Wiley, Praxis Pub., pp. 446.

Svedhem, H., Titov, D, Taylor, F., Witasse, O., 2009, Venus Express mission, J. Geophys. Res. 114, E00B33, doi:10.1029/2008JE003290.

Taylor et al., 1980, Structure and meteorology of the middle atmosphere of Venus Infrared remote sensing from the Pioneer orbiter, *J. Geophys. Res.* 85, 7963-8006.

Toigo, A., P.J. Gierasch, M.D. Smith, 1994, High resolution cloud feature tracking on Venus by Galileo, Icarus, 109 (1994), pp. 318–336.

Tomasko, M.G., Doose, L.R., Smith, P.H., 1985, The absorption of solar energy and the heating rate in the atmosphere of Venus, *Adv. Space Res.*, 5, 71–79.

Urey, H. C., 1952. The Planets. Yale University Press, New Haven.

Vaisberg, O.L. and Zelenyi, L.M., 1984, Formation of the plasma mantle in the Venusian magnetosphere, *Icarus*, 58 (6), 412-430.

Vaisberg, O.L, S.A. Romanov, V.N. Smirnov, I.P. Karpinsky, B.I. Khazanov, B.V. Polenov, A.V. Bogdanov, and N.M. Antonov, 1976, Ion Flux Parameters in the Solar Wind-Venus Interaction Region, in: *Physics of Solar Planetary Environment*, Ed. by D.J. Williams, AGU, Boulder, p. 904–917.

Verma, S. P., Guevara, M., Agrawal, S., 2006. Discriminating four tectonic settings: Five new geochemical diagrams for basic and ultrabasic volcanic rocks based on log–ratio transformation of major-element data. Journal of Earth System Science. 115**,** 485-525.

Vermeesh, P., 2006. Tectonic discrimination of basalts with classification trees. Geochemica et Cosmochimica Acta. 70**,** 1839-1884.

von Zahn, U., Kumar, S., Niemann, H. Prinn, R., Composition of the Venus atmosphere, 1983, in Venus (A83-37401 17-19), Hunten, D. M., Colin, L., Donahue, T. M., and Moroz, V. I., eds., Tucson, AZ, University of Arizona Press, 299-430.

Way M.J. et al., 2016, Was Venus the first habitable world of our solar system? *Geophys. Res. Lett.*, 43 (16), 8376-8383.

Wilhelms, D.E., 1990, Geologic mapping in: *Planetary Mapping*, R. Greeley and R.M. Batson, Eds.

Winchester, J. A., Floyd, P. A., 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements. Chemical Geology. 20**,** 325-343.

Young, R.E., R.L. Walterscheid, G. Schubert, A. Seiff, V.M. Linkin, and A.N. Lipatov, 1987, Characteristics of gravity waves generated by surface topography on Venus: Comparison with the VEGA balloon results, *J. Atmos. Sci.* 44 (18), 2628–2639.

Zelenyi, L. M., and Vaisberg, O. L., Venus Interaction with the Solar Wind Plasma as a Limiting Case of the Cometary Type Interaction, 1985, *Advances in Space Plasma Physics*, P. 59.

Zasova, L.V., V.A. Krasnopolsky, V.I. Moroz, 1981, Vertical distribution of SO_2 in the upper cloud layer and origin of the UV absorption, *Adv. Space Res.*, 1 (1), pp. 13–16.

Zasova, L.V. and Moroz, V.I., Latitude Structure of the Upper Clouds of Venus, *Adv. Space Res.*, 1992, 12, pp. 79–90.

Zasova, L.V. et al., 2007, Structure of the Venus atmosphere; *Planet. Space Sci.* 55, 1712–1728.

Appendix A: Technology Summary Table

Data Sheet Completed	Instrument or Specific Subsystem	Description	Physical Properties	Source/ Contact Info	Heritage	Science Priority High, (H) Med (M), Low (L)	Current TRL 1-3, 4-5, 6 and higher	Time (years) Required to Be Ready for Mission (1–3 yrs., 4–5, >5yrs)	What Further Development Is Required?	What Testing / Lab Experiments Required?	Rationale / Other Comments
Orbiter											
Instrument											
✓	UV mapping spectrometer	Imaging ultraviolet spectrometer 190–490 nm, ΔΛ=0.3 nm, Continuous imaging during mission, ~ 1 s/image	0.003 m^3, 4W, 3kg, (cm^3), 40 kB/x, 60 MB/sess. (30 min)	Italy (IAPS INAF) or Russia (IKI)	Flew on Omega -VIS /MEX. Alternatively, "Ozonometer" (IKI, O. Korablev, Yu. Dobrolensky) 2003	H	4–7		Performance upgrades desired. New space qualified electronics need to be identified. Working Engineering model in hand ...	Qualification testing in Venus like orbit temperatures. Low risk	
✓	PFS-VD Fourier transform spectrometer	Thermal IR Fourier transform spectrometer Spectrum 250–2000 cm^{-1} λ=5–45 µm, Δv = 1cm^{-1} 1 s/spectrum, whole mission	0.015 m^3,15 W 15 kg, 400×300×200 mm 5 kb/s	Moshkin B., Grigoriev A., Zasova L. IKI Russia (IKI), Germany (DLR), Italy (IAPS INAF)	PFS Mars Express, PFS Venus Express (development team), AOST/Phobos Grunt, ACS-TRVIM/ExoMars TGO (PI & development team)–2016	H	6–7		Instrument design is very similar to ACS-TIRVIM/ExoMars TGO, but CsI beam splitter, pyroelectric detector without cooling. Radiative stable electronics	Calibration facilities	
✓	VMC Monitoring camera	Monitoring camera 4 channels, λ=0.285, 0.365, 0.500, 1 µm	1 dm^3 13/21 W 1 kg 126 MB/image set	D. Belyaev IKI	VMC/Venus Express, FCB/SAGE 2006–2014	H	5–7		Adaptation of modern detectors and latest optics technologies for best instrument performance. Electronics components review to further enhance reliability.	Calibration and tests with new filter on 0.285 µm	
✓	VENIS, UV-IR Imaging Spectrometer	Visual and Infrared imaging spectrometer 2 channels: 0.4–1.9 µm Δλ=2 nm and 1.5-5.7 µm Δλ=5 nm; FOV 3.4º, IFOV=1.125 µrad IR and VIS hyperspectral cubes to characterize atmosphere and, in lesser extent, solid surface. Typical acquisition time about 20 min., per cube. Arbitrary frequency	0.55×0.50×0.23m 22 kg 21 W 1.7 Gbit per cube, after compression	D. Grassi IAPS INAF (Italy), LESIA (France)	OMEGA/Mars Express, VIRTIS/Venus Express The instrument concept is largely based on heritage from VIRTIS-VEX, VIRTIS-Rosetta, JIRAM- Juno	H	5–9	4	Testing of improved optical design: increased spectral range and spectral resolution w.r.t. VIRTIS-VEX	Emissivity experiments Results can be interpreted on the basis of currently available theoretical information. Further laboratory work (currently in progress in IAPS laboratories) on specific topics (e.g., CO_2 CIA) can greatly improve the confidence on results.	Instrument radiator must be placed on a cold face of the orbiter (direct sunlight must be avoided), to retain effective cooling of IR channel.
✓	Solar and star occultation spectrometer	3 spectrometers (UV, near IR and middle IR) for atmospheric studies 0.7-1.7; 2.2-4.4 µm, Δλ =1 nm and 118–320 nm	11 kg, 18 dm^3, 24W	A. Trokhimovsky, Russia (IKI), France	SPICAM /Mars Express, SPICAV-SOIR/Venus Express (Co-PI and development team)	H	5–7		Adaptation of modern detectors and latest optics technologies for best instrument performance. Electronics components review to further enhance reliability	A number of optical tests, qualifications test for electronics and for mechanical interface.	Clouds: IR 75–90 km UV 85–110 km Gases (IR): H_2O 70–110 km, HDO 70–100 km, CO 70–140 km, HF 70–110 km, HCl 70–115 km, OCS and H_2CO upper limit at 70–80 km, H_2O_2 not possible, H_2S unlikely - strong CO_2 absorption. For (UV): SO_2, SO, and O_3: 85–110 km, CO_2 85–150 km
✓	MM-radiometer	Millimeter Wave Radiometer; Ka, V and W bands; scanning antennas; remote sensing of low Venus atmosphere by 3 bands. 3 channels: f = 100 GHz (3 mm), 60 GHz (5 mm) и 30 GHz (1 cm) with Δf=20, 10, and 5 GHz, respectively	3.5 liter 6 W 2 kg 10 Mbytes	Alexander Kosov Space Research Institute RAS Russia (IKI)	On balloon, Earth's atmosphere sensing, 10 years ago Relict	H	3–4	3	Development of W channel, scanning antenna		

Data Sheet Completed	Instrument or Specific Subsystem	Description	Physical Properties	Source/ Contact Info	Heritage	Science Priority High, (H) Med (M), Low (L)	Current TRL 1-3, 4-5, 6 and higher	Time (years) Required to Be Ready for Mission (1–3 yrs., 4–5, >5yrs)	What Further Development Is Required?	What Testing / Lab Experiments Required?	Rationale / Other Comments
✓	Radio-science two-frequency duplex occultation in (L?) S- and X-bands.	Signal from satellite received by a ground station or sub-satellite and receive signals from ground or sub-satellite	0.5 dm³, 0.5 kg, 1W, 5 kbps	Russia (FIRE RAS, NII KP, NPOL)	Venera-15, 16, Vega-1,2	H	7 - for S and X, 3–4 - for L		Detector prototype is available	propagation experiments with L band	
✓	Suite of 3 plasma instruments Panoramic energy mass-analyzer of ions CAMERA-O, electron spectrometer ELSPEC, fast neutrals analyzer FNA	Panoramic ion energy-mass-analyzer CAMERA-O, electron spectrometer ELSPEC, and neutral particles detector NPD Ions, electrons and neutrals 10 eV-15 keV	4 dm³, 4 W, 3.5 kg, 4 kByte/s	Vaisberg, Oleg Russia (IKI), France (LATMOS)	Venera-9, 10, Mars-96, Phobos-Grunt, BepiColombo	M	6–7 for ions, 3 for electrons and neutrals	1–3	ELSPEC and NPD use existing technology, prototypes are under development. Need time and money	Complete test laboratory exists	All technologies and experience of the team are available
✓	Energetic particle spectrometer	Electron and ion energy spectrometer for 20–2000 keV	3-4 kg, 3–5W, 1 Kbyte/s	Anatoli Petrukovich, Space Research Institute (IKI), Russia, Slovakia (IEF)	Spectr-R, 2011-Interball, Resonance	M	6		Refreshed electronic components and design Improvement of sensor lifetime	Preflight calibration , Single test on laboratory ion and electron beam	
Color Code: For TRL column: Red box indicates TRL is between 1-3, Yellow box is TRL 4 or 5 and Green box is TRL 6 or greater; For Time to Required Maturity: Red box indicates TRL is between 1-3, Yellow box is TRL 4 or 5 and Green box is TRL 6 or greater											

Orbiters

Data Sheet Completed	Instrument or Specific Subsystem	Description	Physical Properties	Source/ Contact Info	Heritage	Science Priority High, (H) Med (M), Low (L)	Current TRL 1-3, 4-5, 6 and higher	Time (years) Required to Be Ready for Mission (1–3 yrs., 4–5, >5yrs)	What Further Development Is Required?	What Testing / Lab Experiments Required?	Rationale / Other Comments
✓	FM-V Magnetometer	Flux-gate magnetometer (two vector sensors and electronic box) ±500 nT	3 kg, 150×150×150 mm; 70×30×30 mm, 7W, <10 Kbyte/s	Alexandre Skalsky, Space Research Institute RAS, Russia (IKI, IZMIRAN)	Phobos-Grunt, ExoMars2018 International Space Station, 2011	M	4–5	5–6	New upgrade of electronics due to newly available components. Redesign of electronics Time and money	Calibration and qualification tests, Test facilities are needed to verify the sensor's design	
✓	GROZA-SAS2-DFM-D	System for detection and investigation of electromagnetic waves generated by lightning and other electric phenomena in the Venusian atmosphere.	100×110×100 mm, 4 ≤ 4.5W 500 g (electronics) + 300 g (antenna and sensors) + 100 g cable ~ 4 – 5 kbps	L. Ksanfomality IKI RAN S. Klimov IKI RAN	VENERA; SAS 3 on Chibis satellite	M	6	1	Antenna; Heat protection for the electronic parts.		Needs Sensor on boom. Dependent on the telemetry sharing.
	Solar Wind monitor BMSV-V	Solar wind monitoring with high resolution	2.7 kg, 3.2W	Zastenker G., IKI RAS Charles University, Nemecek Z, Shafrankova, Ja.	Radio astronomy	M	7	1–3			
	Ion and electron spectrometers and Neutral particle detector	3D ion distributions of ions 0.01–50 keV and electrons 0.01–5 keV with temporal resolution up to 1 sec. Flux of neutrals 0.3–10 keV	1.7 kg, 3–9W	IKI RAS, A. Grigoryev, Sweden	MEX, VEX, Chandraayan-1	M	6–7				

Data Sheet Completed	Instrument or Specific Subsystem	Description	Physical Properties	Source/ Contact Info	Heritage	Science Priority High, (H) Med (M), Low (L)	Current TRL 1-3, 4-5, 6 and higher	Time (years) Required to Be Ready for Mission (1–3 yrs., 4–5, >5yrs)	What Further Development Is Required?	What Testing / Lab Experiments Required?	Rationale / Other Comments
	IR Imager	Fast imager in the 2–4 and 10–14 micron bands	Similar to IR cameras on Akatsuki	Similar to IR cameras on Akatsuki	Similar to IR cameras on Akatsuki	L	TBD	TBD	Upgrade electronics and design for Venera-D resolution needs and final orbit parameters Time and money	Calibration and qualification tests, Test facilities are needed to verify the sensor's design	
✓	IVOLGA, Infrared heterodyne spectrometer	Ultra-high resolution (λ/Δλ = 1E7-1E8) spectroradiometer for solar occultation's and nadir observations; several narrow channels from 4.5 to 12 µm	5 kg, 4 dm^3	Russia (MIPT, IKI), Japan, Germany, France	ExoMars-2018	L	3–4	5	Analog operating at 3.3 mm is under development for the ExoMars lander; TRL=7 is expected by 2021.	Critical technologies that require additional testing include single mode waveguide/fiber couplers for thermal IR spectral range	Uncertain if instrument can implement desired measurements. Proof of performance needs to be demonstrated early to support development for this application
	VEM (Venus Emissivity Mapper)	Pushbroom multispectral imager operating at ~0.8–1.5 µm, 15 nm spectral bandwidth,	5.4 kg, 15W, 190 kbps	Joern Helbert (DLR)	Proposed on Venus Discovery mission. Pre-development unit exists	L	5	3	Complete development of filter array and flight like unit	Environmental testing and qualification	
Subsystem											
	Informational subsystem		1,8 kg	IKI	CORONAS-PHOTON, Spectr-R, -RG, -UV, Phobos-Grunt	H	7				
	Communication	Orbiter-Earth X band Up to 17 Mbits/s (not continuous) Ka - not certain yet	X, Ka?	Roscosmos, NASA?	Many prior missions, minimal augmentation needed for the 17 Mbit/s rate	H	7		KA ground station, if that is needed or to be used		Ka ground stations not yet in place in Russia
	Communication	Orbiter-Lander	UHF, ~50 MHz	Lavochkin	Prior systems operated at over 100Mhz	H	5	2	50 Mhz system to be designed. No development issues expected		No challenges expected but propagation tests are suggested
	Communication	Orbiter - Subsatellite	TBD	Lavochkin	TBD	M			TBD		
	Propulsion	Orbit insertion (bi-prop-Nr-H4, N_2O_4)	TBD	Lavochkin		H					Propulsion system may change depending on orbit selections, for example may use aerobraking

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Landers

Data Sheet Completed	Instrument or Specific Subsystem	Description	Physical Properties	Source/ Contact Info	Heritage	Science Priority High, (H) Med (M), Low (L)	Current TRL 1-3, 4-5, 6 and higher	Time (years) Required to Be Ready for Mission (1–3 yrs., 4–5, >5yrs)	What Further Development Is Required?	What Testing / Lab Experiments Required?	Rationale / Other Comments
Main Lander											
Instrument											
✓	Mossbauer Spectrometer / XRF (or APXS)	Mineralogy of Fe-containing rocks, oxidation state of iron, analysis of rock-forming elements. Bulk chemical composition	0.5 kg, <4W, ~500 kbyte/sample	University of Mainz, Dr. Klingelhoefer PI, IKI RAS, Dr. D. Rodionov	MER, Phobos-Grunt	H	2	>5 yrs.	Demonstrate that the instrument can make the needed measurement, in the time available under the given conditions		Detector cooling and integration time requirements may make this instrument infeasible for this lander concept. **Grey shading signifies ingested sample required.**
✓	Panoramic Cameras	Visible range color imaging system consisting of 1 landing, 4 panoramic and 1 close range cameras, mass memory/data compression unit and cables. 5 + 2, 4 MB images , Stereo imaging during the landing 30–45 grad, panoramic image of the surface at landing place	3 l 12W 3.3 kg 16 Mbit per session At least three sessions, more is better, number of imaging sets is limited by data downlink capacity.	Ivan Polyanskiy IKI	TabletSat microsatellite, 2011	H	4	2	Special optics has to be designed and developed. Thermal accumulator (extra MPV).	optical properties of atmosphere at various depths	Dependent on TV systems for Russian Lunar Landing missions (Luna-25…27), Exmore's 2018 lander
✓	Chemical analyses package (CAP)--Gas Chromatograph Mass Spectrometer	Gas Chromatograph Mass Spectrometer (GCMS) + Laser Induced Mass-Spectrometry (LIMS) + Chemical composition of the atmosphere, cloud aerosols, analysis of rock-forming elements, isotopic composition of noble gases and other elements	~10L, 10.5 kg, ~60W, 1Mbyte/measurement	Mikhail Gerasimov, IKI RAS	Phobos-Grunt, ExoMars2018	H	3–7 2–7	5	Sampling System for atmospheric gases/aerosols, Coupling of MS with LIMS	Development tests of the soil and gases/aerosols sampling systems, Venus atmosphere simulator	**Grey shading signifies ingested sample required.**
✓	Possible stand-off Raman /LIDAR	Remote Time-resolved Raman and Lidar Multi-Sensor Instrument Mineralogy, and atmospheric aerosols, molecular species (e.g., H_2SO_4, SO_2, H_2S, CO_2)	30×30×25 cm 80W 8 kg 70 Mbits	Shiv Sharma University of Hawaii Nurul Abedin NASA LaRC	Still in development	H	5	3	Environmental tests for Instrument maturation to TRL6. Calibration activities	Atmospheric effects over distance, window effects	One of 2 Raman options - Inside the lander and needs optical window. Proposed for maturation under NASA MatISSE Time-resolved Raman instrument has been selected for Mars 2020 mission using UH Raman instrument as prototype
✓	Compact Integrated Raman Spectrometer (CIRS)	Two probe concept - Mineralogy and fast gas composition	10,000 cm^3, 18w typical, ~7 kg, .82 M bytes for 100 mineral spectra plus 100 atmosphere spectra. Also 8 M byte/context image	University of Washington / Alian Wang and JPL support	Still in development	H	5	1	Environmental tests for Instrument maturation to TRL6	Atmospheric effects Minimum lab work needed	One of two Raman options - Inside the lander or need optical window and sample held against it. Funded under NASA Matisse. Sample manipulation will require significant integration. **Grey shading signifies ingested sample required.**

Data Sheet Completed	Instrument or Specific Subsystem	Description	Physical Properties	Source/ Contact Info	Heritage	Science Priority High, (H) Med (M), Low (L)	Current TRL 1-3, 4-5, 6 and higher	Time (years) Required to Be Ready for Mission (1–3 yrs., 4–5, >5yrs)	What Further Development Is Required?	What Testing / Lab Experiments Required?	Rationale / Other Comments
✓	METEO-Lander-VD Fields Package	meteorological instruments (T,P,dT,E,ω,H) Measure the vertical structure of the atmosphere during landing and on the surface	(~1 L) max~2W self-powered ~1 kg 0.1 Kbyte/measurement	Alexander Lipatov IKI	Vega 1 and Vega 2, Mars -96 1986, 1996	H	2–7	3	Requires constructive integration to the lander. Designing	Laboratory layout Calibration facilities	
✓	ADRON (Active Detection of Radiation of Nuclei)	Active gamma-ray and neutron spectrometer, subsurface elemental composition	6.7 kg, 9.5 dm^3	M. Litvak, Russia (IKI)	DAN/MSL, ADRON for Luna-Glob & Luna-Resource	H	6–7	1–2	Tests / calibration for environmental / and vessel effects		Consists of two pieces to be separated but both located near vessel bottom
✓	X-ray Fluorescence spectrometer	Elemental composition	0.5 l, 300W, 0.5 kg, <100kb / sample	G. Klingelhofer (Univ of Mainz)	MER, MSL, Rosetta	H	4	4	Tailor for Venera-D application	Calibration, integration with other instruments inside vessel and sample handling system	Could use on mobile platform for atmosphere chemistry. **Grey shading signifies ingested sample required.**

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Landers

Data Sheet Completed	Instrument or Specific Subsystem	Description	Physical Properties	Source/ Contact Info	Heritage	Science Priority High, (H) Med (M), Low (L)	Current TRL 1-3, 4-5, 6 and higher	Time (years) Required to Be Ready for Mission (1–3 yrs., 4–5, >5yrs)	What Further Development Is Required?	What Testing / Lab Experiments Required?	Rationale / Other Comments
✓	"ISKRA-V": Diode Laser Spectrometer (DLS) with multiple channels and Atmosphere Gas Sampling (AGS) system.	"Investigation of Sulphurous Components of Rarefied Atmosphere of Venus": retrieving in situ vertical profiles of sulphurous and minor gases and isotopic ratios in the dense Venusian atmosphere down to the surface level. SO_2, CO_2, CO, H_2O, OCS; 13C/12C, 16O/17O/18O, D/H, 34S/33S/32S.	7 kg (4 kg of DLS, 3 kg of AGS); 9 litres volume (5 litres of DLS, 4 litres of AGS), 25 W peak; 20 Kbyte/min, >3h continuous operation with 1 min per one cycle. Placement inside protected lander. External atmosphere gas sampling interface.	Imant I. Vinogradov. Russia (IKI, MIPT, Prokhorov GPI), France (Reims University).	Phobos-Grunt, ExoMars2018, Luna-Resource.	H	**4–7 for functional blocks and subsystems.**	<5yrs	QCL DFB lasers and MIR photodetectors controls adaptation, analytical optical cell adaptation and interfacing, reference cell adaptation, ambient atmosphere sampling system adaptation, testing of a system for the processed gas sample evacuation.	8 ISO clear workplace, equipment (optical, mechanical, gas mixing, vacuum, electronics and control) for testing and qualification. Temperature and climatic chamber and ISKRA-V instrument testing and calibration.	
✓	VERBA (infrared radiometer for atmospheric transparency windows)	Measurements of upward and downward radiative fluxes in transparency windows Active part of descent trajectory	0.25 liter 5W 500 g 1 Mb	Alexander Rodin MIPT	Venera and Pioneer Venus probes	H	5	2	New electronic and optical components. Optical and mechanical design, miniaturization		Need to confirm TRL in future discussion
Subsystem											
	Sample Acquisition	Utilize Venera / Vega heritage system	Details to be confirmed.	Lavochkin	Prior soviet landers	H	5		Integration of previous sample acquisition system with new manipulation and processing system required	Testing required with Venus simulants and in Venus temp / pressure conditions.	
	Sample handling / processing	New design	Still to be developed	Lavochkin	None	H			Significant develop and testing required. Different processing may be required for different instruments	Testing required with Venus simulants and in Venus temp / pressure conditions.	Most significant technology item on the mission at this time
	Thermal Control	Passive thermal control system	Phase-change material and thermal insulation TBD	Lavochkin	Will leverage previous soviet landers experience, unclear of same materials	H			Utilize Venera / Vega heritage system but update to current materials, processes	Performance, environmental and qualification	

Data Sheet Completed	Instrument or Specific Subsystem	Description	Physical Properties	Source/ Contact Info	Heritage	Science Priority High, (H) Med (M), Low (L)	Current TRL 1-3, 4-5, 6 and higher	Time (years) Required to Be Ready for Mission (1–3 yrs., 4–5, >5yrs)	What Further Development Is Required?	What Testing / Lab Experiments Required?	Rationale / Other Comments
	Communication	Lander-Orbiter ~50 MHz UHF r-Earth		Lavochkin	Previous soviet landers	H	7		VLBI to increase data transfer rate (e.g., like for Huygens-Cassini)	Performance, environmental and qualification	
	Power	Primary batteries	Power to support descent and 1 hour on surface (minimum requirement) but design for at least 2 hours on surface	Lavochkin	TBD	H	7		Leverage heritage design but use currently available materials and components	Performance, environmental and qualification	
	Vessel	Utilize Venera / Vega heritage system - sphere shape	Details to be confirmed.	Lavochkin	Previous soviet landers	H	7		Leverage heritage design but use currently available materials and components	Testing required with Venus simulants and in Venus temp / pressure conditions. Need to qualify flight unit	
	Avionics	New design	Details to be confirmed.	Lavochkin		H			Leverage heritage design but use currently available materials and components	Performance, environmental and qualification	
	Chute/drag	Utilize Venera / Vega heritage system	Details to be confirmed.	Lavochkin	Previous soviet landers	H	7		Leverage heritage design but use currently available materials and components	Performance, environmental and qualification	
	Landing	Assume landing with toros base. If using absorbing "leg" approach will need development, testing and qualification	Details to be confirmed.	Lavochkin	Previous soviet landers	H			Leverage heritage design but use currently available materials and components	Performance, environmental and qualification	If new landing system will be used it would require development, landing and test. SDT not recommending landing in rough terrain
	Nav	New design	Details to be confirmed.	Lavochkin	Previous soviet landers	H	???		Leverage heritage design but use currently available materials and components	Performance, environmental and qualification	Uncontrolled parachute and then free fall
Environmental Testing											
	Facility for testing and qualification of lander	Need facilities for testing / qualifying full-scale lander	Will need to accommodate full size lander and have capability to reach Venus surface pressure and temperature and simulate the descent profile with those parameters	Lavochkin	Possible design information still available. Prior facilities have been dismantled	H			Re-design, build and test		Facilities for testing / qualifying full-scale lander doesn't exist at this time
	Environmental test facilities to test, calibrate and qualify instruments, subsystems at full size instrument subsystem scale	External instruments and subsystems may be tested at GEER	3′ dia x 4′ long internal size. Small keep out space along bottom for heaters	GEER available for complete simulation or partial simulation at other facilities. Tibor Kremic, NASA		H					
	Sample Acquisition	External instruments and subsystems may be tested at GEER	3′ dia x 4′ long internal size. Small keep out space along bottom for heaters	Tibor Kremic, NASA		H	9				

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Mobile Aerial Platforms

Data Sheet Completed	Instrument or Specific Subsystem	Description	Physical Properties	Source/ Contact Info	Heritage	Science Priority High, (H) Med (M), Low (L)	Current TRL 1-3, 4-5, 6 and higher	Time (years) Required to Be Ready for Mission (1–3 yrs., 4–5, >5yrs)	What Further Development Is Required?	What Testing / Lab Experiments Required?	Rationale / Other Comments
Mobile Aerial Platform											
Instruments											
	Anemometer / accelerometer / and meteo package	meteorological instruments (T,P,W,W',dT,E,ω,H)	0.6 kg	IKI	Prior Venus balloon payload missions	H			Environmental and calibration tests		
	GC-MS	Specific instrument and requirements still need to be identified	Specific instrument and requirements still need to be identified	Specific instrument and requirements still need to be identified	Specific instrument and requirements still need to be identified	H	TBD	TBD	TBD	TBD	Vertical measurements every 10km
	UV spectrometer	200–600 nm. Specific instrument and requirements still need to be identified	Specific instrument and requirements still need to be identified	Specific instrument and requirements still need to be identified	Specific instrument and requirements still need to be identified	H	TBD	TBD	TBD	TBD	
✓	Raman-Lidar	Remote Time-resolved Raman and Lidar Multi-Sensor Instrument Mineralogy, and atmospheric aerosols, molecular species (e.g., H_2SO_4, SO_2, H_2S, CO_2)	12"x12"x10" 80W 8 kg 70 Mbits	Shiv Sharma University of Hawaii Nurul Abedin NASA LaRC	Still in development	H	5	3	Environmental tests for Instrument maturation to TRL6. Calibration activities	Atmospheric effects over distance, window effects	
	Net Flux radiometer	up/ down looking	Specific instrument and requirements still need to be identified	Specific instrument and requirements still need to be identified	Specific instrument and requirements still need to be identified	H	TBD	TBD	TBD	TBD	
	Near IR 1 micron camera	fast camera to peer at surface for location determination	Akatsuki like IR imagers. Specific instrument and requirements still need to be identified	Specific instrument and requirements still need to be identified	Specific instrument and requirements still need to be identified	H	TBD	TBD	TBD	TBD	
US Balloon											
✓	Balloon (Super pressure) - Balloon with vertical mobility may be considered. **Data shown in this row is for conventional Venus balloon.**	A wind driven balloon, separated and inflated after atmospheric entry to float in the atmosphere. Depending on the size of the balloon and payload, it may be possible to include 2 or more balloons in the mission. Would consider adding IMU. Balloon with vertical mobility may be considered.	Variable - For a 25 kg payload at 55 km float mission for several months the mission mass impact is ~400–500 kg	Jeffery L Hall JPL	Vega Balloon	H	3-5	3-4	Superpressure and zero-pressure balloons: confirm full scale performance with prototype testing. Other types of balloons will require more development. All balloon types must be supported with development activity for aerial deployment and inflation technology.	Life, scaling, deployment. Location determination	Can support long-duration flights around the planet. Higher TRL than propulsive platforms. Short float times could be done with much less mass
VEGA Based Long-Lived Balloon											
✓	Long-lived Balloon (LLB)	A wind driven balloon, separated and inflated after atmospheric entry to float in the atmosphere. Depending on the size of the balloon and payload, it may be possible to include 2 or more balloons in the mission.	(~100 L) max~12W ~21 kg payload 0.5 Mbites/day - mission mass impact ~125 Kg	Alexander Lipatov IKI	Vega 1 and Vega 2 1986	H	2-7	~4	Requires modification integration at Orbiter, Scientific and system payload Designing	Using long-baseline interferometry Helicopter or balloon test	Climate, atmospheric dynamics, cloud aerosols, infrasound waves. Flight duration 20 days. Required separation system from the lander and the radio line with orbiter and earth

Data Sheet Completed	Instrument or Specific Subsystem	Description	Physical Properties	Source/ Contact Info	Heritage	Science Priority High, (H) Med (M), Low (L)	Current TRL 1-3, 4-5, 6 and higher	Time (years) Required to Be Ready for Mission (1–3 yrs., 4–5, >5yrs)	What Further Development Is Required?	What Testing / Lab Experiments Required?	Rationale / Other Comments
VAMP											
✓	Mobile aerial platform	Powered lifting shaped inflatable vehicle capable of operating in roughly the 55–60km range, maintain flight for 30 days or longer and higher and carry a subset of the required, some of which can be operated at night under normal conditions	450 kg system mass, ~3m×6m volume but parameters are flexible based on need and constraints. 15 kg or more science payload, communicate with the orbiter and have capability to return to location on subsequent planet traverse	Northrop Grumman	None	H			Significant development required including developing final design to accommodate launch vehicle, and mission interfaces, prototype development including test flights, entry tests, deployment, and entry		Flexibility of basic concept offers opportunities. Large volume and mass of Pathfinder and larger scale vehicles require significant and early interactions between VAMP vendor and Lavochkin
Color Code: For TRL column: Red box indicates TRL is between 1-3, Yellow box is TRL 4 or 5 and Green box is TRL 6 or greater; For Time to Required Maturity: Red box indicates TRL is between 1-3, Yellow box is TRL 4 or 5 and Green box is TRL 6 or greater											

Other Mission Elements

Data Sheet Completed	Instrument or Specific Subsystem	Description	Physical Properties	Source/ Contact Info	Heritage	Science Priority High, (H) Med (M), Low (L)	Current TRL 1-3, 4-5, 6 and higher	Time (years) Required to Be Ready for Mission (1–3 yrs., 4–5, >5yrs)	What Further Development Is Required?	What Testing / Lab Experiments Required?	Rationale / Other Comments
Long-Life Station											
Instrument											
✓	Meteo	Temp, pres. and wind speed and direction sensors	<2 kg, fits within 20 cm cube station	Tibor Kremic NASA Glenn	in development - prototypes demonstrated	H	3	5	validate life at conditions, develop wind sensor for battery version	system level tests with other probe elements , demo comm for orientation	TRL driven by wind speed / direction sensing
✓	MEMS Chem sensor	Detect and measure concentration of pre-selected element set	<0.2 kg, fits within 20 cm station	Tibor Kremic NASA Glenn	terrestrial application in high temperature environments	H	5	3	validate life at conditions	system level tests with other probe elements	
Subsystem											
✓	Dropsonde / long-lived mini probe	Long lived station to collect temperature, pressure, wind, chemistry and possibly radiance measurements	~8000 cm³ (stowed) Self powered 8–10 kg	Tibor Kremic NASA Glenn	NA-S batteries tested on ISS (1997) operating at 350C, electronics tested at VENUS conditions in the Glenn Extreme Environment Rig (GEER) test facility (2016)	H	3	3-4	Confirm power solutions, develop comm system to transmit to orbiter, develop low power circuits	Need to test life and performance, especially wind powered version. GEER is suitable for needed tests and is already being used.	Currently assuming it will enter with the lander and be pushed off or dropped from balloon / VAMP. Strong technology impact for future Venus missions
	NAV	System to determine location to +/- 10km	Utilize comm links with orbiter and sub-satellite to triangulate position	Tibor Kremic NASA Glenn		M	5	4	Verify and demonstrate approach for orientation		Applies to independently dropped stations. Requires sub-satellite
Sub-Satellite											
Instrument											
✓ (See orbiter)	Panoramic energy mass-analyzer of ions CAMERA-O, electron spectrometer ELSPEC, fast neutrons analyzer FNA	Ions, electrons and neutrals 10 eV-15 keV	3.5 kg	Russia (IKI), France (LATMOS)	Venera-9, 10, Mars-96, Phobos-Grunt, BepiColombo	M	6 for ions, 3 for electrons and neutrons		Time and money	Complete test laboratory exist	

Data Sheet Completed	Instrument or Specific Subsystem	Description	Physical Properties	Source/ Contact Info	Heritage	Science Priority High, (H) Med (M), Low (L)	Current TRL 1-3, 4-5, 6 and higher	Time (years) Required to Be Ready for Mission (1–3 yrs., 4–5, >5yrs)	What Further Development Is Required?	What Testing / Lab Experiments Required?	Rationale / Other Comments
✓ (See orbiter)	Energetic particle spectrometer	Electron and ion energy spectrometer for 20–2000 keV	3–4 kg	Russia (IKI), Slovakia (IEF)	Spectr-R, Interball, Resonance	M	6		Improvement of sensor lifetime		
✓ (See orbiter)	Magnetometer	±500 nT	3kg	Russia (IKI, IZMIRAN)	Phobos-Grunt, ExoMars2018	M	4–5		Time and money	Calibration and qualification tests	
✓ (See orbiter)	Radio-science two-frequency duplex occultation in (L?), S-and X-bands.	Transmit / receive signal with main orbiter	0.5 kg	Russia (FIRE RAS, NII KP, NPOL, METRON)		M			Detector prototype is available	propagation experiments with L band	
Subsystem											
	Communication to orbiter	Orbiter - Subsatellite	TBD	Lavochkin	TBD	M			TBD		
Launch Vehicle											
	Launch >6500 Kg to Venus encounter trajectory	Angara-5	Max payload launched is ~ 7000kg	Tsniimash	In development	H			In development		
Ground / Ops Systems											
Radio Signal Source											
	Ground Station	Ground-based radio telescope				H			Radio science experiments with the orbiter and a ground station. S, C, and X-band for neutral atmosphere, and L-band for ionosphere sounding.		Ground stations needed around Earth, Goldstone / DSN desired. Consider for balloon tracking also
Ground Stations											
	Aerial platform tracking	Use VLBI techniques to track aerial platform		Roscosmos, NASA, and other possible sources	Prior utilization for similar purposes	M					
	Ground Station	Ka -range deep space network		Roscosmos, NASA, and other possible sources		H			Ka band to be incorporated in Russian ground stations around 2020		
Instrument and System Testing / Qualification											
	Environmental test facilities to test, calibrate and qualify instruments, subsystems at full size instrument subsystem scale	External instruments and subsystems may be tested at GEER or other possible locations, Calibrations and lab experiments can also be run with GEER	3' dia x 4' long internal size. Small keep out space along bottom for heaters	Roscosmos, NASA, and ESA sources possible	Recent lab experiments and testing	H					Other facilities such as VICI (NASA GSFC), PEL (DLR) and more exist
Entry System											
	Lander system (with potential long lived station and /or balloon)	Rigid blunt body heat shield for main lander / with/without standard balloon		Roscosmos	Prior soviet missions	H	9??				
	Mobile aerial platform	If using VAMP additional deployment / entry work would be needed		Northrop Grumman		M					Entry of an inflated VAMP like lifting body would be needed. Still TBD if this would require a direct entry ~11 km sec or entry from orbit would be possible

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