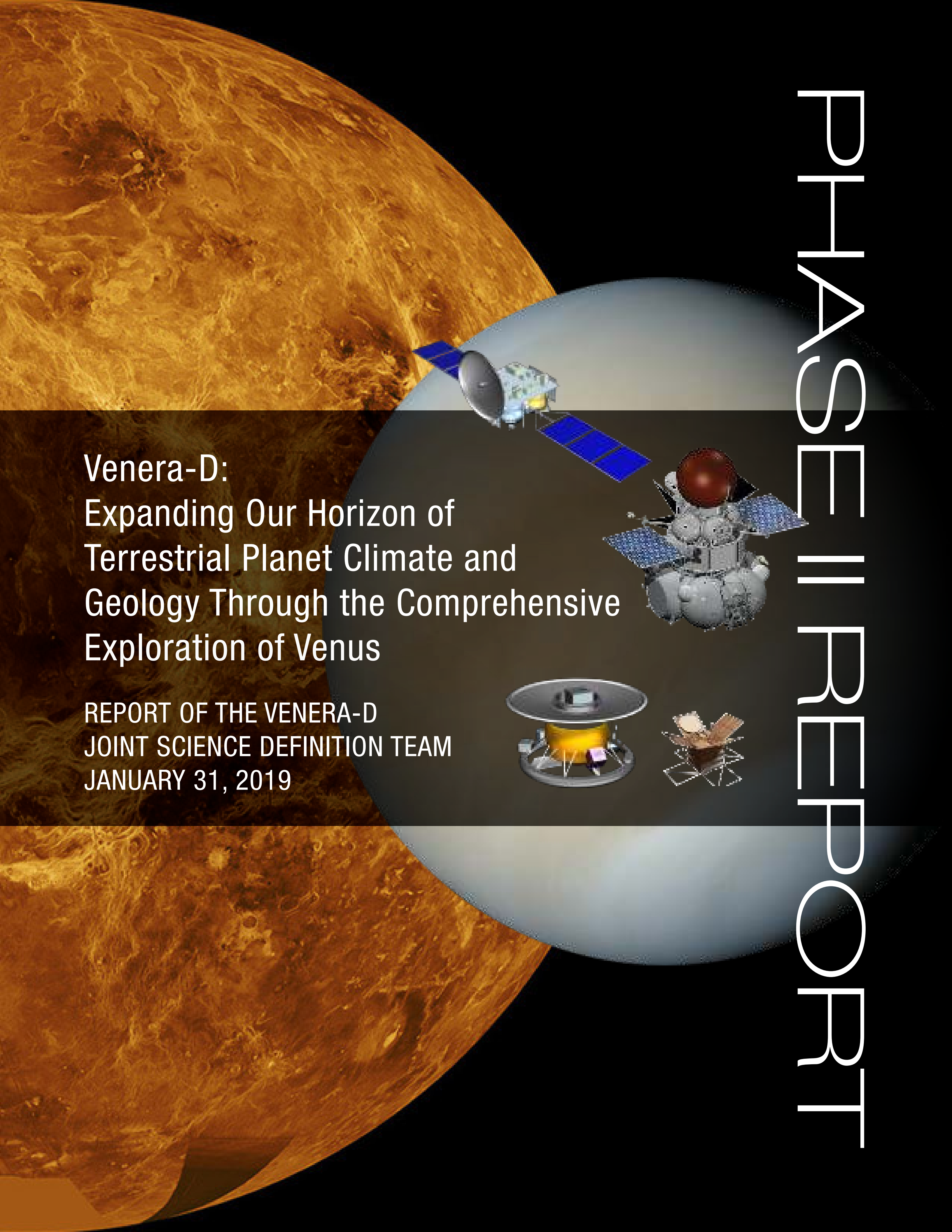

PHASE II REPORT

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
JANUARY 31, 2019

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Phase II Final Report

Report of the Venera-D Joint Science Definition Team
January 31, 2019

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Thank you for all of your patience, help, and support in completing this Phase II report.

"The blue distance, the mysterious Heavens, the example of birds and insects flying everywhere —are always beckoning Humanity to rise into the air."

--Konstantin Tsiolkovsky

"We tend to hear much more about the splendors returned than the ships that brought them or the shipwrights… These spacecraft, their designers, builders, navigators and controllers are examples of what science and engineering, set free for well-defined peaceful purposes, can accomplish."

--Carl Sagan

Contents

Summary

The Russian Space Agency (Roscosmos), the Institute Kosmicheskih Issledovanyi (Space Research Institute of the Russian Academy of Sciences--IKI RAS) and the National Aeronautics and Space Administration (NASA) chartered the Venera-Dolgozhivuschaya (Venera-D) Joint Science Definition Team (JSDT) in 2014 with the task of defining the science and architecture of a comprehensive mission to Venus (called Venera-D, where D stands for the Russian word for "long-lived"). The Venera-D Phase I report was published in January 2017. In this Phase II report, *we have defined the baseline mission architecture and a nominal orbit for a Venera-D mission with the theme of understanding Venus as a system,* from the top of the atmosphere to the surface and interior.

A *baseline Venera-D mission would consist of an orbiter and a VEGA-type lander with an attached Long-Lived, In-Situ Solar System Explorer (LLISSE).* The orbiter would be in a near-polar (90°±5°), 24-hr orbit with a lifetime of ≥3 yr. The lander would sample the atmosphere and image the surface during descent and then land in a high-latitude region of the northern hemisphere; a lifetime of 2 to 3 hr is expected. The attached LLISSE (a NASA contribution) would survive for ≥60 days on the Venusian surface, returning compositional and physical information about near-surface winds. *Venera-D launch readiness dates are from 2026, which provide optimal science return to 2033.*

The described *baseline Venera-D mission would achieve breakthrough science and build upon the knowledge gained from previous and current missions* (the USSR's Venera and VEGA missions; NASA's Magellan; the European Space Agency's (ESA's) Venus Express (VEX); Japan Aerospace Exploration Agency's (JAXA's) Akatsuki) as well as future missions (the Indian Space Research Organisation's (ISRO's) recently announced 2023 mission to Venus). Being able to examine the atmosphere simultaneously from orbit and from the lander on the surface is only one of many powerful and unique aspects of the science return anticipated from Venera-D. (See Appendix B and Appendix C for more detailed comparisons between Venera-D and other Venus missions.)

Science return from a Venera-D mission would be enhanced with the addition of optional mission elements (herein called "augmentations"). Incorporating two or more long-lived small stations capable of measuring seismicity and heat flux, for example (Seismic and Atmospheric Exploration of Venus, or SAEVe), would provide views of Venus' interior *for the first time, and the JSDT considers this to be a high science priority*. A vertically maneuverable aerial platform would collect *unprecedented information* about Venus' atmosphere and cloud layers. Subsatellites strategically placed in orbit around Venus at Lagrange points would help to *answer fundamental questions* about the interaction between the Venusian atmosphere and the solar wind. (See Section 8 for a full discussion of these augmentations.)

Additional technological investigations and investments are required to bring any of the recommended augmentations to a technology readiness level (TRL) required for launch in a post-2026 timeframe. Even the baseline Venera-D mission would need resuscitation of a full-scale Venus environmental chamber to adequately test the lander and its components before launch. More granular studies into communications, concept of operations, and the mass-power-volume

envelope are needed to further refine the Venera-D mission concept; see Section 12 for JSDT recommendations for future work. A few of the JSDT recommendations for the path forward and work to go are listed below.

(1) Development of capable facilities to test mission-enabling instruments and spacecraft at the component and system level in a simulated Venus environment.
(2) Formulation and prioritization of synergistic science goals for the mission architecture between baseline mission elements and possible augmentations.
(3) Refinement of the envelope (mass, power, volume (MPV)) for the payload of the baseline elements.
(4) Refinement of potential augmentations: instrument capabilities and system requirements.
(5) Assessment of data communications and capability between the obiter and Earth; the orbiter and lander; LLISSE and orbiter; and possible augmentations (aerial platform, additional small long-lived stations, subsatellites) and orbiter.
(6) Expand the JSDT to include a preproject team that contains engineers (such as telecom and structural and thermal engineering) to work with the present team of scientists.

To maintain the positive momentum launched by the V-DJSDT collaboration and to advance the development of the Venera-D mission, *the VDJSDT accepts the recommendation by the "Venera-D Study Directors" during the October 2018 briefing to organize an international workshop in 2019 to investigate (1) potential landing sites for the Venera-D lander and (2) habitability in the Venusian clouds and astrobiology*. This workshop will be held in the days prior to the 10^{th} Moscow Solar System Symposium (10M-S^3). The dates for 10M-S^3 are from October 7 to 11, 2019; the recommended Landing Site/Habitability workshop would be held at IKI from October 2 to 5, 2019. We anticipate 2 days for discussing landing site selection and 2 days on habitability and astrobiology aspects of the cloud layer.

Furthermore, to advance our understanding of solar system evolution (including Earth and its history), we must vastly increase our understanding of our nearest solar system neighbor: Venus. Comparable in their physical attributes, Venus and Earth should be twins, and were likely more similar in the past—yet their evolutionary paths clearly diverged at some point in time, with Venus losing its surface water and becoming hot. Understanding Venus' present is the first step in revealing its past, and Venus' history is able to tell us about Earth's past as well and provide an exoplanets scientific baseline.

Together to Venus!

Вместе к Венере!

1 Executive Summary—Motivation for the Venera-D Mission: Understanding Venus as a System Through Time

Background. Formed in the inner solar system from the same protoplanetary material as Earth, Venus should be Earth's twin. Like Earth, for example, Venus once hosted an abundance of water and may have been a habitable world. However, Venus' current climate is fueled by a massive CO_2 atmosphere with a surface pressure of 90 bar (~90 times greater than Earth), producing an enormous greenhouse effect, a surface temperature of 470 °C compared to Earth's average surface temperature of 15 °C, and no liquid water on the surface. The lack of an intrinsic magnetic field on Venus suggests that its interior structure may also be different from Earth's. Without an internally generated magnetic field, Venus interacts with the solar wind differently than Earth; the solar wind induces a magnetosphere and creates a comet-like ion tail at Venus. The cumulative effects of this solar wind interaction with Venus have yet to be fully characterized. Thus, at some point in the past, Earth and Venus diverged to follow substantially different evolutionary paths. Earth is currently the only known planet hosting an active biosphere, and therefore we are compelled to ask when and why the Venusian system (from the top of its atmosphere to deep within the planet) diverged so dramatically from Earth's evolutionary path.

Investigation of these questions requires detailed and long-term (hours to years) observations of the processes that formed and modified Venus' surface, focusing on (1) mineralogical and elemental composition of surface materials; (2) energetic, chemical, biological, dynamical, microphysical, radiative, and transport processes active in the atmosphere; and (3) chemical and physical processes related to the interaction of the surface and the supercritical atmosphere. To improve our current understanding of magnetosphere and exosphere conditions and to simulate how these processes may have affected the evolution of the Venusian atmosphere through geologic time, the impact of variable solar forcing needs to be explored.

Although water is no longer present on Venus' surface, available geomorphology data indicates a history of a surface shaped from recent volcanism, faulting, and folding, which may be linked to the past presence of water (e.g., Müller et al., 2008). If life evolved (or existed) during an earlier Venus wet period, life may remain extant today in Venus' ~20-km-thick sulfuric acid clouds, where the local climate may be habitable in the broadest sense (Way et al., 2016; Limaye et al., 2018a). This compels us to better understand when it may have been habitable in Venus' past. Additionally, Venus' water history (e.g., Donahue et al., 1997; Barabash et al., 2007) and its observed cloud-layer climate makes the study of the evolution of Venus—including the potential formation and loss or migration of microbial life forms from the surface to the clouds—an appealing, accessible, and compelling destination for the study of habitability and the potential for life on other Earth-like planets.

- The Venera-D ("D" stands for "*Dolgozhivuschaya,*" Russian for "long-lived") mission concept, as described in this report, is designed to address these fundamental issues. The Venera-D Joint Science Definition Team (JSDT) recommends, as a baseline mission, an orbiter and a VEGA-type lander with an attached long-lived small station, specifically, a Long-Lived In-Situ Solar System Explorer (LLISSE) (Kremic et al., 2017). LLISSE is predicted to survive ~60 days on Venus' surface. Additional breakthrough science could be achieved by augmenting the baseline mission with additional elements, and the proposed launch vehicle (on all probable launch dates) has ample volume and lift to include multiple potential mission augmentations (including additional long-lived stations, subsatellites, and an aerial platform (AP) for atmospheric investigations). This document describes the science return achievable for each of these potential mission architecture elements.

Venera-D Concept and Architecture. The Venera-D concept is the logical next step in the highly successful series of Venera and VEGA missions of the 1970s and 1980s (Marov et al., 1973, 1978; Avduevskii et al., 1977; Florensky et al., 1977; Barsukov et al., 1982, 1986; Surkov et al., 1984; Moroz et al., 1985, 1990, 1996; Sagdeev et al., 1986, 1992). Science objectives of the Venera-D mission concept address key questions about atmospheric dynamics, emphasizing atmospheric superrotation and radiative balance; the processes that have formed and modified Venus' surface, highlighting the mineralogical and elemental composition of surface materials; and the chemical processes occurring at the interface of the surface and the atmosphere. For each baseline component, the following goals would be addressed.

Venera-D and Potential Synergistic Missions to Venus. During the course of JSDT Phase II activities, the Indian Space Research Organisation (ISRO) announced an orbiting mission to Venus to be launched in 2023. The payload for this mission will include a dozen indigenous instruments (including a synthetic aperture radar (SAR)) as well as internationally contributed instruments, with capabilities to study Venus' atmosphere, surface, and surface topography (via S-band and L-band SAR with spatial resolution of ~10 m/px (Karmer, 2019), an order of magnitude better resolution than Magellan SAR). New results about the surface and atmosphere of Venus that may be obtained by the ISRO mission prior to the launch of Venera-D could provide important contextual data that may be used to enhance the development and potential science returns of the Venera-D mission. The ISRO and other potential missions to Venus are briefly described at the end of Section 3.

Venera-D JSDT Objectives. To refine the mission science goals, priorities, and architecture, the National Aeronautics and Space Administration (NASA) and Institut Kosmicheskih Issledovanyi (Space Research Institute (IKI))/Roscosmos established a JSDT in 2015 to evaluate the Venera-D concept with the following objectives:

- Identify, prioritize and develop science goals, investigations, and measurements consistent with the current Venera-D concept.
- Assess the Venera-D mission architecture, including possible modular options (e.g., subsystems or augmentations) for collaboration opportunities and required instrumentation capabilities. Assess technology readiness level (TRL) to implement the mission concept and identify areas for which development is required.
- Identify mission components (e.g., mission elements, subsystems, or instruments) that are candidates for potential international collaboration. Outline a general maturation schedule needed to support a Venera-D mission for launches post-2025.

- 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 and pressures and temperatures found in the atmosphere or at the surface of Venus).
- Evaluate how Venera-D will advance the scientific understanding of Venus and how results will enhance future missions with the ultimate goal of sample return.

To help achieve these objectives, a greater engagement of the broader Venus science community was perceived and enacted. Two workshops on Venus modeling were held in 2017: one at the NASA Glenn Research Center (GRC) and another at IKI in Moscow. Proceedings ("Venera-D Venus Modeling Workshop") are published in IKI (2018) and can be found online (http://venera-d.cosmos.ru./fileadmin/user_upload/documents/Workshop2017_Proceedings.pdf).

As part of its duties, the JSDT traced the science of the baseline Venera-D mission to the science outlined in the NASA commission National Research Council (NRC) Planetary Decadal Survey (Space Studies Board (SSB), 2011) and further mapped the science to specific objectives and investigations identified by NASA's Venus Exploration Analysis Group (VEXAG) (Herrick et al., 2014), showing direct links between the Venera-D objectives and science goals, the Planetary Decadal Survey, and VEXAG's priorities. The JSDT studies indicate that several of VEXAG and Decadal Survey goals might be more comprehensively realized by augmentations to the defined Venera-D baseline payload and mission architecture. The studied augmentations would improve, enable, or enhance Venera-D's ability to trace cloud formation processes and the spatial distribution of the unknown ultraviolet (UV) absorber(s); complete detailed analysis of Venus' surface chemistry, seismic activity, and interior structure; and investigate the temporal evolution of the solar wind interaction.

A subset of the potential augmentations considered here (in prioritized order) is listed below, and a more detailed discussion of these augmentations is presented in Sections 3 and 8.

- Specific instruments such as X-ray diffraction (XRD) and X-ray fluorescence (XRF) for measuring surface composition and Raman-Laser Imaging, Detection and Ranging (LIDAR) for constraining aerosols' microphysics and composition.
- Possible additional flight elements such as:
  - Two small, long-lived surface seismic and weather stations (Seismic and Atmospheric Exploration of Venus (SAEVe) (Kremic et al., 2018));
  - A vertically maneuverable AP; and
  - A small subsatellite in same orbit as main orbiter (Roscosmos contribution) or small satellites at Lagrange point 1 (L1) (between Venus and the Sun) or Lagrange point 2 (L2) (between Venus and Earth).

Technology Assessment. Temperature and pressure extremes make the operation of a landed 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) facilities to test and qualify a full-scale lander and its components at Venus surface conditions, and (3) maturation, testing, and validation of instruments that need to operate in Venus ambient surface conditions. Additional flight components such as a vertically maneuverable AP and one or more small long-lived stations offer great promise for advancing scientific understanding but require maturation to reach the needed TRL.

To ensure scientific success of the Venus science goals, laboratory experiments will be fundamental to validating results. Multiple high-priority studies are required, including the analysis of (1) spectral line profiles at high pressures and temperatures (orbiter); (2) optical properties of the lower Venus atmosphere in the visible (VIS) to NIR wavelengths (lander); (3) the compositional change of the trace gas components due to the temperature and pressure drop during atmospheric sampling throughout descent (lander); (4) a reliable and efficient trace- and noble-gases enrichment procedure (lander); (5) the pressure and temperature effects on remote sensing instruments (lander and orbiter); (6) supercritical properties of Venus-like atmospheres (lander); and (7) spectral absorption experiments designed to characterize and identify atmospheric absorbers (both abiotic and biological) and identify insolation energy deposition over a broad range of altitudes (via lander descent or a variable altitude balloon, for example).

JSDT Findings and Recommendations. The JSDT identified priorities for the science goals and objectives. The JSDT considered a baseline mission concept consisting of a single orbiter and a single lander with a LLISSE attached to it. The lander would be the primary mission element to address surface composition and surface-atmosphere interactions. The orbiter would help to resolve questions about atmospheric dynamics, superrotation, recent volcanic activity, atmospheric loss, and the compositional variability of the surface and atmosphere by making observations of the night side of the planet in the NIR. In the assessment of possible mission enhancements, in situ measurements (both at the surface and aloft made over many hours to months) are enabling, particularly for understanding the processes that drive the atmosphere, the ionosphere, and the magnetosphere. Mobility within the atmosphere is also deemed of high priority to enhance our understanding of the location of the unknown UV absorber(s) and identifying its composition.

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

- Lander instrument validation and maturation to ensure robust and successful operation in the harsh Venus environment (470 °C and 90 bar) or the thermal environment of the orbiter;
- Laboratory work to characterize the chemistry of the Venus atmosphere at high temperatures and pressures;
- Development of capable facilities to test instruments and the spacecraft at the component and system level in a simulated Venus environment; and
- Continued development regarding all potential mission augmentations.

Framework for Future Work. The Venera-D JSDT has completed its formulation (*Phase II*) of science goals and priorities along with its assessment of key areas for technology maturation. The JSDT also considered potential augmentations to the baseline concept, which would result in a more complete realization of the Venera-D scientific goals. The next phase (Phase III) of development would focus on a deeper examination of the science and instruments of the baseline and augmented elements along with a more complete definition of the spacecraft requirements. Within this context, the following topics deserve attention and will be examined.

Baseline Mission Tasks:

Definition of a comprehensive focused mission concept, including

(1) Definition of a concept of operations for the LLISSE+lander combination, including a timeline of science observations, strategy for sample acquisition, handling, analysis, data flow, and downlink.
(2) Refinement of baseline LLISSE+lander and orbiter instrument capability relative to the prevailing environmental conditions to confirm its ability to achieve the science goals.
(3) Refinement of the envelope (mass, power, volume (MPV)) for the payload of the baseline elements.
(4) Maturation of the baseline small station interface, instrumentation, and concept for targeting and deployment of LLISSE+lander.
(5) Assessment of data communications capability between
    (a) Up/down links between Venera-D orbiter and Earth stations at X and Ka bands;
    (b) Downlink from lander to Venera-D orbiter.

Core + Contributed Element Tasks:

Definition of a comprehensive focused mission concept with core and prioritized science enhancing elements AP, long-lived stations, small satellites at L1 and L2 points), including

(1) Formulation and prioritization of synergistic science goals for the mission architecture between instruments of the baseline elements and possible contributed elements.
(2) Refinement of the AP accommodation deployment, requirements, optimization, and operations relative to science priorities and instrumentation.
(3) Refinement of the multiple additional contributed long-lived weather and seismic stations accommodation and requirements.
(4) Refinement of the subsatellite platform accommodation, orbit parameters, instrument priorities, and requirements.
(5) Assessment of data communications capability from
    (a) Downlink between AP and
        (i) Venera-D orbiter
        (ii) Additional LLISSEs (or SAEVes)
        (iii) Subsatellite in orbit around L1 location
        (iv) Subsatellite in orbit around L2 location
    (b) Up/down link between Venera-D orbiter and L1 and L2 satellites
    (c) Up/down link between L1/L2 satellites and Earth stations.

To accomplish several of these goals, the expansion of the current JSDT membership to include preproject engineers with expertise in telecom engineering, structural and thermal engineering, system engineering, and so on, is required. Additionally, continued and increased engagement of the broader science community is required. Thus, a Venera-D landing site selection workshop is being planned for early October 2019, in IKI, Moscow. The habitable zone in the Venus cloud layer is a critical topic for more comprehensive participation of the astrobiology community. Venus similarly intrigues the exoplanet community because they have found many exoplanets that appear to be Venus-like. Laboratory experiments for candidate terrestrial microorganisms that have spectral, physical, and chemical properties compatible with the known properties of cloud particles are needed to measure their survival and evolution in the Venus cloud layer. Together, workshops and lab experiments 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 how and why Earth and Venus are siblings—but not identical twins.

2 Summary of Phase I and Workshop Updates

2.1 Introduction

Formed in the inner solar system out of the same protoplanetary material as Earth, Venus is considered Earth's twin. 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 of 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 from that of Earth's. These differences indicate that Earth and Venus had distinct evolutionary paths. What remains unanswered is when, why, and how their paths diverged. Additionally, it remains that 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 lead to a habitable planet. The Venera-D mission concept is designed to address these provocative and timely questions.

2.2 Venera-D Mission Concept and Science Priorities

2.2.1 Mission Elements

The Venera-D mission concept studied by the JSDT includes baseline and augmented elements. Baseline elements are an orbiter and lander. The orbiter would be instrumented to make observations focused on solving the main mystery of Venus' atmospheric dynamics: superrotation, atmospheric structure, chemistry, and clouds. The mission scenario would place the spacecraft in a highly inclined, near-polar orbit with a period of 24 hr. The expected operational lifetime of the orbiter would be more than 3 yr. Depending on the science to be achieved, there is flexibility in trading the 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 3 hr with time allocated such that the baseline science could be achieved in 1 hr with the second hour allocated as margin for continuing or repeating measurements. The JSDT recommends that baseline concepts include a small long-lived station be incorporated as an instrument on the lander—operating for a period long after the main lander ceased to make 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. Augmented elements include additional small, long-lived atmosphere and seismic surface stations (SAEVes), a variable-altitude balloon, and a subsatellite.

2.2.2 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 Venus' atmosphere and surface. To direct the development of the mission concept, the JSDT prioritized (high, medium, and low) the goals and objectives for the mission's orbital and landed components. The science goals defined in the summary (see below) for the orbiter are presented in priority order. Orbiter objectives (Table 2.1) that are related to understanding the structure, dynamics, and chemistry of the atmosphere and clouds on both the day and night sides are of highest priority, whereas the orbiter objectives that focus on the ionosphere, magnetosphere, solar wind interactions, and particle environment are of medium priority. For 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 has low priority as it was concluded that the relatively short period of time available to the lander (three or more hours) for which measurements could be made would be insufficient for positive detections. Lander objectives (Table 2.2) related to atmospheric composition are of high priority and objectives 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 for those related to the search for seismic activity and electromagnetic fields because the latter may be done from orbit.

Prioritized 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;
- Study the composition of the low atmosphere and low clouds, surface emissivity, and search for volcanic events on the night side; and
- Investigate the upper atmosphere, ionosphere, electrical activity, magnetosphere, the atmospheric escape rate, and solar wind interaction.

Table 2.1.—Prioritized Science from Orbit

Objective Title	Science Objectives	Measurements	Instrument	Priority
O1a. Vertical structure of mesosphere, temperature, clouds, and dynamics of cloud-born gases	Characterize the three-dimensional (3D) atmospheric composition, including SO_2 and H_2O, temperature field, cloud structure and thermal winds, thermal tides, and thermal balance in 55 to 100 km on both the day and night sides	(1) Measure the spectrum between 5 and 45 µm with a sampling of $\Delta\nu = 1$ cm^{-1} (2) Depending on latitude and local time, retrieve the temperature profiles at 55 to 100 km and vertical aerosol profile to recover dynamics, structure and composition of upper clouds, altitude of upper boundary of clouds and scale height, and upper boundary of the middle clouds SO_2, H_2O between 55 and 75 km	Fourier Transform Spectrometer (planetary Fourier spectrometer-Venera-D (PFS-VD))	High
O1b. Vertical structure of troposphere, temperature, clouds, composition, and dynamics	Determine the structure, composition, dynamics, and thermal balance of the atmosphere from 10 to 60 km on both day and night sides. Simultaneous measurements with PFS-VD allow obtaining atmospheric structure and dynamics from 10 to 100 km	Perform measurements from 10 to 90 GHz (0.3 to 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
O2. Atmospheric dynamics and airglow	(1) Determine limb and nadir detailed UV spectral characteristics to identify the "unknown" UV-absorber(s) (2) To study small-scale atmospheric dynamics, cloud structure, and cloud tracking (3) Analyze cloud components (SO_2, SO, "unknown UV absorbers") and search for night side airglow	(1) Measure spectra and perform imaging at 190 to 490 nm with a sampling of $\Delta\lambda < 0.4$ nm (2) Map SO_2 and SO abundance from 0.19 to 0.32 µm (3) Map the 'unknown' UV absorber(s) in the 0.32 to 0.49 µm range with high spectral and spatial resolution (~100 m) (4) Map cloud structure and wind speed from imaging between 0.19 and 0.49 µm (5) Measure NO, CO, and O_2 to study night glow	UV imaging spectrometer (e.g., Venus Ultraviolet-visual Mapping Spectrometer (UVMAS))	High
O3.Structure, composition, and dynamics of clouds, hazes, and surface thermal emissivity	(1) Determine the structure, composition, dynamics, thermal balance, and structure of the clouds and haze (0 to 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 subsolar (SS) and antisolar (AS) modes of circulation (90 to 110 km) (3) Surface emissivity and 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 with VIS-NIR, 1.5 to 5.1 µm with IR; with spectral sampling of $\Delta\lambda = 0.002$ and 0.005 µm, respectively) (2) Map the thermal structure, distribution of minor constituents, clouds, surface emissions, non-local thermodynamic equilibrium (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 and 980 nm in the day side; 1.74 µm (at 50 km) on the night side (5) Map the 3D temperature field on the night side of Venus from 65 to 90 km (6) Mapping the non-LTE O_2, OH, O, NO, and CO_2 dynamics from 90 to 140 km (7) Measure the surface temperature and search for possible emissivity anomalies	UV-infrared (IR) imaging spectrometer (e.g., VIS and NIR spectrometer (VENIS))	High
O4. Vertical structure and composition of 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 to 160 km)	(1) Measure IR spectra in the wavelength range of 2.2 to 4.4 µm with a spectral sampling of $\Delta\lambda = 0.1$ nm (2) Measure UV spectra in the wavelength range of 118 to 320 nm with a spectral sampling of $\Delta\lambda = 1.3$ nm	UV and IR solar and stellar occultation spectrometer	High
O5. Atmospheric circulation, dynamics, and evolution of contrasts	(1) Track clouds to measure atmospheric circulation and characterize the evolution of known (SO_2 and SO) and unknown absorbers creating contrasts in day side and night side cloud cover (2) Map surface thermal night side emissions near 1 µm to evaluate surface geology (3) Map low-cloud emission near 2 µm—low atmosphere circulation (4) Map at 10 µm—circulation in upper clouds	Perform imaging at 0.285 µm, 0.365 µm, 0.500 µm on day side; at 1 µm and 10 µm on both day and night sides; 2 µm on night side	Imaging system	High
O6. Ionosphere and atmosphere	(1) Determine the free electron and neutral gas density in the ionosphere and thermosphere (2) Determine the electron density (profiles) of the ionosphere (3) Determine the temperature, pressure, and concentration of sulfuric acid vapor (profiles) of the atmosphere (4) Determine the surface scattering properties, permittivity, and density of the surface material	Measure 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. Atmospheric density, temperature, wind velocity, mesospheric minor constituents, and CO_2 dayglow	(1) Determine density and temperature vertical profiling between 80 to 160 km altitude by means of solar occultation (2) Determine wind velocity between 90 to 160 km altitude (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 between 10 to 11 µm in nadir geometry and solar occultation mode with a resolution of $\lambda/\Delta\lambda$ ~107 to 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 between 10 to 11 µm in nadir geometry with resolving power $\lambda/\Delta\lambda$ ~107 to 108 (5) Measure dayglow between 10 to 11 µm in nadir geometry and solar occultation mode with resolving power $\lambda/\Delta\lambda$ ~107 to 108	IR heterodyne spectrometer	High

Objective Title	Science Objectives	Measurements	Instrument	Priority
O8. Solar wind, solar UV emission, and space weather phenomena	(1) Characterize the interplanetary magnetic field (2) Characterize solar UV emission (3) Trace interplanetary weather	(1) Measure magnetic field vector(s) in the amplitude range of ±300 nT in the frequency range of 0 to 2 Hz with a sensitivity of 0.1 nT (2) Measure solar wind ions in the energy range 50 eV to 10 keV (e.g., Ares V) (3) Measure the ionizing solar radiation (4) Measure characteristics the solar wind and interplanetary magnetic field on the subsatellite	**Plasma and UV package**—magnetometer (e.g., Fluxgate Magnetometer for Venus (FM-V)), ion spectrometer (e.g., Ares V), and UV monitor	Medium
O9. Magnetosphere of Venus and its interaction with the solar wind	(1) Characterize the interaction between the solar wind and the induced magnetosphere at Venus (boundaries, dynamics) (2) Determine the structure and properties of day side magnetosphere (3) Determine the structure and dynamics of Venus' plasma-magnetic tail (4) Characterize ultra low frequency (ULF) waves resulted from solar wind-magnetosphere interaction	(1) Measure magnetic field vector(s) in the amplitude range of ±1,000 nT in the frequency range of 0 to 32 Hz with a sensitivity of 0.1 nT (2) Measure energy, flux, and temperature of ions in 2π field-of-view with mass-separation (5 eV to 15 keV) (3) Measure electron density and temperature in the energy range between 10 eV and 10 keV	**Plasma package**—magnetometer (e.g., FM-V), ion spectrometer (e.g., Ares V), electron spectrometer ELSPEC, plasma wave analyzer, and UV monitor	Medium
O10. Solar wind influence and magnetosphere interaction with ionosphere	(1) Monitor solar wind parameters and Venusian magnetosphere (2) Characterize the moment flux from the magnetosphere to ionosphere (3) Monitor the accelerated ionospheric ions flux (4) Monitor downstream neutral particles flux	(1) Measure the total ions moment in the lower magnetosphere (2) Measure the ionospheric ions energy distribution (3) Measure the Ion temperature between 1 and 100 eV. Plasma density between 1 and 105 cm^{-3}	**Plasma package**—ion energy-mass analyzer (e.g., Ares V), ELSPEC, Langmuir probe, and magnetometer	Medium
O12. Escaping flux of planetary ions and its role in evolution of atmosphere	Characterize escape of planetary ions: (1) Determine escape flux through the magnetosphere, ionosphere, and ionosheath on the night side (2) Characterize the fraction of escaping ions and precipitation ions on the night side (3) The acceleration processes and escape in Venusian tail (4) Determine role of solar wind and UV radiation variations, and catastrophic events in controlling escape	(1) Measure ion composition and flux and their variations between 30 eV and 5 keV (2) Measure magnetic field in magnetosheath, magnetosphere, and ionosphere (3) Measure accelerated ionospheric plasma at terminator region and in the tail	**Plasma package**—ion energy-mass analyzer (e.g., Ares V), ELSPEC, Langmuir probe, and magnetometer	Medium
O13. Venus energetic particles environment and 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.	**Energetic particles**—electron and proton spectrum analyzer (e.g., neutron decay spectrometer (aSPECT-V))	Medium
O14. Electromagnetic fields–1	Characterize electrical activity and conductivity of the atmosphere of Venus	Measure the spectrum (two-channel spectrum analyzer) in the low frequency range between 10 Hz and 15 kHz	Atmospheric detector (e.g., Groza small astronomy satellite 2 (SAS2)-O)	Medium
O15. Electromagnetic fields–2	Investigation of plasma waves in magnetosheath and magnetosphere and their role in the solar wind-Venus interactions	Measurements of electromagnetic waves in the frequency range from 1 Hz to 100 KHz	Plasma wave analyzer	Medium

Table 2.2.—Prioritized Venera-D Descent and Landed Science

Objective Title	Science Objectives	Measurements	Instrument	Priority
Atmospheric Science				
L1. Atmosphere composition during descent	Determine composition, chemistry, greenhouse, photochemistry, origin, and evolution of the atmosphere, dynamics, and atmosphere-surface interaction	In situ measurements of chemical composition of atmosphere, including abundances of gases SO_2, CO, COS, H_2O, NO_2, HCl, and HF and their isotopologues and isotopic ratios D/H, $^{13}C/^{12}C$, $^{18}O/^{17}O/^{16}O$, and $^{34}S/^{33}S/^{32}S$ during descent from 65 km and after landing	Multichannel tunable diode laser (MTDL) spectrometer	High
	Determine 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 chemical composition of Venus' atmosphere and of aerosols of clouds	Chemical analyses package (CAP)—gas chromatograph-mass spectrometer (GC-MS)	High
L2a. Atmosphere composition at the surface L2b. Near-surface atmospheric composition	Determine the chemical composition of the atmosphere and clouds Long-term study of possible variation of near-surface atmospheric composition	At surface, measure the chemical composition of the atmosphere Measure abundances of predefined components	CAP—GC-MS LLISSE attached to lander	High

Objective Title	Science Objectives	Measurements	Instrument	Priority
L3a. Atmospheric structure and dynamics	Determine atmospheric structure, dynamics, turbulence, convection, and thermal balance	Measure temperature, pressure, wind speed, temperature gradient, and acceleration from 120 km altitude to and at the surface; incident and reflected radiation	Temperature, pressure, wind (TPW) package (accelerometer/altimeter, photometer) and infrared radiometer for Venera-D (VERBA)	High
L3b. Near-surface meteorological (METEO) parameters (pressure, temperature, wind speed, and direction)	Study of long-term characteristics of near-surface dynamics, waves, thermal tides, and atmosphere-surface interaction	Long-term measurements of near-surface temperature, pressure, wind speed, and direction; incident and reflected radiation	LLISSE attached to lander	High
L4a. Radiative balance of the atmosphere, net fluxes, H_2O, UV absorbers, and sulfur compounds vertical profile	Radiative fluxes on different atmospheric levels, vertical profiles of species, spectral characteristics, and illuminance	Measurements of upward and downward radiative fluxes in transparency windows. Net fluxes and UV-Vis-NIR spectral measurements of clouds and gases. Active part of descent trajectory	Infrared radiometer (VERBA) with an integrated UV-Vis-NIR spectrometer.	
L4b .Solar fluxes on the surface	Surface albedo. Study of factors that influence solar illumination (cloud opacity, local time, local relief, etc.)	Measurements of incident and reflected solar radiation over 60 days	LLISSE	
L4c. Physical properties of atmospheric aerosols	Evaluate aerosol microphysics, composition, vertical profile, cloud formation and chemistry, and thermal balance	Measure atmospheric aerosol particle number density, size distribution, and optical properties.	Raman-LIDAR	Medium
Surface Geology and Geophysics				
L5. Surface structure and morphology	Characterize surface structure, morphology, and relief at 10 to 100 m/pixel during descent; characterize the surface at 1 m to 0.01 m/pixel at surface. Sample characterization at <0.2 mm/pixel	(1) Surface imaging during descent and measuring optical properties of the atmosphere (2) Imaging on the surface and measuring optical properties of the near surface atmosphere (3) Stereo imaging of surface (field of view (FOV) 30° to 45° and angular resolution ~0.0005 rad) starting from an altitude of several kilometers and on the surface (4) Panoramic stereo imaging of the surface. Detailed stereo imaging of surface with the spatial resolution better than 0.2 mm	Imaging system (descent imager, panoramic camera, and microscopic imager)	High
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. 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., Active Gamma and Neutron Spectrometric Soil Analysis (AGNESSA)) • XRF mode of Mössbauer spectrometer • CAP • XRD/XRF	High
L7. Mineral phases	Identification of mineral phases, containing Fe (Fe^{2+}, Fe^{3+}, Fe^{6+}). To address atmosphere and surface evolution along with surface minerals (search for any possible bound water e.g., phyllosilicates)	Measure Mössbauer spectra of the surface rocks	Miniaturized Mössbauer spectrometer (MIMOS-2A)	High
L8a. Global and regional seismic activity	Assess global and regional tectonic activity	Measurement of planetary seismic background and self-oscillations to constrain crustal thickness over 3-hr lander lifetime	Seismometer	Low*
L8b. Venus' internal structure, heat flow, and seismic activity	Asses global tectonic activity at multiple locations	Measurement of planetary seismic background and self-oscillations to constrain crustal thickness over 120 days; measure heat flux	SAEVes	High*
L9. Electromagnetic fields	Determine electromagnetic fields, electrical activity, and conductivity of Venus' atmosphere	Measure of emissions in the range of 10 Hz to 100 kHz	Wave package (e.g., Groza-SAS2)	Low

*See Section 8.3 for SAEVe discussion. One seismometer, operating for only 3 hr, is a low priority because the anticipated data return is low. Multiple seismometers coupled with heat-flux measurements, operating over 120 days, is a high priority because of the high likelihood of meaningful data return.

Prioritized Lander+LLISSE Goals:

- Measure elemental and mineralogical abundances of the surface materials and near subsurface (a few cm), including radiogenic elements.
- Study the 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 cloud aerosols.
- Characterize the geology of local landforms at different scales.
- Study variation of near-surface wind speed and direction, temperatures, and pressure over 3 months (LLISSE).
- Measure incident and reflected solar radiation over 3 months (LLISSE).
- Measure near-surface atmospheric chemical composition over 3 months (LLISSE).
- Detect seismic activity, volcanic activity, and volcanic lightning.

2.3 Venera-D Joint Science Definition Team (JSDT)

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 VEXAG (Herrick et al., 2014), a joint IKI-Roscosmos/NASA science definition team (SDT) 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 JSDT and their roles are provided in Table 2.3 and Figure 2.1.

To direct the work of the JSDT, a joint NASA/IKI charter was established and signed in 2015 by the directors of the IKI and NASA Planetary Division, Lev Zeleny and Jim Green, respectively. 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 TRL 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 timeframe;
(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); and
(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.

Table 2.3.—Members of the Venera-D JSDT

SDT Member	Institution	Expertise
L. Zasova, Co-Chair	Space Research Institute (IKI)	Atmosphere
T. Gregg, Co-Chair	University at Buffalo	Surface geology
A. Burdanov	Central Research Institute for Machine Building (TsNIIMASH)	Project expert
T. Economou	University of Chicago	Chemical analyses
N. Eismont	IKI	Orbital mechanics
A. Feofanov	Lavochkin (NPOL)	Engineering (orbiter)
M. Gerasimov	IKI	Surface and atmosphere chemistry
L. Glaze	NASA Headquarters	Past U.S. Co-Chair
D. Gorinov	IKI	Atmosphere
J. Hall	NASA Jet Propulsion Laboratory (JPL)	Engineering
N. Ignatiev	IKI	Atmosphere
M. Ivanov	Vernadsky Institute	Surface geology
K.L. Jessup	Southwest Research Institute	Atmosphere
K. Khatuntsev	IKI	Atmosphere
O. Korablev	IKI	Atmosphere
A. Kosenkova	NPOL	Engineering (lander)
T. Kremic	NASA Glenn Research Center	Technology
S. Limaye	University of Wisconsin	Atmosphere
I. Lomakin	NPOL	Technology
A. Martynov	NPOL	Engineering (spacecraft)
A. Ocampo	NASA Headquarters	NASA JSDT
P. Pisarenko	NPOL	Engineering (orbiter)
D. Senske	JPL	Past U.S. Co-Chair
O. Vaisberg	IKI	Solar wind, plasma
V. Voron	Roscosmos Headquarters	Roscosmos JSDT
V. Vorontsov	NPOL	Technology

Figure 2.1.—Venera-D JSDT. Top figure, left to right: O. Vaisberg, S. Teselkin, translator, O. Zakutnaya, L. Zasova, A. Burdanov, D. Senske, M. Gerasimov, S. Limaye, D. Gorinov, T. Kremic, T. Economou, TJ. Tilman, A. Ocampo, K.-L. Jessup, V. Vorontsov, E. Maroko, N. Ignatiev, and N. Eismont. (Not pictured: L. Glaze, T. Gregg and D. Senske.) Bottom figure, left to right: A. Martynov, A. Kosenkova, P. Pisarenko, and A. Feofanov.

To address these tasks, the JSDT organized itself into three subgroups: (1) Atmosphere, (2) Surface-atmosphere interaction, and (3) Technology. In the course of its work, individual subgroups met regularly via teleconferences and held splinter meetings during the full JSDT face-to-face meetings or other available meetings. The full JSDT met through teleconferences on alternative weeks throughout the year. In 2018, the full JSDT had three, 1-week-long face-to-face meetings in Moscow in April, August, and October for detailed discussions. Additionally, a vital element of the JSDT is the engagement of the broader Venus science community. Thus far, two workshops on Venus modeling have been held: one at NASA GRC in May 2017 and another at IKI in Moscow, Russia in October 2017. Additional future workshops are desired, such as the Venera-D landing site selection workshop planned for October 3 to 5, 2019, in IKI, Moscow.

Venera-D Venus Modeling workshop. From October 5 to 7, 2017, IKI, Moscow, hosted a Venera-D Venus modeling workshop, organized by IKI and NASA, and convened by the Co-Chairs of the JSDT (Drs. L. Zasova and D. Senske). The workshop focused on the Venera-D mission in light of the current knowledge base of Venusian models (e.g., general circulation models (GCMs) and models of the surface and interior structure and plasma environment). Discussion topics included priorities and motivations for landing site selection, as well as the types of measurements needed to parameterize and adequately constrain theoretical geophysical models and the experiments needed to validate or refute results derived from these models. The intent was to form a basis for identifying the mission architecture elements required to achieve key Venera-D science goals defined in the Roscosmos/IKI-NASA JSDT Phase I report (such as atmosphere probes, APs or aerobots, long-lived surface stations, and a lander). Workshop findings provide a basis for identifying the suite of instrumentation that would provide the highest science return from each mission element.

The JSDT Phase I report is available online (https://www.lpi.usra.edu/vexag/reports/Venera-D-STDT013117.pdf). The proceedings ("Venera-D Venus Modeling Workshop") are published in IKI 2018 and also available online (http://venera-d.cosmos.ru./fileadmin/user_upload/documents/Workshop2017_Proceedings.pdf).

3 Science Investigation Targets

3.1 Updated Review of Venera-D Atmospheric Science Goals and Objectives and Traceability

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., European Space Agency (ESA), and Japan Aerospace Exploration Agency (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 growing knowledge about Venus has brought us more questions than answers, which have been discussed in a collection of chapters in Venus III (Bézard et al., 2018).

Venus hosts one of the most extreme atmospheric environments in our inner solar system and one that is dramatically different from that of present-day Earth. The predominantly CO_2 atmosphere with a small amount of N_2 exerts a pressure of about 90 bar on the surface, and is responsible for a surface temperature of ~470 °C 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. The atmosphere also harbors H_2O, CO, and SO_2, which all have strong absorption bands in the IR 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 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 Earth and Venus 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 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 questions we have about Venus' atmosphere are

- Why does the atmosphere of Venus rotate faster than the solid planet?
- What are the absorbers in the atmosphere and clouds that determine the spectral albedo and produce variable contrasts in the cloud cover? Why aren't the absorbers well mixed? What determines their spatial distribution and evolution? Are they biologic?
- When and why did Venus take a different evolutionary path from Earth and what are the mechanisms responsible for Venus' evolution and the process that led to the present climate?

- What are the effects of the two primary atmospheric constituents (CO_2 and N_2) being in supercritical state in the lower atmosphere? Are these constituents well mixed in the troposphere or do they show a vertical gradient?
- What processes are involved in the surface-atmosphere interaction?

To answer these questions, it is paramount that measurements are made using capable instruments both remotely and in situ. The Venera-D baseline mission has the potential to address a significant set of the outstanding questions listed previously about the Venus atmosphere, including making important advances in determining the mechanisms that support Venus' atmospheric superrotation. A baseline mission would consist of an orbiter in a high-inclination orbit and a lander descending to the surface with a simple, long-lived surface station (LLISSE) to provide critical measurements of the atmosphere (pressure, temperature, and wind direction and speed) at the surface-atmosphere boundary for three months, or almost half of a Venus solar day (~117 Earth days). The science return from the mission would be significantly enhanced by supplementing the baseline architecture with an AP capable of making measurements over and ~10 to 15 km altitude range in the cloud layer (47 to 72 km) for long-term monitoring of the ambient atmospheric properties and circulation within the cloud layer. The addition of this type of sustained in situ AP is needed for achievement of Venera-D's primary atmospheric science goal to investigate the superrotation of Venus' atmosphere. Increased science return would also be obtained from long-lived surface stations, monitoring near-surface meteorology (temperature (T), pressure (P), wind speed and direction, wave, tides, and momentum exchange), atmosphere composition, solar fluxes, and seismology.

Additional significant science return can be achieved by addition of a small secondary subsatellite either in the same orbit around Venus as the main orbiter, or about two of the Venus-Sun Lagrange points. If placed in orbit around one or two of the Lagrange points (L1 between the Sun and the planet and L2 on the other side of the planet along the Sun direction), this additional platform (when combined with the baseline orbiter mission) has the potential to allow the first 3D study of Venus' solar wind interaction and enhance atmospheric studies. Observations made from this supplementary platform at the Lagrange points would also be independent of any significant phase variation. Thus, increasing the accuracy to which periodicities in Venus' radiance values on Venus' day (if in orbit at L1) or night side (if in orbit at L2) may be defined over the lifetime of the mission. Such improvements could support important advances in the investigation of the evolution of Venus' cloud top albedo, atmospheric opacity, atmospheric circulation, and overall climate as will be further outlined below. In the following sections, we describe how Venera-D could achieve these scientific goals 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 taken by the spacecraft (Mariner 10, Galileo Orbiter, Venus Express (VEX), and now Akatsuki), ground-based images, and from tracking the Venera landers, Pioneer Venus entry probes, VEGA balloons, and VEGA 2 lander (Figure 3.1). The VEX mission has

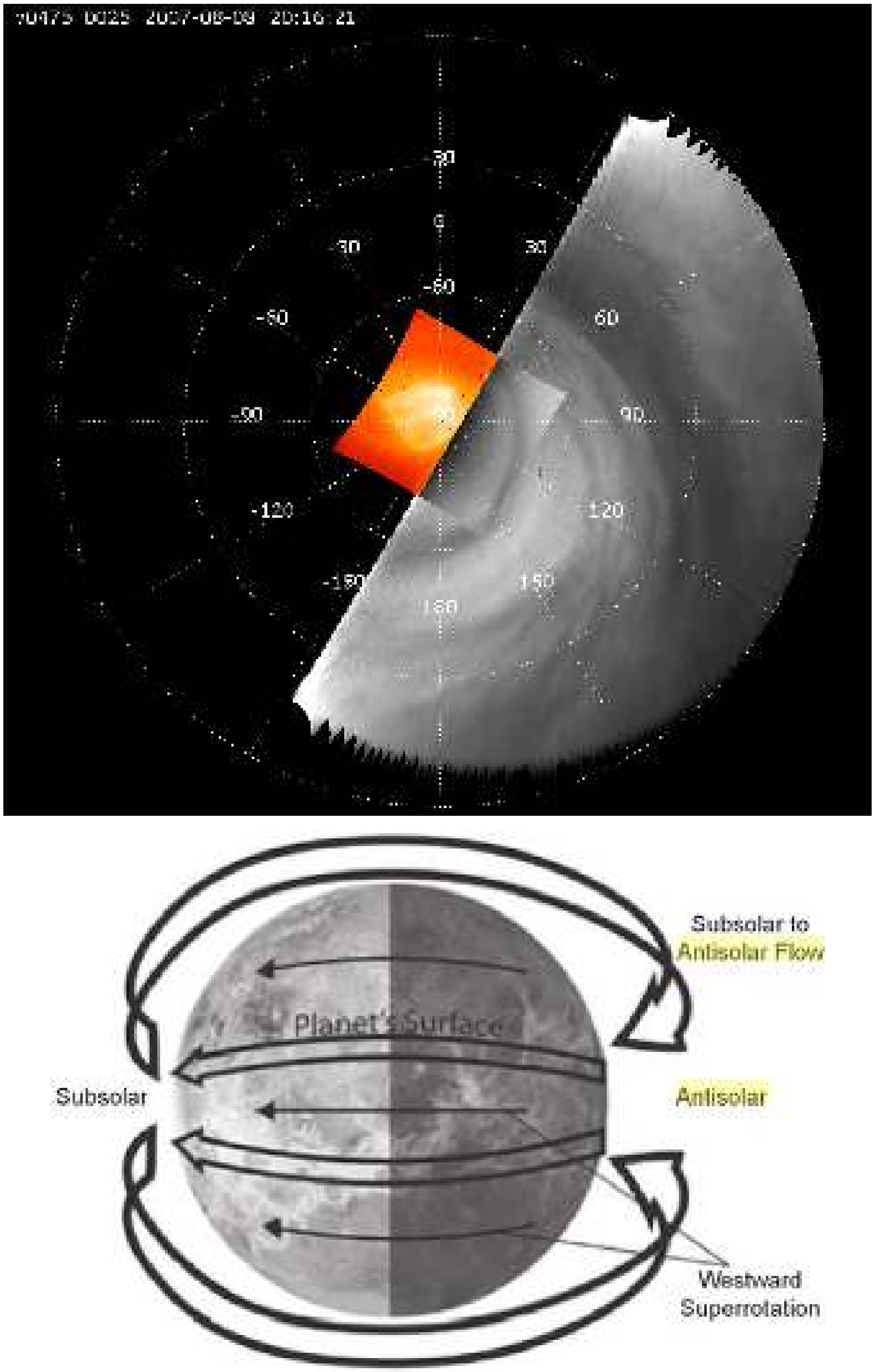


Figure 3.1.—(Top) A composite of Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) (Coradini et al., 1998) image showing the night side view of the polar region and day side view of the sunlit hemisphere superposed on a 365-nm image taken from the Venus Monitoring Camera (VMC) (Markiewicz et al., 2005), 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. (Bottom) 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 SS to AS point circulation above the cloud tops (from Bullock and Grinspoon, 2013). Zonal superrotation returns at higher altitudes (>115 km) when the meridional temperature gradient again changes sign.

provided new information about atmospheric circulation and now Akatsuki data are providing new data. One of these is that both the cloud cover and the cloud motions exhibit periodicities with periods ranging from the period of superrotation, one Venus solar day, to as long as the Venus rotation period (Kouyama et al., 2013; Lee et al., 2015; Khatuntsev et al., 2017; McGouldrick, 2017). Another new discovery is that the atmosphere from the cloud deck up to the mesopause (55-100 km) is influenced by the surface topography, resulting in correlation between surface topography and wind speed, altitude of the upper boundary of upper and middle clouds, isotherms at different levels (Patsaeva et al., 2015; Zasova et al., 2015; Khatuntsev et al., 2017; Gorinov et al., 2018), and cloud-level albedo variations (Bertaux et al., 2016; Jessup et al., 2019) as well as 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) Measurements of the wind fields at all possible altitudes on day and night side, over a lifetime long enough to reliably characterize the mechanisms controlling the atmospheric flow;
(2) Increased knowledge of the global characteristics of the solar energy deposition in the atmosphere and at the surface;
(3) Long-term monitoring of temperature profiles from near-surface levels to the thermosphere and of thermal tides;
(4) 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 to 0.55 μm; and
(5) Measurements to characterize the meridional transfer of momentum and heat. Additionally, these measurements need to be made with sufficient spatial and temporal coverage to resolve the contributions from transports by thermal tides and other waves.

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. The radiative balance, energy deposition, and cloud contrast origin are discussed in Section 3.1.1.5.

Middle Cloud Level and Below. Vertical profiles of wind velocity from the surface up to 60 km were measured by Venera and VEGA landers along with the Pioneer Venus probes. It was found that the wind speed increased from 0.5 to 1.5 m/s near the surface from 60 to 70 m/s at 60 km. Wind speeds at the cloud top and in the middle clouds (Figure 3.2) 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 day side from the Mariner 10 (Limaye and Suomi, 1981), Pioneer Venus (Rossow et al., 1980, 1990; Limaye et al., 1988), VEX (VIRTIS, VMC) (Moissi et al., 2009; Hueso et al., 2012; Khatuntsev et al., 2013; Patsaeva et al., 2015), and Akatsuki (ultraviolet imager (UVI)) (Horinouchi et al., 2018), 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 from about 53 to 55 km altitude while floating for 48 hr 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 Aphrodite Terra (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 (Bertaux et al., 2016; Jessup et al., 2019) 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.

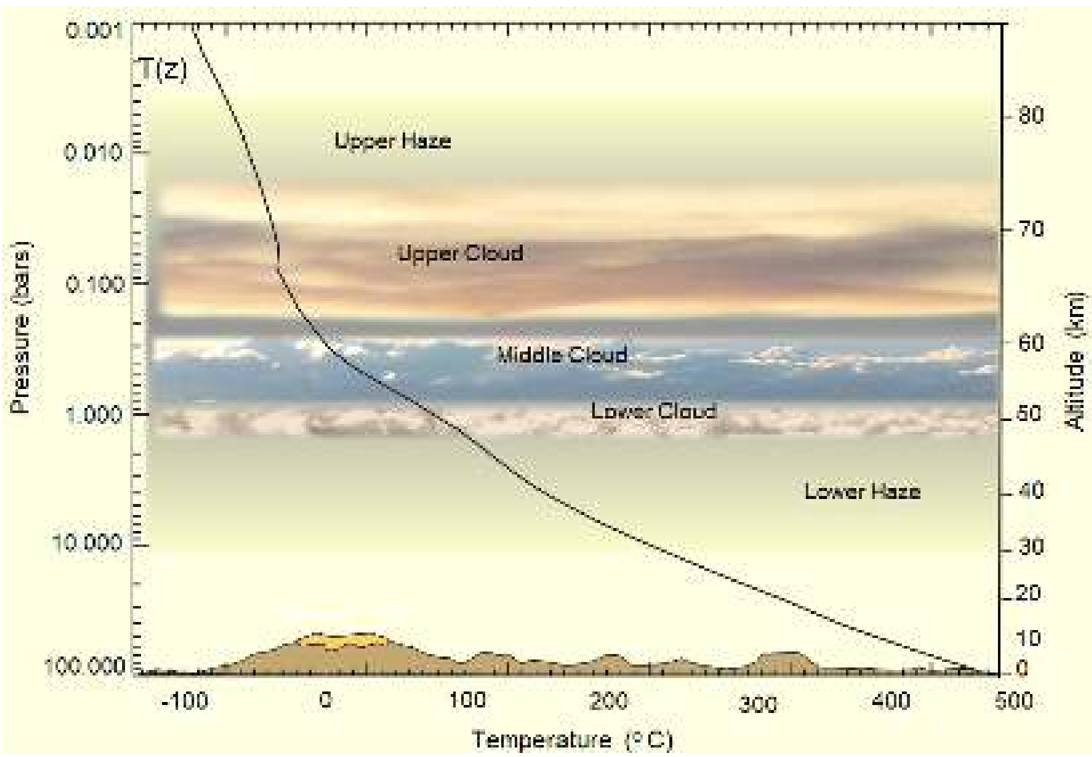


Figure 3.2.—Venus International Reference Atmosphere (VIRA) Temperature Profile (Seiff et al., 1980); haze and cloud layers inferred from previous in situ descent probe and lander results. The upper cloud layer extending to ~73 km is consistent with recent results from VEX and the Hubble Space Telescope (Jessup et al., 2015; Berzard et al., 2018).

These data are sparse and were obtained at different times. The most complete dataset is from VEX VMC data (8 yr of remote sensing observations of predominantly the southern hemisphere) and the intersection of Hubble Space Telescope observations with these data, which has been used to help clarify the relative importance of latitude, local time, and longitude relative to underlying surface elevations at southern latitudes (Jessup et al., 2019). Additional detailed long-term global monitoring is needed to further understand periodic behaviors inferred from the VMC data as well to better understand similarities and differences that may exist between Venus' northern and southern hemispheres. The Akatsuki orbiter is now filling in some of these gaps by observing Venus from a near-equatorial orbit. However, Akatsuki suffered an unfortunate loss of its IR1 and IR2 cameras, which sensed the surface on the night side (IR1) and altitudes of 30 to 50 km in its 1.73, 2.26, and 2.32 µm filters (IR2) on the night side (see Section 3.1.1.5) about ten months after orbit insertion. The NIR camera on the Venera-D orbiter can recover these losses, assuming that information about the winds at lower cloud levels can be obtained by images in the NIR spectral windows on the night side. These results, together with day side winds retrieved from cloud-tracking completed from the Venera-D orbiter at UV and NIR wavelengths will improve our knowledge of the circulation in the cloud layer. Venera-D will also regularly monitor the temperature structure on the day and night sides in the mm-spectral range (sensing the altitudes extending from 60 km down to 10 to 20 km). *Venera-D will be the first mission to complete mm-wave observations at Venus from obit, allowing for significant advances in our understanding of atmospheric circulation below the clouds.*

Measurements from within the atmosphere have not been made since the VEGA landers descended to the surface in 1985 and the VEGA balloons traversed near the equator for 48 hr at about 54 km altitude. Data from these platforms have provided several wind profiles in the middle clouds and below. *However, a long-lived in situ 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 (see Section 8).*

Mesosphere (60 to 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 VEX orbiters (Newman et al., 1984; Piccialli et al., 2012), while direct cyclostrophic winds were obtained from Pioneer Venus radio occultations (Limaye, 1985). The geometry of the orbiter-Venus-Earth radio occultations does not yield 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 orbiter infrared radiometer (OIR) on Pioneer Venus (Schofield et al., 1983), the Fourier spectrometer (FS) on board Venera-15 (Zasova et al., 2007), and the VIRTIS VEX (Piccialli et al., 2008). The geometry of Venera-15 allowed the calculation of the thermal zonal wind without zonal averaging, and local time behavior of the zonal wind speed was observed by Venera-15 (FS-V15). In the mid-latitude jet, the minimum of thermal wind speed was found in the afternoon (above Ishtar Terra) and maximum in the morning (above Atalanta Planitia).

The cyclostrophic balance breaks down at 80 to 90 km of altitude because the dynamical regime becomes more complex and cannot be described by simple equations of cyclostrophic balance. Observations indicate (Zasova et al., 2000, 2002) that below these levels (the precise altitude depends on local time), 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 to 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 70 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 of which are required to maintain the observed circulation.

Utilizing state-of-the-art cameras on the orbiter, Venera-D will provide the needed long-term monitoring of mesospheric circulation patterns based on UV and NIR cloud contrasts (sensitive to 65 to 75 km altitudes) and UV nightglow observations (sampling 100 to 120 km altitudes). Likewise, spectroscopic observations completed from the Venera-D orbiter at UV, VIS, and IR wavelengths will provide the global temperature profile measurements needed at these altitudes to adequately investigate the thermal drivers of Venus' mesospheric circulation patterns.

Upper Atmosphere above 90 km. The main method to study circulation above 90 to 140 km has been 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 to 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 (Hodges and Tinsley, 1982; Chaufray et al., 2012). Doppler shifts of spectral lines provide clues about the SS and AS circulation near 110 km altitude (Clancy et al., 2012). Tracking the horizontal motions of the O_2 1.27-μm nightglow by an imaging spectrometer (such as VIRTIS/VEX) provides distribution of the wind speed at 90 to 110 km (Hueso et al., 2008) and the topographic influence on horizontal atmospheric motion; in particular, Gorinov et al., 2018 found that topographic influence is one of the factors leading to deviation of the circulation patterns from the SS to AS flow at these altitudes.

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 superrotation remain ill defined. A study of atmospheric circulation patterns and an understanding of energy transfer are both required to fully understand superrotation. This latter issue relates both to our knowledge of the thermal structure (discussed in detail in Section 3.1.1.2) and the importance of Venus' UV absorber(s), which is (discussed in Section 3.1.1.5).

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

3.1.1.2 Atmospheric Thermal Structure

Characterization of the thermal and cloud structure of the atmosphere is crucial to understanding the processes that drive 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 (LST) with high accuracy, from the surface to thermosphere, while simultaneously measuring atmospheric composition, cloud properties, and thermal balance. To date, these measurements have been only obtained in very specific altitude ranges at varying local times from IR remote sensing, radio, solar IR and stellar UV occultations (Piccialli et al., 2015), and from entry probes. A comparison of recent thermal structure results from VEX and ground-based measurements with the VIRA model was presented by Limaye et al., 2017, and results on the thermal structure and inferences about the thermal balance has been reviewed by Limaye et al., 2018b.

Vertical profiles of temperature, pressure, and density in the troposphere (<60 km) as well as 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 °C. Temperature profiles, obtained before VEGA, were summarized in VIRA (Seiff et al., 1985); local time-dependent updates of VIRA thermal structure for the northern hemisphere has been updated (Zasova et al., 2007). 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. The peak of high stability was observed by VEGA-2 to be around 15 km but is not pronounced in the VIRA profile. Below this peak, the VEGA-2 profile shows the highest instability in the range of 2 to 4 km altitude. Above the tropopause, the Venus atmosphere is stable.

Thermal profile data obtained over a greater diversity of LSTs and latitude have been derived from previous orbiter observations at altitudes of ~60 to 140 km at LSTs extending over the night side and at the dawn/dusk terminators (Limaye et al., 2018b). The 3D thermal structure of the middle atmosphere has also been inferred from the Pioneer Venus OIR (Taylor et al., 1980) and Venera-15 Fourier spectrometry (Zasova et al., 2007) data on both the day and night sides. Additional data on the night side structure has been derived from VIRTIS VEX (Migliorini et al., 2012). Each of these datasets contributes to our understanding of the forcing of the thermal structure by diurnal variations. Additionally, the spectral range, spectral resolution, and observation geometry gave Venera-15 the ability to retrieve from each spectrum, in a self-consistent way, vertical temperature profiles (55 to 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 versus latitude and altitude and the solar-related dependence of the altitude of upper clouds (Zasova et al., 2002, 2007). Thermal tides result from the absorption of solar energy deposited on Venus in the upper clouds (within 10 km) by an 'unknown' 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 wind distribution in coordinates (pressure, latitude) with high vertical and horizontal resolution extending from the surface to upper atmosphere—all while tracking the distribution of the unknown absorbers.

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 >10 °C higher than the surroundings. An S-shaped dipole feature was discovered by the Pioneer Venus OIR (Taylor et al., 1980) over the north pole. VEX revealed a similar feature over the south pole (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. However, many details of the vortex organization of the circulation are unknown. Vertical temperature profiles (FS-V15) allowed the position of the temperature maximum in the vortex to be identified from 58 to 60 km, but the vertical circulation in the core region remains unknown. The core region of the vortex in the 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 the VMC.

Another puzzling structure is a "cold collar" between 65° to 75° latitude in both hemispheres. The cold collar exhibits a tidal nature (Zasova et al., 2007). The diurnal and semidiurnal amplitudes exceed 10 and 6 °C, 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 surroundings (Zasova et al., 1992). The maximum difference in temperature between areas near the evening and morning terminators was observed to be 30 °C (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 of 5 °C at low latitudes, providing a temperature difference >20 °C at 95 km with lower temperatures in the afternoon, compared to the morning terminator (Zasova et al., 2007). Gravity waves are also generated in this region, revealed through the O_2 1.27-μm airglow vertical profiles (Altieri et al., 2015). 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. Thermal tides have also been detected from cloud motions in data returned from Mariner 10 to VEX (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 modeled (Pechman and Ingersoll, 1984).

The observations described above only provide part of the picture relative to the nature of the thermal tides and the thermal structure that supports them. 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 spatial and temporal coverage and vertical resolution from previous observations of both the circulation and the thermal structure of Venus' atmosphere so that unanswered questions about the dynamics of the atmosphere 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, in concert with detailed studies of the vertical and spatial distribution of the atmospheric species controlling Venus' radiative budget as a function of time. Admittedly, we cannot make such comprehensive measurement with only the Venera-D baseline mission. Thus, we advocate using remote sensing observations from orbit (for 3 yr) ***supplemented*** by both (1) continuous atmospheric measurements that may be acquired from a long-lived, in situ platform (see Section 8) and (2) in situ measurements that the Venera-D lander will take during its descent to the 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 IR 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 any currently available capability; hence, in situ measurements are required 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 and the relationship between the energy and momentum transport and the vertical distribution of Venus' key absorbing species.

Measurements of the circulation from the Venera-D orbiter supplemented by an in situ atmospheric platform and long-lived surface stations have the potential to shed light on the following significant aspects of the Venus atmosphere, including

- The small-scale structure of the circulation on the day and night side within the cloud layer, where most of the heat is deposited by absorption of the incident sunlight on the day side at different altitudes;
- The nature and identity of the absorbers responsible for the absorption of sunlight from UV to NIR wavelengths and whether any of them are biologic;
- The altitude of the lower boundary of Hadley circulation, where the mean flow is expected to be equatorward;
- The temporal behavior of the global circulation in hemispheric vortices;
- The structure of the thermal tides;
- The 3D temperature field in the troposphere and possible existence of Hadley cells in the undercloud atmosphere; and
- Circulation links to surface topography and the responsible mechanisms.

3.1.1.3 Atmosphere Composition

To characterize Venus' origin and evolution through time, accurate assessment of the composition of the atmosphere atmosphere's composition is essential. Like 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 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 formed from comet or asteroid impacts. 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 be resolved is the accurate measurement of the vertical profile of Venus' bulk atmosphere constituents. Measurements to date of the bulk composition of the atmosphere provide surprising results that challenge our expectations of the atmospheric structure; an adequate explanation of these results requires accurate in situ investigations and measurements of the relative nitrogen and carbon dioxide abundances throughout the accessible atmosphere (surface to 70 km). 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, and to 3.41% (± 0.01) at 21.6 km altitude (Figure 3.3). This result contradicts the expectation that the atmosphere is well mixed, and therefore, constant with altitude in the lower thermosphere and troposphere. Inferences of CO_2 concentrations obtained by Pioneer Venus show that the CO_2 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 well-mixed atmospheric state. At this stage, we must resolve whether the inferred results represent a real variation in the vertical profiles or if the use of the hydrostatic law to infer the thermal structure is creating an implicit and artificial bias (e.g., could the gases be behaving as supercritical 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 AP be added to the mission architecture, with the proper design, such a vehicle could provide critical measurements on the bulk atmosphere state between 50 and 60 km altitude or perhaps higher altitudes (see Section 8).

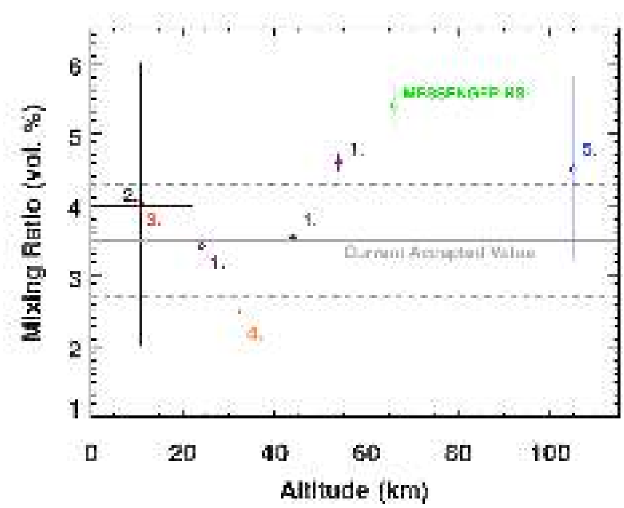


Figure 3.3.—Peplowski and Lawrence (2016) present this figure comparing the MErcury Surface, Space ENvironment, GEochemistry and Ranging (MESSENGER) Neutron Spectrometer (NS) (green) results to previous N_2 measurements and the accepted VIRA value, which is an average of all in situ measurements made prior to 1980. The measurements presented for comparison are (1) PVLP Gas Chromatograph, (2) PVLP Mass Spectrometer, (3) Venera 11 and 12 Mass Spectrometer, (4) Venera 12 Gas Chromatograph, and (5) Pioneer Venus Multiprobe Bus Mass Spectrometer (Zahn et al., 1983).

The outstanding composition questions that may be addressed by a thoughtful Venera-D mission design are as follows:

- 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 understanding 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, and H_2S) are needed down to the surface to constrain the oxidation state of the lower atmosphere and surface and determine the stability of various minerals (Bezard and de Bergh, 2007).

Several of these profiles may only be obtained by utilizing instrumentation on the descent lander. Optimization of the sampling rates and vertical resolution of the lander instrumentation will be a Phase III activity.

3.1.1.4 Clouds

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

For detailed characterization of the thermal balance, it is necessary to know cloud structure, composition, and microphysics. The required 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 impact 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 yr 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), PVLP (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.

Venus' clouds have a vertical depth of ~20 km ($\tau \sim 20$ to 40). There are three separate layers of clouds (Figure 3.2) with each layer showing its own peculiarity. The size of the cloud particles is distributed in three modes: the Mode 1 particle radius, r, is 0.2 to 0.3 µm, these particles exist from 30 to 90 km; 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). Surprisingly, the upper clouds are diffuse with an upper boundary from 68 to 72 km and a scale height of 4 km at low and middle latitudes (composed of Mode 2 and 1 particles); and the altitude of the upper boundary of clouds decreases poleward of ~60° from 60 to 62 km (Mode 3 particles). Variations in local time show tidal behavior (Zasova et al., 2006, 2007). In general, the clouds are composed of sulfuric acid aerosols, but other species may be 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 indicates that the low clouds are condensing. Other aerosol and/or particle species may also be present. For example, in the low cloud layer, the VEGA-2 lander found sulfur, phosphorus, and chlorine particles (Surkov et al., 1987).

The outstanding cloud microphysics issues that may be addressed by a deliberate Venera-D mission design are

- Rigorous identification of the composition of the Mode 1 and 3 particles.
- Robust 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 lander)?
- Characterization of the vertical structure (as measured by a lander during descent) and horizontal structure (as observed by an orbiter) of the clouds, their local time variations, and solar-related structure.
- Insight regarding the influence of the surface-atmosphere interaction on the cloud formation/dissipation and cloud circulation.

3.1.1.5 Cloud Contrasts and Dynamics Tracers

The Role of the Absorbers of solar radiation and NIR opacity sources in Venus clouds. Venus' disk in reflected light is practically featureless in the VIS and NIR spectral ranges (contrasts maximum of 2 to 3%), but in the UV they reach or exceed 30% at 365 nm (Figure 3.4). The albedo of Venus decreases from a value of ~0.8 at wavelengths >550 nm to as low as 0.3 at UV wavelengths. The cloud contrast peaks at 365 nm. UV contrasts observable between 0.33 μm and 0.5 μm are the result of absorption produced by a species of unknown origin. UV-absorption at 0.32 to 0.5 μm was observed to disappear below 58 to 60 km by the Pioneer Venus probes (Tomasko et al., 1985). Thus, absorption by Venus' UV absorbing species has primarily been associated with the upper clouds. However, the VEGA lander measurements taken during descent show that the absorption of UV radiation (220 to 400 nm) occurs down to 47 km altitude, indicating presence of absorbers whose identities are still unknown (Bertaux et al., 1996). Spatial variations in this absorption create contrasts in day side images and are a means of inferring bulk motions in the cloud top atmosphere. Measurements of small-scale feature motions over latitudes and longitudes yield information about the superrotation of Venus' atmosphere at the level of the cloud contrasts. The UV absorption of incident sunlight is responsible for ~50% of the total energy deposition from the Sun into Venus atmosphere (Crisp, 1986). The local time variation of this absorption results in the generation of the thermal tides and is one of the processes that drive the superrotation (Gierasch et al., 1997). At $\lambda < 0.32$ µm (Figure 3.4, bottom left), the main absorbers are SO_2 and SO and absorption from these species occurs in the clouds and below (Bertaux et al., 1996)—however, contributions from an additional unidentified continuum absorber are also present at these wavelengths (Marq et al., 2011; Jessup et al., 2019).

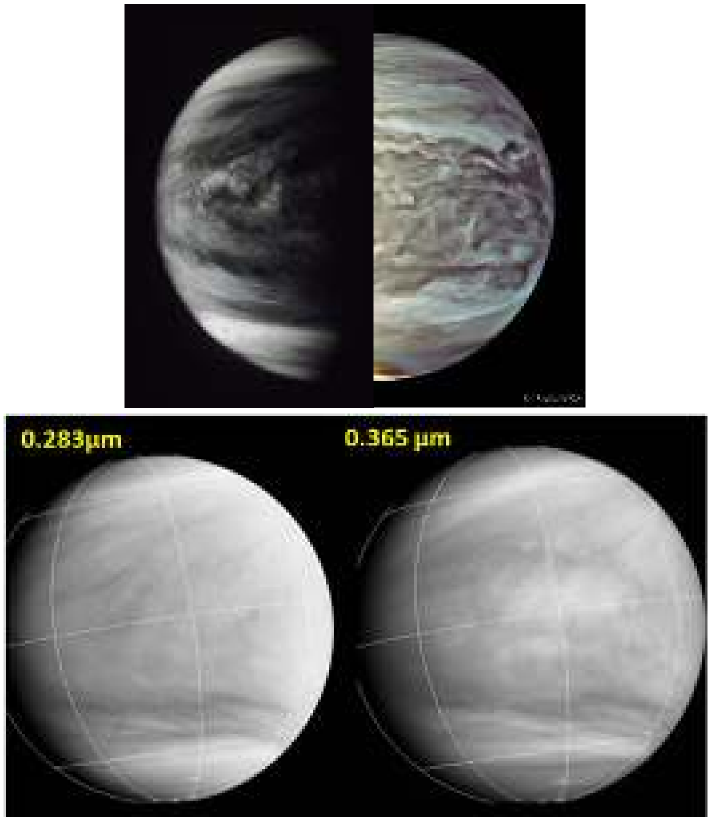


Figure 3.4.—Top: Venus' day side at 0.380 µm (left, NASA), composite of Akatsuki image of Venus' night side at 1.74, 2.26, and 2.4 µm (right, JAXA). Bottom: images of Venus in reflected sunlight shown at 0.283 µm and 0.365 µm. (Limaye et al., 2018a.)

Both the vertical distribution and the composition of the UV-absorbing species are poorly known. The few available profiles of Venus' UV flux obtained between the cloud top and surface indicate that the UV absorber is present in the middle and upper clouds (between ~ 47 to 72 ±2 km) but may at times be found in the upper haze (~70 and 80 km) (Lee et al., 2015). It is currently unclear whether the cloud level abundance of the absorber is a result solely of material upwelled from below, or if it is dependent on the chemical reactions of upwelling and downwelling species. Currently, the strongest candidates for the composition of the 'unknown UV absorber(s)' are allotropes of sulfur (Carlson et al., 2016) and an aerosol composed of ~1% $FeCl_3$ in sulfuric acid (Zasova et al., 1981; Krasnpolsky, 2006). Both species are able to replicate most aspects of the disk-integrated UV Venus spectrum (0.32 to 0.50 µm); however, recent spatially resolved data show that absorption exists above 0.5 µm (Jessup et al., 2017). More study is needed to determine if this behavior can be replicated by either of these species or if more than one species is responsible for Venus' unknown absorption at VIS wavelengths. Additionally, more data are needed to confirm or refute if the expected chemical properties and/or vertical profiles of either species are consistent with other known Venus atmosphere characteristics (Jessup et al., 2018). For example, Zasova et al. (1981) pointed out that the lifetime of a solution of $FeCl_3$ in H_2SO_4 is ~2 weeks at room temperature (approximately the 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 the photochemically calculated sulfur abundance at the cloud tops is insufficient to match the observed unknown absorber profiles and that a $FeCl_3$-based aerosol is the more likely absorbing species.

There may be other possible sources of the UV contrasts (Jessup et al., 2018; Limaye et al., 2018a; Perez-Hoyos et al., 2018). Recent information about the 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 the possibility of a biogenic origin for the UV absorber (Limaye et al., 2018a).

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 (Jessup et al., 2018).

The Role of NIR Imaging. Night side IR imaging of Venus' disk between 1 to 3 µm (Figure 3.4) reveals contrasts (~2 to 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 presumed level from which the 1 µm NIR radiation originates (Khatuntsev et al., 2017). The origin of the contrasts is not certain and they may be related to variations in cloud opacity. These NIR contrasts do not correlate with those observed in UV images on the day side.

CO_2 spectral winds at NIR wavelengths (1, 1.18, 1.74, and 2.3 µm) allow Venus' lower altitude cloud levels to be sensed. Contrast created from the cloud opacity variations allow for the winds at lower altitude to be calculated, where the highest contrasts are detected in the 2.3-µm window. Long-term observations of these properties, that may be obtained from an AP, 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 UV and VIS wavelength ranges.

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' dynamics tracers are

- What are the spectral absorbers (e.g., organic, inorganic, aerosol, gas?) and what controls their distribution?

- Why are these absorbers observed to occur in patches, causing 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 and aerosol properties of Venus' atmosphere at the altitude level where the UV absorber is anticipated to be present. 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 UV and VIS wavelength ranges.

3.1.1.6 Solar Wind-Venus Interaction and Venus Magnetosphere

As Venus does not have an intrinsic magnetic field, the solar wind interacts directly with Venus' atmosphere (Figure 3.5). 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 primarily 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, heavy-ions mass loss is an important process in Venus' atmospheric loss.

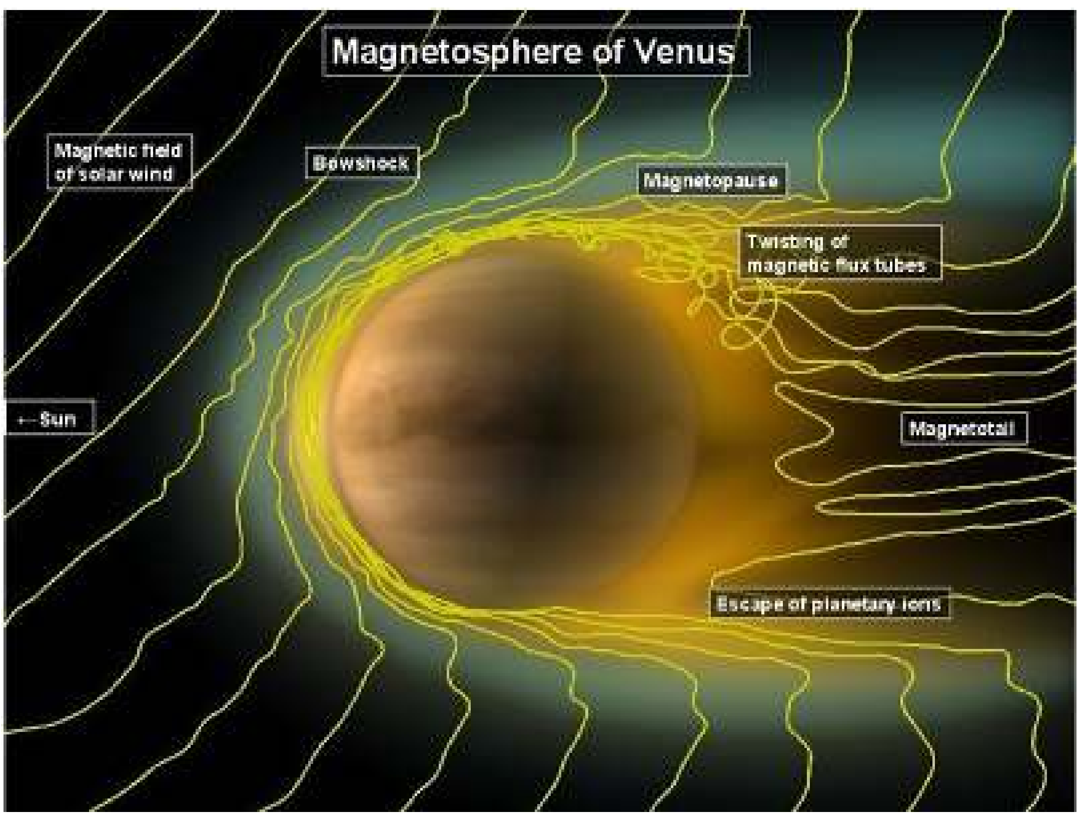


Figure 3.5.—Artist's impression showing how the solar wind shapes the magnetospheres of Venus. (Used with permission from Max Planck Institute).

The solar wind and the interplanetary magnetic field contribute to the structure of the magnetosphere that consists of a thin magneto-plasma layer between the shocked plasma flow and ionosphere and the long ion and plasma tail (Figure 3.5). As the solar wind and interplanetary magnetic field are variable on a time scale ranging from several to tens of minutes, which is the same order of magnetospheric regions formation, the properties of the magnetosphere and the moment transmitted to the ionosphere are variable. Thus, the heavy planetary ions' escape is also variable. Other time-variable factors that play an important role in controlling the properties of the outer envelope of the planet are so-called catastrophic events: interplanetary shocks, coronal mass ejections (CMEs), and co-rotation interaction regions (CIRs) between fast and slow solar wind streams.

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 subsequent 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, VEX also performed investigations of the solar wind interaction with Venus (Barabash et al., 2007; Futaana et al., 2017). The discovery of the comet-like planetary plasma interaction and processes leading to atmospheric losses allowed us to estimate how these losses vary with solar and interplanetary conditions and their potential for producing significant changes to the chemical composition of the Venusian atmosphere over time. In spite of significant progress achieved by previous Venus missions, there are outstanding problems in the study of the solar wind-Venus interaction and Venus escape processes over recent and millennial time scales. They include

- What is the escape rate of hydrogen versus deuterium? What does it tell us about the history of water on Venus? Did Venus have an ocean that escaped to space?
- What is the fate of the primordial nitrogen in the Venus atmosphere? How much escaped to space?
- What are the responses of the Venus solar wind interaction to solar and interplanetary events (e.g., flares, CMEs, solar energetic particles)? How did Venus interact with the solar wind during epochs of the more active early Sun, and what are the long-term consequences?
- What are the absolute (total) planetary ion escape fluxes and compositions over the range of present-day solar extreme ultraviolet radiation (EUV) and solar wind conditions?
- How does the induced magnetosphere of Venus respond to the variable solar wind, interplanetary shocks, CMEs, and interplanetary field sector boundary crossings?
- How are ionospheric dynamics driven by the solar wind? How are they coupled? How do they influence escape?
- To what extent do solar wind ions precipitate and accumulate in the atmosphere?
- What processes comprise the complex web of competing escape channels (e.g., upper atmosphere and ionosphere pickup, ionosphere scavenging or erosion in the form of ionospheric clouds and streamers, ambipolar electric fields, current/plasma sheets)? What

factors (e.g., solar wind, magnetic, plasma wave conditions) determine which escape process dominates at a given time? How do these processes interact?
- What is the role of plasma waves in the acceleration, heating, and escape of planetary ions?
- How does ion-neutral coupling affect the electrodynamics of the induced magnetosphere?
- What role does friction between the ionosphere and thermosphere play in atmospheric superrotation?
- How does reconnection operate in the induced magnetosphere tail and how much does it contribute to ion escape?

To resolve these problems, the following measurements or investigations must be completed under varying solar wind, magnetosphere, and solar activity conditions among different regions of Venusian magnetosphere.

- Determination of the mass-composition of planetary ion outflow, besides H+, He+, O+, and its variations under changing conditions and in different regions of Venusian magnetosphere.
- 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 to understand the origin of this boundary.
- Investigation of mass-loading processes at an atmospheric obstacle (here, Venus), determination of loss rate, and influence of strong solar wind disturbances.
- Estimation of critical factors that control atmospheric escape to estimate the evolution of atmosphere in millennia.
- Investigation of acceleration processes for current layers.

This list of measurements and investigations emphasizes that an important next step in Venus magnetospheric and exospheric studies as well as Venus' long-term atmospheric evolution modeling is an improved understanding of the impact of external, time-variable events on Venus' upper atmospheric conditions and solar wind interaction. This requires that two-point measurements are made to trace the near-Venus environment while the upstream solar wind conditions are monitored. Investigation of the Venusian environment and solar forcing with comprehensive, high temporal resolution plasma instrumentation on the Venera-D main orbiter and a small subsatellite can achieve this requirement, thereby providing the first detailed picture of the true time-dependent structure and properties of the solar wind interaction with Venus' induced magnetosphere and related ion escape. With the two-point measurement capability, open questions related to Venus' exosphere, magnetosphere, and ionosphere evolution may be answered. In addition, questions related to the evolution of the bulk atmosphere and the time scale at which Venus' cloud-top albedo evolves, the relationship of this evolution to the solar cycle, and the impact that Venus' evolving cloud top albedo may have on Venus' overall climate could be addressed. This information informs our understanding of Venus' possible habitability through time. Achieving these advances requires that the 3D structure of the solar wind interaction is continuously monitored over the lifetime of the Venera-D mission (see Section 8).

3.1.2 Measurements Needed to Understand the Dynamics, Structure, and Composition of the Venus Atmosphere and Magnetosphere

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, and 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 small long-lived surface station(s) combined with a supplemental AP. 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 the lander, orbiter, atmospheric platform, and long-lived station(s) 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 atmospheric composition, including 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 (obtaining vertical profiles), and AP (collecting 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 to 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 will also 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 AP with the capability to map both the vertical and horizontal distribution of the aerosol and UV absorber species from the orbiter.

(7) Measurements of the magnetic field, ion, and electron characteristics, including the temperature, velocity, composition, and density of energetic ions and electrons and the characteristics of the plasma wave phenomena at high temporal cadence over long time periods. The outstanding problems in the study of the solar wind-Venus interaction and mass losses will be best solved by the plasma instrument suite located on the orbiter, working in concert with a small satellite strategically positioned to map upstream solar wind conditions and sampling of the down-tail region at distances of 0.5 and 3 to 5 Venus radii. It is critical that the observing platforms are outfitted with state-of-the-art UV and neutral analyzers (see Section 8).

Previous missions have provided significant insight into many aspects of Venus atmospheric studies. The new knowledge that has been gained from these missions defines the next Venus atmospheric investigations. Venera-D's baseline mission, consisting of an orbiter and a lander, could fulfill these investigations. Specifically, instruments on the orbiter would have higher spatial and spectral resolution as well as greater mapping capability at UV and IR wavelengths than those previously flown. The orbiter would have instruments able 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 remotely, in situ, and on the surface over a long time (months). The single-trajectory measurements that would be obtained from the lander during descent will 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 demonstrated the possibilities and importance of long-duration measurements in the atmosphere, particularly within the cloud layer. The JSDT considered different types of APs and found that the vertically variable balloon offers the most science for the least cost (in volume, mass, and energy). With the appropriate payload, a mobile AP could potentially acquire crucial observations of the atmospheric structure, circulation, radiation, composition (along with cloud particles and aerosols), and the unknown UV absorber(s). However, detailed study of the long-term survivability of the aerial vehicle envelope material in the Venusian atmosphere is needed as well as a detailed study of the allowable payload mass versus achievable operational altitude (see Section 8).

Another set of important measurements that will have a significant impact on our understanding of the superrotation are long-term meteorological measurements on the surface. One set of these measurements will be obtained from the proposed small long-lived station (LLISSE) included in the baseline mission architecture. This station will provide sporadic monitoring of meteorological parameters at the surface over three months, possibly identifying the origin of gravity waves, which have been evident in the atmosphere over a broad altitude range extending up to at least 90 km. Multiple stations (which would be an augmentation to the baseline architecture) could provide enhanced surface coverage by extending the capability of the Venera-D mission to several points (observing possibly two LSTs and/or latitudes simultaneously). This would improve our understanding of the impact of local topography, solar time, and meridional transport processes on the superrotation mechanism.

3.2 Updates to Venera-D Surface Science Goals and Objectives

3.2.1 Venus Surface Geology

The strong greenhouse effect on Venus limits the range of possible geological processes operating on this planet. The surface temperature, ~470 °C, and apparently low-temperature and pressure gradients in the lower atmosphere cause the hyperdry, 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. Although rare, dunes have been observed on the Venusian surface (Weitz et al., 1994); thus, only three geological processes currently dominate on the planet: volcanism, tectonism, and impact cratering.

There are <1000 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 (Phillips et al., 1992; Schaber et al., 1992; McKinnon et al., 1997)), and (2) the contribution of impact craters to global resurfacing is minor. Thus, volcanism and tectonism remain the principal geological processes during the observable geologic history of Venus (Figure 3.6).

Regardless of their volcanic or tectonic nature, there are two classes of Venusian landforms: simple and complex. The morphologically homogeneous terrains represent the simple landforms; their homogeneity suggests that they formed under the dominance of a specific process. Examples of the simple terrains are lava plains with a specific morphology or graben swarms. When the simple terrains are tied by common evolution and aggregated, they produce complex terrains. Coronae represent classic examples of the complex terrains.

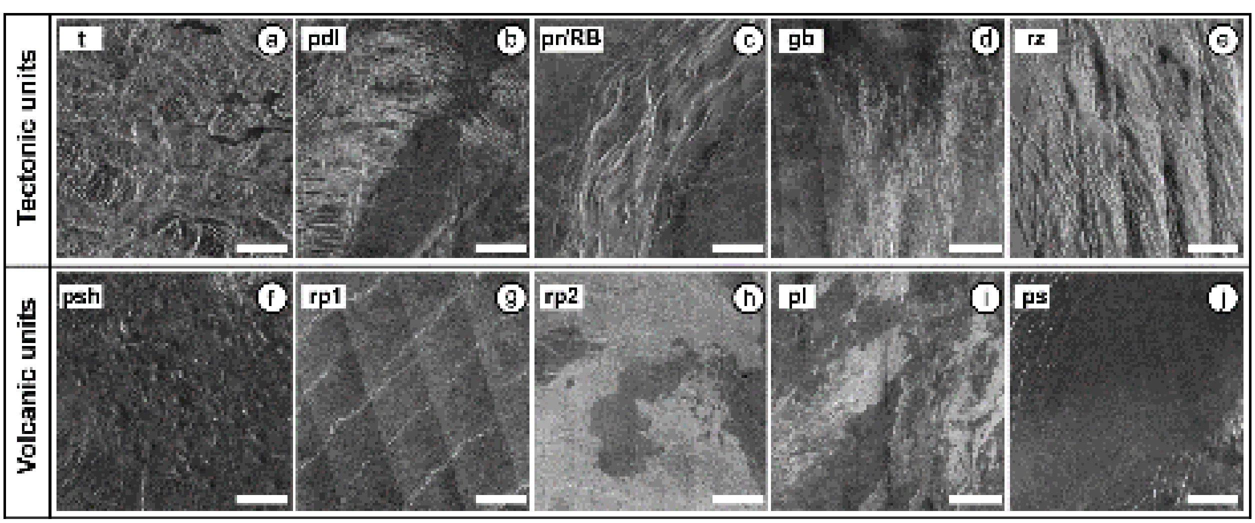


Figure 3.6.—The major tectonic and volcanic units that make up the surface of Venus. Each scale bar is 25 km. North is at the top of all images.

Simple terrains constitute morphologically homogeneous units that establish the basis or interpret the geologic histories of planets (Wilhelms, 1990). Inspection and comparison of units mapped by many geologists on Venus has 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 a global geological map of the planet that shows the distribution of units in space and time. Because the morphologically and stratigraphically 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 resurfacing regimes: (1) the global tectonic regime, (2) the global volcanic regime, and (3) network rifting-volcanism regime (Figure 3.7) (Ivanov and Head, 2015).

The Global Tectonic Regime. Tectonic resurfacing dominated during the earlier stages of the observable geologic history of Venus and resulted in the formation of strongly tectonized terrains (Figure 3.6) 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 3.1). The apparent beginning of the global tectonic regime is related to the formation of t, which is among the oldest material unit on the planet and may represent the only "window" into Venus' deep geologic past. The age relationships of tectonic structures within t indicate that this terrain is the result of crustal shortening and may be a mosaic of crustal blocks (Senske, 2010). This crustal shortening suggests that the global tectonic style during the t 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 t. Densely lineated and ridged plains are partly overlapping in time with t. 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 3.7).

The Global Volcanic Regime. Volcanism overwhelmed tectonic activity during the global volcanic regime and caused formation of vast volcanic plains subsequently deformed by tectonic structures (Figure 3.6). Three types of plains are observed (Figure 3.7): (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 3.1) and show a clear stratigraphic sequence from the older psh to the younger upper unit of regional plains (Ivanov and Head, 2004). The distinct morphologies of the plains (Figure 3.6) reflect the different volcanic styles of their formation. Shield plains (psh) contain numerous small (<20-km-basal diameter) volcanic constructs that were the sources of the plains material. In contrast, the lower unit of regional plains shows no evidence for volcanic sources and the style of its formation resembles terrestrial or lunar flood basalts.

The upper unit of regional plains formed by the emplacement of individual extensive lava flows commonly erupted from large (>100 km basal diameter) 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 third of the visible geologic history of Venus. During this time, ~80 to 85% of the surface of the planet was resurfaced.

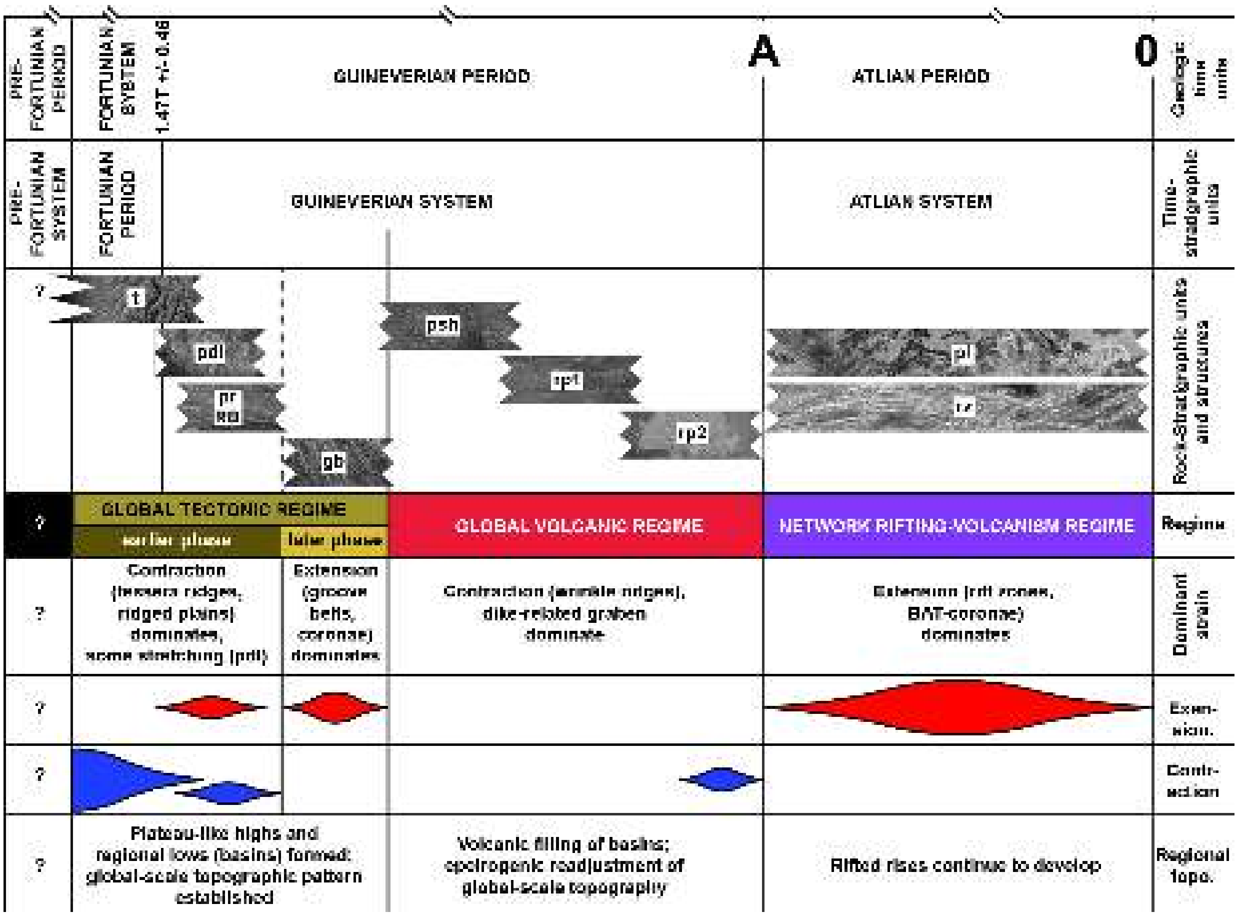


Figure 3.7.—Regimes of resurfacing that operated throughout the visible portion of the geologic history of Venus. A marks the current mean age of the surface (based on the density of all impact craters; ~750 Ma); 0 is the present time). BAT is Beta-Alta-Themis.

Table 3.1.—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 3.7). Three units represent the major components of the regime (Figure 3.6): lobate plains (pl), rift zones (rz), and smooth plains (ps). These units are broadly synchronous with each other and units of volcanic nature (pl and ps) are about twice as abundant (Table 3.1) as unit rz, as determined by surface area. Although the volcano-tectonic regime characterized ~2/3 of the visible geologic history of Venus, only 15 to 20% of the surface was rejuvenated during this time. This means that the level of endogenous activity during the volcano-tectonic regime (Figure 3.7) dropped by about an order of magnitude compared with the earlier regimes.

3.2.1.1 Open Surface Science Questions and the Venera-D Concept

Despite the detailed view of the surface provided by the Magellan and Venera data, questions remain 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 (mb) of Ishtar Terra, which rise up to 11 km above the mean planetary radius? Are 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 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 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, 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 (Solomon et al., 1999; Phillips et al., 2001) that records of climate change 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 and terrains; obtaining this information for the Venusian tessera would provide insight into the oldest exposed rocks. These data 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 evolved, silica-rich volcanic deposits?

3.2.1.3 Science Rationale for Landing Site Selection

Although the results from the Venera landers indicate that the surfaces that they sampled are primarily basaltic in composition, there is morphologic evidence suggesting that a range of rock compositions may be present. Rock types reflect their geologic and tectonic settings. 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 the following:

Tessera (t) (e.g., Alpha Regio)—It has been suggested that some occurrences of t may be composed of low-density, continental-like crust. To investigate this hypothesis, geochemical sampling and optical imaging of a region of t 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 be representative of Venus, morphologic evidence hints at the presence of more exotic compositions such as carbonatites (Kargel et al., 1994). It has also been suggested that broad homogeneous lava flow fields may be analogous to terrestrial flood-basalt or plains-style volcanism. 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 common and typical surface materials, it would be useful to investigate the chemistry of the rocks that may represent a large part of the Venus crust.

3.2.1.4 Landing Site Assessment

For the selection of landing sites for the Venera-D mission, we used a set of criteria that account for (1) potential landing safety of specific terrains, (2) representativeness of materials at the landing site, (3) potential simplicity and quality of geochemical signal at the landing site, and (4) orbital restrictions of the mission.

3.2.1.4.1 Safety of Terrains on Venus

Mission safety is the most important constraint for landing site selection. We used this criterion to isolate of areas where safe landing is not possible based on either obviously or apparently enhanced roughness of the surface. Comprehensive morphologic analysis of Magellan SAR images revealed that the surface of Venus is composed of a relatively small number of terrain types (units) (Basilevsky and Head, 1995, 1998; Johnson et al., 1999; Chapman, 1999; Bender et al., 2000; McGill, 2000; Rosenberg and McGill, 2001; Campbell and Campbell, 2002; Bridges and McGill, 2002; Stofan and Gest, 2003; McGill, 2004; Campbell and Clark, 2006; Copp and Gest, 2007; Grosfils et al., 2011; Ivanov and Head, 2011, 2013, 2015). They can be divided into three categories: (1) tectonized terrains, (2) volcanic terrains, and (3) impact-related materials.

Tectonized terrains include t, pdl, pr/RB, circum-Lakshmi mb, gb, and rz. The characteristic feature of these units is the presence of sets of numerous tectonic structures that strongly deform the original, likely volcanic, materials of the precursor terrain.

Tessera (t, Figure 3.8a) is one of the most tectonically deformed types of terrain on Venus and occupies about 8% of its surface (Table 3.2). Tessera (t) massifs vary in size from a few tens up to a few thousands of kilometers (Ivanov and Head, 1996). At least two sets of intersecting contractional (ridges) and extensional (graben, fractures, scarps) structures characterize the surface of t.

Densely lineated plains (pdl, Figure 3.8b) are characterized by densely packed linear and curvilinear lineaments (Figure 3.8b). The lineaments (fractures) are narrow (few hundred meters wide), short (a few tens of kilometers long), and parallel or subparallel. The tectonic structures of pdl almost completely erase the original morphologic characteristics of the underlying materials (Figure 3.8b). The total area of pdl is small (~2% of the surface of Venus, Table 3.2).

Ridged plains/ridge belts (pr/RB, Figure 3.8c) are linear and curvilinear ridges (5 to 10 km wide, several tens of kilometers long) that dominate the surface of ridged plains (Figure 3.8c). A characteristic feature of ridged plains is that their ridges are commonly collected into prominent ridge belts. Ridged plains and ridge belts occupy about 2.2% of Venus' surface (Table 3.2).

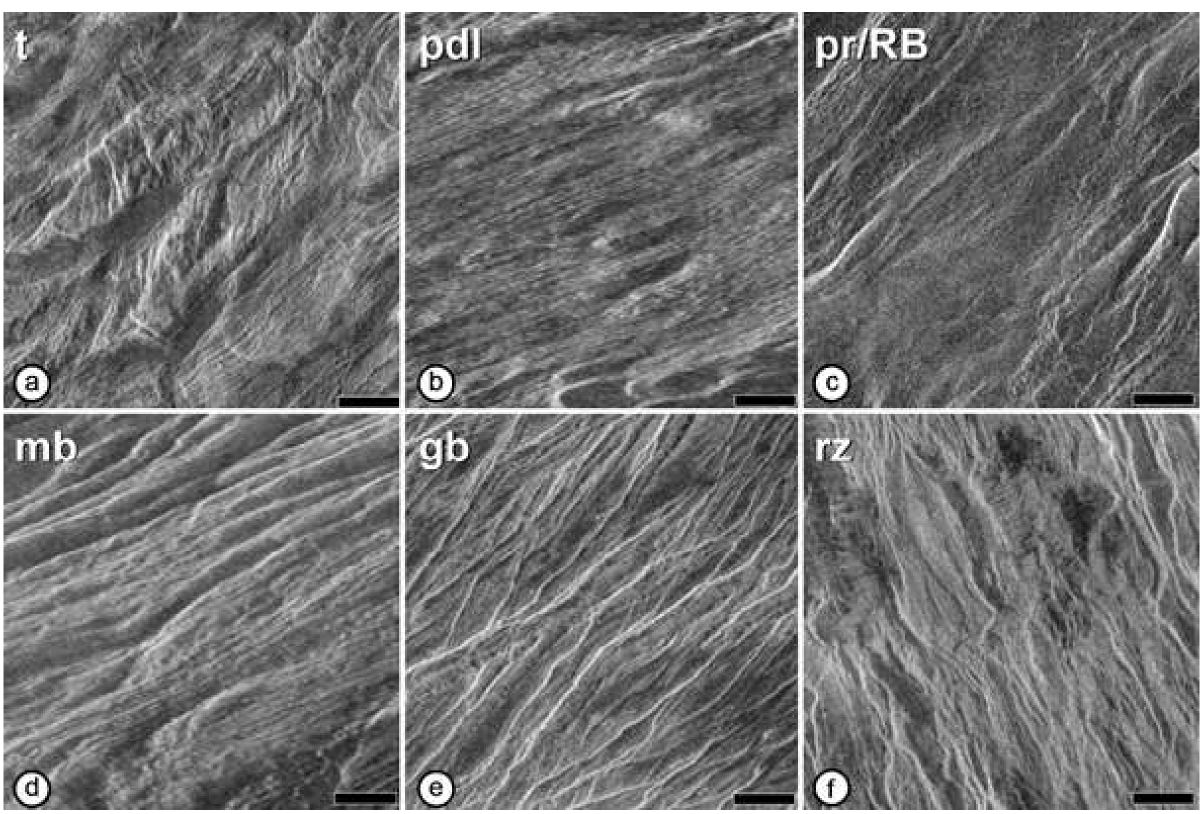


Figure 3.8.—Examples of tectonized terrain on Venus. Each scale bar is 10 km. North is at the top of all images. The dominant feature of ridged plains is that their ridges are commonly collected into ridge belts.

Table 3.2.—Area of Units Mapped on the Global Geological Map

Unit	Area, 10^6 km^2	Percent of the Surface of Venus
t	33.2	7.3
pdl	7.2	1.6
pr/RB	9.6	2.1
mt	1.3	0.3
gb	37.1	8.1
psh	79.3	17.4
rp1	141.8	31.1
rp2	42.0	9.2
sc	3.3	0.7
rz	22.6	5.0
ps (v+i)[a]	10.3	2.3
pl	37.8	8.3
Craters	2.6	0.6
Gaps	28.1	6.2

[a]i is impact and v is volcanic.

Mountain belts (mb, Figure 3.8d) surround Lakshmi Planum represent the only real mountain ranges on Venus that are 6 to 12 km high; they make up a negligible portion of the surface of Venus (~0.3%, Table 3.2).

Groove belts (gb, Figure 3.8e) are defined as zones of densely packed extensional structures (fractures and graben). The typical widths of these structures are several hundred meters and up to 1 to 2 km, and individual fractures can reach several tens of kilometers in length. Groove belts occupy ~8.7% of the surface of Venus (Table 3.2) and occur as zones of many hundreds (up to a few thousands) of kilometers long and tens to a few hundred kilometers wide.

Rift zones (rz Figure 3.8f) as well as groove belts represent a structural unit that consists of numerous and densely packed fractures and graben. In many rz, there are deep (several kilometers), steep-sided canyons or valleys that can be several tens of kilometers wide. In contrast to groove belts, structures of rz on average are broader, longer, and somewhat less densely packed than structures of groove belts. Rift zones (rz) occupy ~5.0% of the surface of Venus (Table 3.2) and preferentially occur within the equatorial region where they are associated with large highlands, such as eastern Aphrodite, and outline the BAT region.

Although both contractional and extensional structures deform the surface of t (Hansen and Willis, 1996; Ivanov and Head, 1996), the youngest and most prominent feature of this terrain are fractures and graben (Ivanov and Head, 1996, 2015). Individual and multiple steep scarps up to several hundred meters high represent walls of these structures. The characteristic width of t extensional structures varies from hundreds of meters up to a few tens of kilometers and they separate fragments of the pre-existing terrain with relatively flat and subhorizontal or gently undulating surface. Typical dimensions of these fragments vary from several kilometers up to a few tens of kilometers.

The specific pattern of interlacing of the flat-looking areas and the steep-sided extensional structures in t resemble, both morphologically and in scale, the surface in the interior of Grand Canyon where a safe landing is practically impossible (Figure 3.9). Thus, despite its high scientific importance, t terrain cannot be considered as a potential candidate for a landing site.

Tensional forces dominated the formation of pdl, gb, and rz and resulted in the emplacement of abundant extensional structures. Numerous fractures, graben, and canyons of various width and length on the surface of units pdl, gb, and rz form a specific pattern that resembles the surface of the Canyonlands region in Utah (Figure 3.10). These types of the tectonized terrains of Venus are dangerous for landing (Figure 3.10). Both the morphology and scale of structures that form the circum-Lakshmi mb are similar to those of Earth's high-standing mountain ranges (e.g., the Himalayas) where the chances for safe landing are also small.

The quantitative analysis of the distribution of the short-wavelength (1 to 3 m baseline) slopes in the terrestrial analogs of some tectonized terrains on Venus (t and pdl) shows that the steep slopes (>15°) prevail in these units (Ivanov et al., 2017). Thus, both qualitative and quantitative assessments of the shape of the surface of the majority of the tectonized terrains on Venus (t, pdl, mb, gb, and rz) indicate that these units are inappropriate candidates for landing.

The ridged plains and ridge belts (pr/RB) appear to have a morphologically smooth surface complicated by relatively low (several hundred meters high) hills and ridges with gentle slopes. Morphologically, this type of tectonized terrain of Venus may resemble the mature terrestrial mountain ranges such as Southern Urals (Figure 3.11). From the morphological point of view, the surface of unit pr/RB may provide sites for safe landing.

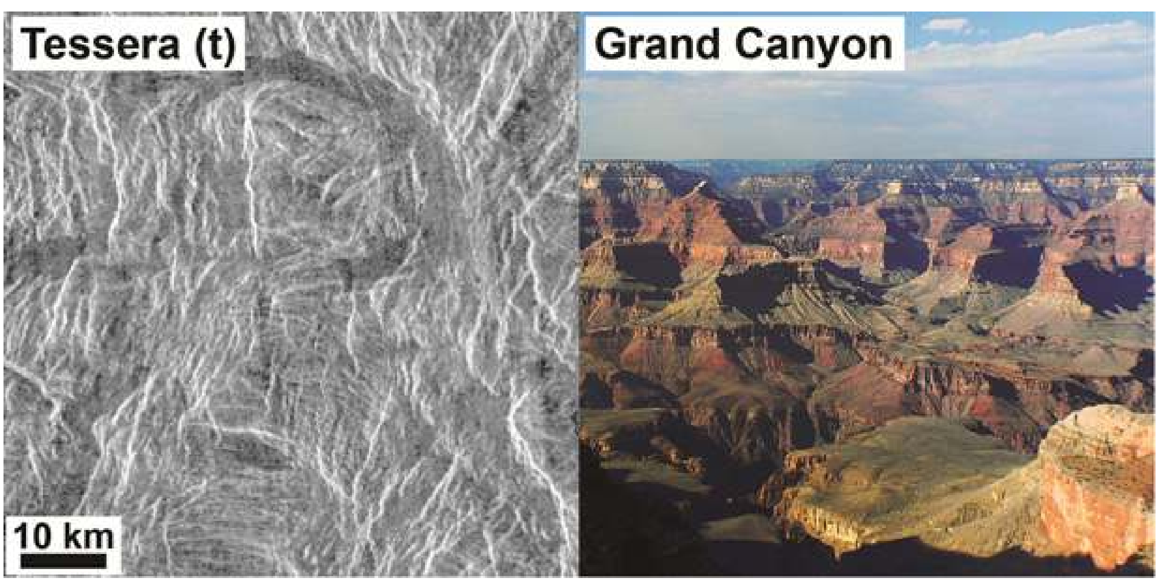


Figure 3.9.—The Grand Canyon may represent a possible terrestrial analogue of t terrain.

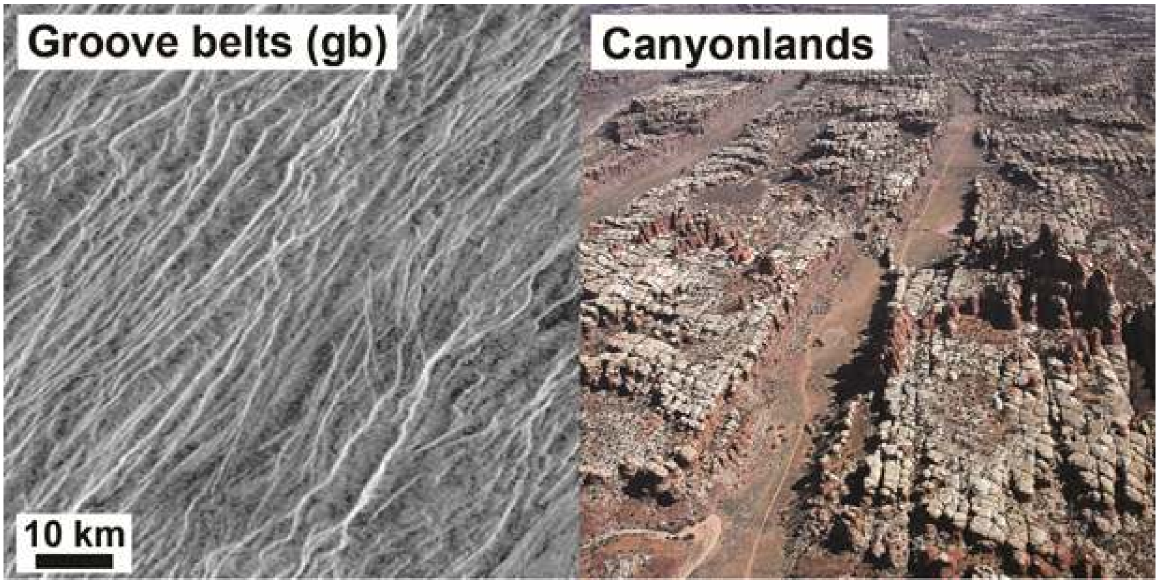


Figure 3.10.—The Canyonlands region may represent a possible terrestrial analogue of pdl, gb, and rz.

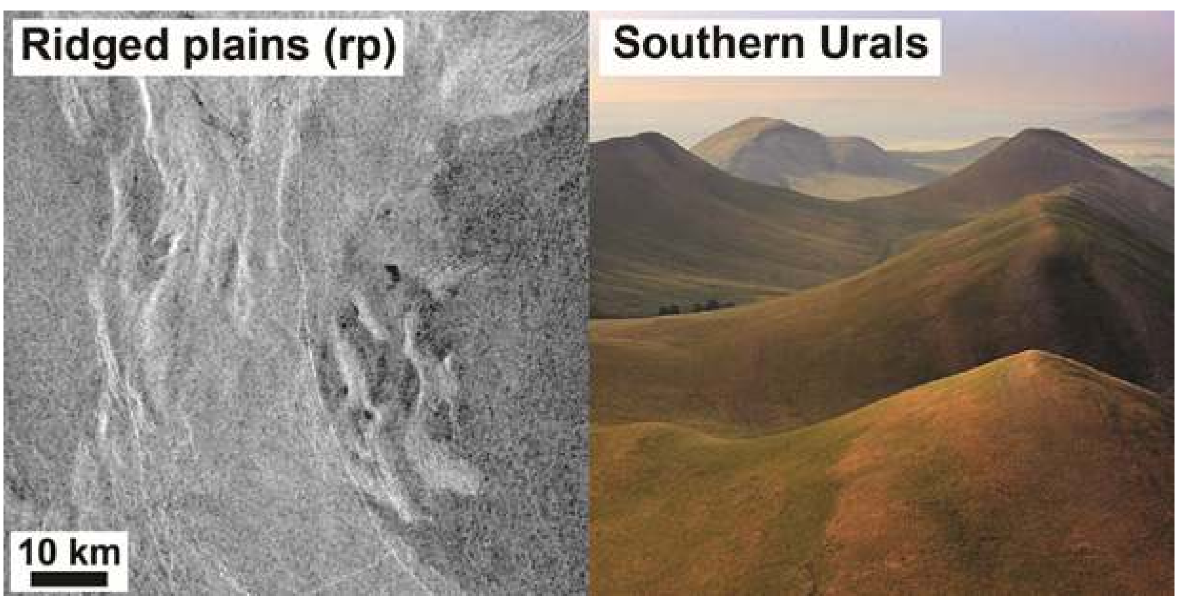


Figure 3.11.—Low mountain ranges (e.g., the southern Urals) may represent a possible terrestrial analogue of pr/RB.

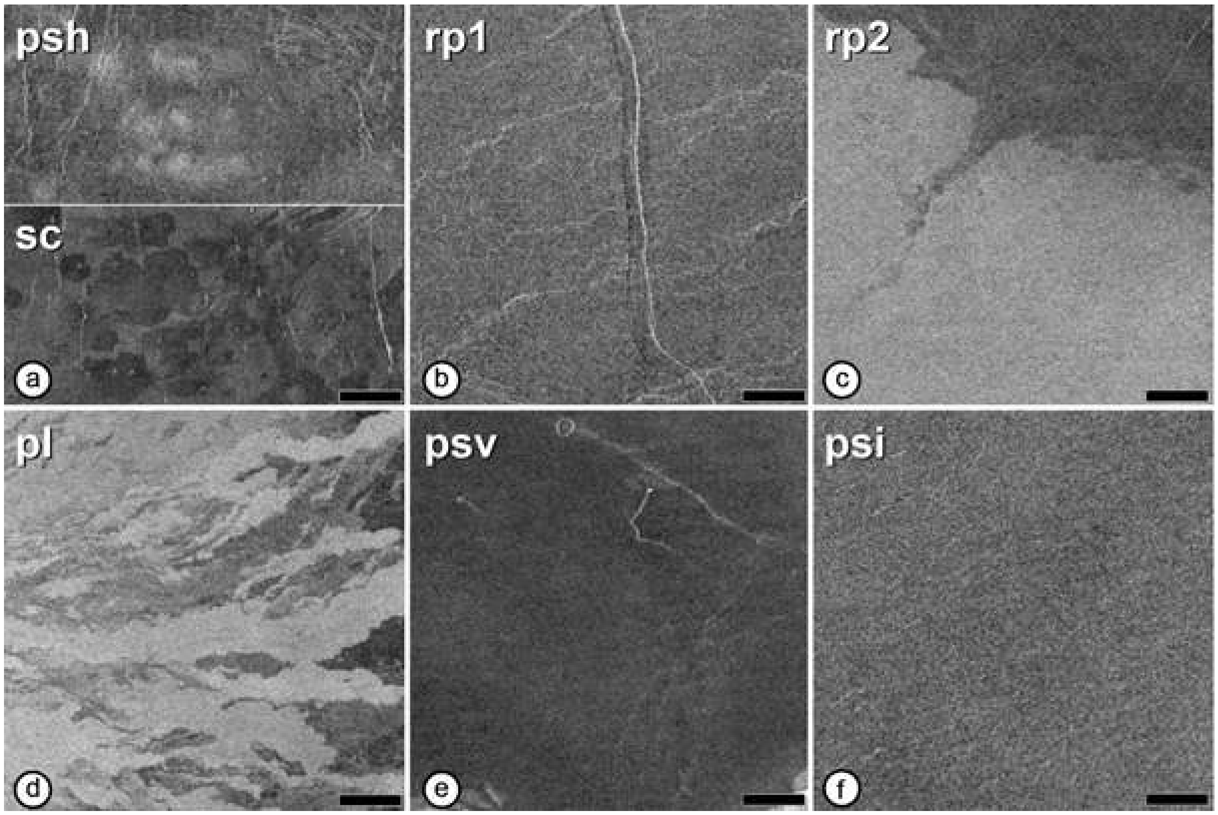


Figure 3.12.—Examples of volcanic units on Venus. Each scale bar is 10 km; north is at the top of all images.

Volcanic terrains on Venus include a variety of lava plains. These plains are as follows:

Shield plains (psh, Figure 3.12a) have a great number of small (from 1 to 2 km up to 10 km) shield- and cone-like mounds that are interpreted as volcanic edifices (Figure 3.8f). The volcanic emplacement of materials played the major role in formation of psh and later tectonic deformation (mostly by wrinkle ridges) was less important. Shield plains (psh) are abundant on Venus and their exposed area comprises ~18.5% of the surface of Venus (Table 3.2).

Regional plains, lower unit (rp1, Figure 3.12b), have a morphologically smooth surface with homogeneous and relatively low radar backscatter. Although the regional networks of wrinkle ridges deform the surface of the unit, the ridges do not obscure its original morphological characteristics. The lower subunit of regional plains (rp1) is the most abundant and ubiquitous unit on Venus. Its exposed occurrences make up ~33.0% of the surface of Venus (Table 3.2) and they can be traced almost continuously around the globe.

Regional plains, upper unit (rp2, Figure 3.12c), are characterized by a morphologically smooth surface that is moderately deformed by the same family of wrinkle ridges that cut the surface of rp1. In contrast to the relatively low radar backscatter of rp1, the backscatter of the upper unit is noticeably higher and the radar pattern is either homogeneous or consists of faint flow-like features. The upper subunit of regional plains (rp2) is less widespread and covers ~9.8% of the surface of Venus (Table 3.2) and its flow-like features superpose the surface of rp1.

Shield clusters (sc, Figure 3.12a)—the surface of this unit is morphologically similar to that of psh. In contrast to psh, however, sc are mostly undeformed tectonically and commonly display small lava flows superimposed on the surrounding regional plains. Shield clusters (sc) cover about 0.7% of the surface of Venus.

Lobate plains (pl, Figure 3.12d) usually have morphologically smooth surfaces that are locally disturbed by few extensional features. The radar backscatter of pl consists of numerous radar bright and dark flow-like features. Lobate plains (pl) occupy ~8.8% of the surface of Venus (Table 3.2).

Smooth plains of volcanic origin (psv, Figure 3.12e) have a morphologically smooth, tectonically undisturbed, and featureless surface. Areas of ps are usually characterized by a low radar backscatter and appear dark on Magellan SAR images. Smooth plains (ps) make up a small portion of the surface, about 2.3% of Venus (Table 3.2).

The significantly smaller abundance of tectonic structures within the volcanic terrains make their surfaces to be more even, without numerous large-scale scarps and slope breaks that complicate the tectonized terrains. However, the surface of the volcanic units can have enhanced small-scale (meter-decameter) roughness, which is reflected by the higher radar backscatter. The higher radar return of a unit indicates the presence of numerous reflecting facets (i.e., large boulders) on its surface (Ford et al., 1993). Among the volcanic units on Venus, rp2 and some lava flows of pl are characterized by the enhanced brightness, and thus may be similar to the terrestrial lava flows with rough surfaces (Figure 3.13). Landing on lava flows of this type would not be safe.

The surfaces of psh, sc, and the lower unit of regional plains (rp1, hereafter, regional plains) are moderately tectonized and their radar backscatter is noticeably lower than that of the upper unit of regional plains and pl. Typical morphology of psh and sc (Figure 3.14a) suggests that they may resemble terrestrial shield fields (Figure 3.14b) and the lower unit of regional plains (Figure 3.14c) appears to resemble vast lava plains on the continents of Earth (Figure 3.14d). The quantitative analysis of the distribution of the short-wavelength (1 to 3 m baseline) slopes in the terrestrial

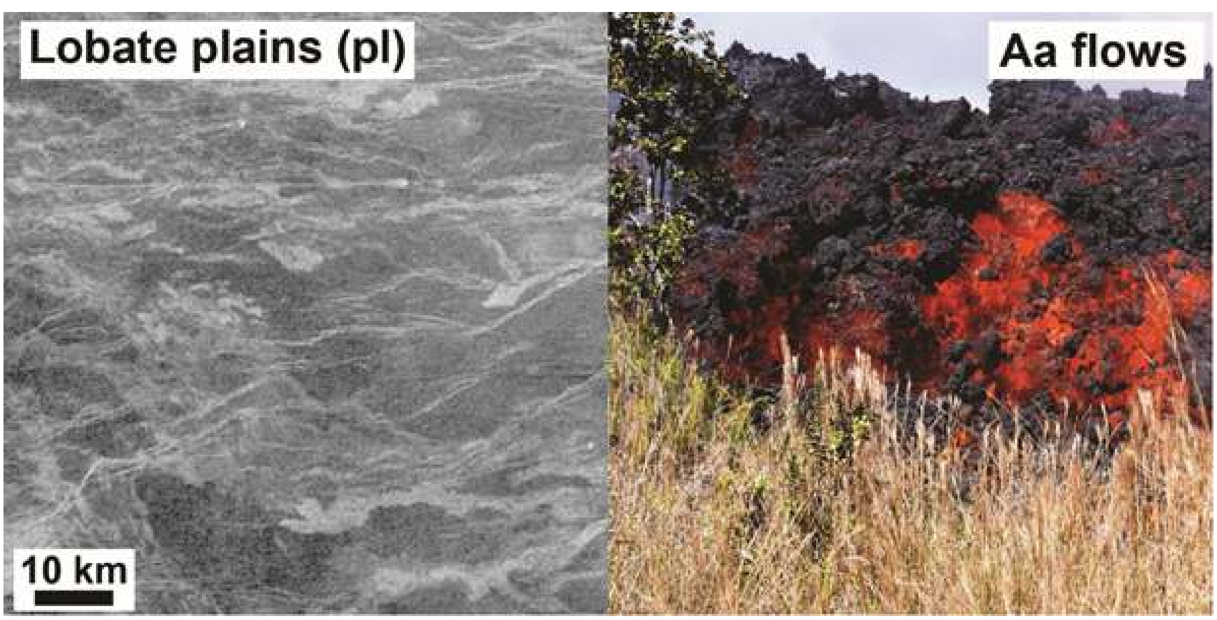


Figure 3.13.—Lava flows of aa-type may represent a possible terrestrial analogue of rp2 and the radar-bright slows of pl.

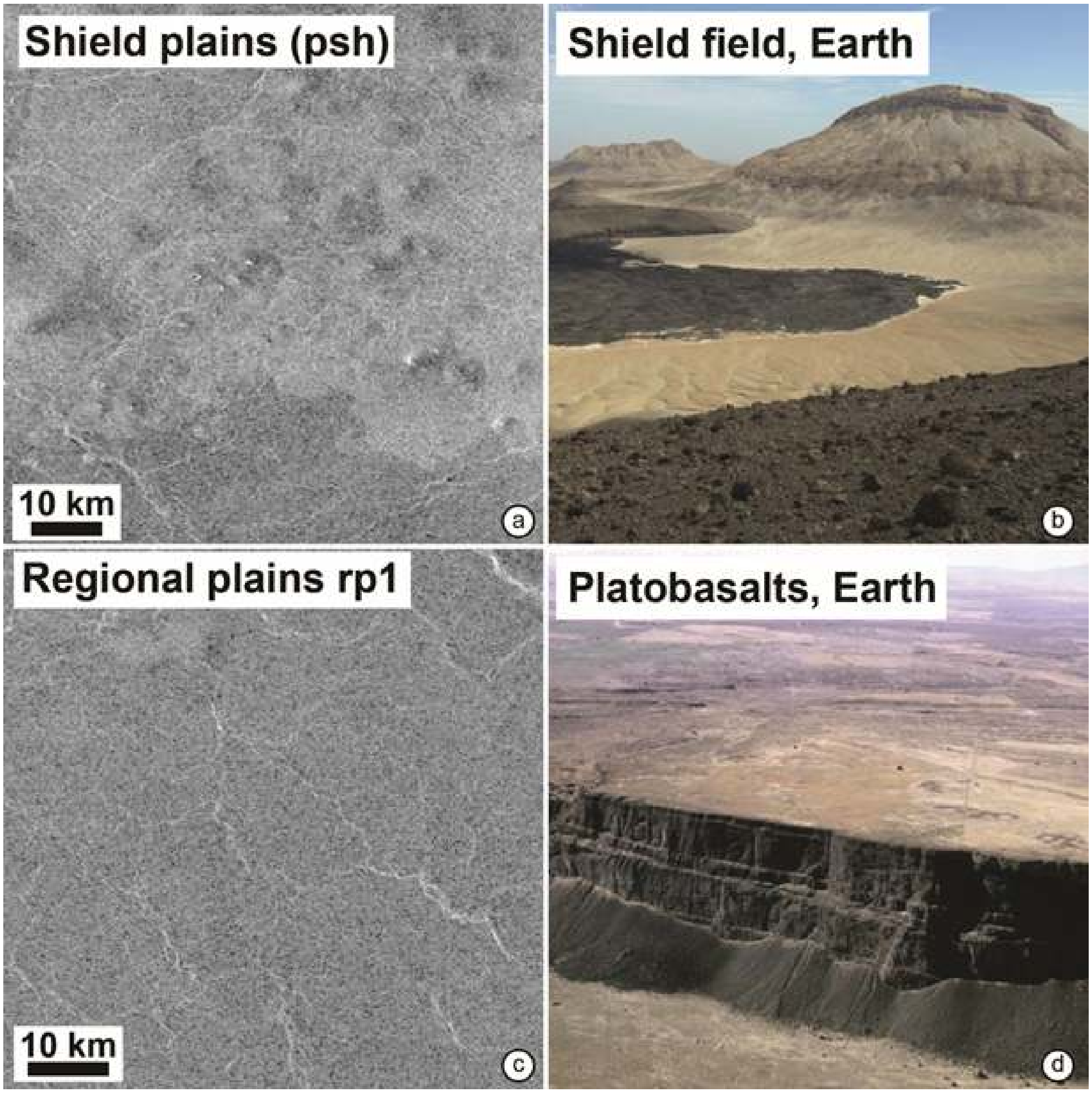


Figure 3.14.—(a) Typical surface of psh on Venus. (b) Possible terrestrial analogue of psh (a shield field, Yemen). (c) Typical surface of rp1 on Venus. (d) Possible terrestrial analogue of regional plains (flood basalts, Columbia River).

analogs of shield and regional plains shows a prevalence of gentle (<7°) slopes (Ivanov et al., 2017). Thus, the volcanic units of regional plains and psh or sc appear to provide safe surfaces for landing. The same holds true for the non-tectonized and radar-dark surfaces of the psv.

The impact-related materials on Venus comprise the floor, walls, and contiguous ejecta of impact craters and extensive radar-dark parabolas (Campbell et al., 1992) and haloes (Izenberg et al., 1994) in association with some craters (Figure 3.12(f)). The usually enhanced radar brightness of the deposits within impact craters and in their contiguous ejecta suggests that these materials are too rough for safe landing. In contrast, the radar-dark parabolas and haloes likely represent deposits of fine-grained materials with flat and smooth surfaces, some of which extend for hundreds of kilometers. The distribution of the short baseline slopes in the terrestrial analogs of the parabolas/haloes shows a prominent peak for the slopes smaller than 7° (Ivanov et al., 2017). Thus, these impact-related dark parabolas (smooth plains of impact origin (psi)) represent a type of terrain that could provide a safe landing.

3.2.1.4.2 Representativeness of Materials within Potential Landing Sites

After applying the safety criterion to the variety of the terrains that make up the surface of Venus, the list of units appropriate for landing includes (Figure 3.15) (1) pr/RB, (2) psh, (3) sc, (4) rp1, (5) psv, and (6) psi (dark parabolas and haloes).

The pr/RB, psv, and sc occupy a small portion of Venus (Table 3.2). Materials of these units likely reflect some specific regimes of volcano-tectonic activity that occurred locally in space and time and do not comprehensively characterize the major endogenous processes on Venus. Therefore, ridged plains, sc, and the psv have low scientific priority among the units that provide safe landing.

Individual dark parabolas and haloes are associated with larger impact craters (greater than tens of kilometers in diameter) and represent their distal, fine-grained ejecta excavated from a depth approximately equal to 1/10 of the crater diameter (Melosh, 1989). Materials of the radar-dark parabolas and haloes are, in fact, fallouts from impact ejecta lofted into the thick Venusian atmosphere. Convection in the plume of ejecta mixes up components of the ejected materials, and thus may provide a well-averaged sample of the upper crust directly beneath that impact site. A specific impact site may not be representative for the entire crust, however. The scientific value of this ejecta remains high because it may help to address a vital question about the presence or absence of the non-basaltic components in crustal materials on Venus. Thus, the scientific priority of the dark parabolas or haloes, despite their low representativeness, is higher than that of the ridged and smooth volcanic plains and sc.

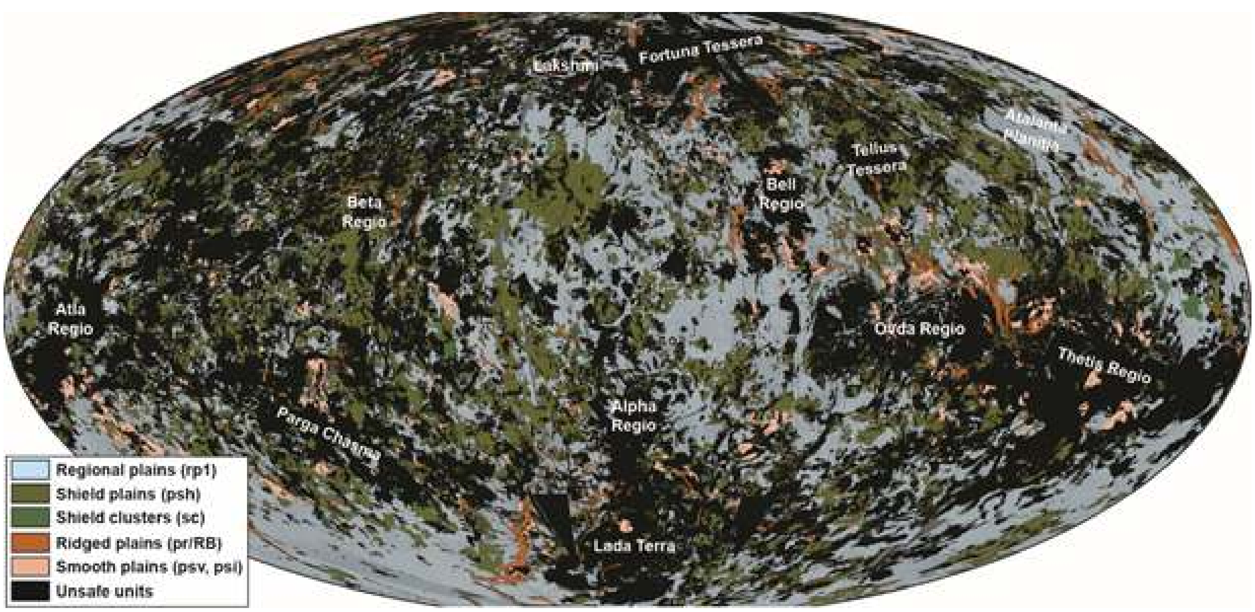


Figure 3.15.—Geological map of Venus; unsafe units are shown in black. Equal-area Mollweide projection where central meridian is 0.

The most abundant and pervasive units on Venus are psv and regional plains that occupy ~18 and 30% of the surface of the planet, respectively (Table 3.2). The uniform morphologies of each of these units suggest a prevalence of specific volcanic processes forming both shield or regional plains. The large areas covered by both plains types indicate that they represent the dominant components of Venus' volcanic evolution.

3.2.1.4.3 Simplicity and Quality of Geochemical Signal

After applying the safety and representativeness criteria, only three reliable candidates for landing sites are left. These are (1) psh, (2) regional plains, and (3) psi. To select the most appropriate target for landing, we apply the criterion of the potential simplicity of the geochemical signal that can be received.

In this respect, psh represent a less desirable type of terrain. The characteristic features of psh are abundant small volcanic constructs. By analogy with similar terrestrial shield fields, the shields likely formed from small, shallow, and isolated sources. All models of formation of terrestrial shield fields include as an essential component, the existence of transient magma reservoirs that receive melts from the source regions in mantle and feed small volcanic eruptions on the surface. Melts in these reservoirs may stall and have a complex history. As a result, erupted lavas in shield fields may have a broad spectrum of compositions that reflect a complex pre-eruption history. Numerous samples are needed to constrain the factors controlling the formation of shield-field lavas. A single analysis of shield-field materials will bring results that will be difficult to interpret. The potentially large ambiguity in interpretation of the chemical analysis significantly lowers the scientific priority of this unit.

The psi appear to be less complicated geochemical target because they likely consist of fine-grained materials that have been well mixed. Materials of the radar-dark parabolas and haloes, however, have traveled through the atmosphere as small (and possibly hot) particles and may have experienced chemical alteration.

Regional plains represent a better candidate for a single chemical analysis because of the following characteristic features of the plains. (1) The uniform morphology of the plains suggests that they have the same mode of origin everywhere on Venus. (2) The plains form the most abundant unit on Venus (Table 3.2), and thus are the most representative materials on the planet. (3) The lack of volcanic constructs indicates that they formed by massive melting in the source regions and rapid delivery of melts to the surface. This reduces the chances of either fractional differentiation or contamination by the crustal materials. (4) The small number of impact craters obviously embayed by materials of the plains (Ivanov and Head, 2015) suggests that the plains were emplaced within a relatively short time. All these characteristics of regional plains suggest that their mode of origin is similar to that of basalts in terrestrial large igneous provinces (LIPs) and that the plains may represent an unbiased sample of the upper fertile mantle of Venus, regardless of specific geodynamic models of evolution of the planet. In summary, rp1 appear as the safe and representative target of a very high scientific importance (Figure 3.16), and thus they are at the top of the list of the terrains on Venus appropriate for landing.

3.2.1.4.4 Orbital Restrictions

The final criterion for the selecting of a specific landing site comes from the ballistic restrictions of the mission. Depending upon the precise launch and arrival dates, potential landing spots are arranged along specific arcs (attainability arcs) that cross all types of terrains (Figure 3.17). We used the attainability arcs that have been calculated for different arrival dates to locate potential landing spots within the uncertainty ellipses, which we set to be 300 km in diameter based on VEGA and Venera landing ellipses.

Analysis of the different attainability arcs shows that in all cases we can locate an uncertainty ellipse, which is either completely within regional plains or with a tiny fraction of the unsafe and low priority units within the ellipse (Figure 3.15 to Figure 3.17). Table 3.3 summarizes coordinates of the potential landing sites. Further assessment of the proposed landing sites should take into account conditions of illumination and radio link with the orbiter.

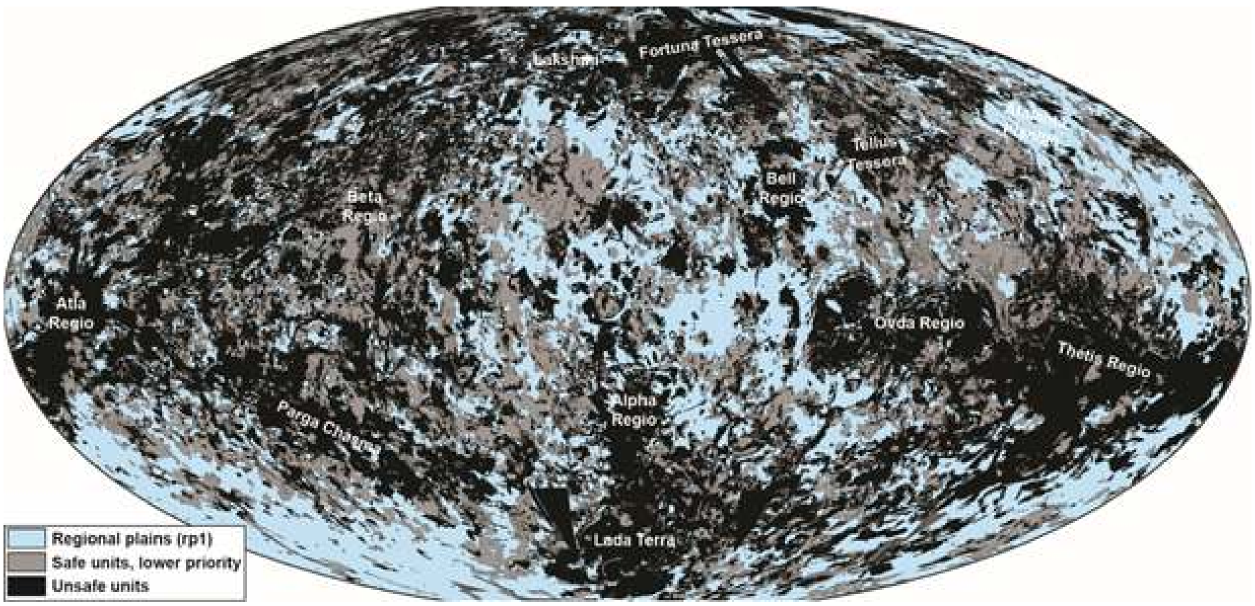


Figure 3.16.—Simplified geologic map of Venus; unsafe units are shown in black and low-priority units are show in gray. Equal-area Mollweide projection where central meridian is 0.

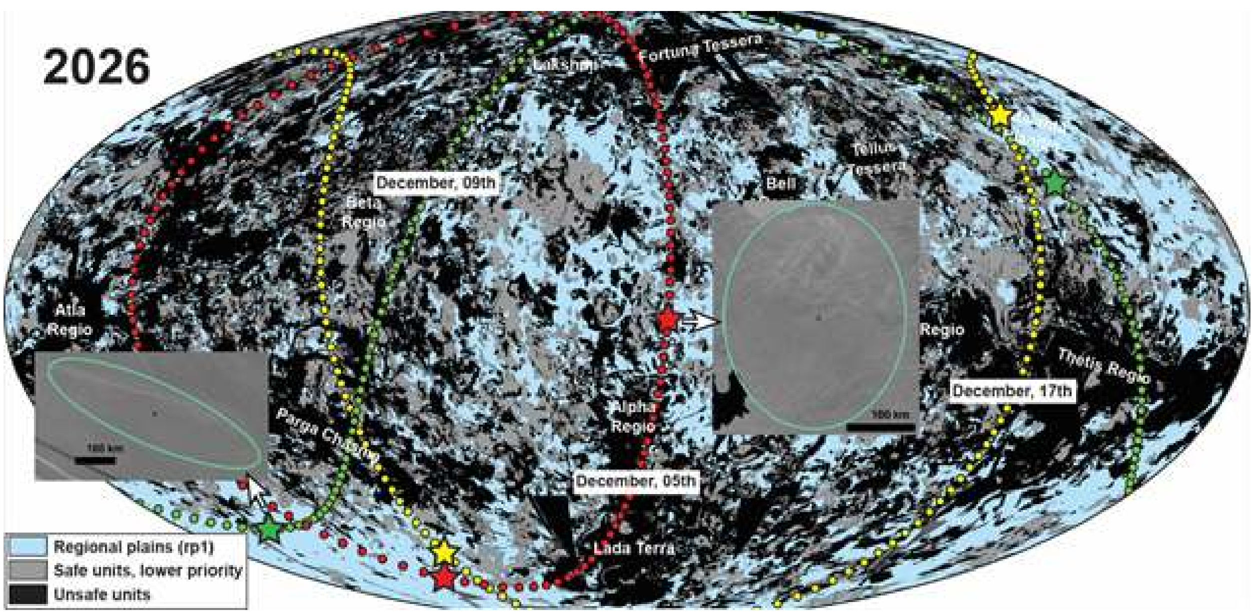


Figure 3.17.—Position of the attainability arcs for 2026. Insets show examples of the uncertainty ellipses for two selected landing sites. The other landing sites (stars) are listed in Table 3.3.

Table 3.3.—Potential Landing Sites for the Venera-D Mission

Arrival Date	Selected Site		Fraction of Units,%	
	Longitude (+ east, – west)	Latitude (+ north, – south)	Regional plains	Unsafe/low priority
2026, December 5	11.7	–1.7	100	
2026, December 5	–98.6	–68.3	100	
2026, December 9	135.6	31.4	100	
2026, December 9	–143.0	–53.5	100	
2026, December 17	136.9	46.6	98	2
2026, December 17	–82.3	–62.1	100	
2028, July 12	144.4	42.7	100	
2028, July 12	–82.4	–62.6	100	
2028, July 20	161.6	34.3	99	1
2028, July 20	98.8	–60.5	100	
2028, July 27	170.7	28.0	95	5
2028, July 27	96.2	–59.6	100	
2031, September 30	–17.6	42.9	100	
2031, September 30	–123.6	–49.5	100	
2031, October 9	–31.7	47.2	100	
2031, October 9	–139.0	–55.6	100	
2031, October 13	–177.6	3.3	100	
2031, October 13	–162.7	–77.2	98	2

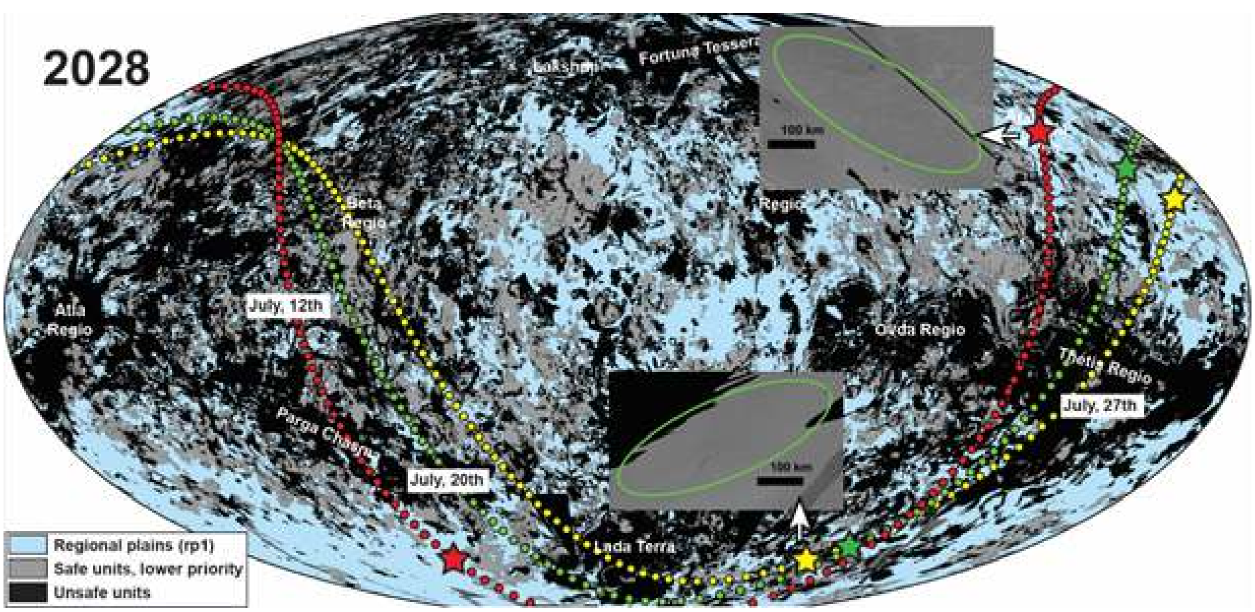


Figure 3.18.—Position of the attainability arcs for 2028. Insets show examples of the uncertainty ellipses for two selected landing sites. Other landing sites (stars) are listed in Table 3.3.

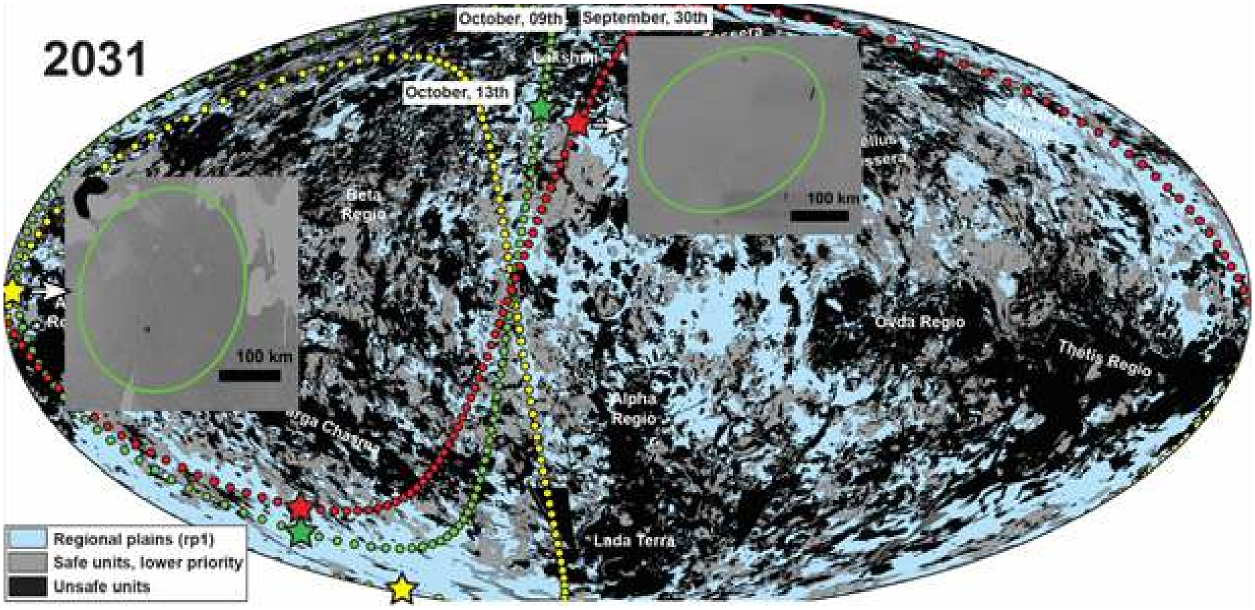


Figure 3.19.—Position of the attainability arcs for 2031. Insets show examples of the uncertainty ellipses for two selected landing sites. The other landing sites (stars) are listed in Table 3.3.

3.2.2 Venus Geochemistry

Venus is the “Terra Incognita” of the inner solar system, and our knowledge of its surface geochemistry is limited. Yet, Venus is vital for understanding the formation and evolution of our solar system. The question of why Earth and Venus, the two sister planets that appear to be similar in many aspects (size, density, rocky type) are so different in other ways (atmosphere, surface temperature, tectonics, rotation) is one of the main goals of Venera-D mission. The understanding of differences between these two planets will provide clues about the origin and evolution of all terrestrial planets. However, the environmental conditions on Venus (both high atmospheric pressure and surface temperature) are inhospitable and will make any measurement challenging.

The only means by which the geochemical data from Venus’ surface can be obtained are the landers. Several landers visited the planet in a period from 1972 (Venera-8) to 1985 (VEGA-1 and 2) and reported the only data on the chemical composition of soils on the surface of Venus. Chemical measurements were made at seven sites that are concentrated in the Beta-Phoebe region and in Rusalka Planitia to the north of Aphrodite Terra (Figure 3.20). 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 implemented.

At four landing sites (Venera-8, -9, -10, and VEGA-1), concentrations of the three major thermal-generating components, K, Th, and U, were determined by gamma spectrometry (Table 3.1) (Surkov, 1997). The mean values of their concentrations on Venus are well within the range that is typical of terrestrial basalts (Kargel et al., 1993; Nikolaeva, 1995, 1997). However, enhanced concentrations of K, Th, and U in soils at the Venera-8 landing site raises the possibility for the presence of a non-basaltic material on Venus (Nikolaeva, 1990).

In two landing sites (Venera-13, and -14), the concentrations of major oxides (without Na_2O) were measured by the XRF method (Table 3.4) (Surkov, 1997). At the VEGA-2 site, both methods (gamma spectrometry and XRF) were used separately and the concentrations of the thermal-generating elements and major oxides were measured (Table 3.4) (Surkov, 1997). The XRF data also suggested that rocks of basaltic composition make up the landing sites (Surkov et al., 1984, 1986; Kargel et al., 1993).

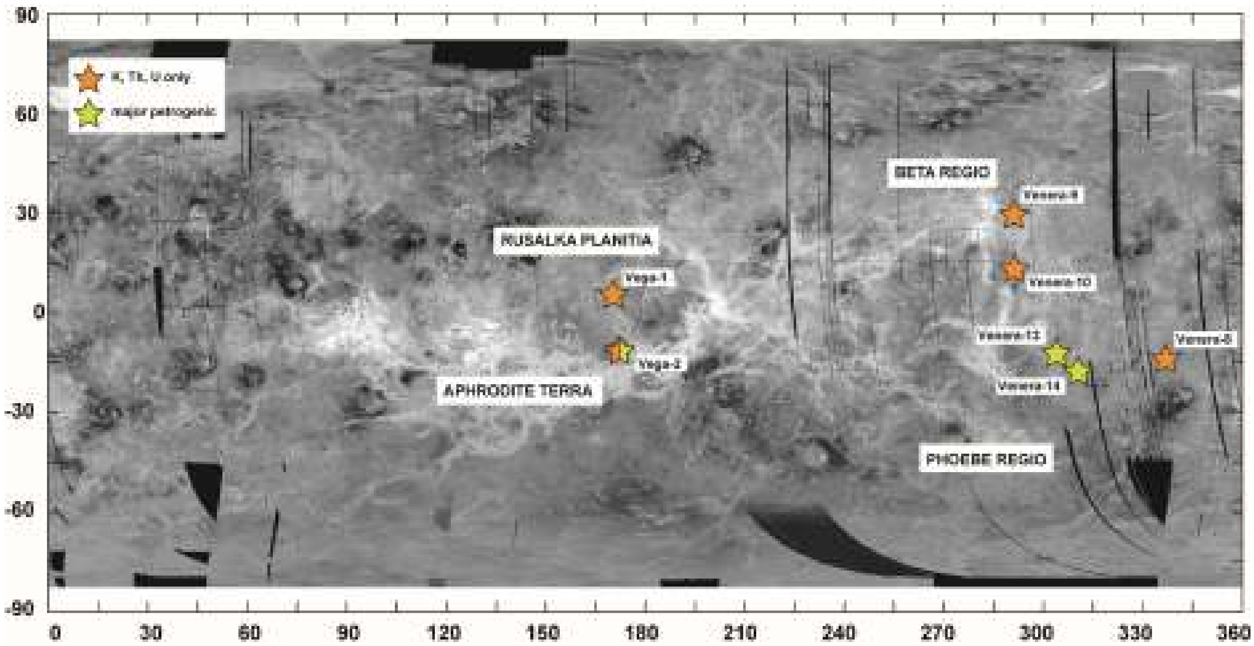


Figure 3.20.—Landing sites of the Soviet stations of the Venera-VEGA series.

Table 3.4.—Results of Chemical Analyses (Given as wt.%) 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

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

The first major problem is that we do not know the exact position of the landers. All stations landed somewhere within their own landing circle, which is ~300 km in diameter and usually embraces terrains of different origin and age. For example, the landing circle of Venera-10 includes six different, extensive units. According to the Venera-10 panorama (Figure 3.21) and the inclinometer data, the station is on a subhorizontal surface. This type of surface favors vast volcanic plains (psh or regional plains) as the hosting units for the lander and disfavors the tectonized units such as t, pdl, and groove belts, although these later units cannot be ruled out.

Thus, in the Venera-10 landing circle and in all other landing sites, 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.

The second and most important limitation of the Venera and VEGA geochemical data is the low precision of the measurements (Table 3.4). The large errors preclude detailed and confident interpretation. For example, on a ternary plot that shows relationships of the major thermal-generating elements (Figure 3.22), points of terrestrial magmatic rocks form a prominent trend that reflects broad variations of Th/K 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-rich) end of the trend and the Venera-9 error ellipse overlays rocks from continental magmatic provinces and oceanic volcanic islands, both 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 mantle plume-related environments to subduction zones (i.e., island 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 3.22). However, the error ellipses of these measurements are so large that the data are almost completely unconstrained.

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 3.4).

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.

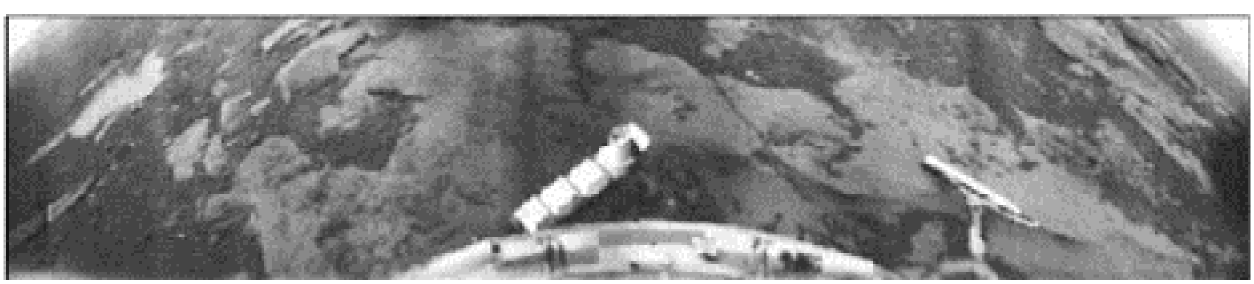


Figure 3.21.—Panoramic taken by the camera system on the Venera -10 lander.

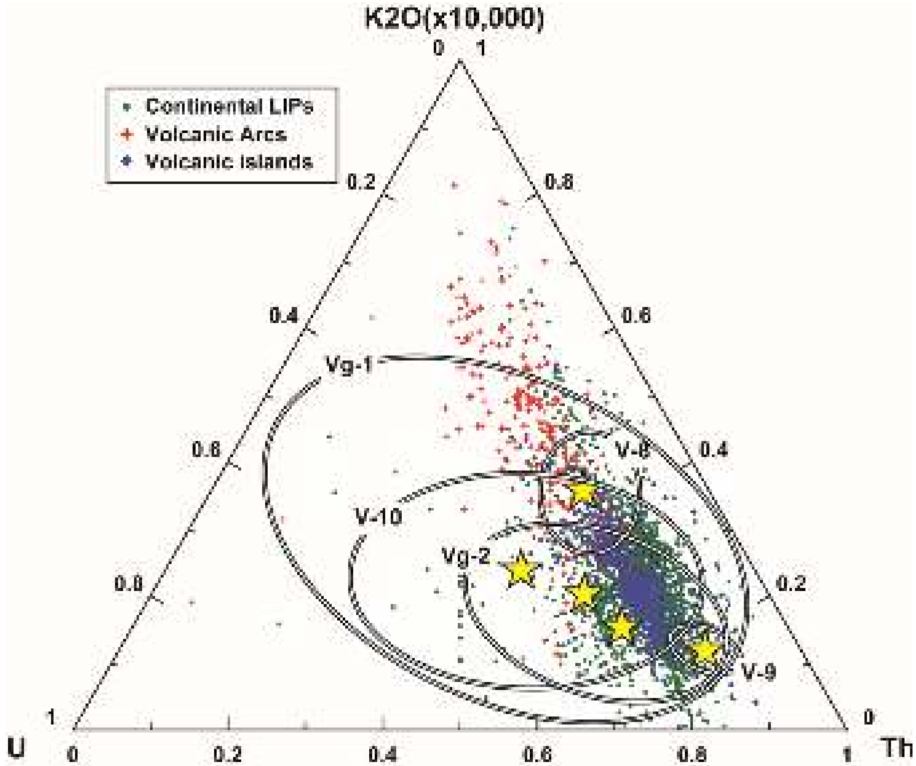


Figure 3.22.—Ternary plot that shows relationships of the major thermal-generating elements for volcanic rocks from different geodynamic settings on Earth. Yellow stars correspond to the mean values of the measurements by the Venera-VEGA landers. Ellipses around the stars correspond to the measurement errors.

3.2.2.1 Open Questions

Questions related to the geochemistry of Venus' surface 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 the resurfacing of Venus during the last billion years? Are resurfacing and climate change related? Is Venus still geologically active? Most models of Venus' recent past point to a surface completely reworked and resurfaced within the last hundreds of millions of years. The absence of obviously 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, and 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 (Urey, 1951; Lewis, 1970; Fegley and Treiman, 1992). Current models

disfavor CO_2-buffering, but favor buffering of sulfur gases and oxidation state (Hashimoto and Abe, 1998). Measurement of volatile abundances in fresh basalt at the surface could constrain their pre-eruptive volatile contents, and thus the atmospheric 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 be distinguished by their geochemistry (e.g., Pearce, 1976, 2008; Winchester and Floyd, 1977; Verma et al., 2006; Vermeesh, 2006). By analogy, different geodynamic settings on Venus would generate distinct volcanic products. For example, basalts within rz might be alkaline, and extensive plains volcanism might be comparable to that of LIPs on Earth.

3.2.2.2 Needed Investigations

Based on several Venus Workshops (VEXAG, Moscow 2017) and discussions, addressing geochemical problems requires new, precise analytical data obtained by the landers. Two types of measurements are paramount.

(1) Elemental chemical analyses of soils and rocks.

Of the many analytic techniques available, an active gamma-ray spectroscopy has the potential for measuring the bulk elemental composition in a volume within 1 m^3 under the lander. The same instrument can also operate in passive mode to determine the important radiogenic elements K, Th, and U. The XRF/alpha particle X-ray spectrometer (APXS) is the choice instrument to obtain the complete and detailed elemental bulk composition of the soil and rocks of Venus. Quick elemental analysis of main rock-forming and trace elements down to tens of ppm level can be done by laser-induced mass spectrometry (LIMS).

(2) Mineralogical analyses, determining the crystalline compounds that contain those elements.

Measurements of these categories would allow understanding rock compositions, and thereby inferring mantle processes that produced surface rocks and atmospheric processes that modified surface rocks. Definitive mineral identification can be achieved by an XRD spectrometer, similar to the Chemin instrument on Mars Science Laboratory (MSL) rover, which requires some sample preparation, or by a Mössbauer spectrometer that determines the iron-bearing minerals. The Raman spectrometer can provide mineralogical analyses of samples outside the lander or on acquired samples inside the lander.

Some of the above instruments require a sample to be acquired by the Sample Acquisition and Distribution Device and distribute it to the individual instruments. This device is in the early design stage and will require substantial development (see "Suggested Next Steps" in Section 12).

To understand the chemical interaction Venus' atmosphere with its surface material, we have to determine the elemental and isotopic composition of atmosphere at the surface and consider the chemical reactions between the surface and the atmosphere. That could be accomplished with the same GC-MS instrument that will be used to determine the vertical atmospheric composition during the descent to the surface. Meteorological measurements obtained from LLISSE (atmospheric temperature, pressure, wind speed, and wind direction), combined with chemical analyses of the atmosphere, will provide input to models of chemical weathering of Venusian rocks and soils. These will inform rates of alteration for Venus' surface materials.

From a scientific perspective, it is interesting to collect such objects as dust, weathered crust of rocks, and internal part of rocks. The dust may represent a globally mixed weathered material in case the wind is efficient for transfer of fine-grained material. The weathered crust of rocks can be sampled by mechanical abrasion of first few millimeters of stones. This will provide information on surface-atmosphere interaction. Solid stone material can be sampled by regular drilling of several centimeters into a rock. It is also worth considering the possibility of using video cameras to document the sampling objects on the surface.

In general, the Soil Sampling System (VB-02) from previous Venus missions can be used as a prototype for the Venera-D due to its quick and reliable operation at Venus surface.

3.2.3 Venus Interior and Seismology

Our current knowledge on Venus' interior is mostly theoretical and derived from compositions of Earth. In the absence of data to constrain the density profile of Venus, its interior structure is commonly a rescaled model of Earth (one-dimensional preliminary reference model (PREM)), modified for Venus' mass and radius (Zharkov et al., 1981; Zharkov and Zasurskiy, 1982; Kozlovskaya, 1982; Yoder, 1995; Mocquet et al., 2011; Aitta, 2012; Gudkova et al., 2018). This is convenient because PREM includes the influence of temperature on the equations of state, and the internal temperature distribution in both planets is assumed to be similar for depths >200 km (but there are no available data to contradict these assumptions).

The thickness of the Venusian crust is under debate. Based on terrestrial observations and laboratory simulations, the Venusian crust was assumed to be 60 to 70 km thick based on the gabbro-eclogite transition occurring at that depth. Estimates of Venusian mean crustal thickness, obtained from the models of thermal history and interpretation of the gravity and topography data, range from 15 to 35 km (Breuer and Moore, 2007; Wieczorek, 2007). Jiménez-Dìaz et al. (2015) present a crustal thickness model wherein the majority of Venusian crust is 20 to 25 km thick, with thicker crust under the highlands. Yang et al. (2016) concluded that the global crustal thickness calculated from isostatic components of the topography and gravity is in the range of 12 to 65 km from a mean crustal thickness of 25 km and is consistent with the current understanding of Venusian dynamic evolution (Dumoulin et al., 2017). Surface compositions of various landers give the current estimate of Venusian crustal composition and density of 2,700 to 2,900 kg/m^{-3} (Grimm and Hess, 1997), which corresponds to basaltic rocks.

Currently, Venus' seismicity may be only theoretically estimated, but the range of fresh volcanic and tectonic morphologies suggests that Venus is a seismically active planet (e.g., Stofan et al., 1993; Knapmeyer et al., 2006). Prediction suggests that 100 quakes of surface wave magnitude greater than 5 could be released. The events of magnitude 6 will occur 5 times less frequently (the maximum magnitude is 6.5).

3.3 Traceability

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 *Visions 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 matrix 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 3.5). As conceived, Venera-D would address each key objective identified in the Decadal Survey.

Flowing from the broad Decadal Survey science goals are specific VEXAG goals, objectives, and investigations from which mission science 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 (Table 3.6, Table 3.7, and Table 3.8). 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 Table 2.1 and Table 2.2 (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 3.5.—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' crust	• Lander chemical and mineral analysis of crustal rocks • Orbiter measurement of 1 μm emissivity
		What are the volatile budgets in the interiors, surfaces, and atmospheres of the inner planets?	• Venus' 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 insight 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 time scales?		
	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 time scale 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
		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' atmosphere, especially the noble gases and nitrogen-, hydrogen-, carbon-, and sulfur-bearing species? What was Venus' original volatile inventory, and how has this inventory been modified during Venus' evolution? How and to what degree are volatiles exchanged between Venus' atmosphere and its solid surface?		
		Are Venus' 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 time scales 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-μm 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, time scales, 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
	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 subsatellite 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?		

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 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' global circulation better within the theoretical framework of modeling techniques developed for terrestrial GCMs and to understand the chemistry and dynamics of Venus' 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 atmospheric escape processes at Venus with orbital and in situ investigations	• Potential subsatellite simultaneous measurements would constrain atmospheric escape
		What are the key processes, reactions, and chemical cycles controlling the chemistry of the middle, upper, and lower atmosphere of Venus?		
		How does the atmosphere of Venus respond to solar-cycle variations?		• Measure solar wind properties and interactions from orbiter and possible subsatellite 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' surface rocks, and effects of that interaction at depth in Venus' 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 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 UV flux and solar wind influence atmospheric escape in the early solar system?	• Examining the geology and mineralogy of the t on Venus to search for clues to ancient environments.	

Table 3.6.—Mapping of Science Capability of Venera-D to the VEXAG Objectives and Investigations for Atmospheric Science

Decadal Survey future directions for investigations and measurements		Priority	
(light blue)	Understand the origin and diversity of terrestrial planets	(green)	High
(light purple)	Understand how the evolution of terrestrial planets enables and limits the origin and evolution of life.	(yellow)	Medium
(light grey)	Understand the processes that control climate on Earth-like planets.	(pink)	Low

Venus Atmosphere: Decadal Survey			Venus Atmosphere: VEXAG goal	VEXAG Goals, Objectives and Investigations (Goals are not prioritized; Objectives and Investigations are in priority order): Objective	Investigation (items listed in red cannot be achieved by the baseline orbiter/lander)	Venera-D as Currently Defined: Venera-D objective	Venera-D flight element(s)	Applicable Venera-D instrument(s)	Technology needs and 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 abundance 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 L2a. Atmosphere composition at the surface L2b. Near-surface atmospheric composition	Lander LLISSE LLISSE	1. CAP 2. MTDL spectrometer Investigation of Sulphurous Komponents of Rarefied Atmosphere of Venus (ISKRA-V)	Delivery of the atmospheric probes, rarefying for multichannel tunable diode laser (MTDL)	N/A
X	X				2a. Measure the isotopes of noble gases (especially Xe and Kr), D/H, and 15 N/14 N	L1. Atmosphere composition during descent	Lander	1. CAP 2. MTDL 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 and IR solar and stellar occultation spectrometer 2. Plasma package	N/A	Subsatellite: 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 superrotation and the atmospheric greenhouse?	1. Characterize and understand the atmospheric superrotation and global circulation, including solar-AS 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 GCMs 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 [AP] [Subsatellite] [Small long-lived station]	1. Fourier transform spectrometer PFS-VD 2. Monitoring camera VMC 3. UV-IR imaging spectrometer VENIS 4. UV imaging spectrometer 5. UVMAS 6. Radio occultations 7. Heterodyne hi-res IR spectrometer	N/A	AP: measurement of P,T over range of altitudes (50 to 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 Subsatellite: simultaneous remote observing would help for higher altitudes—best from subsatellite 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 [AP] [Subsatellite] [Small long-lived station]	1. Fourier transform spectrometer PFS-VD 2. Radio occultations 3. Millimeter wave (MMW)-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 AP: flying AP can provide details 50 to 65 km Subsatellite: remote sensing from subsatellite orbiter for additional altitudes Small long-lived station: drop sondes/probes needed for lower altitude measurements
		X			2b. Determine the atmospheric radiative balance based on characterization of the deposition of solar energy in the cloud layers and reradiation 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	Orbiter, lander, LLISSE [AP] [Subsatellite] [Small long-lived station]	1. Fourier transform spectrometer PFS-VD 2. Radio occultations 3. MMW-radiometer 4. UV imaging spectrometer UVMAS 5. UV and IR solar and stellar occultation spectrometer	N/A	A measurement of the horizontal variation of cloud structure, composition and microphysics is needed to meet this goal AP: AP can provide details 50 to 65 km (flying) or 50 to 55 km (floating) 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			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 and requirements	Missing measurements (orbiter/lander inadequacy described in red; other colors highlight capabilities of alternative measurement platforms)
						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		6. T,P,W METEO package 7. Optical package		**Subsatellite**: remote sensing from subsatellite 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 [AP]	1. Infrared heterodyne fiber analyzer (IVOLGA-V) 2. Monitoring camera CMV 3. UV-IR imaging spectrometer	N/A	**AP**: 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, LLISSE [AP]	1. UV imaging spectrometer; 2. UVMAS 3. UV and IR solar and stellar occultation spectrometer 4. Radio occultations	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** **AP**: 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 L1. Atmosphere composition during descent L3. Atmospheric structure and dynamics L4. Physical properties of atmospheric aerosols	Orbiter, lander, LLISSE [AP]	1. UV and IR solar and stellar occultation spectrometer 2. Radio occultations 3. UV-IR imaging spectrometer VENIS 4. UV imaging spectrometer UVMAS 5. Fourier transform spectrometer PFS-VD 6. MTDL spectrometer ISKRA-V	Delivery of the atmospheric probes, rarefying for MTDLS	**AP**: 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
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 [AP]	1. Groza-SAS2-D	N/A	**AP**: 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, and 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, LLISSE, orbiter [AP]	1. CAP 2. MTDL spectrometer ISKRA-V 3. UV and IR solar and stellar occultation spectrometer	Delivery of the atmospheric probes, rarefying for MTDLS	**AP**: CAP for aerosol; MTDL spectrometer ISKRA-V—may be installed on flying platform

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

Table 3.7.—Mapping of Science Capability of Venera-D to the VEXAG Objectives and Investigations for Surface Science

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

Venus Surface and Interior: Decadal Survey			VEXAG Goals, Objectives and Investigations (Goals are not prioritized; Objectives and Investigations are in priority order): VEXAG goal	Objective	Investigation	Venera-D as Currently Defined: Venera-D objective	Venera-D flight element(s)	Applicable Venera-D instrument (s)	Technology needs and 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' history	L1. Atmosphere composition during descent	Lander	1. CAP—GC-MS	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) [SAEVe]	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 submillimeter 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 t, 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. CAP	Raman spectroscopy is desirable for mineralogy	N/A
						L7. Mineral phases	Lander	Miniaturized Mössbauer spectrometer (MIMOS-2A)	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
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), to constrain estimates of crustal volume and lithospheric structure and processes	L8. Global and regional seismic activity	Lander [SAEVe]	1. Seismometer (very limited and low priority for Venera-D) 2. SAEVe seismometer	1. Provide strong coupling between the ground and the instrument	SAEVe-would need at least 2 SAEVes placed 300 to 800 km apart
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 [SAEVe]	1. Seismometer (very limited and low priority for Venera-D) 2. SAEVe seismometer	1. Provide strong coupling between the ground and the instrument	SAEVe-would need at least 2 SAEVes placed 300 to 800 km apart
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	L8. Global and regional seismic activity	[SAEVe]	SAEVe Seismometer	Provide strong coupling between the ground and the instrument	SAEVe-would need at least 2 SAEVes placed 300 to 800 km apart

Table 3.8.—Mapping of Science Capability of Venera-D to the VEXAG Objectives and Investigations for Surface-Atmosphere Interaction

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

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			VEXAG Goal	Objective	Investigation	Venera-D objective	Venera-D flight element(s)	Applicable Venera-D instrument (s)	Technology needs and 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 to 140 km) of the atmosphere	Orbiter	1. UV and IR solar and stellar occultation spectrometer	N/A	N/A
						L1. Atmosphere composition during descent	Lander	1. 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; Quantum Cascade Laser (QCL)-laser technique and optical fibers for longer wavelengths (λ > 5 µm); integrated cavity output spectroscopy (ICOS) spectrometry for long optical paths (1 m to 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 t	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 to understand changes in planetary water budget and atmospheric composition over time	N/A	N/A	N/A	N/A	
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. CAP 2. “ISKRA-V”: DLS with multiple channels and 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 to 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 (MIMOS-2A) + 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) CAP 2. “ISKRA-V”: DLS with multiple channels and 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 (λ > 5 µm); ICOS spectrometry for long optical paths (1 m to 1 km); challenge of taking atmospheric samples at different levels in the atmosphere	Raman Spec.
		X			3. Determine the abundance 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, to characterize sources of chemical disequilibrium in the atmosphere and to understand influences on the current climate	L1. Atmosphere composition during descent	Lander	1. CAP 2. “ISKRA-V”: DLS with multiple channels and 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 to 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, and 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. CAP 2. “ISKRA-V”: DLS with multiple channels and 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 to 1 km); challenge of taking atmospheric samples at different levels in the atmosphere	N/A

3.4 Science Enhancements and Enablements From Augmentations

The JSDT has identified several Venera-D mission goals that may be more adequately realized by elements not included in the baseline Venera-D concept and has suggested options to resolve these “science gaps.” For surface science, Mössbauer 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 of the lander.

To better address the drivers of atmospheric superrotation and characterize the chemical composition and dynamics in situ in the atmosphere, the JSDT concluded that the addition of a capable/semiautonomous long-lived atmospheric platform operating at 55 to 65 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, a Raman Sensor, and a UV spectrometer over a time period of ~1 Venus day. In situ measurements obtained using these instruments would also greatly advance the investigation of the nature of the enigmatic species known to absorb strongly at near-UV (~360 nm) wavelengths.

Inclusion of a small long-lived surface station with capabilities to take atmospheric state, mineralogy, seismology, and rock morphology could provide for the first time continuous monitoring of the surface-atmosphere interactions over a full Venus solar day (see Section 8). Another exciting possibility for atmospheric science is the inclusion of a secondary subsatellite orbiting around Venus’ L1 or L2. At either location, Venus’ full disk will be consistently observed, resulting in either continuous monitoring of Venus’ day side cloud cover (at L1) or night side emission and lower atmosphere dynamics (at L2). In each case, the L1 or L2 vantage point would allow the evolution of the atmospheric properties to be monitored independent of phase-angle effects that will be encountered from the main satellite orbiter. This would remove ambiguities regarding the degree of day side albedo and atmospheric opacity variations over the lifetime of the mission—allowing for self-consistent calibration of the absolute radiance levels observed by the instruments aboard the main orbiter. Small satellites in tight orbits around L1 and L2 (about 1,000,000 km away from Venus) also have the potential to provide a communications relay capability for the atmospheric and surface platforms (see Section 8).

3.5 Venera-D Science Relative to Ongoing and Potential Future Missions

The science that could be achieved by Venera-D builds upon and would be synergistic with that from past and current missions. Appendix B provides a comparison between the baseline Venera-D payload and instruments carried on VEX and Akatsuki; see Appendix C for comparisons with future and potential missions.

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

When the JSDT began its consideration of the Venera-D mission, ESA’s VEX had just concluded about 8 yr of observations and JAXA’s Akatsuki was about to attempt orbit insertion.

Since then, Akatsuki has been collecting Venus observations from a near-equatorial orbit with a 10.5-day period and no other mission to Venus was on the horizon until the potential launch of Venera-D in 2026 (or other dates through 2031).

The ISRO recently issued a call for international proposals to participate in its mission to Venus to be launched in 2023. The science goals of the mission include investigating Venus' surface and subsurface, atmosphere, ionosphere, plasma environment, and the Sun-Venus interaction. To date, the proposed instruments from ISRO include a SAR with 20 to 30 me/pixel mapping capability, ground-penetrating radar, thermal IR and UV cameras, a spectropolarimeter, an airglow photometer to investigate the ionosphere, and instruments to monitor the solar wind interaction with Venus. It is apparent that the Venera-D science goals and those of the comprehensive ISRO mission are similar and complementary. A successful implementation of the ISRO Venus mission will benefit Venera-D by refining science return using results from the new mission. JSDT encourages the agencies to be engaged in the progress of the ISRO Venus mission.

There are other potential opportunities that may come during the development and implementation phases of the Venera-D mission. In early 2019, a call for competed, medium-class mission proposals to solar system targets will be issued by NASA with launch of the selected mission(s) to take place no later than 2025. It is anticipated that proposals for missions to Venus to study its surface and atmosphere will be submitted, and the selections will be made in 2021. ESA's Cosmic Vision Medium-class mission competition (Mission-class 5 (M5)) is underway and EnVision radar mapping mission (Ghail et al., 2018) is under consideration. If selected, it will be launched in 2032.

Both the ISRO Venus mission and EnVision (Ghail et al., 2018) will map Venus' surface at better than Magellan resolution, and neither will deploy atmospheric platforms, probes, or surface landers to make meteorological and chemical measurements of the surface; Venera-D does not have a radar mapper. Thus, there is great synergy between Roscosmos, ISRO, ESA, and NASA interests in Venus exploration. The Venera-D mission should exploit all potential opportunities to advance Venus science, given the complementary nature of their mission objectives.

4 Mission Architecture

As the supplier of the flight system and mission design, the NPOL 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 augmentations, cruise to Venus and orbit insertion, and a preliminary evaluation of telecommunications.

4.1 General Summary

The Venera-D spacecraft is designed for remote sensing and in situ research of Venus using scientific equipment that can operate in Venus' orbit, in the dense atmosphere during descent to the surface, and on the surface of Venus. Its baseline consists of an orbiter and lander with an attached LLISSE, and accommodated scientific equipment.

The «Angara-A5» carrier rocket with either a KVTK (Кислородно-водородный тяжёлого класса (*КВТК*)) or a DM-03 (*«ДМ-03»*) upper stage is planned to be used to deliver the spacecraft to Venus' orbit. The launch would be from the Vostochny site in 2026, 2028, 2029, or 2031. The departure mass of the spacecraft from Earth must be within the limits of 6.2 to 7 tonnes, depending on the launch year (Table 4.3).

The orbiter includes a two-component power propulsion unit (nitrogen tetroxide + unsymmetrical dimethylhydrazine (UDMH)) with a maximum fuel mass of 2.1 to 2.15 tonnes; a power supply system with adjustable solar panels with a surface area of ~11 m^2; and total power of 2,400 W at the end of its active lifetime. For position precision and stabilization, flywheel motors are used. The active lifetime of the orbiter is about 3 yr, starting from the departure from Earth orbit.

The lander is planned to operate for 3 hr after landing; the attached LLISSE will operate for 3 months after landing. The lander consists of a thermally insulated titanium pressure vessel with thermal storage batteries and all systems and construction elements necessary for landing and to provide the required inner temperature that allows the instruments to function for the needed duration.

4.1.1 The Baseline Venera-D Architecture

The abbreviations used in the following discussion are shown in Table 4.1.

Table 4.1.—Abbreviations Used in this Section

Russian		English	
Abbreviation	**Description**	**Abbreviation**	**Description**
ОМ	Орбитальный модуль	**OM, orbiter**	Orbital module
ПМ	Посадочный модуль	**LM, lander**	Landing module
ПК	Приборный контейнер	**IC**	Instrument container
ВП	Воздушная платформа	**AP**	Aerial platform
КА	Космический аппарат	**SC**[a]	Spacecraft

[a]Provided as a reference to the original Russian term only.

To provide remote sensing and in situ research of Venus, the baseline spacecraft consists of two main modules:

- **Orbiter module (orbiter, *OM*)** is designed for transportation of the spacecraft to Venus and functioning in the Venus orbit and for transmitting information received from all components of the spacecraft to Earth.
- **Landing module (lander, *ПМ*)** is designed for landing and functioning on the surface of Venus and to carry a LLISSE that would continue to operate after the main lander stops.

The spacecraft might also include additional elements that can operate separately at some distance from the OM or the LM. Such elements are, for example, APs, small surface stations, and subsatellites.

The main areas of operations to be resolved are indicated in Table 4.2.

For all figures shown here, the composition and technical characteristics of the spacecraft and its modules are not final and may have modifications, depending on precise scientific equipment requirements, operation timeline, launch date, or general mission concept.

The general view and sectional diagram of the spacecraft are given in Figure 4.1 and Figure 4.2.

For the launch, it is intended to use the carrier rocket «Angara-A5» with either a KVTK or a DM-03 («ДМ-03») upper stage as mentioned above. It is also hoped that in 2026, the DM-03 will be in a stage of better readiness and starting from 2028, the KVTK will also reach the necessary level of readiness. The Venera-D is planned to be launched from Vostochny site.

It is planned to use a KVTK launch vehicle fairing (LVF) with a payload zone within the lower cylinder part of 6,635 (height) by 4,600 (lower) by 4,480 (upper) mm (diameter) and an upper cone part (see Figure 4.3 and Figure 4.4).

Dates of launch and maximum launch masses in the transit Earth-Venus trajectory are given in Table 4.3.

Table 4.2.—Main Areas of Spacecraft Operations During Mission Period

Area of Operations	Component Element of Spacecraft
Retransmission of information from the spacecraft to Earth	OM
Science phase during Earth-Venus transit and in Venus orbit	OM, subsatellite(s)
Science phase in the cloud layers	Augmented payload
Science phase during landing	LM, LLISSE
Science phase on Venus surface	LM, LLISSE

Figure 4.1.—General view of the spacecraft. The large cylinder on top represents the volume available for additional payload beyond the baseline vehicle.

Figure 4.2.—General view of the baseline spacecraft.

Table 4.3.—Launch Dates and Maximum Payload Masses for Each Considered Launch Window

Launch Date	2026, June	2028, January	2029, November	2031, June
Transit mass to Venus (Angara-A5, КВТК), kg	7,000	6,300	6,400	7,000
Transit mass to Venus (Angara-A5, ДМ-03), kg	6,900	6,200	6,300	6,900

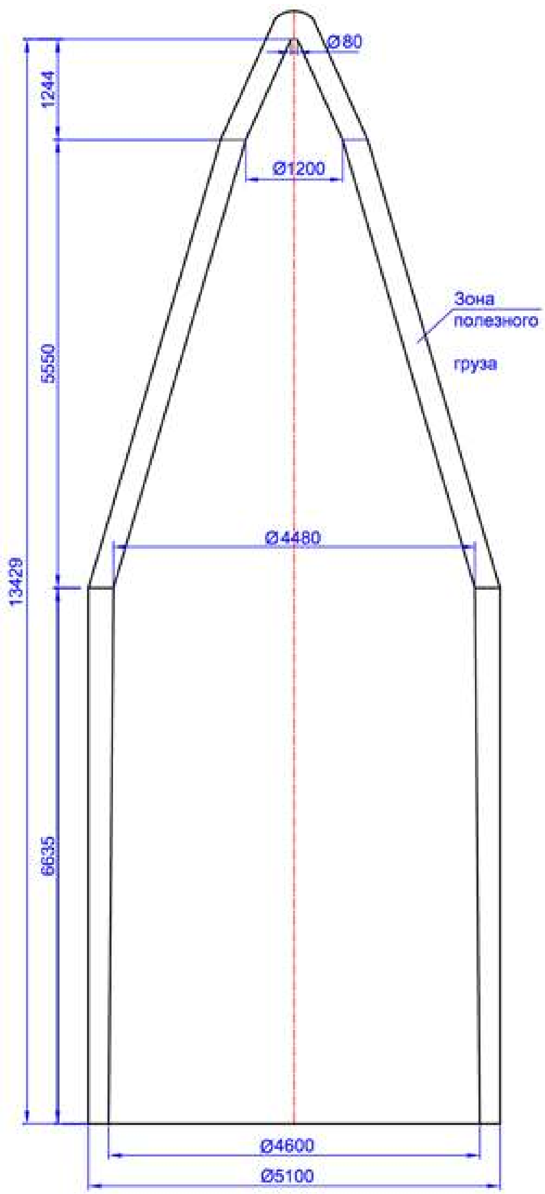


Figure 4.3.—LVF dimensions.

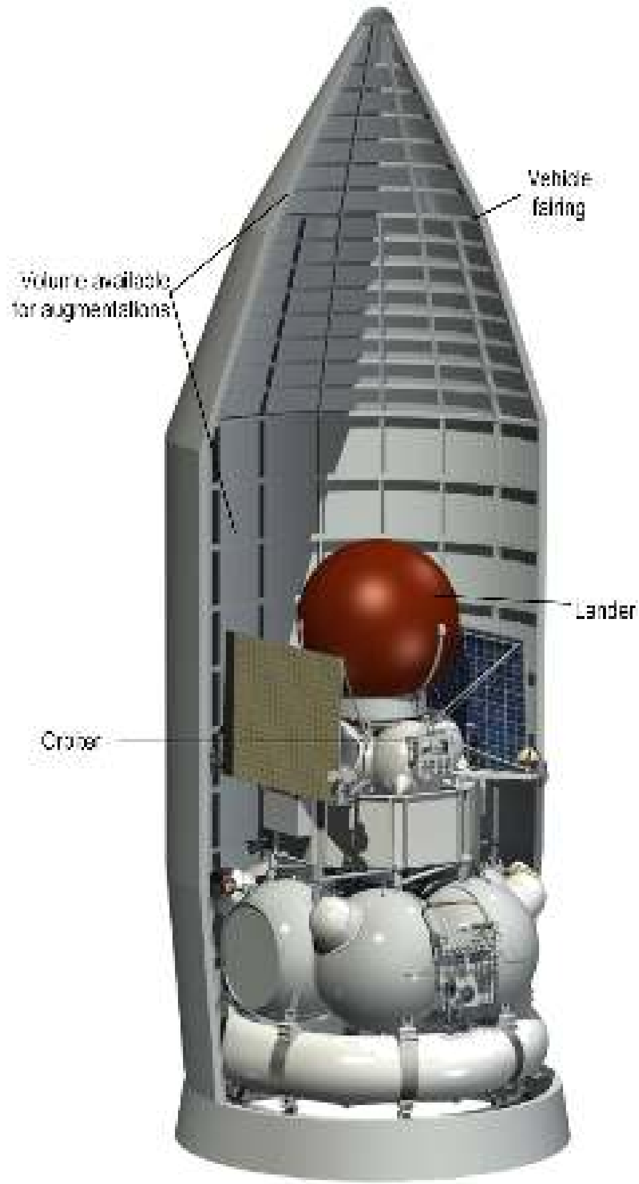


Figure 4.4.—Example of spacecraft and accommodation for potential augmentations under head fairing.

During selection process of spacecraft design, the following restrictions are imposed:

(1) Spacecraft mass should not exceed 6,400 kg for optimal composition or 6,200 kg for the worst-case modification;
(2) Geometrically, the spacecraft is restricted by payload zone dimensions of the LVF. Note that in the latest Angara documentation, there are small changes in payload zone dimensions of the LVF; thus, the zone may be reduced beyond what is shown in Figure 4.4;
(3) Static momentum of the spacecraft with adapter from the plane of adapter and lander-upper stage joint with upper stage must not exceed 18.5 tonne×m; and

(4) Overall dimensions and mass of the LM should not exceed those of Venera and VEGA landers to be able to accommodate more equipment or to increase the lifetime of LM on the surface.

Mass and fuel budgets for every considered window of launch are shown in Table 4.4 to Table 4.11, with power consumption budgets in Table 4.12. It is assumed that the "orbiter payload" line item includes both the baseline set of instruments (approximately 100 kg) plus a large amount of mass that can be used for optional elements such as an aerial vehicle or subsatellite. If the optional element does not have to be placed into orbit first (e.g., direct entry of an aerobot inside an entry vehicle), then more mass would be available because of the reduced propellant need to get into orbit.

Table 4.4.—Mass Budgets for 2026 (May 30, 2026 to June 20, 2026), Three Possible Launch Windows; Worst-Case Scenario Shown, Including Lowest Engine Thrust Level of 500 kg

Part of the Spacecraft	Mass, kg
	KBKhM (500 kg)
1. Orbiter	**4,796**
1.1 Orbiter dry mass	1,169
1.2 Orbiter payload	1,333
1.3 Fuel	1,943
1.4 Reserve for orbiter dry mass	351 (30%)
2. Lander	**1,720**
2.1 Lander dry mass	521
2.2 Lander detachable system	710
2.3 Lander payload	120
2.4 Reserve for lander dry mass *(of 2.1+2.2)*	369 (30%)
3. Free mass	**384**
Total spacecraft mass:	**6,900**

Table 4.5.—Fuel Budgets for Конструкторское бюро химического машиностроения имени А.М. Исаева (KBKhM) (500) for 2026 (May 30, 2026 to June 20, 2026); Three Possible Launch Windows Considered; Worst-Case Scenarios Shown

Phase	ΔV, m/s	Reserve, %	ΔV with reserve, m/s	Isp, s	Fuel, kg	Duration, s
1st correction	80	50	120	327	258.7	196
2nd correction, lander separation	20	50	30	302	66.3	335
Braking into Venus orbit, payload separation	899	3	926	327	1,190.7	815
Orientation, stabilization, maneuvers	425	7	455	290	413.3	3,445
Total:	**1,424**	–	**1,531**	–	**1,929.0**	**4,791**

Table 4.6.—Mass Budgets for 2028 (December 25, 2027 to January 16, 2028); Three Launch Windows Considered; Worst-Case Scenario Shown, Including Lowest Engine Thrust Level of 500 kg

Part of the Spacecraft	Mass, kg
	KBKhM (500 kg)
1. Orbiter	**4,600**
1.1 Orbiter dry mass	1,169
1.2 Orbiter payload	1,333
1.3 Fuel	1,843
1.4 Reserve for orbiter dry mass	255 (21.8%)
2. Lander	**1,600**
2.1 Lander dry mass	521
2.2 Lander detachable system	710
2.3 Lander payload	120
2.4 Reserve for lander dry mass *(of 2.1+2.2)*	249 (20.2%)
3. Free mass	**0**
Total spacecraft mass:	**6,200**

Table 4.7.—Fuel Budgets for KBKhM (500 kg) for 2028 (December 25, 2027 to January 16, 2028); Three Launch Windows Examined and Worst-Case Scenario Shown, Including Lowest Engine Thrust Level of 500 kg

Phase	ΔV, m/s	Reserve, %	ΔV with Reserve, m/s	Isp, s	Fuel, kg	Duration, s
1st correction	80	50	120	327	232.7	178
2nd correction, lander separation	20	50	30	302	59.3	299
Braking into Venus orbit, payload separation	1,058	3	1,090	327	1,206.7	826
Orientation, stabilization, maneuvers	425	7	455	290	330.3	2,753
Total:	**1,583**	–	**1,695**	–	**1,829.0**	**4,056**

Table 4.8.—Mass Budgets for 2029 (November 8, 2029 to November 18, 2029), Two Possible Launch Windows Examined; Worst-Case Scenario Shown with Engine Thrust Level of 500 kg

Part of the Spacecraft	Mass, kg
	KBKhM (500 kg)
1. Orbiter	**4,700**
1.1 Orbiter dry mass	1,169
1.2 Orbiter payload	1,333
1.3 Fuel	1,851
1.4 Reserve for orbiter dry mass	347 (29.7%)
2. Lander	**1,600**
2.1 Lander dry mass	521
2.2 Lander detachable system	710
2.3 Lander payload	120
2.4 Reserve for lander dry mass (of 2.1+2.2)	249 (20.2%)
3. Free mass	**0**
Total spacecraft mass:	**6,300**

Table 4.9.—Fuel Budgets for KBKhM (500 kg) for 2029 (November 8, 2029 to November 18, 2029), Two Possible Launch Windows Examined; Worst-Case Scenario Shown

Phase	ΔV, m/s	Reserve, %	ΔV with Reserve, m/s	Isp, s	Fuel, kg	Duration, s
1st correction	80	50	120	327	235.7	180
2nd correction, lander separation	20	50	30	302	60.3	304
Braking into Venus orbit, payload separation	1,017	3	1,090	327	1,194.7	818
Orientation, stabilization, maneuvers	425	7	455	290	346.3	2,886
Total:	**1,542**	–	**1,653**	–	**1,829.0**	**4,056**

Table 4.10.—Mass Budgets for 2031 (May 25, 2031 to June 15, 2031), Three Launch Windows Examined and Worst-Case Scenario Shown, Including Engine Thrust Level of 500 kg

Part of the Spacecraft	Mass, kg
	KBKhM (500 kg)
1. Orbiter	**4,845**
1.1 Orbiter dry mass	1,169
1.2 Orbiter payload	1,333
1.3 Fuel	1,992
1.4 Reserve for orbiter dry mass	351 (30%)
2. Lander	**1,720**
2.1 Lander dry mass	521
2.2 Lander detachable system	710
2.3 Lander payload	120
2.4 Reserve for lander dry mass *(of 2.1+2.2)*	369 (30%)
3. Free mass	**225**
Total spacecraft mass:	**6,900**

Table 4.11.—Fuel Budgets for KBKhM (500 kg) for 2031 (May 25, 2031 to June 15, 2031), Three Launch Windows Examined; Worst-Case Scenario Shown

Phase	ΔV, m/s	Reserve, %	ΔV with Reserve, m/s	Isp, s	Fuel, kg	Duration, s
1st correction	80	50	120	327	258.7	196
2nd correction, lander separation	20	50	30	302	66.3	335
Braking into Venus orbit, payload separation	950	3	979	327	1,248.7	854
Orientation, stabilization, maneuvers	425	7	455	290	404.3	3,370
Total:	**1,542**	–	**1,653**	–	**1,829.0**	**4,056**

Table 4.12.—Power Consumption Budgets

Name of Position	Power Consumption, W	
	Average	Maximum
1. Transit Earth-Venus:	**1,150**	**1,700**
— Service systems OM	700	1,100
— Heating of LM	400	500
— Service systems LM	25	50
— Payload	25	50
2. OM functioning:	**850**	**1,500**
— Service systems OM	650	1,250
— Payload	100	250
3. LM functioning on surface:	**400**	**700**
— Service systems LM	350	500
— Payload	50	200

4.1.2 Orbiter Design

The orbiter module (*OM*, orbiter) is designed for Earth-Venus transit, delivery of the lander and payload equipment (PE) to Venus, functioning while in orbit, collecting data, transmitting collected data to Earth and data from the lander, and, potentially, for additional mission elements. A simplified general view of the OM is given in Figure 4.5.

Mass characteristics are indicated in Table 4.4.

Figure 4.5.—Simplified, general view of the OM. HGA is high-gain antenna.

The design of the OM appears as a framework structure with a four-tank propulsion engine in a polyhedron shape with solar batteries and the necessary service equipment to provide OM functioning during all stages of the transit flight to provide LM functioning until the moment of its separation and for communication with LM after its landing on the surface of Venus.

The OM is not pressurized and the equipment is functioning under the conditions of outer space.

Temperature control is provided with the help of thermal pipes, radiators, heaters, sensors, screen-vacuum thermo-insulation, and thermo-optical coverings. The following temperature ranges of elements and equipment location are supported:

- –150 °C up to +150 °C—for framework elements;
- –50 °C up to +50 °C—for mechanisms; and
- –20 °C up to +40 °C—for service/scientific equipment.

The spacecraft power supply is provided by two retractable solar panels on a single-stage drive, with the entire effective area of 10.9 m^2 that generates 2,400 W at the end of lifetime. One or two Li-ion rechargeable batteries with a capacity of 90 A/hr are used to store electrical energy.

Onboard scientific equipment, depending on the requirements, can be accommodated on the side or upper thermal sandwich panels, upon solar batteries, retractable poles, or other elements of the structure.

The main principles of design were

- Minimal height,
- Maximal usage of horizontal space, and
- Minimal arm of the spacecraft's center of mass with respect to the rocket's interface.

The suggested accommodation is also universal when the succession of LM and AP separation from the spacecraft is not yet certain.

4.1.2.1 Radio Communication Procedures

The following radio systems will be used (bit rates listed are for a 500 km by 66,000 km orbit) for communication with Earth and any elements in the Venus atmosphere and Venus' surface:

(1) A set of low-gain antennas (LGAs) for receiving/transmitting service information to and from ground stations in X-band at the rate of about 2 to 16 bit/s;
(2) An HGA with a diameter of 2.6 m on a double-stage drive for transmitting scientific information to Earth in X-band at the rate from 32 to 512 Kb/s; and
(3) A set of LGAs for receiving and transmitting service and scientific information as well as to and from separately functioning scientific equipment and LM in the range of frequencies from 50 to 150 MHz and 420 MHz. The rate depends on the transmitter parameters of separately functioning scientific equipment and LM.

Ka-band may be utilized for the transmission of scientific information to Earth through an HGA. In this case, the transmission rate will be from 3.2 to 26 Mb/s for approximately similar dimensions of antenna.

The reference distance (for estimation only) is taken to be 100,000 km. The Venera-D lander-orbiter radio link can be implemented at 50 MHz carrier frequency using LGA transmit (TX) 3dB, LGA receive (RX) 5dB, TX power 10 W, RX noise 100 K, and Turbo ¾ forward error correction (FEC).

The data transmission rate reaches 470 Kb/s, and 1.6 Gb (of 200 Mb) of information may be transmitted for 1 hr with LGA and 50 MHz (without pointing the antennas).

Radio signal travel time from the OM to Earth requires from 2 min 6 s (38 million km) to 14 min 30 s (261 million km) to arrive at the minimum and maximum range.

The transmission of scientific information to Earth is affected by the direct radio visibility of surface stations. When there is no line-of-sight, collected information is stored in the lander's onboard memory unit, which can be >128 MB.

In accordance with the preliminary operational timeline, the combined volume of generated scientific information is

(1) On the lander—200 MB per lifetime (3 hr), i.e., necessary rate must be not less than 256 Kb/s (including 15% reserve); and
(2) On the orbiter (including separable scientific equipment and active LM)—303 MB/hr + 50 MB/hr transmission from LM, i.e., necessary rate must be not less than 928 Kb/s (including 15% reserve).

4.1.2.2 Control and Orientation

Solar sensors and star trackers, gyroscopes, and momentum wheels are used to orientate the spacecraft.

For generation of thrust impulses during active maneuvers and creation of the control momentum around the three axes of the spacecraft, a two-component liquid-propellant unit with the following characteristics is used:

- Oxidizer and fuel (dinitrogen tetroxide and UDMH);
- Four tanks (two for oxidizer, two for fuel) with an outer diameter of 1,000 mm each and a total four-tank fuel and oxidizer capacity of 2,100 to 2,050 kg;
- One main thruster of 4,706 N of thrust and average specific impulse of 319 s to generate braking and correction impulses;
- Eight thrusters of 98 N each and average specific impulse 302 s for correction impulses, orbit corrections, rough orientation, and stabilization; and
- Four thrusters of 6 N each and average specific impulse 207 s for precise orientation and stabilization.

Two-component liquid-propellant unit is practically the single possible choice for this mission, because unlike electrically powered propulsion engine or a one-component liquid-propellant unit, it is the only one that allows performance of the required maneuvers with sufficient thrust and velocity change.

4.1.3 Main Lander Design

The landing module (*ПМ*, lander) is designed for performing scientific measurements during the descent and on Venus' surface by using scientific instrumentation installed in it.

The general lander design closely resembles Venera and VEGA LMs. The choice is due to the absence of high-temperature avionics, though activity in this direction is continuing (see Section 7), and proven readiness of the previous structure and thermal control subsystems. Future work is desired to produce improvements of these materials and onboard avionics equipment (OE).

The design of the lander includes a titanium structure developed for accommodation of OE; IC with OE, including a temperature-resistant cover that allows the LM to operate on Venus' surface for not less than 3 hr; the landing device with the damper, designed to absorb vibrations of the LM during atmospheric entry and to land on the surface; and a separable structure with a parachute system, designed to aerobrake the lander.

Scientific equipment can be accommodated on any available space inside the IC, on the brake shield, landing device, and outer surfaces of the LM.

Several optical windows and electrical feedthroughs can be accommodated in the insulated pressure vessel to provide optical and wiring access to the outside. The windows may be covered from outside by protective covers ("shutters") on pyro-bolts that are fired by a remote command to reduce the influx of heat prior to usage.

The simplified general outlook of the LM and in cross section are shown in Figure 4.6 and Figure 4.7.

Mass characteristics are indicated in Table 4.4 in the previous section.

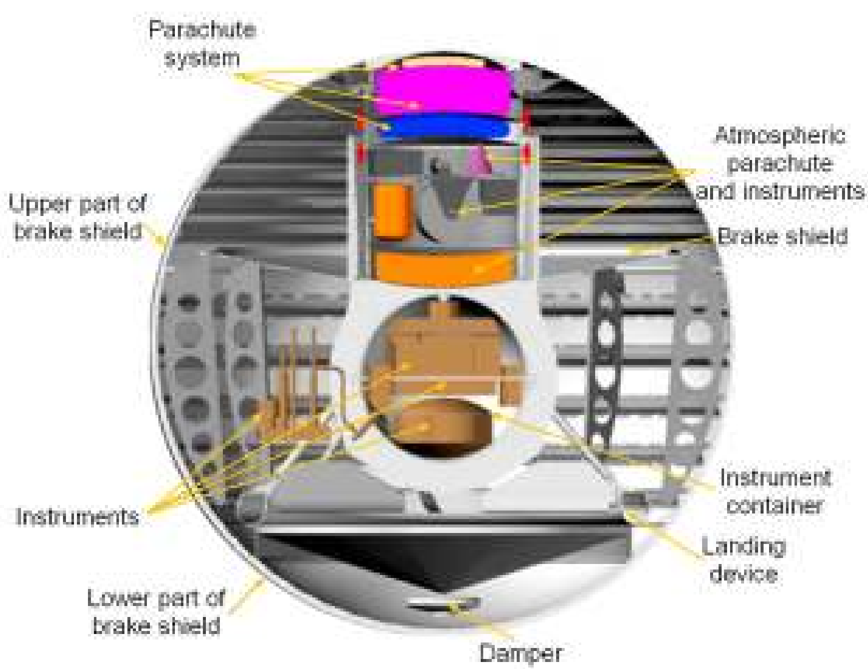


Figure 4.6.—Example of lander accommodation design.

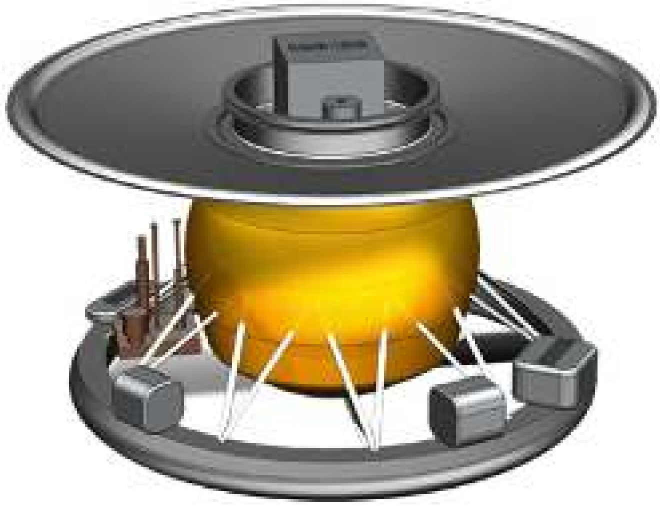


Figure 4.7.—Simplified general outlook of the lander.

4.1.3.1 Radio Communication

LM communications with Earth will be via the OM, which serves as a retransmission link. For communication with the OM, the LM utilizes the following radio systems (bit rates are indicated for the reference distance to the OM of 100,000 km:Kb/s).

4.1.3.2 Orientation and Landing

After entering Venus' atmosphere, landing is carried out in automatic mode.

The descent cycle is generally designed in accordance with the same principles that Venera and VEGA landers used. The entry begins at the velocity of 11 km/s and then is reduced to subsonic speeds by aerodynamic braking. After that, a pilot (drogue) parachute is deployed, and the upper hemisphere is separated and then carried away. Next, the main parachute is deployed and, the lower hemisphere is separated. The LM descends using the parachute, simultaneously performing measurements with its scientific equipment. Finally, the parachute is separated at an altitude of 45 km, the descent proceeds using the drag plate to moderate the speed, and the LM touches down on the Venus surface, where it continues to function for about 3 hr. The total time of descent is about 40 min. The maximum overload during the Venus atmosphere entry phase is 120g.

The descent diagram is shown in Figure 4.13.

The LM is designed in such a way that its center of mass is located closer toward its lower part; thus, during descent in Venus' atmosphere and landing on the ground, it is aerodynamically stable and automatically maintains a vertical position. Starting from parachute deployment, carrying out scientific experiments becomes possible.

The LM descending procedure can be subdivided into three stages:

(1) Aerodynamic braking;
(2) Parachute-controlled descent; and
(3) Descent using the drag plate to moderate the speed.

4.1.3.3 Temperature Mode and Operational Conditions

The LM contains an IC, which will maintain conditions necessary for the instruments to function inside the container during its lifetime on the surface. The entire structure must be kept at <1 atm. Thermal protection will be provided by insulation that reduces the heat transfer from the outer environment and also by a phase-change heat sink material (lithium nitrate trihydrate) that absorbs heat that enters the IC and maintains the desired operating temperature. This thermal design approach is based on the previous Venera and VEGA series landers that likewise did not benefit from the use of high-temperature electronics.

Inside the IC, the following conditions will be maintained during lander lifetime (about 3 hr):

- Pressure from 0.02 up to 1 atm (2 to 101 kPa); and
- Temperature from –50 up to +50 °C.

After exhaustion of the heat sink's capacity, the temperature inside the IC begins to increase. The end of LM functioning is considered to be at the moment of thermal "death" of radio transmitting equipment; i.e., when the temperature inside the IC reaches 90 to 120 °C.

The lifetime of LM and equipment inside the IC depends upon the following factors:

(1) Thermal dissipation of equipment inside the IC;
(2) Maximum allowed temperature for functioning of separate instruments;
(3) Heat capacity of equipment inside the IC;
(4) Operations timeline of separate instruments in the IC;
(5) Performance of the thermal insulation on the pressure vessel; and
(6) Quantity, dimensions, and parameters of windows in the thermo-protective layer of the LM and techniques of thermal shielding.

Although this IC design is based on the prior Venera and VEGA landers, there are possibilities for engineering improvements to be considered, including

- Use of new structural and thermal materials developed over the past three decades;
- Use of multiple heat sink materials with different phase transition temperatures to improve thermal performance;
- Division of the IC into two parts: the first part should accommodate equipment with a short required lifetime, using a small amount of heat sink material; equipment with a longer required lifetime should be placed in the second part that would be protected with a larger heat sink; and
- Use of high-temperature electronic components that reduce the thermal protection requirements and/or increase operating lifetime. This option is further described in the next section.

Thus, at this stage, we should study how to increase the functioning period of the LM on Venus surface without using high-temperature electronics.

4.1.3.4 Prospective Technology—Maneuverable Entry Vehicle (MEV)

The suggested LM based on Venera and VEGA missions has a spherical shape and is a ballistic vehicle with zero aerodynamic quality at hypersonic velocities that do not allow maneuvering during descent in the atmosphere. A potential development is the possibility of employing other configurations of landers such as MEV, able to perform maneuvering and provide a wider scope of landing site selection. MEVs can be used both for the main lander design and for additional small surface stations, which can land separately at some distance from the main lander to enable more science (Kosenkova et al., 2018). Such an option can be considered in more detail at later stages.

4.1.4 Long-Lived In-Situ Solar System Explorer (LISSE): Small Surface Stations

Recent advances in high-temperature systems, especially electronics, have opened up opportunities to generate new concepts to explore the surface, interior, and deep atmosphere of Venus. Where previous missions and concepts were limited to a surface life expectancy of a couple hours at best, new concepts are changing the paradigm of what science questions can be tackled and how that may occur.

Technology advances have been made possible through years of investment in systems, sensors, and electronics for harsh environments, driven primarily by aeronautics applications. Recently NASA has invested in a project known as LLISSE, which is developing two prototype probes of the same name.

LLISSE probes are being developed to demonstrate, via testing at Venus surface conditions and chemistry, that key measurements can be made and returned over extended timeframes from the surface of Venus. This capability is intended to help make progress in our understanding of Venus and planetary bodies in general. As with Venera-D, the science questions that LLISSE targets are traced to the Planetary Decadal Survey and the Venus exploration goals, objectives, and investigations documents. The key goals of LLISSE and its long-duration measurements are to increase our knowledge of superrotation of the atmosphere, the climate and its evolution, and surface-atmosphere interaction. These goals are achieved by taking measurements of wind speed and direction, temperature, pressure, incident and reflected solar radiance, and abundance of local selected atmospheric chemical species.

4.1.4.1 Concept Overview

LLISSE probes are small and lightweight (~20 cm and 10 kg) but will function on the surface of Venus for 90 days or longer (Figure 4.8). The LLISSE project includes the design and development of two probes (battery and wind powered) and demonstration tests to confirm functionality over the desired life at Venus surface conditions.

Low-power, high-temperature sensors are being employed to take the periodic meteorology measurements listed above and chemical composition. These periodic measurements (assumed to be every 8 hr) would occur over 60 days, covering at least one terminator.

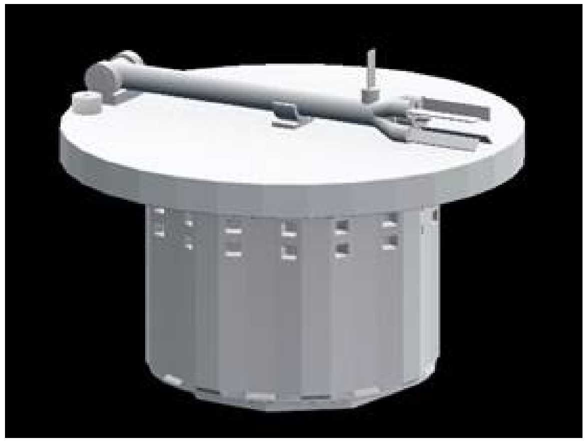


Figure 4.8.—Notional concept for the battery powered version of LLISSE (with sensor mast stowed).

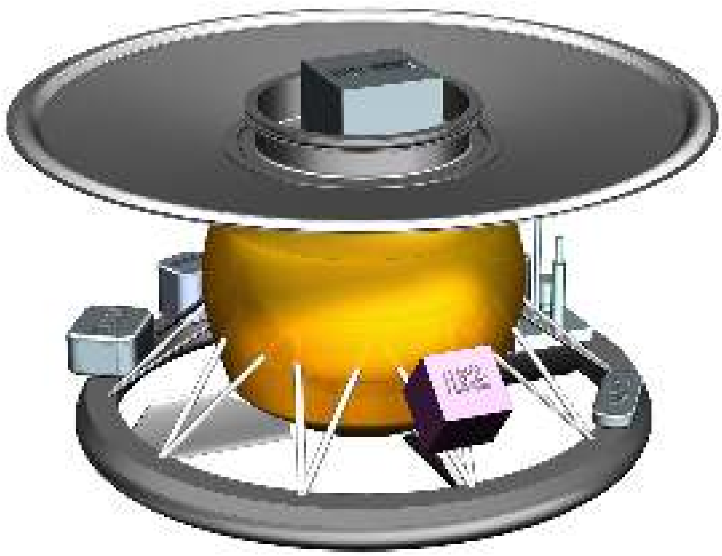


Figure 4.9.—One potential position of LLISSE carrier on the Venera-D lander. Image courtesy of NPOL.

In the recommended baseline mission, LLISSE serves as a companion to Venera-D in that (1) Venera-D will include a long-duration orbiter, which will perform the necessary data relay functionality, and (2) Venera-D will include a main lander, which will serve as host to help deliver the small LLISSE probes to the Venus surface. The main Venera-D lander will have sophisticated instruments and sensors that can complete their mission in ~2 hr. Inclusion of a contributed LLISSE probe will allow for continued weather and chemical species variability data to be collected at that site for months, and thus enhancing the science in a unique way. Figure 4.9 reflects one concept for a LLISSE carrier to be attached to the main lander.

4.1.4.2 Development Status

As of December 2018, the LLISSE project has made notable progress toward its objectives. The capability of the core electronics has been increased by over an order of magnitude since the start of the project less than 2 yr ago. Versions of most sensors have demonstrated survival and basic operations at Venus conditions for extended periods, several for the full 60-day life goal. Components of some of the important subsystems, like communications, have been developed and proof-of-concepts have been demonstrated. A recent test verified successful integrated operations between driving electronics and the supported sensor. If the project continues on its successful path, it will demonstrate a battery-powered version of a breadboard fidelity probe in late 2019 to early 2020. The system-level demonstration test will be conducted in the NASA Glenn Extreme Environments Rig (GEER) (Figure 4.10), which will replicate Venus surface temperature, pressure, and chemistry. The system is planned to have full functional capability (although not with a flight-like structure and not at the final communication frequency it will have in flight). This demonstration will provide a high degree of confidence that the probe will work on Venus. Final demonstration of full communication capability (operations between 50 and 150 MHz) is planned in the project schedule in 2021. A lower fidelity wind-powered version of LLISSE is also being developed in the same timeframe (Figure 4.12).

Figure 4.10.—The NASA Glenn GEER facility is used to simulate Venus conditions for experimental, development, and test purposes.

4.1.4.2.1 High-Temperature Electronics and Sensors

Advancements in high-temperature electronics are enabling for the LLISSE probes. Standard electronics do not operate at Venus temperatures. This implies a need to use wide-bandgap electronics. The LLISSE probe electronics and sensors systems require moderately complex integrated circuits and SiC-based electronics are the most mature and viable technology at this time.

Recent work has produced the world’s first microcircuits of moderate complexity that have shown sustained operation at 500 °C. This enables a range of onboard data processing, including signal amplification and local processing. Operational life at 500 °C for thousands of hours has been demonstrated for key circuits.

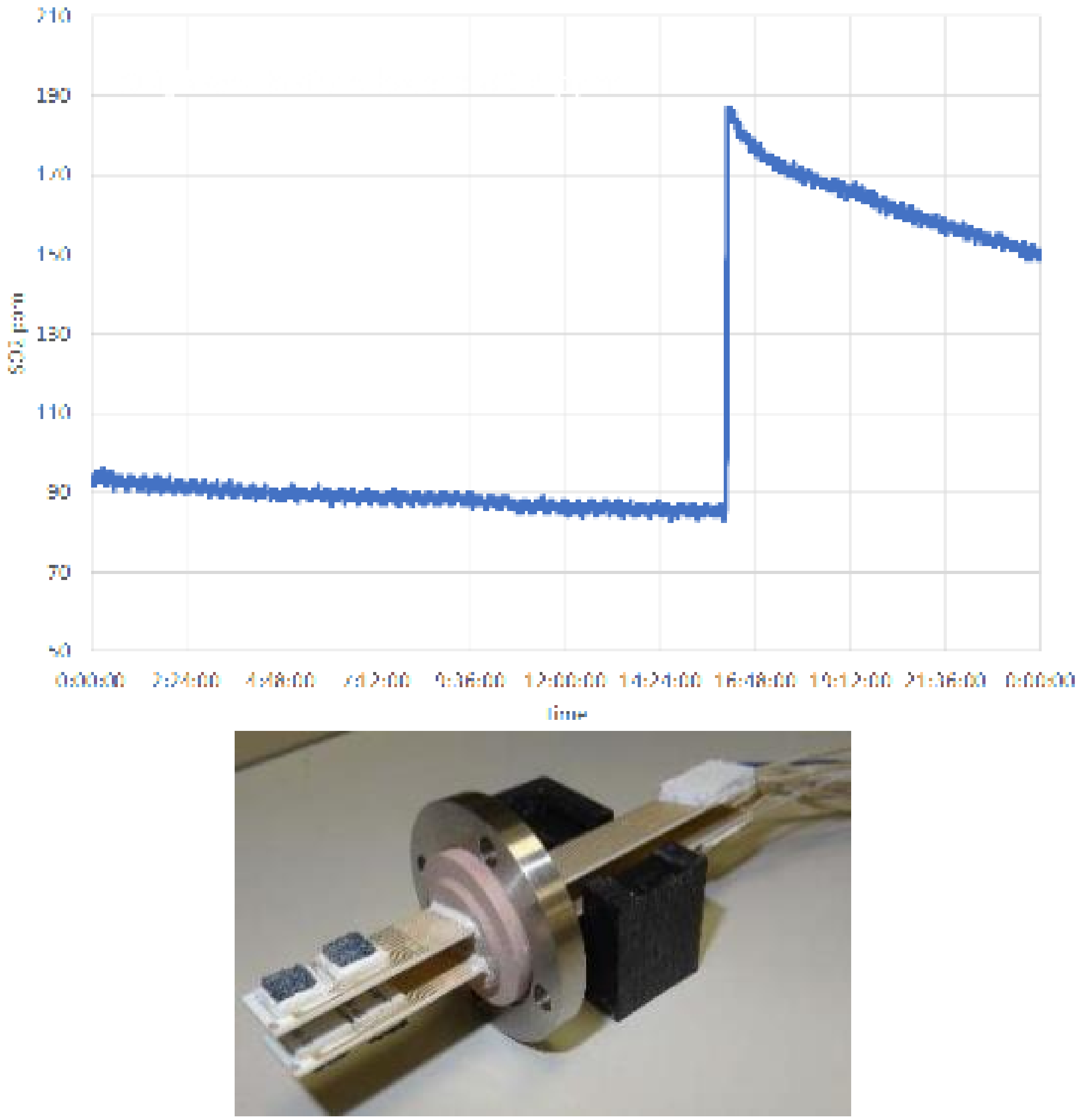


Figure 4.11.—Makel Engineering Inc, chemical species sensor and data from recent test in GEER at Venus surface conditions. Successful capture by sensor of SO_2 concentration boost is shown.

4.1.4.2.2 Power

NASA has a dual-approach for battery development. The first approach is to develop a high-temperature tolerant battery (HTTB) technology to achieve safe, long-life, high specific energy operation, and powered only by the primary battery. The LLISSE battery, and therefore, probe would stay dormant during cruise and launch. It automatically powers on and begins operation at the surface of Venus. High-temperature battery development is in progress, and due to the criticality of the battery to mission success, parallel efforts are being funded.

A rechargeable battery will also be developed under the project to support the wind-powered version of the LLISSE probe. Surface winds on Venus would charge the rechargeable battery via a small wind turbine mounted on the top of LLISSE, perhaps appearing as depicted in Figure 4.12.

The wind-powered version could theoretically have indefinite life. Current development plans are to build a scale version of the wind-powered probe for testing in GEER. The GEER will be outfitted with capability to produce and sustain controlled winds for this test. The final demonstration test of the wind powered LLISSE will be at Venus conditions and run for 60 days.

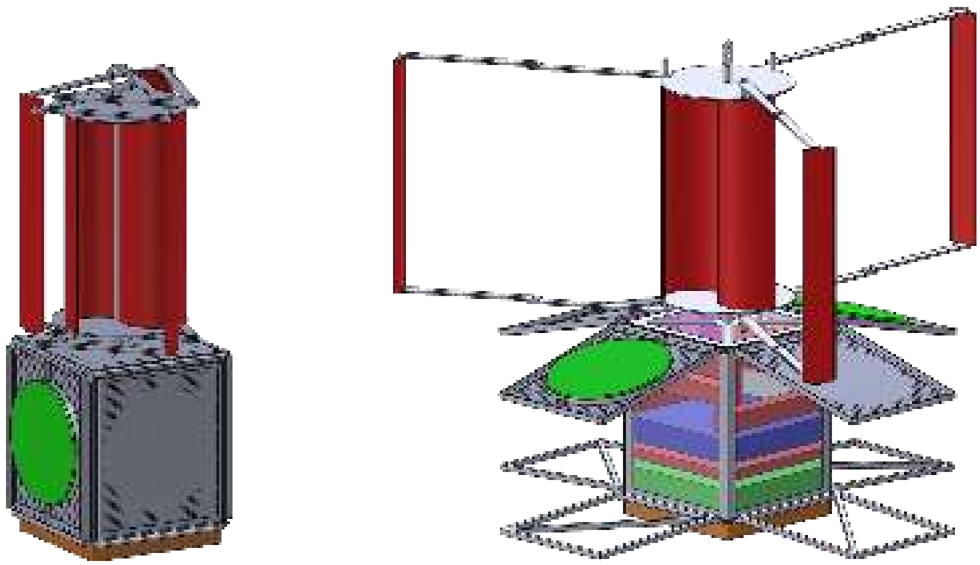


Figure 4.12.—Concept model of LLISSE-W (wind-powered).

4.2 Mission Level

4.2.1 Concept of Operations (CONOPS)

The scheme of the mission includes the following stages (the detachment of elements is feasible starting from stage 3):

(1) Lift off of the spacecraft into the cruise trajectory from the “Vostochnyi” launch site using Angara-A5, transition into Earth-Venus trajectory by means of KVTK, and detachment of the spacecraft;
(2) About 4 months transfer along Earth-Venus trajectory with correction maneuvers that bring the spacecraft to Venus;
(3) Final targeting maneuvers to provide the specified conditions of LM entry into the Venus atmosphere;
(4) LM and its adapter separation from the OM 1 to 2 days before the planet approach;
(5) Redirection of the OM to prevent it from entering the Venus atmosphere with a periapsis altitude up to 500 km;
(6) Orbit insertion maneuver with the main propulsion system to transfer the orbiter to an elliptical orbit and start of nominal phase of the orbiter;
(7) Lander operation for 3 hr after landing
    (a) Orbiter serves as telecom relay for lander for lander lifetime; and
(8) Orbiter operation for 2 yr and 8 months after insertion into the targeted orbit.

This timeline would need additional steps for the deployment of any optional spacecraft elements such as subsatellites and an aerial vehicle carried in a separate entry aeroshell.

Orbit and time of OM approach are selected in such a way that the lander, descending in the atmosphere, was in the OM's radio visibility zone during the landing and entire surface lifetime (total from 3 to 4 hr). At the same time, the distance between the LM and OM should be minimized to achieve maximum information transfer rates.

The sequence of lander deploymentis presented in Figure 4.13.

Preliminary timelines of the baseline elements of operation from the beginning of the lander landing process are shown in Table 4.13 to Table 4.15 for the orbiter, lander, and LLISSE.

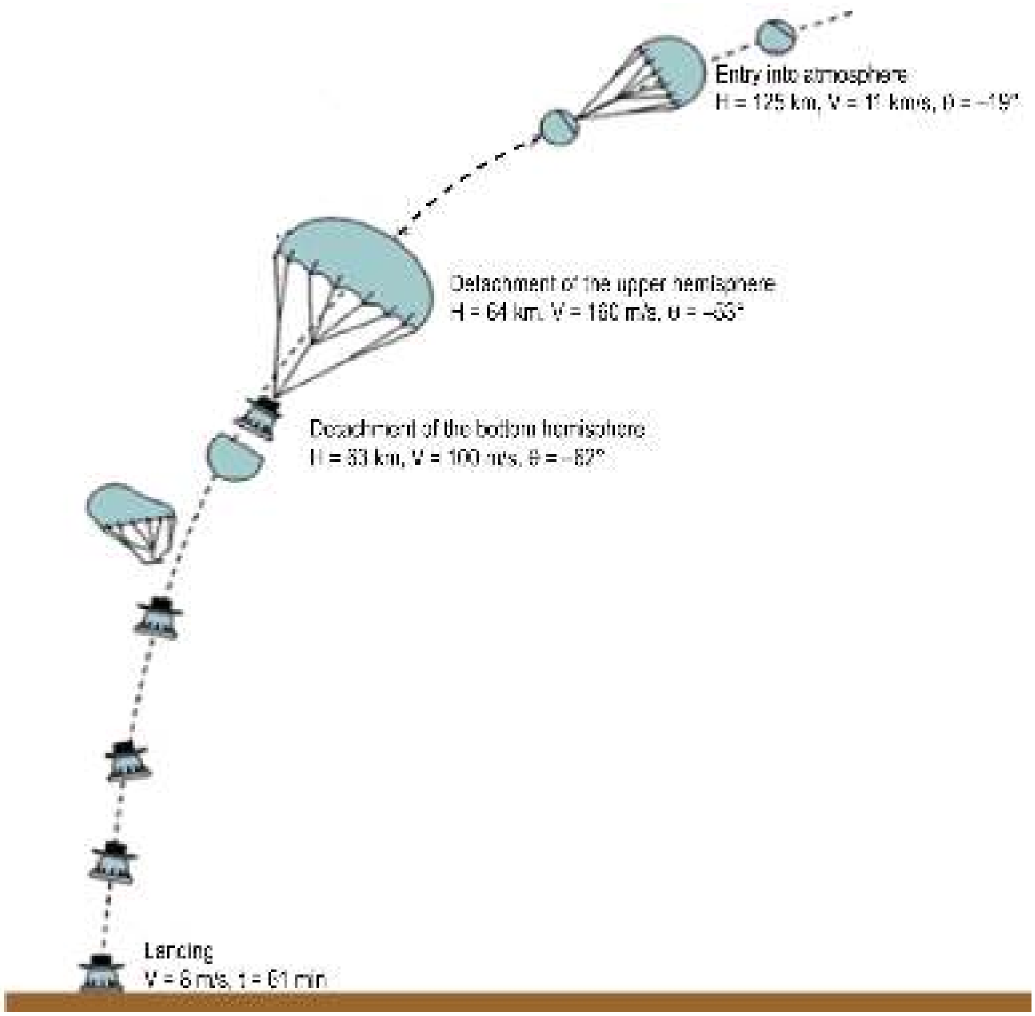


Figure 4.13.—Concept of operations for lander.

Table 4.13.—Preliminary Timeline for Orbiter Operation

Day	Time, hr:min	Operation
1	T1 –8:00	• Initiation of radio-link with Venus (LGA, transmission/receiving of housekeeping/science information, 420 MHz, 150 MHz). • Start of the insertion into orbit.
	T1 –0:40	• Accomplishment of insertion into orbit procedure.
	T1 –0:38	• Start of installation procedure of a radio link with the lander and small stations using LGA, and possibly receiving the lander science information. • Start of the lander search procedure using medium-gain antenna (MGA).
	T1	• Receiving of activity signal from LLISSE.
	T1 +5:50	• Prescribed termination of radio link with the lander (including 100% backup). • Start of procedure of search and radio link installation with detached elements and formation of working schedule.
	T1 +9:00	• Designed termination time of procedure of search and radio link installation with detached elements and formation of working schedule. After that, the orbiter is functioning in accordance with the working schedule. • Start of test procedure of the radio link with Earth.
	T1 +12:00	• Receiving of activity signal from small stations. • Termination of test procedure of the radio link with Earth.
2	T2	• Receiving of activity signal from small stations.
	T2 +8:00 >T60	• Receiving of activity signal from small stations. • Orbiter communication with LLISSE terminated.
980	T980	• Estimated time of termination of the orbiter functioning.

Table 4.14.—Preliminary Timeline for Lander Operation

Day	Time, hr:min	Operation
1	T1 –0:40	• Start of the lander entry into the Venus atmosphere.
	T1 –0:38	• Detachment of the front shield, deployment of parachute. • Detachment of aerial probe, balloons (if any), and start of their functioning and transmission of housekeeping/science information to the orbiter. • Start of functioning of scientific payload (including sampling of atmospheric gases and aerosols). • Start of functioning of radio system of the lander (LGA, receiving/transmission of housekeeping information). • Start of procedure of radio link installation with the orbiter using LGA.
	T1	• Landing on the surface of Venus. • Completion of radio link installation with orbiter using LGA. • Start of search of orbiter using MGA of the lander. • Deployment of small stations. • Start of soil sampling.
	T1 +0:15	• Completion of surface sample acquisition. • Start of soil samples analyses.
	T1 +0:45	• Completion of orbiter search using MGA (mean time of redirection is ~15 s). • Start of science data transmission using MGA.
	T1 +3:00	• Thermal death of the radio-system. Designed time of the lander functioning. • Designed volume of transmitted scientific data: - 325 MB of scientific data while using MGA of the lander during 2 hr 15 min, and - 15 MB of housekeeping/scientific data while using LGA of the lander during 3 hr 40 min.

Table 4.15.—Preliminary Timeline for Small Station (LLISSE) Operation

Day	Time, hr:min	Operation
1	T1 –0:38	• Start of functioning of LLISSE(s) within the lander (precise time depends on LLISSE temperature). • Sending of a series of test signals (from 2 to 8 signals, 8 to 32 byte altogether).
	T1	• Sending of activity signal (1 to 16 bits). • Start of measurements with transmission of scientific data to the orbiter (~3,000 bytes or more).
	T1 +8:00	• Measurements with transmission of scientific data to the orbiter (~3,000 bytes or more).
	T1 +16:00	• Measurements with transmission of scientific data to the orbiter (~3,000 bytes or more). • Sending of activity signal (1 to 16 bits).
	T1 +24:00	• Measurements with transmission of scientific data to the orbiter (~3,000 bytes or more).
2	T2	• Measurements with transmission of scientific data to the orbiter (~3,000 bytes or more). • Sending of activity signal (1 to 16 bits).
	T2 +8:00	• Measurements with transmission of scientific data to the orbiter (~3,000 bytes or more).
	T2 +16:00	• Sending of activity signal (1 to 16 bits).
	T2 +18:00	• Measurements with transmission of scientific data to the orbiter (~3,000 bytes or more).
60	T60	• Designed time of the end of functioning of LLISSE(s).

4.2.1.1 Long-Lived In-Situ Solar System Explorer (LISSE): Detailed Review of Operations, Data, Power and Time, and Orbiter Support Needs

To provide comparative measurements, the chemical and atmospheric sensor suite on the LLISSE will commence taking measurements when it reaches a specific internal temperature (details will be worked out for Phase III) and communications to the main orbiter are established.

The long-lived stations are not expected to have any memory for storing data and measurements are immediately sent to the transmitter for reception by any available communications receiver on the main orbiter or other relay assets such as the small satellites around L1 and/or L2 points (which will likely provide longer communication windows as the planet slowly rotates).

4.2.2 Communications

To transmit the scientific data from the lander and other surface or atmosphere mission elements to the orbiter, it is suggested to use LGAs and transmitters that could meet all the requirements. It is planned to use the ultrahigh frequency (UHF) band for this communication.

To transmit the scientific information from the orbiter to Earth several communication options, it is suggested to use HGAs and ground-based stations:

(1) X-band at 8 Mb/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 hr would be ~20 GB in this case;

(2) X-band, 12 to 17 Mb/s data rate. This option is currently under development within projects that are expected to be launched by 2020 to 2022. The data would be received by already existing ground-based stations with some level of augmentation necessary. The average data volume per 24 hr would be from 35 to 50 GB in this case; and

(3) Ka-band, 100 Mb/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 hr would be from 100 to 200 GB in this case.

4.2.3 Orbital Mechanics

The trajectory analysis presented here assumes launch opportunities in 2026 and 2027 (Figure 4.14 and Figure 4.15). 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 Earth-Venus flight trajectory using (hydrogen) KVTK or Briz («Бриз») upper stage vehicle;
(3) Flight along 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) 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 optional balloon may enter inside the descent module;
(7) Transfer of the orbital module onto a high elliptical orbit by the use of the rocket engine;
(8) Separation of a subsatellite (if provided); and
(9) Nominal scientific operations assuming data transmission from the Venus surface and subsatellite to Earth through the orbiter.

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

(1) Orbiter and subsatellite and their scientific payload; and
(2) Descent module and its scientific payload (including small-surface station(s) and balloon).

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 4.16. For a backup launch in 2027, the parameters are given in Table 4.17. Trajectory plots are shown in Figure 4.14 and Figure 4.15. 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 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 an astronomical reference frame (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 hr;
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; and

α_2^∞	right ascension of the arriving relative vector of asymptotic velocity in coordinate J2000, degrees.

Table 4.16.—Key Trajectory Parameters for 2026 Launch Date

Parameter	First Date for Launch Period	Middle Date for Launch Period	Last Date for Launch Period
Date of launch	May 30, 2026	June 9, 2026	June 20, 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, deg	210.04	206.57	209.05
Date of arrival	December 5, 2026	December 9, 2026	December 17, 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»): 6,500 kg.
Mass of the orbital module after putting it onto Venus satellite orbit with 24-hr period and 500-km pericenter altitude: more than 3,100 kg.

Table 4.17.—Key Trajectory Parameters for 2027 Launch Date

Parameter	First Date for Launch Period	Middle Date for Launch Period	Last Date for Launch Period
Date of launch	December 25, 2027	January 6, 2028	January 6, 2028
ΔV_1, km/sкм/c	4.302	4.198	4.112
V_1^∞ (C_{31}), км/c	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, deg	224.29	224.76	225.55
Date of arrival	July 12, 2028	July 20, 2028	July 27, 2028
ΔV_2, км/c	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»): 6,400 кг.
Mass of the orbital module after putting it onto Venus satellite orbit with 24-hr period and 500-km pericenter altitude: more than 2,900 кг.

As an example, Figure 4.14 illustrates trajectories of spacecraft transfer to the Venus 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 $\theta_{in} = -15°$. This means that the maximum load during entry into atmosphere would not exceed 100g.

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) and the second is position of the entry point (or the height of virtual pericenter). This means that this is 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 4.14, 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 Earth. This was done to reach the most favorable conditions for relay of the lander signal to Earth from the lander.

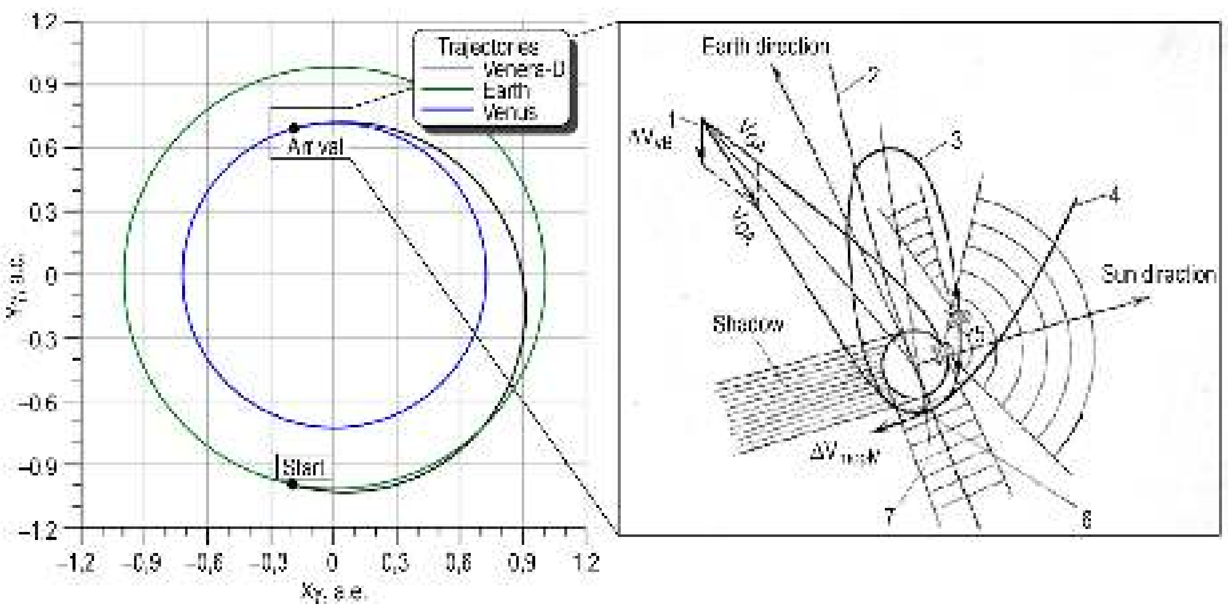


Figure 4.14.—(Left) Trajectory of transfer Earth-Venus with start in June 2026. (Right) Arrival in detail. Notes: (1) separation and trajectory offset, (2) Venus orbit, (3) orbiter's orbit, (4) flyby trajectory, (5) area of orbiter-lander communication, (6) braking and transferring the orbiter onto the orbit around Venus, and (7) radio shadow of Venus.

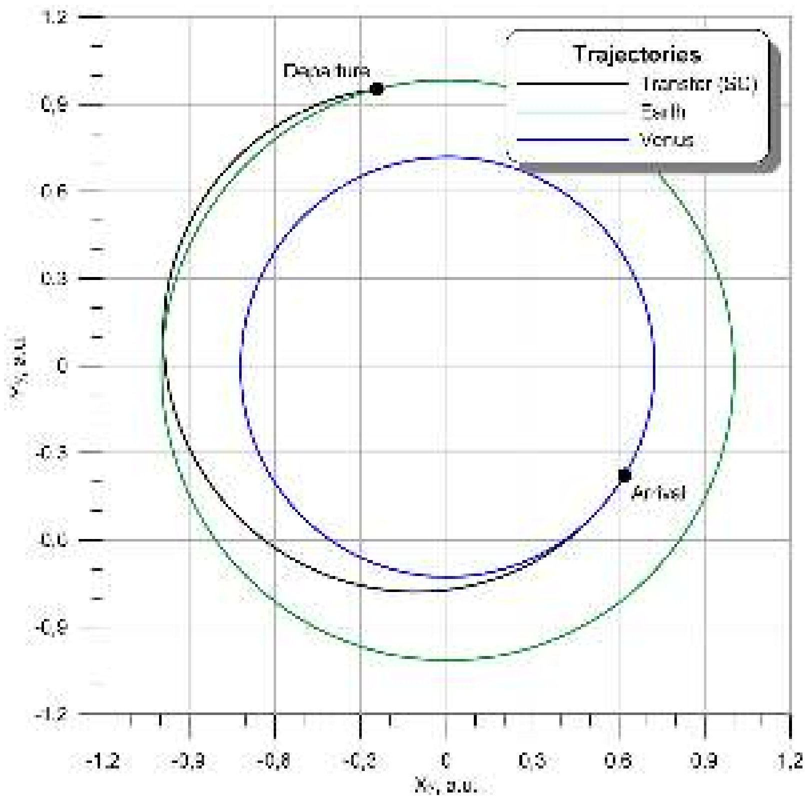


Figure 4.15.—Trajectory of transfer from Earth to Venus with a launch in December 2027.

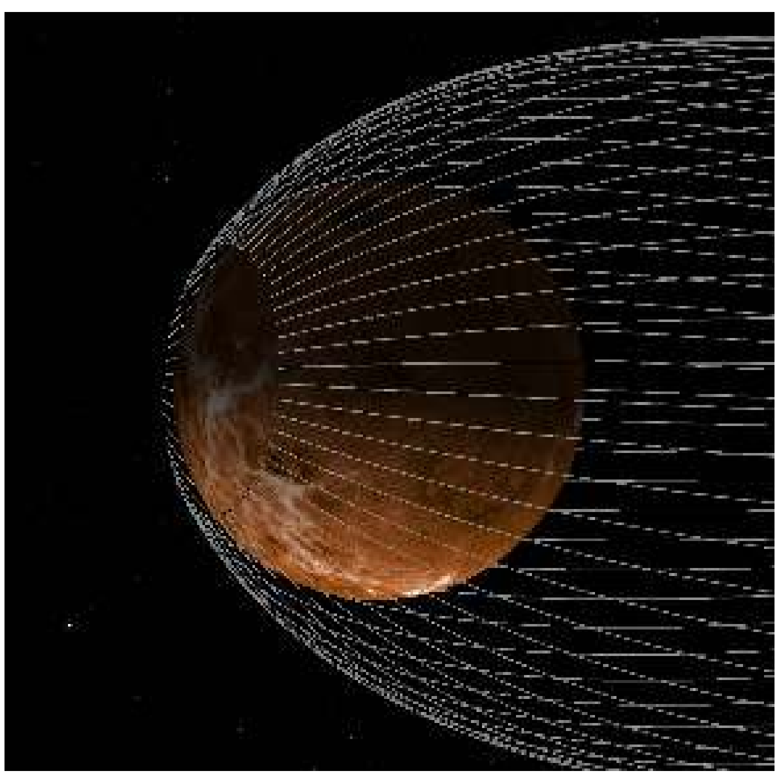


Figure 4.16.—Family of possible arriving hyperbolic trajectories.

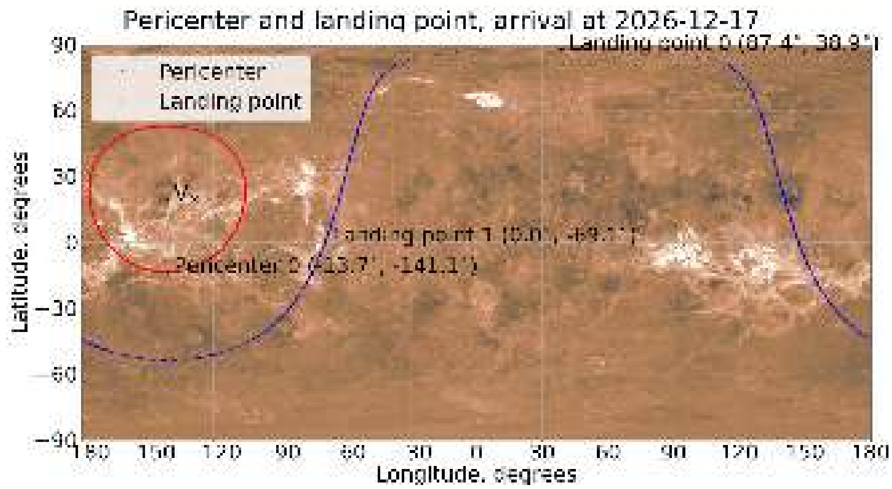


Figure 4.17.—Landing (blue) and perigee (red) points for date of arrival December 17, 2026.

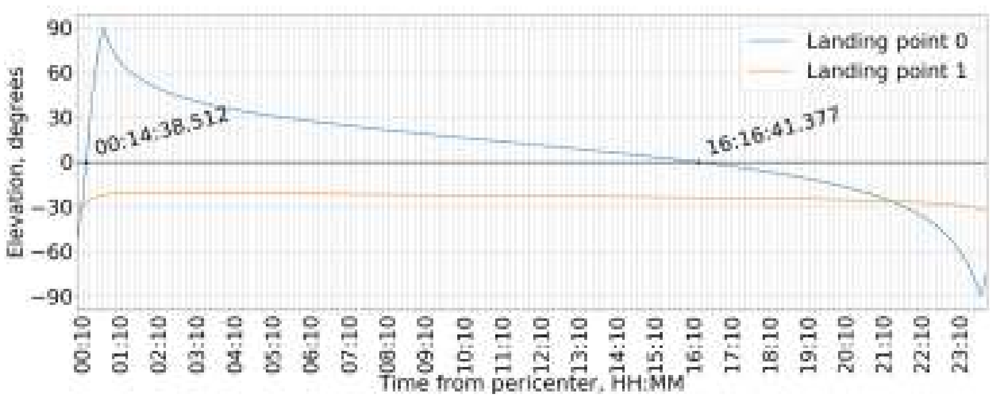


Figure 4.18.—Elevation of orbiter after perigee arrival (hours, minutes, seconds) over the local horizon of lander. Landing point has maximum latitude and orbiter pericenter has minimum latitude. Date of arrival December 17, 2026.

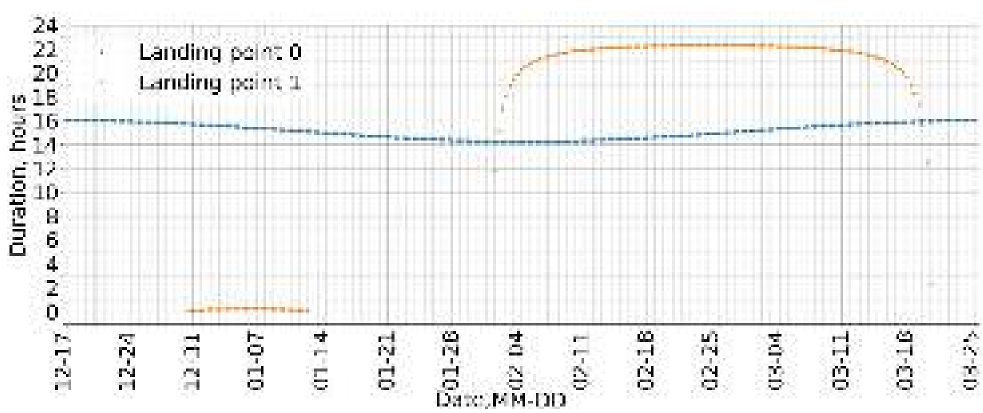


Figure 4.19.—Duration in hours of lander visibility from orbiter per one orbit (24 hr) for landing point with equatorial latitude (blue) and maximum latitude (yellow). Date of arrival December 17, 2026.

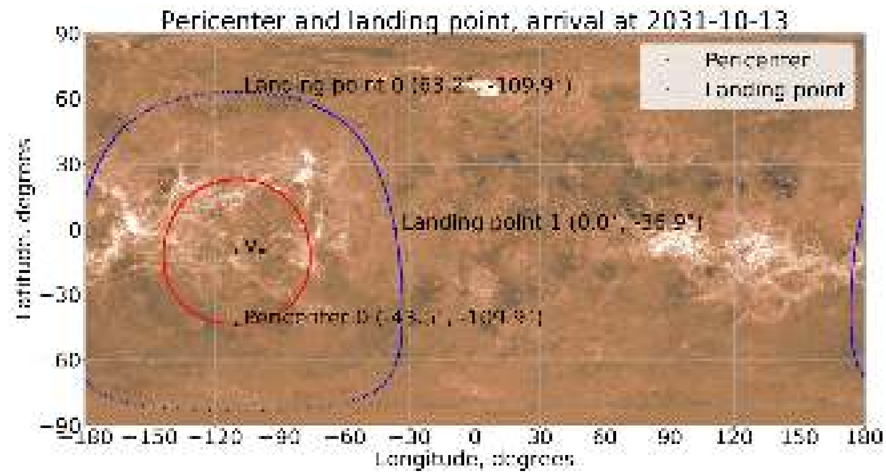


Figure 4.20.—Landing (blue) and perigee (red) points for date of arrival October 13, 2031.

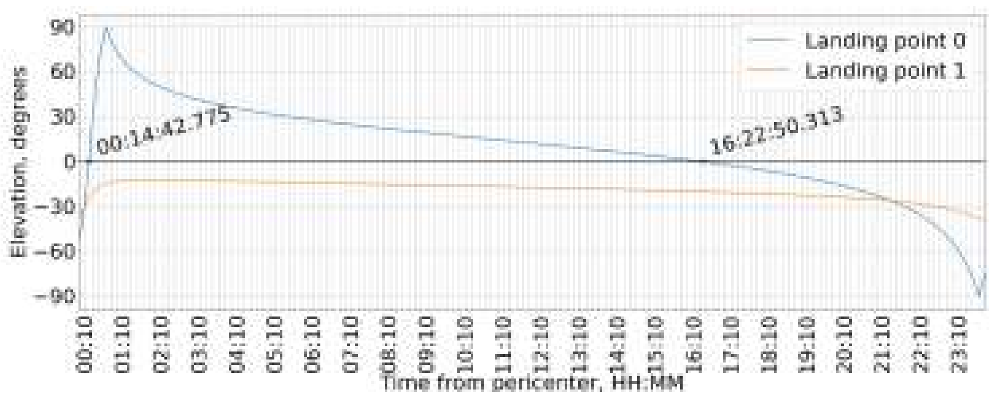


Figure 4.21.—Elevation of orbiter after perigee arrival (hours, minutes, seconds) over the local horizon of lander. Landing point has maximum latitude and orbiter pericenter has minimum latitude. Date of arrival October 13, 2031.

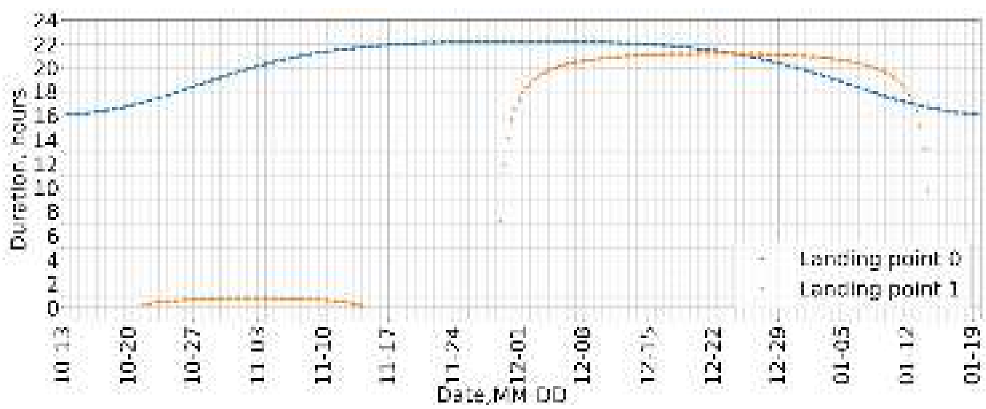


Figure 4.22.—Duration in hours of lander visibility from orbiter per one orbit (24 hr) for landing point with equatorial latitude (blue) and maximum latitude (yellow). Date of arrival October 13, 2031.

4.2.4 Ground Support

Currently, the Russian Deep Space Network (DSN) includes three functioning deep-space antennas:

- Bear Lakes (~40 km north of Moscow) has an antenna with 64 m diameter equipped with X-band receiver and transmitter.
- Kalyazin (~150 km to north of Moscow) has an antenna with 64 m diameter equipped with X-band receiver and will be equipped with transmitter facilities at the end of 2020.
- Ussuriysk (far east of Russia) with a 70-m-diameter antenna equipped with X-band receiver and transmitter.

We should also note that there is an antenna system with a diameter of 70 m in Yevpatoria. Currently, this antenna is not working and is in the recovery stage.

Antennas in Bear Lakes and Kalyazin already joined in the Consulting Committee for Space Data Systems (CCSDS) compatible infrastructure in the frame of Russian Complex for Receiving of Science Data (RKPNI) for the ExoMars mission and successfully provide Space Link Extension (SLE) services and well as planning and scheduling and auxiliary services, according to CCSDS. Inclusion of other antennas in the CCSDS compatible infrastructure is planned for near future.

Also, within the framework of the RKPNI project, technology for interagency interactions (including the necessary communication links) has been developed with the European antenna infrastructure control Center (ESTRACK). This technical solutions and tools can also be used for the Venera-D mission.

Therefore, it can be noted that for options 1 and 2 of communication with the spacecraft (see Section 4.2.2) we have an almost ready ground-based infrastructure to ensure the involvement of almost all the geographical parts of Russia.

Regarding the use of Ka-band, it can be noted that such antenna systems are currently under development. According to preliminary plans, these systems will be installed in Russia as well as in the Southern Hemisphere of Earth. Despite the physical absence of these antenna systems at the moment, it seems possible to consider the use of option 3 as the most promising, possibly in limited functionality, for example, only for the downloading of scientific information to Earth.

4.2.5 Hardware Development, Integration, and Testing

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 four fuel tanks and rocket engines mounted onto it, shaped as a four- or eight-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.

Figure 4.23.—Notional concept of the composite spacecraft and an accommodation options.

Regarding the choice of LVF, it is suggested for the Venera-D mission to use a KVTK fairing (currently under development). It consists of three conical parts. The lowest part 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.

The crucial payload element is the lander because of its mass (1,600 kg).

5 Ground Support and Communication Links

Various communications links are possible and needed. The communication link between the Venera-D orbiter and Earth stations is crucial since the orbiter will also be a primary link for relaying the data from the lander (2 to 3 hr during descent and after landing), a possible AP (up to 120 days), LLISSE station(s) (60 days) and L1/L2 satellites (mission life of 3 yr), and any SAEVe stations that may be deployed. Since the range of the L1 and L2 satellites from Venus is about 15 times the maximum separation of Venera-D orbiter from Venus, it is appealing to consider using a subsatellite at about L1/L2 points as communication relays for the in situ elements, as they provide continuous links when the in situ platforms are on the day (L1) or night (L2) side of the planet, enabling a large increase in the amount of data to be collected as those platforms are not expected to have store and forward capability. Thus, data collection is possible only when a communication link is available. The multiple links considered are

- Venera-D orbiter ↔ Russian and NASA stations (Uplink and Downlink)
- Lander–Venera-D → orbiter (downlink to orbiter)
- Lander–Earth stations → (downlink to Earth stations)
- AP → Venera-D orbiter
- AP → Earth stations
- AP → L1 satellite
- AP → L2 satellite
- LLISSE-1 → Venera-D orbiter
- LLISSE-2 → L1/L2 satellite
- L1 satellite ↔ Venera-D orbiter
- L2 satellite ↔ Venera-D orbiter
- L1 satellite ↔ Earth
- L2 satellite ↔ Earth
- SAEVe 1 → Venera-D orbiter
- SAEVe 2 → Venera-D orbiter
- SAEVe 3 → Venera-D orbiter

6 Top-Level Technology Assessment and Considerations for Baseline Mission

6.1 Major Technology Demonstrations/Targets

As discussed in previous sections, the baseline mission consists of a long-lived orbiter, a short-lived lander, and one LLISSE. Recent mission experience such as VEX and Akatsuki, as well as a number of critically reviewed orbital mission proposals submitted to NASA and other agencies, suggest that all needed instrumentation anticipated for an orbiter is at TRL 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 orbiter instrumentation with an identified TRL less than 6 relates to development of L and W band systems for atmosphere probing. This is reflected in the top-level summary of overall technology readiness for the highest risk mission elements in Table 6.1. Overall, relative technology readiness is found in Table 6.2. The colors used in the assessment tables in this section 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 D.

Table 6.1.—Technology Readiness for Highest Risk Mission Instruments
(High Priority Science but Low Maturity and/or Long Development Time Expected)

Platform	Instrument/Subsystem	Development Required	Overall Assessment
Orbiter	MMW 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/ subsatellite	Suite of three plasma instruments Panoramic energy mass-analyzer of ions Ares V, ELSPEC, and fast neutrals analyzer (FNA)	ELSPEC and neutral particle detector (NPD) need developing, but rely on existing technology. Prototypes are under development	
Orbiter	IR imager	Adapt Akatsuki—like cameras for Venera-D needs	
Main lander	Mössbauer spectrometer/APXS	Demonstrate feasibility to make the measurements at the temperatures and within the available time	
Main lander	CAP—GC-MS	Sampling system for atmospheric gases/aerosols; coupling of mass spectrometry (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 of up to four instruments in vessel interior	

Implementation of the main lander is more challenging, but there have been numerous examples of successfully landing and operating missions similar to what is planned for Venera-D. While 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, 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. There are facilities in the United States that can perform some of these tests including the GEER facility at NASA GRC, which can replicate precise chemistry in addition to surface temperature and pressure. The current GEER vessel is not large enough to accommodate the planned main lander.

The bulk of the technology-related efforts for the lander, however, will be in (1) development of the sample acquisition and processing system, especially for multiple sample processing, (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, and (4) maximizing lander life and data recovered from the lander.

Current plans are to acquire two 5-cm^3 samples from different depths through a pressure lock and distribute portions of the samples to different potential instruments (e.g., GC-MS, possible Mössbauer spectrometer/APXS, and possible XRD/XRF), which would be inside the landed vessel. The acquisition and distribution system must minimize heat transfer during the acquisition process to maximize lander life. A system that ingests the required volume of sample and minimizes heat transfer has been proven on previous Venera missions but for only one sample. The sample processing and distribution system inside the vessel would be new and needs complete development and testing. Sample handling and processing is a critical element of the lander and needs significant development and testing that should begin as soon as possible.

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 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.

In situ exploration of the Venus surface has been limited by the harsh conditions, which have constrained 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 science questions. Recent advances in high-temperature electronics and other subsystems are enabling 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 (scheduled for demonstration in 2021), then LLISSE, the long-lived station, will be on a path to take and transmit these measurements long after the main lander ceases to function.

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. Maximizing bandwidth, lander life, and use of lossless compression coding techniques will help return maximum science. Other opportunities to maximize lander life should also be considered. Some of these include minimizing power consumed within the vessel, utilizing high efficiency electronics/designs, minimizing heat sources in the vessel, vessel penetrations and window areas, and special coatings to minimize heat transfer through the vessel wall.

Table 6.2.—Overall Relative Technology Readiness

Platform	Instrument/Subsystem	Development Required	Overall Assessment
Baseline Mission			
Orbiter and/or subsatellite	Given prior successful orbiting missions, including the recent VEX 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 to 2 hr 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 Mössbauer spectrometer/APXS and the integrated GC-MS. Facilities will need to be established to test and qualify systems, particularly notable is the ability to test the full-scale lander.	
LLISSE	LLISSE offers unique new science with its extended surface life. This is enabled by high-temperature electronics and systems. Nearly all sensors have demonstrated functionality at Venus surface conditions. While all subsystems have made strong progress toward goals, many still have to demonstrate full performance for the desired life. This is expected to occur in the 2019 to 2021 timeframe. Until that happens, LLISSE as a system will be in the TRL 3 to 4 range and relatively high technology risk.	Continue subsystem and system level development. Demonstrate operations and life in simulated Venus conditions.	

The JSDT developed a spreadsheet tool to identify, summarize, and assess instruments and subsystems for readiness to implement the Venera-D mission concept. This tool has been kept up-to-date as instruments were identified and assessed for applicability to the science goals and the concept has been refined with ongoing analysis. All planned instruments, subsystems that may need technology development, and all potential augmentations and their instruments and subsystems have been captured in the tool. The instruments are shown in priority order for the given mission element. The spreadsheet based tool is presented in Table 6.3.

In addition to the summary, for nearly all instruments and subsystems a "Technology Data Sheet" was produced by the instrument Principal Investigator (PI) or knowledgeable representative for the various subsystems. Those data sheets are available to the JSDT members and contain additional information about contacts, more details on type of heritage and development needed, and other relevant information. The data sheets have not been included in this report to keep it to a more reasonable length, however, an example of a data sheet has been provided in Appendix D.

This section defines critical project technologies for the baseline mission that require special attention through all stages of research and development (R&D). The detailed description of possible technology risks are stated in Section 9.

Table 6.3.—Technology-Based Summary of Instruments and Subsystems by Mission Element and Potential Contributed Elements

Instrument Number (in priority order by platform)	Data Sheet(s) Completed	Instrument or Specific Subsystem	Description	Rough Characteristics/Physical Properties (worst expected case shown)	Science Priority High, (H) Med (M), Low (L)	Approx. TRL 1 to 3, 4 to 5, 6 and Higher	Time (yr) Required to be Ready for Mission (1 to 3 yr, 4 to 5, >5 yr)	Rationale/Other Comments
Color/Letter Code:								
In general the use of Red in the table implies higher importance or earlier attention required				GB is gigabytes, Kb is kilobits, KB is kilobytes, Mb is megabits, and MB is megabytes.				
For "Approximate TRL" column, Red box indicates TRL is from 1 to 3, Yellow box is TRL 4 or 5, and Green box is TRL 6 or greater			☒	- This mark signifies that the datasheet is not needed				
For "Time to Required Maturity" column, Red box indicates TRL is from 1 to 3, Yellow box is TRL 4 or 5, and Green box is TRL 6 or greater			✓	- This mark signifies that a datasheet is complete and available				
Orbiter								
Instrument								
1	✓	FS	Thermal IR Fourier transform spectrometer Spectrum 250 to 2,000 cm^{-1} λ = 5 to 40 µm, Δv = 1cm^{-1} 1 s/spectrum, whole mission	400×300×200 mm, 15 W 15 kg, 5 Kb/s	H	6 to 7	3	
2	✓	UV mapping spectrometer	Imaging UV spectrometer 190 to 490 nm, $\Delta\Lambda$ = 0.3 nm, continuous imaging during mission, ~1 s/image	150×150×200 mm, 4 W, 3kg, 40 Kb/s, 120 Mb/h	H	4 to 7	?	
3	✓	Visible to MIR spectrometer	Visual and IR imaging spectrometer multiple channels: need 0.4 to 1.9 µm $\Delta\lambda$ = 2 nm and 1.5 to 5.7 µm $\Delta\lambda$ = 5 nm; typical acquisition time about 20 min per cube. Arbitrary frequency	550×500×230 mm, 25 kg, 21 W 1.7 GB per cube, after compression, 650 Mb/h	H	5 to 9	4	Instrument radiator must be placed on a cold face of the orbiter (direct sunlight must be avoided), to retain effective cooling of IR channel
4	✓	UV-NIR imaging	Monitoring camera channels to include λ = 0.285, 0.365, .500, and 1.000	220×220×430 mm, 4.1 kg, 19 to 34 W, 2 MB/image	H	5 to 7	?	
5	✓	Solar and star occultation spectrometer	Three spectrometers (UV, NIR, and MIR) for atmospheric studies. 0.7 to 1.7; 2.2 to 4.4 µm, $\Delta\lambda$ =1 nm and 118 to 320 nm $\Delta\lambda$ = 0.1 nm	300×300×200 mm, 11 kg, 24 W, 90 Kb/s	H	5 to 7	?	Clouds: IR 75 to 90 km, UV 85 to 110 km
6	✓	MMW radiometer	MMW radiometer; Ka, V, and W bands; scanning antennas; three channels: f = 100 GHz (3 mm), 60 GHz (5 mm) и 30 GHz (1 cm) with Δf = 20, 10, and 5 GHz, respectively	200×150×100 mm, 6 W, 2 kg 10 Mb/h	H	3 to 4	3	
7	✓	IR heterodyne spectrometer	Ultra-high resolution ($\lambda/\Delta\lambda$ = 1×10^7 to 1×10^8) spectroradiometer for solar occultations and nadir observations; several narrow channels from 4.5 to 12 µm (IVOLGA)	200×200×100 mm, 8 kg, 40 W, 25 Mb/h	L	3 to 4	5	Uncertain if instrument can implement desired measurements. Proof of performance needs to be demonstrated early to support development for this application
8	☒	Radio-science two-frequency duplex occultation	Signal from satellite received by a ground station or subsatellite and receive signals from ground or subsatellite in (L?) S- and X-bands	0.5 dm^3, 0.5 kg, 1 W, 5 Kb/s	H	7 for S and X, 3 to 4 for L	?	Part of the general orbiter design
9	✓	Thermal IR camera	Thermal IR camera detecting wavelengths from 8 to 12 µm (single band) by using an uncooled micro bolometer array	100×100×200 mm, 7 W, 1 kg, 1.6 MB/image	H	7	2 to 3	Sunlight must not enter to the detector during observations
10	✓	IR imaging camera	Imaging in multiple bands (water and others) and fast imaging in 2 to 4 µm band (lower priority)	9.5 dm^3, 5 kg, 15 W, 900 Kb/s	H	5 to 7	3 to 4	Nadir pointing required
11	✓	Electromagnetic waves detection	System for detection and investigation of electromagnetic waves generated by lightning and other electric phenomena	100×110×100 mm + 800-mm antenna, 4 ≤ 4.5 W, 0.9 kg ~4 to 5 Kb/s	M	5 to 6	1	Needs Sensor on boom Dependent on the telemetry (TM) sharing
12	✓	Panoramic energy mass-analyzer of ions	Panoramic ion energy-mass analyzer with energy range from 50 eV to 5 keV. Ion distribution function and ion mass composition in nearly 2π FOV	140×156×156 mm, 2.5 kg, 4 W, 4Kb/s	M	6 to 7	1 to 3	2π FOV should be directed to the Sun and should not be blocked
13	✓	ELSPEC	Fast electron energy analyzer with energy range 10 eV to 10 keV. Electron distribution function	114×120×165 mm, 2 kg, 2.5 W, 4 Kb/s	M	3	1 to 3	FOV should be directed to 90° of the Sun
14	✓	Neutral particle spectrometer	Neutral particle mass composition	109×145×145 mm, 1.4 kg, 2.5 W, 1 Kb/s	M	3	1 to 3	FOV should be directed to the Sun
15	✓	Energetic particle spectrometer	Electron and ion energy spectrometer for 20 to 2,000 keV. Energy spectra of energetic ions and electrons in several directions	180×200×100 mm, 3 to 4 kg, 3 to 5 W, 1 Kb/s	M	6	2 to 3	Location in sun shadow preferred (no direct or refracted Sunlight on detectors)
16	✓	Magnetometer	Flux-gate magnetometer (two vector sensors and electronic box) ±500 nT. Quasi static magnetic field (three components)/Venus ionosphere and plasma environment	150×150×150 mm; 70×30×30 mm, 3 kg, 7 W, <10 Kb/s	M	4	5 to 6	Boom for the instrument sensors

Instrument Number (in priority order by platform)	Data Sheet(s) Completed	Instrument or Specific Subsystem	Description	Rough Characteristics/Physical Properties (worst expected case shown)	Science Priority High, (H) Med (M), Low (L)	Approx. TRL 1 to 3, 4 to 5, 6 and Higher	Time (yr) Required to be Ready for Mission (1 to 3 yr, 4 to 5, >5 yr)	Rationale/Other Comments
Color/Letter Code:								
In general the use of Red in the table implies higher importance or earlier attention required				GB is gigabytes, Kb is kilobits, KB is kilobytes, Mb is megabits, and MB is megabytes.				
For "Approximate TRL" column, Red box indicates TRL is from 1 to 3, Yellow box is TRL 4 or 5, and Green box is TRL 6 or greater			☒	- This mark signifies that the datasheet is not needed				
For "Time to Required Maturity" column, Red box indicates TRL is from 1 to 3, Yellow box is TRL 4 or 5, and Green box is TRL 6 or greater			✓	- This mark signifies that a datasheet is complete and available				
Subsystem								
		SIO informational subsystem	Data acquisition and instruments handling system. Gathering TM from instruments and save it to long-term memory, transmitting TM to radiochannel, transmitting telecommands (TCs) from onboard computer (OBC) to instruments	226×126×242 mm, 3.2 kg, 7 W, 8 Mb/h	H	7		
		Communication	Orbiter—Earth X-band up to 16 Mb/s (not continuous) Ka - not certain yet	X, Ka?	H	7		Ka ground stations not yet in place in Russia
		Communication	Orbiter—long-lived station(s)	UHF ~100 MHz	H			No challenges expected but propagation tests are suggested. Orbit coordination needed
		Communication	Orbiter-lander	To be determined (TBD)	H	5	2	No challenges expected but propagation tests are suggested. Orbit coordination needed
		Communication	Orbiter-AP	TBD	H	5	2	No challenges expected but propagation tests are suggested. Orbit coordination needed
		Communication	Orbiter-subsatellite	TBD	M			No challenges expected but propagation tests are suggested. Orbit coordination needed
		Propulsion	Orbit insertion (bi-prop-Nr-H_4, N_2O_4)	TBD	H			Propulsion system may change depending on orbit selections, for example may use aerobraking
Main Lander								
Instrument								
1	·	XRD/XRF	Elemental composition	275×162×190 mm, 30 W, 5 kg, <100 KB/sample	H	5	?	**Grey shading signifies ingested sample required.** Sample volume required is 50 to 200 mg of <150 µm grain size
2	✓	Mössbauer spectrometer	Backscattering Spectrum of Mössbauer radiation. Mineralogy of Fe-containing rocks, oxidation state of iron, analysis of rock-forming elements. Bulk chemical composition	40×40×100 mm, 0.5 kg, 3 W, 150 KB/sample	H	7	3	Detector cooling and integration time requirements may make this instrument infeasible for this lander concept. **Grey shading signifies ingested sample required.** Distance to sample as close as possible (in the range 1 to 2 cm, or closer), if possible even mechanical contact (but not required) Pressure: high vacuum (10 to 6 mbar) to several bar; temperature: (a) operating: –100 °C to about +30/+40 °C; (b) non-operational: –100 °C to +70/+90 °C. Sample volume required is TBD
3	✓	Camera system	Visible range color imaging system consisting of one landing, four to five panoramic and one close range cameras, mass memory/data compression unit (DCU) and cables. Five + two images, each image up to 2048×2048 px. Stereo imaging during the landing 30 to 45 grad, panoramic image of the surface at landing place	Camera heads 80×80×60 mm each, lens TBD at the Phase III, DCU 100×120×80 mm, camera heads 0.2 kg each, lens TBD at the Phase III, DCU 1.5 kg, 12 W 0.6 MB per image (compressed), i.e., 2.4 MB panorama, 0.6 MB closeup. Total estimate: descent phase: 1…8 MB; landing phase 9.3 MB	H	4	2	Dependent on television systems for Russian lunar landing missions (Luna: 25…27), Exomars 2018 lander. Electronics temperature range up to +50 °C. At least three sessions, more is better, number of imaging sets is limited by data downlink capacity
4	✓	CAP—GC-MS	GC-MS + 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	Gas chromatography (GC) 260×180×130 mm, MS 250×150×110 mm, gas sampling system 120×110×110 mm, used gas receiver–sphere Ø150 mm, 10.5 kg, 60 W, 1 MB/measurement; 18 MB on descent, 3.5 MB on surface	H	3 to 7 2 to 7	5	**Grey shading signifies ingested sample required. Sample volume required is TBD.** Measurements every 10 km on descent
5	✓	Raman (potential integration with auxiliary LIDAR, laser-induced breakdown	Remote time-resolved Raman and possibly integrated with LIDAR, LIBS, or other instrument	Nominally 300×300×250 mm, 80 W peak 8 kg	H	5	3	Several Raman options exist - Some may require a sample to be brought in or up close to a window

Instrument Number (in priority order by platform)	Data Sheet(s) Completed	Instrument or Specific Subsystem	Description	Rough Characteristics/Physical Properties (worst expected case shown)	Science Priority High, (H) Med (M), Low (L)	Approx. TRL 1 to 3, 4 to 5, 6 and Higher	Time (yr) Required to be Ready for Mission (1 to 3 yr, 4 to 5, >5 yr)	Rationale/Other Comments
Color/Letter Code: In general the use of Red in the table implies higher importance or earlier attention required For “Approximate TRL” column, Red box indicates TRL is from 1 to 3, Yellow box is TRL 4 or 5, and Green box is TRL 6 or greater For "Time to Required Maturity" column, Red box indicates TRL is from 1 to 3, Yellow box is TRL 4 or 5, and Green box is TRL 6 or greater GB is gigabytes, Kb is kilobits, KB is kilobytes, Mb is megabits, and MB is megabytes. ☒ - This mark signifies that the datasheet is not needed ✓ - This mark signifies that a datasheet is complete and available								
		spectroscopy (LIBS), or other complimentary instrument)	Mineralogy and possibly chemistry, atmospheric aerosols, molecular species (e.g., H_2SO_4, SO_2, H_2S, CO_2)	70 Mb/s, heat rejected 2 to 2.5 W				Time-resolved Raman instrument has been selected for Mars 2020 mission using University of Hawaii (UH) Raman instrument as prototype
6	✓	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. ~2 W self-powered, ~1 kg, 0.1 KB/ measurement; total 0.6 MB for descent and 0.65 MB for surface	H	2 to 7	3	
7	✓	Gamma and NS	Active gamma-ray and NS, subsurface elemental composition	6.7 kg, 9.5 dm³, 5/19 W	H	6 to 7	1 to 2	Consists of two pieces to be separated but both located near vessel bottom
8	✓	Multichannel diode laser spectrometer with gas sampling system	Multichannel Laser Absorption Spectrometer (MLAS) and AGS system. 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	100×120×450 mm, 6.3 kg MLAS unit; 90×120×400 mm, 3.6 kg AGS unit, 25 W average (5 W standby to 48 W peak) 20 Kb/min for active phase; total 5 MB for descent and 11 MB for surface	H	4 to 7 for functional blocks and subsystems	<5 yr	
9	✓	IR radiometer and UV-VIS spectrometer	Measurements of upward and downward radiative fluxes in transparency windows. Active part of descent trajectory. Integrated with this is a UV-VIS spectrometer operating from 0.23 to 0.66 μm, 0.3 nm resolution 0.23 to 0.32 μm, broad ~1.0 nm resolution longward	Radiometer: 200×200×300 mm at the outer spacecraft deck; 80×80×40 mm inside spacecraft, 5 W, 0.5 kg, 1 MB UV-VIS Spectrometer: 120×250×500 mm, 35 W, 10 kg, 8 KB per image (uncompressed); ~5 MB total	H	3	6 to 8	UV-VIS will need a small window, and accommodation of external gas chamber comparable to that used on VEGA Descent Lander
Subsystem								
		Sample acquisition	Utilize Venera/VEGA heritage system as much as possible. New multiple-sample system needs development	Details to be confirmed	H			
		Sample handling/processing	New design	Still to be developed	H			Most significant technology item on the lander at this time
		Thermal control	Passive thermal control system	Phase-change material and thermal insulation TBD	H			
		Communication	Lander-orbiter UHF r-Earth		H	7		
		Navigation (NAV)	New design	Details to be confirmed	H	???		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	H			Facilities for testing/qualifying full-scale lander do not exist at this time
		Environmental test facilities to test, calibrate and qualify full-scale instruments and subsystems	External instruments and subsystems may be tested at GEER	GEER is 3-ft diameter by 4-ft-long internal size. Small keep out space along bottom for heaters	H			
		Sample acquisition	External instruments and subsystems need to be tested		H			GEER may be an option depending on size
LLISSE - Long-Life Weather Station								
Instruments								
	✓	METEO	Temperature, pressure, radiance, and wind speed and direction sensors	<0.2 kg, fits on 20-cm station	H	4 to 5	5	TRL driven by radiance sensing
	✓	Microelectromechanical systems (MEMS) chemical sensor	Detect and measure concentration of preselected element set	<0.2 kg, fits within 20-cm station	H	5	3	
	Subsystem							

Instrument Number (in priority order by platform)	Data Sheet(s) Completed	Instrument or Specific Subsystem	Description	Rough Characteristics/Physical Properties (worst expected case shown)	Science Priority High, (H) Med (M), Low (L)	Approx. TRL 1 to 3, 4 to 5, 6 and Higher	Time (yr) Required to be Ready for Mission (1 to 3 yr, 4 to 5, >5 yr)	Rationale/Other Comments
Color/Letter Code:								
In general the use of Red in the table implies higher importance or earlier attention required				GB is gigabytes, Kb is kilobits, KB is kilobytes, Mb is megabits, and MB is megabytes.				
For "Approximate TRL" column, Red box indicates TRL is from 1 to 3, Yellow box is TRL 4 or 5, and Green box is TRL 6 or greater				☒ - This mark signifies that the datasheet is not needed				
For "Time to Required Maturity" column, Red box indicates TRL is from 1 to 3, Yellow box is TRL 4 or 5, and Green box is TRL 6 or greater				✓ - This mark signifies that a datasheet is complete and available				
	✓	LLISSE high-temperature subsystems	Long-lived station to collect temperature, pressure, wind, chemistry, and radiance measurements for 60 days	~8,000 cm^3 (stowed) Self powered 8 to 10 kg	H	3 to 4	5	Currently assuming baseline LLISSE will enter and be attached to the lander Strong technology impact for future Venus missions
	·	NAV	System to determine location to ±10 km	Utilize communication links with orbiter and subsatellite to triangulate position	M	5	4	Applies to independently dropped stations. Requires subsatellite
SAEVe - Potential Contributed Element - A Long-Life Seismic and Weather Station (Refer to Section 8.3)								
Instruments								
	✓	METEO	Temperature, pressures, radiance, and wind speed and direction sensors	<0.2 kg, fits on 20-cm station	H	4 to 5	5	TRL driven by radiance sensing
	✓	MEMS chemical sensor	Detect and measure concentration of preselected element set	<0.2 kg, fits within 20-cm station	H	5	3	
	·	Seismometer	Detect and measure seismic events for one Venus solar day	0.3 kg, fits inside SAEVe aeroshell and the lander envelope. Three axis, 0.1 to 100 s period. Sensitivity better than 1 ng/rtHz	H	2	6	
	·	Heat flux sensor	Detect and measure heat from the interior over a Venus solar day	0.3 kg, fits inside SAEVe aeroshell and the lander envelope. Range is 10 mW to 1 W/m^2	H	3	6	
	Subsystem							
	·	SAEVe long-lived station with seismic sensors	Long-lived station to collect temperature, pressure, wind, chemistry, radiance and seismic measurements for 120 days. Not connected to main lander	45-kg total mass with science payload and entry shell. Approximately 0.6 m diameter shell. Lander approximately 0.5 m diameter and 0.25 m tall	H	2	7	Spin table and release system needed on orbiter. High-temperature seismometer development is driving instrument for TRL
	·	NAV	System to determine location to ±10 km	Utilize communication links with orbiter and subsatellite to triangulate position	M	5	4	Applies to independently dropped stations Requires subsatellite
Mobile AP (Refer to Section 8.2)								
Instruments								
1	✓	METEO package (sensors)	Meteorological instruments (T,P,W,W',dT,E,ω,H)	1 dm^3, 0.5 kg, 2.5 W max., 0.14 KB/measurement	H	2 to 7	3	
2	✓	Raman	Raman, possibly in combination with LIDAR Atmospheric aerosols, molecular species (e.g., H_2SO_4, SO_2, H_2S, CO_2)	12×12×10 in. 80 W 8 kg 70 Mb/s	H	5	3	
3	✓	UV-VIS spectrometer	UV-VIS spectrograph operating from 0.23 to 0.66 µm, 0.3-nm resolution 0.23 to 0.32 µm, broad ~1.0 nm resolution longward	120×250×500 mm, 35 W, 10 kg, 8 KB per image (uncompressed); ~5 MB total	M	3	6 to 8	Will need a small window, and accommodation of external gas chamber comparable to that used on VEGA Descent Lander
4	✓	Life detection microscope	Imaging of submicron particles	6.2 dm^3, 6.2 kg, 30 W, 40 MB total (10 min/sample)	L	3	5	Requires inlet and exhaust of ambient air
5		Net flux radiometer	Up/down looking	0.2 kg solar spectrum, Venus cloud tolerant	H	TBD	TBD	Phase III
6		GC-MS	Focus on performance but small and lightweight package	Still to be designed	H	TBD	TBD	Phase III
	Subsatellite (Refer to Section 8.4)							
	Instrument							
1	✓	Panoramic energy mass-analyzer of ions	Panoramic ion energy-mass analyzer with energy range from 50 eV to 5 keV. Ion distribution function and ion mass composition in nearly 2π FOV	140×156×156 mm, 2.5 kg, 4 W, 4 Kb/s	M	6 to 7	1 to 3	2π FOV should be directed to the Sun and should not be blocked
2	✓	ELSPEC	Fast electron energy analyzer with energy range 10 eV to 10 keV. Electron distribution function	114×120×165 mm, 2 kg, 2.5 W, 4 Kb/s	M	3	1 to 3	FOV should be directed to 90° of the Sun
3	✓	Neutral particle spectrometer	Neutral particle mass composition	109×145×145 mm, 1.4 kg, 2.5 W, 1 Kb/s	M	3	1 to 3	FOV should be directed to the Sun

Instrument Number (in priority order by platform)	Data Sheet(s) Completed	Instrument or Specific Subsystem	Description	Rough Characteristics/Physical Properties (worst expected case shown)	Science Priority High, (H) Med (M), Low (L)	Approx. TRL 1 to 3, 4 to 5, 6 and Higher	Time (yr) Required to be Ready for Mission (1 to 3 yr, 4 to 5, >5 yr)	Rationale/Other Comments
Color/Letter Code:								
		In general the use of Red in the table implies higher importance or earlier attention required		GB is gigabytes, Kb is kilobits, KB is kilobytes, Mb is megabits, and MB is megabytes.				
		For "Approximate TRL" column, Red box indicates TRL is from 1 to 3, Yellow box is TRL 4 or 5, and Green box is TRL 6 or greater		☒ - This mark signifies that the datasheet is not needed				
		For "Time to Required Maturity" column, Red box indicates TRL is from 1 to 3, Yellow box is TRL 4 or 5, and Green box is TRL 6 or greater		✓ - This mark signifies that a datasheet is complete and available				
4	✓	Energetic particle spectrometer	Electron and ion energy spectrometer for 20 to 2,000 keV. Energy spectra of energetic ions and electrons in several directions	180×200×100 mm, 3 to 4 kg, 3 to 5 W, 1 Kb/s	M	6		Location in sun shadow preferred (no direct or refracted sunlight on detectors)
5	✓	Magnetometer	Flux-gate magnetometer (two vector sensors and electronic box) ±500 nT. Quasi static magnetic field (three components)/Venus ionosphere and plasma environment	150×150×150 mm; 70×30×30 mm, 3 kg, 7 W, <10 Kb/s	M	4	5 to 6	Boom for the instrument sensors
6	☒	Radio science two-frequency duplex occultation	Signal from satellite received by a ground station or subsatellite and receive signals from ground or subsatellite in (L?) S- and X-bands.	0.5 dm^3, 0.5 kg, 1 W, 5 Kb/s	M	7 for S and X, 3 to 4 for L		
	Subsystem							
	Launch Vehicle							
		Launch >6,500 Kg to Venus encounter trajectory	Angara-A5	Max payload launched is ~ 7,000 kg	H			
	Ground/Ops (Operations) Systems							
	Radio Signal Source							
		Ground station	Ground-based radio telescope		H			Ground stations needed around Earth, Goldstone/DSN desired. Consider for balloon tracking also
	Ground Stations							
		AP tracking	Use very long baseline interferometry (VLBI) techniques to track AP		M			
		Ground station	Ka -range DSN		H			Ka ground stations do not currently exist in Russia,, using Ka would enhance ability to return science data
	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, Calibration and lab experiments can also be run with GEER	3-ft diameter by 4-ft-long internal size. Small keep out space along bottom for heaters	H			Other facilities such as Venus In situ Composition Investigations (VICI) (NASA GSFC), Planetary Emissivity Laboratory (PEL) (German Aerospace Center (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		H	9??		
		Long-lived stations deployed independent of main lander	Rigid-body conic-shaped entry system	About 0.6 m diameter		4 to 5		
		Independently deployed mobile aerial platform	If using Venus Atmospheric Maneuverable Platform (VAMP), additional deployment/entry work would be needed		M			An inflated VAMP like lifting body would need to be captured at Venus with orbiter and then deployed for entry. Development and testing required

7 Supporting Laboratory Studies

7.1 Baseline Mission Needs

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 1-µm window would be valuable. Experiments to quantify propagation parameters for the intended communication and sounding frequencies and correlate that to atmosphere composition and properties are 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 shape our knowledge 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 atmospheric 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.

7.2 Other Potential Mission Component (Augmentation) Needs

Laboratory experiments are required in support of potential science from an AP. The in situ instruments will need to be tested and calibrated for expected chemistry, optical and infrasound properties, particulates/aerosols, and local environmental conditions, including corrosive compounds. Experiments on the potential makeup 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 LLISSE, 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.

The subsatellite will require focused testing 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 subsatellite. These include propagation experiments to allow interpretation of future data and perhaps fine-tune instrument parameters.

8 Potential Contributions to the Baseline Venera-D (Trade Space and Scientific Priority Order)

8.1 Introduction and Overview

The baseline mission can be significantly enhanced by adding other elements to the mission such as (i) long-lived surface station(s) to assess geophysical activity, superrotation, surface-atmosphere interaction, internal structure, planet evolution, and other surface geology studies; (ii) mobile AP(s) to enhance climate and superrotation studies; and (iii) a small secondary subsatellite orbiter, which may be placed either in an elongated elliptical orbit or at L1 (between Venus and the Sun) and L2 (behind the planet along the Sun-Venus line). The subsatellite option enables valuable measurements of the solar-wind interaction with Venus to enhance science return associated with studies of Venus' upper atmosphere/ionosphere composition and loss and atmospheric and climate evolution.

In Table 8.1, we trace the impact of these potential mission architecture augmentations to the **prioritized orbiter and lander+LLISSE goals provided in Section 2.2.2**, and in Table 8.2**,** we summarize the technology readiness for each of the potential contributed platforms. In Section 8.2, we summarize the technology readiness of a range of potential APs and the risks associated with these platforms, leaning heavily on the findings provided by the NASA-sponsored Venus Aerial Platform (VAP) study; additionally, we provide an assessment of the science capabilities of each platform relative to the prioritized atmospheric science investigations goals defined in Section 3 and the altitude range that may be achieved by the AP options. In Section 8.3, the science drivers for a long-lived station with seismic and crustal analysis capabilities are given along with details of the anticipated mission accommodation and technologies readiness of this potential contributed element. In Section 8.4, we summarize the science drivers for a small secondary subsatellite and provide a discussion of the impact of the orbit location and altitude of this contributed element on the overall science return of the mission.

8.2 Aerial Platform (AP)

The 1985 VEGA balloon flights (Figure 8.1) were the first to demonstrate the critical science return provided by an AP in the cloud layer of Venus. The two VEGA super-pressure balloons carried only a small 7 kg mass suspended under the balloon, including 1 to 2 kg of science instruments, but were still able to return important temperature, pressure, illumination, and wind speed data for their almost two days of flight at an altitude that ranged from 51 to 54 km. At this altitude, the ambient temperature is 30 to 60 °C, which allows for use of conventional avionics and instrumentation, although protection must be provided against the sulfuric acid aerosols in the clouds. Next generation APs with larger payloads, longer durations, and potentially different altitudes can provide a wealth of new scientific information as described previously in this report.

Table 8.1.—Potential Augmentations Trace to Prioritized Mission Goals

Potential Contributed Platform		Impact to Prioritized Mission Goals	Breakthrough Science Goal	Contributed Priority
SAEVe (two stations placed landed at appropriate distance from each other)		Enables a more complete study of lander+LLISSE Goals 1, 2, 3, 5, 6, 7, 8, and 9; and orbiter Goal 1	Complete long-term (~12 month), multiple station, in situ measurements at the surface of seismic activity (a capability not provided by the lander/LLISSE); plus additional measurement of heat flux, surface-atmosphere interaction via chemistry abundance measurements, rock morphology, atmospheric properties at surface-atmosphere boundary including T, P, wind speed and direction, and upward radiant flux; and allows assessment of crustal thickness at landing site (a capability not provided by lander/LLISSE)	1
AP		Enables a more complete study of orbiter Goals 1, 2, and 3	Complete sustained in situ measurement of aerosol and trace gas composition, cloud formation cycle, and atmospheric state (T, P, wind speed and direction) over time period of ~weeks to 1 month, tracing processes not accessible from main orbiter as a function of LST and underlying topography at altitudes ~50 to 65 km	2
Secondary subsatellite	Orbit at L1	Enables more complete study of orbiter Goal 1, 2,3, and 5	Complete continuous trace of the conditions upstream of the solar wind flow (via subsatellite), enabling high cadence two-point measurement of solar wind interaction based on daily in situ ionospheric processes observed from main orbiter at periapsis through lifetime of mission Complete continuous trace of full disk (=12-hr LST) day side atmosphere radiance through lifetime of mission at or near zero phase, tracing evolution of cloud top albedo (cloud opacity), allows self-calibration of main orbiter observations Complete high cadence radio occultation measurements of T over broad range of latitudes	3
	Orbit at L2	Enables a more complete study of orbiter Goal 1 2,3, and 5	Complete continuous trace of the conditions upstream of the solar wind flow (via subsatellite), enabling high cadence two-point measurement of solar wind interaction based on daily in situ ionospheric processes observed from main orbiter at periapsis through lifetime of mission Complete continuous trace of full disk (=12-hr LST) night side atmosphere radiance through lifetime of mission at or near zero phase, tracing evolution of atmospheric radiative properties (cloud opacity) Complete high cadence radio occultation measurements of T over broad range of latitudes	4
	Elongated, elliptical orbit	Enables more complete study of orbiter Goal 5	Complete periodic two-point measurement of solar wind interaction, tracing in situ ionospheric processes and upstream solar wind conditions (only accessible from second satellite)	5
Second LLISSE		Enables a more complete study of lander+LLISSE Goals 1, 2, 5, and 6; and orbiter Goal 1	Provide long-term monitoring of surface-atmosphere boundary conditions (T,P, and wind speed and direction) and rock morphology from a secondary reference point, allowing increased knowledge of differences in atmospheric conditions relative to LST and/or latitude	6

Table 8.2—Technology Readiness for Potential Augmentations, Subelements, and Infrastructure

Platform	Instrument/Subsystem	Development Required	Overall Assessment
SAEVe	SAEVe is an enhanced long-lived station that builds on LLISSE offering longer life and additional instruments, most importantly seismometers. Because SAEVe uses the same core subsystems as LLISSE, it is in similar state of readiness for most of the platform with the exception of the seismometer, which needs significant development. Therefore, SAEVe has an overall High relative risk assessment.	Continue subsystem and system-level development. Demonstrate operations and life in simulated Venus conditions. Particular emphasis is needed in the development and test of the high-temperature seismometer.	
APs	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 (LLBs) 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
Subsatellite(s)	One or more subsatellites have been discussed as potential contributions. The primary motivation would be to provide complimentary measurements for the orbiter related to atmospheric science, solar wind, and the Venus ionospheric environment. Valuable communication enhancement is also provided for potential landers by a platform that can have line of sight to nearly half of the planet at any time, if that subsatellite were to be at Venus L1 or L2 positions. While subsatellites and small orbiters are common and seen as low relative technical risk, getting them to Venus L1 or L2 locations has not been done before and, depending on the scale of the subsatellites and the distance, propulsion and communication systems may need developed beyond what is available today. Therefore, relative readiness is deemed Moderate.	Propulsion and communication systems are the driving capabilities for the subsatellites, especially if they are positioned at L1 or L2.	
Entry system		For any independent entry, 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 the full-scale lander.	

To assess possible APs that might be used to achieve the Venus atmosphere investigations established by the JSDT in the Phase I report, the JSDT has relied heavily on the recent NASA-sponsored study on VAPs (Cutts et al., 2018) that assessed seven different types of in situ aerial vehicles, all of which are in principle applicable to Venera-D. These vehicles are

- The Venus Atmospheric Maneuverable Platform (VAMP) that was discussed extensively in the Phase I Venera-D report;
- A super-pressure balloon that nominally flies at a constant altitude;
- Four different kinds of variable altitude balloon; and
- A solar-powered airplane.

Figure 8.1.—VEGA balloon. (Image by Geoffrey Landis. Used with permission under a Creative Commons Attribution-Share Alike 4.0 International, https://creativecommons.org/licenses/by-sa/4.0/deed.en.)

Below, we summarize the approach and results of the NASA-based VAPs Study and discuss the implications for possible inclusion of any of these vehicles on Venera-D.

8.2.1 NASA Aerial Platforms (APs) Study Summary

The NASA AP Study consisted of two multiday workshops with intervening time for science and engineering analysis and involved a cross-disciplinary team of scientists, engineers, and technologists drawn from NASA centers, industry, and universities. The purpose was to identify what science could be obtained from different platforms, quantify the resource needs of mass, power, and volume, assess the technological maturity of those platforms, and provide guidance on required technology development investments to achieve flight readiness. Table 8.3 lists the seven platforms and summarizes their key features. Examples of these vehicles are shown in Figure 8.2.

Table 8.3.—Venus Aerial Vehicles Platforms in the Study

Platform Type	Main Buoyancy Method	Envelope Type	Altitude Change Method
Super-pressure balloon	He or H_2	Super-pressure	None
Pumped helium (He)	He or H_2	Zero-pressure	Compress and store buoyancy gas
Mechanical compression balloon	He or H_2	Super-pressure	Compress envelope
Air ballast balloon	He or H_2	Zero- or super-pressure	Compress and store ambient air
Phase change fluid (PCF) balloon	He augmented with a PCF (e.g., H_2O or NH_3)	Zero-pressure	Change of phase of PCF (e.g., H_2O or NH_3)
Solar airplane	Propulsive-driven aerodynamic lift	N/A	Lift modulation
VAMP	He or H_2 buoyancy augmented with aerodynamic lift	Super-pressure	Lift modulation

Figure 8.2.—The seven APs assessed in the NASA-based study. CMET is Controlled Meteorological.

The science analysis performed in the study showed a clear increase in scientific payoff as one progresses through the sequence of APs from drop probes to constant altitude super-pressure balloons to variable altitude super-pressure balloons to fully 3D-controlled vehicles. The NASA-based APs study included not only atmospheric observations but also a broad range of geophysics observations using the AP. With this combination, a clear increase in scientific value is possible if a fully 3D-controlled vehicle can broadly target surface locations (volcanically active or not) and measure them from inside or below the clouds. As an example, identification of a volcanically active region would lead to high science return for both geology and atmospheric-based objectives.

Other advantages that a fully maneuverable aerial vehicle may have over a variable altitude balloon for the atmosphere-based science objectives include fully mapping LST-dependent behaviors over a full solar day at multiple altitudes and repeatedly over a range of latitudes. Realizing these advantages depends on the lifetime, achievable flight speed, power generation as a function of latitude, and battery (stored energy) capacity of the 3D-maneuverable vehicle. If the required 3D-maneuverable vehicle performance metrics cannot be achieved, or at least not achieved quickly enough to meet the Venera-D launch date, then high science return can be obtained with simpler altitude-controlled balloons. Constant-altitude balloons were found to provide significant science return but ranked significantly lower than variable altitude balloons, given their inability to measure vertical changes in winds, solar and IR fluxes, trace chemical species, and cloud aerosol properties.

Another key Venus atmosphere science target unique to the VAMP aerial vehicle option is the acquisition of data at altitudes ranging from >100 km down to the cloud tops. Out of the seven AP options considered in the NASA study, only the VAMP is capable of making measurements across this broad altitude range. However, this measurement would be obtained only ***one time during*** VAMP's initial descent from orbit to Venus' cloud deck altitudes. This is possible because VAMP decelerates to subsonic speed at a high altitude, which enables much earlier instrument observations than competing platforms. Key observables that can be obtained in this region are wind speed, bulk atmosphere, and temperature profiles. As a supplement/alternative to the VAMP data, measurements of the atmospheric thermal structure up to 150 km may be derived from occultations obtained at IR wavelengths; likewise, measurement of the CO_2 gas density and atmospheric wind speed may be obtained from 120 km down to the ~70 km cloud top region based on CO_2 dayglow occultation measurements. We point out that the frequency of these occultation observation opportunities is increased if an L1/L2 subsatellite is included as an augmentation to the baseline Venera-D mission architecture. It should also be noted that independent of VAMP or any other augmentation, the baseline Venera-D orbiter may periodically obtain details of the thermal structure in the 100- to 200-km-altitude range during orbit adjustment maneuvers as was done by VEX (Limaye et al., 2017).

In the NASA-based study, quantitative mass comparisons between the seven platforms were performed in a trade study that baselined a cloud-level exploration scenario across a range of 50 to 60 km altitudes and with a 10-kg science instrument payload. Given that Venus-relevant designs were rudimentary for most vehicle types, the analysis approach relied extensively on extrapolations from similar Earth vehicles or rules of thumb gleaned from various Venus studies and mission proposals. The study team performed crosschecks to try to ensure fair comparisons between the platforms. Exploration below the lower clouds (i.e., at <50 km) is also possible with the variable altitude platforms, although the large reduction in solar flux precludes sustained powered flight with the airplane and hybrid vehicle options. The atmospheric temperature below 50 km generally exceeds existing science instrument operational capabilities, which poses a more serious engineering challenge than finding bulk structural and inflatable materials from which to make the vehicle. Although no detailed trade study was performed to systematically quantify the below-the-cloud AP options, a number of opportunities and constraints were noted in the study to guide future mission planning and technology developments. This information may be useful if investigations from the 45- to 50-km-altitude range become a science target for the Venera-D mission.

All platform options except VAMP require aeroshell protection during the hypersonic atmospheric entry phase of the mission; VAMP enters on its own from a low orbit at ≤8 km/s and is designed to survive the thermal and pressure environment of hypersonic entry. A quantitative comparison between the seven vehicles was completed based on a metric called System Arrival Mass, which was defined to be the total mass of the system arriving at Venus after separation from a carrier spacecraft (column 3 of Table 8.4). It includes the aerial vehicle itself and all other required supporting mass such as the aeroshell, parachutes, and any propulsion system required upon approach.

As Table 8.4 indicates, the simplest option of a constant altitude super-pressure balloon (the same family as the Soviet VEGA balloons) requires the least system arrival mass while the 3D-controlled airplane and VAMP vehicles require the most. The set of four variable-altitude balloons all have comparable system arrival mass requirements between those two extremes. Note that the solar airplane in this study is restricted to all daylight conditions with altitudes above 66 km at or near the SS point. This restriction comes from the need for sufficient sunlight to power the propulsion system and maintain steady flight on the sunlit side of the planet. All of the other options can use buoyancy to float at night and survive on stored energy.

The five balloon options all scale in an approximately linear fashion with increasing science instrument mass. Therefore, doubling to 20-kg science instrument mass will approximately double the flying and system arrival masses listed in Table 8.4. However, the mass requirements for the solar airplane and VAMP do not scale linearly relative to the payload mass. Instead, there is a baseline mass required for the power and propulsion systems that provides the maneuverability capability of the vehicles that is only weakly dependent on the mass of the scientific payload. Therefore, the total arrival mass for these vehicles grows more slowly with additional science instrument mass. To first order, the solar airplane system arrival mass would grow to approximately 900 kg for a 25-kg science instrument payload and the VAMP system arrival mass would grow to approximately 1,300 kg for a 25-kg science instrument payload.

Table 8.4.—Platform Mass Requirements for the 50- to 60-km, 10-kg Science Instrument Scenario

Platform	Altitude Range, km	Flying Mass in Venus Atmosphere, kg	System Arrival Mass at Venus Approach, kg
Super-pressure balloon	54	64	290
Pumped helium balloon	50 to 60	87	380
Mechanical compression balloon	50 to 60	96	420
Air ballast balloon	50 to 60	86	380
PCF balloon	50 to 60	140	400
Solar airplane	66 to 75	128	680
VAMP (aerobraked)	50 to 60	450	1,100ⱡ

ⱡ Assumes self-propulsion requirement. This number is reduced by 335 kg if insertion to Venus orbit is provided by Venera-D main orbiter.

8.2.2 Insights Regarding the Venera-D Mass Allocations Relative to the NASA-Based Aerial Platform (AP) Study

Venera-D has a limited amount of mass available for any included aerial vehicle. This mass depends on multiple factors, including

- Launch vehicle,
- Launch date,
- Mass allocation to the orbiter and lander,
- Propellant required to place the orbiter into Venusian orbit, and
- Mass allocated to other optional elements such as subsatellites and additional long-lived landers.

Table 8.5 shows the results of a trade study that computed the total available mass for optional flight elements after accounting for the requirements of the baseline orbiter, lander, and LLISSE elements; these values are estimates (compare with Table 4.3 to Table 4.10). The available mass varies widely by launch date and launch vehicle, and strongly depends on whether the optional payload is first carried into orbit by the orbiter (e.g., VAMP) or instead separates upon approach to Venus and enters directly (all other APs carried inside an aeroshell). The maximum possible aerial vehicle mass for any given launch vehicle and date will clearly correspond to allocating all of the contribution mass to a single AP. Table 8.6 shows the results of an assessment that selected the 2029 launch opportunity using the Angara-A5 launch vehicle and the dimethyl ether (DME) upper stage. The total available contribution mass for the direct entry case is 1,716 kg, which can be divided into a 1,290 kg current best estimate (CBE) mass plus a 426 kg (33%) mass margin. The total available contribution mass for the enter orbit first case (VAMP) is 1,190 kg, which is divided into a 895 kg CBE and 295 kg (33%) mass margin.

Table 8.5.—Available Mass for Possible Mission Augmentations

Launch date		2026 (June)	2028 (January)	2029 (November)	2031 (June)
a. Mass proton + DM3 (kg)	a	6,500	5,800	5,900	6,500
b. Angara-A5 + (DM3) (kg)	b	6,900	6,200	6,300	6,900
c. Angara-A5 + KVTK (kg)	c	7,000	6,300	6,400	7,000
Orbit insertion ΔV (m/s)		900	1060	900	950
Baseline orbiter including instruments and reserves (dry) (kg)		1,450	1,450	1,450	1,450
Baseline lander+LLISSE including reserves (kg)		1,750	1,750	1,750	1,750

The estimated system arrival mass values shown in Table 8.4 for all but VAMP are all much less than the 1,290 kg availability for this launch date and vehicle on Venera-D. This indicates that all of these options are feasible for Venera-D and with more than the 10-kg science instrument payload assumed in the NASA trade study. At first glance, the VAMP requirement of 1,100 kg in Table 8.4 exceeds the 895 kg (CBE) availability on Venera-D, but this is not actually an accurate comparison. In the NASA study, it was assumed that VAMP used its own propulsion system to get into orbit and not be placed into orbit by a separate spacecraft. When this correction is applied to match the Venera-D design in which the main orbiter spacecraft does the initial orbit insertion maneuver, the required 1,100-kg system arrival mass for VAMP reduces to 760 kg. This is 135 kg below the 895 kg (CBE) availability and indicates that VAMP would be feasible with Venera-D if sized to carry 10 kg of science instruments.

We can invert the design problem to estimate how much science instrument mass can be carried on an aerial vehicle given the 1,290 and 895 kg (CBE) limits for Venera-D, starting with the results from Table 8.4 and scaling up appropriately. The results are shown in Table 8.6. There are small differences between the different platforms, except for VAMP, that can provide only a significantly reduced scientific payload. Note that changes to the assumed operating altitudes will change these predicted masses.

Table 8.6.—Predicted Science Instrument Mass Capability on Venera-D

Platform	Altitude Range, km	Venera-D CBE Mass Availability, kg	Aerial Vehicle Science Instrument Mass, kg
Super-pressure balloon	54	1,290	43
Pumped helium balloon	50 to 60	1,290	39
Mechanical compression balloon	50 to 60	1,290	39
Air ballast balloon	50 to 60	1,290	39
PCF balloon	50 to 60	1,290	39
Solar airplane	66 to 75	1,290	36
VAMP (aerobraked)	50 to 60	895	15

Based on the findings of the NASA-based VAP study, there is a clear differential in payload mass allowance for VAMP versus other AP options.

8.2.3 Altitude and Local Solar Time (LST) Access Summary

(1) **Access to altitudes in the range 50 to 60 km:** Access to this altitude range over a range of LSTs is a high priority for the Venera-D mission as it allows detailed study of the atmospheric properties within the clouds. The number of properties that may be measurable within this altitude range will be dependent on the mass tolerance of the chosen AP. As Table 8.4 indicates, with the exception of VAMP, the anticipated payload will be roughly equivalent for any of the chosen in situ platforms. However, the super-pressure balloon flies at a single altitude, which was chosen as 54 km for the NASA study. Each of the other four variable altitude balloon platforms as well as the 3D-maneuverable VAMP platform can access the 50 to 60 km altitude range at all LSTs. However, the solar airplane does not have this capability. Therefore, the vehicles with the highest mass payload tolerance and altitude flexibility (allowing the broadest range of science investigations) at between 50 and 60 km are the variable altitude balloons. For maximum science return, the JSDT would recommend that the lifetime of an AP should be several weeks. To date, there has not been a systematic study of the APs and their lifetimes within the Venus atmosphere.

(2) **Access to altitudes in the range 50 to 65 km:** All of the balloon options can access this altitude range with properly designed entry trajectory. However, the super-pressure balloon

will remain only at a single altitude, while the other balloons and a 3D-maneuverable vehicle like VAMP may access a range of altitudes diurnally. Thus, these latter AP options enable measurements of the atmospheric behaviors inaccessible by previous balloon missions or remote sensing over a broad range of LSTs and altitudes. These types of measurements are critical for a more complete assessment of the physics of Venus superrotation mechanism and radiative balance. However, trades between the allowed payload mass relative to the achievable altitude must be assessed. This will determine the scope of achievable science investigations.

(3) **Access to altitudes in the range 65 to 70 km:** It is an important milestone for Venera-D to access altitudes of 65 km and higher with an in situ aerial vehicle so that the unknown absorber may be directly observed through the full cloud layer. At this time, only the solar airplane and the VAMP vehicles have the capability to access this altitude range. A careful assessment of the allowable payload mass should be performed for these vehicles across the 50 to 70 km altitude range to determine the impact on the Venera-D science investigation goals and priorities

(4) **Access to altitudes in the range 70 to 90 km:** Of the concepts studied, VAMP can uniquely perform science measurements in the altitude range of ~70 to 90 km and then only one profile during descent. This is because only VAMP can decelerate to subsonic speed above this altitude. However, the timeline of development of VAMP is inconsistent with a mission launch date of 2026 or 2028. For this reason, it would be valuable to explore other alternatives to obtain the critical atmospheric data needed in this altitude range.

8.2.4 Summary of Development Requirements for the Seven NASA-Studied Vehicles

All of the vehicle options studied require significant prototyping and testing to achieve sufficient technological maturation for a Venus flight mission. This includes verification of basic flight performance, packaging survivability, deployment and inflation process, and, for VAMP, the hypersonic entry phase from orbit. The study noted that the VAMP development would likely have to progress in multiple stages of prototyping and flight testing to successfully achieve the full size ~60-m wingspan of the vehicle needed to execute a Venus mission with full maneuvering capability. This conclusion rested in part on parallels between VAMP and the existing NASA Hypersonic Inflatable Aerodynamic Decelerator (HIAD) program that has over the years seen a slowly increasing size of vehicle with Earth orbit hypersonic entry testing at each step.

VAMP: This is by far the least technically mature of the seven vehicles studied by NASA. The combination of inflatable hypersonic entry vehicle and atmospheric lifting aircraft is an engineering challenge not likely to be resolved within a short (≤5 yr) timeframe.

- A successful hypersonic entry flight experiment at Earth with a full-scale vehicle will be required to prove viability of this technology prior to use on Venera-D. It is almost certain that multiple hypersonic flight test experiments will be required for VAMP, starting with relatively small-scale prototypes (~5 m wingspan) and proceeding in steps to the full size of ~60-m wingspan.

- Key technical challenges to be solved in such a program include thermal survivability of the vehicle and its exposed solar arrays during hypersonic flight, aeroelastic stability of the large structure across the full range of hypersonic to subsonic flow, and ensuring that no pinhole defects are created during the entry phase of the mission that would leak gas and curtail the atmospheric flight mission.
- Substantial time and financial resources will be required to execute such a protracted multistage development program, and based on experience with similar NASA programs such as HIAD, the VAP study concluded it was almost certainly not compatible with the development timeframe of Venera D.

Solar airplane: Solar airplanes are feasible for operation near the SS point. However, the concept examined in the NASA-based VAP study is not able to function in darkness because it cannot store enough energy in batteries to operate the propulsion system for the approximately 50 to 70 hr of darkness. Therefore, established solar airplane technology is incapable of enabling science investigation within Venus' atmosphere that requires measurements across a full diurnal cycle (times of day).

Super-pressure balloon: This technology is the most mature of the Venus aerial vehicle options given the VEGA experience and more recent production of 5.5- and 7-m-diameter prototypes by the JPL and its partners. The VEGA balloon material itself does not scale up to the larger sizes needed for the larger payloads needed to address the science identified by the Venera-D JSDT. The newer JPL balloons can carry the desired payloads, but still require further technological development, particularly in the areas of size scaling, proving robust structural design margins and balloon packaging.

Variable-altitude balloons: Any of the four variable-altitude balloon options are predicted to provide almost as much science instrument payload capability as the constant altitude super-pressure balloon. However, no Venus-specific design or prototype of any of these options has been produced and tested. Therefore, R&D is needed to mature Venus variable-altitude balloon technology.

- Recent work on terrestrial vehicles, most notably the Google Loon air ballast balloon, has shown tremendous progress with multimonth flights of thousands of kilometers successfully executed. This is suggestive that a Venus version can be successfully developed, but it must be proven with a technology development program prior to use on Venera-D.
- The existence of sulfuric acid aerosols in the Venusian clouds is a complication for the air ballast balloon option used for Google Loon because it would ingest sulfuric acid into the balloon. This not only poses a corrosion problem for the internal surfaces, but also constitutes a risk of acid accumulation inside the balloon that would continuously add weight over time. The other balloon types do not suffer from this problem.
- The PCF balloon suffers from a flight validation problem. Specifically, the buoyancy fluids that work at Venus (water, ammonia) do not work on Earth due to the different atmospheric profiles of temperature and pressure. Model-based validation will be required that includes sufficient fidelity to capture the relevant fluid mechanic, aerodynamic, thermodynamic and

heat transfer physics. This is a major challenge that will require substantial investments to develop and validate.

8.2.5 Risk Versus Cost Assessments from the NASA Aerial Platform (AP) Study

The NASA APs study concluded that there was an optimal choice in the science benefit versus cost and risk trade that favored variable altitude balloon platforms. This rested on the premise that an increase in altitude access allowed a broader range of science investigations to be conducted versus that achievable with a constant altitude balloon. The study results also suggest that the investment required to adapt and extrapolate recent terrestrial balloon technology advances in this field to the Venus flight environment should be modest relative to starting from scratch. This assessment would appear to be valid for Venera-D as well given the anticipated and desired launch dates in the 2026+ timeframe and the attendant need for near-term technology readiness of the AP.

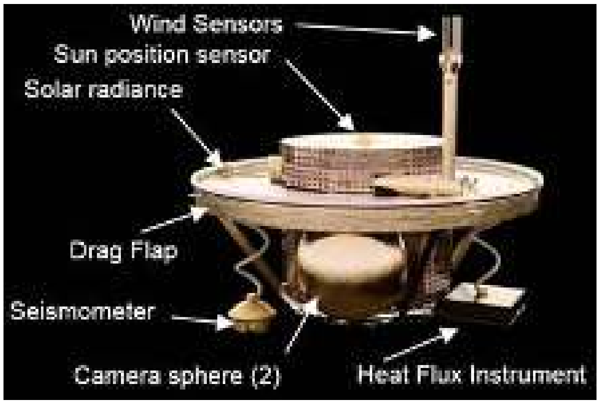
8.2.6 Recommendations Relative to the Venera-D Timeline and Priorities

The inclusion of an AP on the Venera-D mission would allow long duration access to Venus' cloud layer, allowing direct in situ measurements of the atmospheric properties over a range of altitudes on a diurnal basis. As a result, with the proper payload, its inclusion as an augmentation to the Venera-D baseline architecture should enable a more complete study of the physics of Venus atmospheric superrotation and radiative balance, and thus should lead to an overall increase in the science return of the mission. As assessed by the NASA APs study, variable-altitude balloons for Venus are potentially achievable on a near-term time scale given recent technology advances for terrestrial applications and the requirements to adapt that technology for Venus. This makes the inclusion of variable altitude balloons as an augmentation to the Venera-D mission architecture plausible relative to the anticipated and desired 2026+ launch date timeframe. The NASA study concluded that while the VAMP vehicle would provide greater altitude access, leading to a high science return, it would require a very large technology investment over many years, making it highly unlikely to be ready for the desired launch date for Venera-D. Additionally, the payload mass allowance for the variable altitude balloon is higher relative to the 2026+ launch dates considered for Venera-D, which may in principle allow the mission to achieve a more complete study of the physics of Venus atmospheric superrotation and radiative balance at altitudes consistent with the cloud layers.

8.3 Seismic and Atmospheric Exploration of Venus (SAEVe)

SAEVe is a potential mission contribution to deliver small landers (one to three) to the surface of Venus and have them return high-value science for 120 days. The science implemented by SAEVe is primarily focused on seismometry and temporal meteorology measurements that are enabled only by long-duration operations, which remain long-standing gaps in our data on Venus. Table 8.7 presents the science objectives targeted by SAEVe. Figure 8.3 illustrates the SAEVe lander concept and basic dimensions.

The remarkable operating life of SAEVe is enabled by the same three key elements that enable LLISSE, namely (1) high-temperature electronics and systems that operate without cooling at Venus surface conditions, (2) use of simple instrumentation and supporting avionics with emphasis on low data volume instruments and sensors, and (3) minimizing energy utilization through a novel operations approach. Indeed, SAEVe is an enhanced version of LLISSE with longer and increased payload that is made possible with larger mass and volume allocation and with the option of an independent entry and landing on Venus.



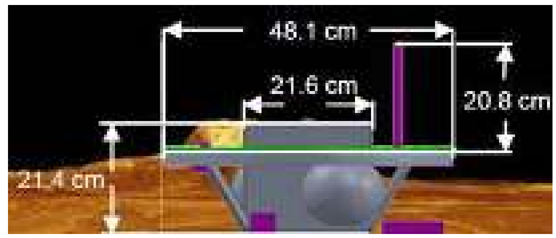


Figure 8.3.—SAEVe lander concept with subset of instruments and basic dimensions.

Table 8.7.—SAEVe Specific Science Traceability

Decadal Survey Goals	SAEVe Science Objectives	Measurements	Instrument Requirements
(A) Characterize planetary interiors	(1) Determine if Venus is currently active, characterize the rate and style of seismic activity	Measure seismic waveform of seismic waves Concurrent wind data at time of seismic measurement	Three-axis (triggered)/one-axis (continuous) seismometer Three-axis wind sensor
	(2) Determine the thickness and composition of the crust and lithosphere	Same as above	Two stations with instrumentation as above
(B) Define the current climate on the terrestrial planets	(3) Acquire temporal meteorological data	Measurement of P, T, wind speed (u), wind direction (v), and light	Three-axis wind sensor measurements, radiance
	(4) Estimate moment exchange between the surface and the atmosphere	Same as above	Same as above during Venus day and night
(C) Understand chemistry of the middle, upper, and lower atmosphere	(5) Determine the key atmospheric species at the surface over time	Measure the abundance of gases H_2O, SO_2, CO, HF, HCl, HCN, OCS, NO, and O_2	Chemical sensor measurements during descent and on surface
(D) Understand the major heat loss mechanisms	(6) Determine the current rate of energy loss at the Venus surface	Measure heat flux at Venus surface	Heat flow measurements, radiance
(E) Characterize planetary surfaces	(7) Determine the morphology of the local landing site(s)	Quantify dimensions, structures, and textures of surface materials on plains unit.	Descent and surface images

8.3.1 Seismic and Atmospheric Exploration of Venus (SAEVe) Key Parameters

Each SAEVe lander will have a mass of approximately 25 kg (~40 kg together with aeroshell, Figure 8.4) and will carry a suite of synergistic instruments and sensors. The instruments are a seismometer, meteorology suite, chemical sensors (same as on LLISSE), heat flux instrument, and an imaging package, consisting of two cubesat cameras, which will operate for a short time at the beginning of the mission. A potential Sun position sensor may be included as a technology demonstration for a possible simple but coarse orientation technique.

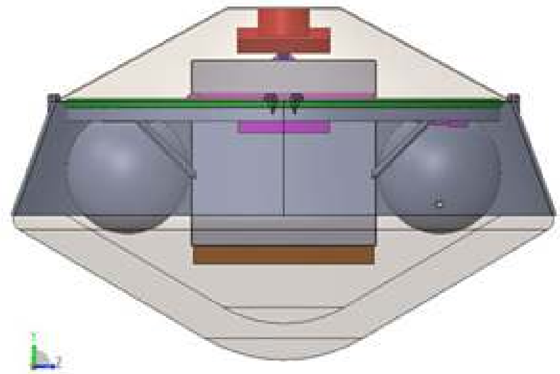


Figure 8.4.—SAEVe in its aeroshell.

8.3.2 Seismic and Atmospheric Exploration of Venus (SAEVe) Science Objectives

A top science priority for SAEVe is to understand how seismically active Venus is and the rate and style of seismic activity. This is accomplished with a short-period MEMS seismometer sensor (based on Insight heritage) coupled with high-temperature electronics. Meteorology is the second science priority to help address climate and its evolution by taking the first long-duration surface data. Energy-related questions are also tackled through the measurement of incident and reflected solar radiation at the surface and the heat flux sensor. Finally, the short-duration camera package not only provides engineering data related to the seismometer placement and coupling but also provides contact images of the landing site and morphology data to understand weathering processes. A summary of the SAEVe's science goals, and their traceability is found in Table 8.7.

Science Objectives Tackled

1) Determine if Venus is seismically active and characterize the rate and style of activity.
2) Determine crust and lithosphere thickness and composition
3) Acquire temporal meteorological data to guide global circulation models
4) Estimate the momentum exchange between the planet and its atmosphere
5) Measure atmospheric chemistry variability
6) Determine current rate of heat loss from the Venus interior
7) Examine rock and soil distribution and morphology

Figure 8.5.—SAEVe science objectives.

8.3.3 Mission Scenario and Requirements for Orbiter

The SAEVe stations inside their aeroshells will be delivered to Venus by the orbiter. The orbiter will need to release the stations into the correct entry trajectory and, when the orbiter is in orbit, listen for transmitted data and relay it back to Earth. The release is accomplished through a standard spin table interface. As with LLISSE, there are no power, data, or thermal controls required for SAEVe during cruise. Several weeks before Venus orbit insertion, the orbiter will orient itself in the correct angle and send the signal to release one of the stations. Shortly thereafter, the orbiter will make the needed pointing adjustments and release the second SAEVe station, and so on. Surface distance between stations should be between 300 and 800 km. The stations will stay dormant during cruise and initial entry, but the entry shell will power on and send critical event data during entry. Details on SAEVe landing sites relative to the main lander will be worked during landing site and mission operations planning.

After release of the SAEVe stations, the orbiter continues with its planned insertion and main lander delivery processes. No additional actions are required from the orbiter during cruise; however, communication with the stations is required during entry and descent. The 24-hr, highly elliptical orbit planned for Venera-D is well-suited for returning data from the SAEVe stations. That orbit period, distance, and frequency of communication contact is the right balance between the transmit power required and view time to allow the mission to maximize station life and science data returned.

As with LLISSE, SAEVe will rely on the orbiter to capture transmitted data and relay it to Earth. Science and engineering data from the lander will be transmitted periodically at data rates of 200 bps or better between 100 and 150 MHz, so the orbiter would need to carry the appropriate receiving antenna and hardware, some of which may also be used for the main lander.

SAEVe includes the required entry capsule and all support elements needed to allow safe entry and landing on the Venus surface. SAEVe enters the atmosphere and gradually slows down during descent due to the thickening atmosphere. At approximately 6 km above the Venus surface, SAEVe separates from the shell, begins taking images, and transmits them as it completes its descent and touches down at under 5 m/s. Temperature, pressure, and chemistry measurements are also collected during this portion of the descent.

After touchdown, an image (supporting morphology and seismometer coupling) is taken. The seismometer and heat flux instruments are dropped to the surface and the remaining images are taken and transmitted. Once all images are returned, the other instruments begin operating and SAEVe continues to transmit data for up to 1 hr continually as long as it does not interfere with main lander science return. After this initial period, SAEVe goes into its nominal operating mode where it turns on and collects and transmits all instrument data for 2 min every 8 hr. The precise frequency and duration of transmissions will be negotiated in later mission planning stages. At all times, SAEVe will be monitoring the vertical axis of the seismometer. This serves as a fast trigger so if an event of specified magnitude is detected, it turns on within 100 ms and begins transmitting data from all three axis of the seismometer as well as wind and pressure data continually for 10 min.

The particulars of the orbit and landing site influence the amount of contact time, and therefore, how many events are expected to be captured, but in ideal conditions, the orbiter could be in view around 90% of the time. Undoubtedly, contact time will not be that high so some transmissions and seismic events may be missed, but a significant fraction will be returned successfully over the 120 Earth days of operations, providing unprecedented insight into Venus surface activity and, if two or more stations are used, its interior structure and composition.

8.3.4 Seismic and Atmospheric Exploration of Venus (SAEVe) Accommodation Flexibility

SAEVe allows for scaling to address mass or volume constraints. An option is to reduce the number of stations although, if reduced to only one station, the potential science on the interior structure and composition will be impacted. There are descope options if mass or volume become an issue at the station level. For example, the short-duration camera pods can easily be descoped from the stations with no impact on the other instruments. The heat flux instrument can also be descoped if needed, still leaving powerful science contributions from each station.

8.3.5 Seismic and Atmospheric Exploration of Venus (SAEVe) Technology Readiness

SAEVe leverages recent technology developments and ongoing development of LLISSE. A summary of technology readiness to implement SAEVe is presented in Table 8.8. This assessment was based on status as of late 2017; further maturation in most areas is ongoing. In fact, a notable takeaway from Table 8.8 is that most technologies are already in development. It should be noted that TRL 6 in Table 8.8 refers to demonstration of performance and life in Venus surface conditions. Current LLISSE development scope does not include vibration or shock testing; however, LLISSE is being designed to successfully pass those and other relevant tests once the launch and other environments are known. With currently allocated budgets, SAEVe could be ready for integration for currently expected Venera-D launch date(s).

Table 8.8.—Technology Readiness Assessment Summary (as of 2017)

Technology	Current TRL	Estimated to be at TRL 6	Funding Source: Ongoing (O to TRL 5 to 6) and Potential (P)
Electronic circuits (SiC): sensors and data handling	4 to 5	2019	LLISSE (O)
Electronic circuits (SiC): power management	3 to 4	2021	LLISSE (O)
Communications (100 MHz)	3 to 4	2021	LLISSE (O)
Wind sensor	4	2019	LLISSE (O)
Temperature sensor	4 to 5	2019	LLISSE (O)
Pressure sensor	4 to 5	2019	LLISSE (O)
Chemical sensors	5	2019	LLISSE/Hot Operating Temperature Technology (HOTTech) (O)
Bolometers	3 to 4	2021	LLISSE (O)
Seismometer	3	TBD	LISSE (O) and possibly Maturation of Instruments for Solar System Exploration (MaTISSE) (P)
Heat flux sensor	3 to 4	TBD	Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) (O)—MaTISSE
Camera/imaging system	3 to 4	2020	Rocket University (O)—MaTISSE if needed
Solar radiance	3 to 4	2020	MaTISSE (P)
High-temperature battery	3	2019	LLISSE and HOTTech (O)
Entry shell	6	TBD	Heatshield for Extreme Entry Environment Technology (HEEET)—need specific SAEVe design

8.4 Secondary Small Satellite

8.4.1 Science Motivations and Objectives

The principal motivation for supplementing the Venera-D baseline mission with a secondary small satellite is to allow accurate characterization of the structure and time variability of the solar wind interaction with Venus' upper atmosphere based on two-point measurements. To complete these investigations, the subsatellite may be placed in either an elongated orbit or at the Lagrange points, however, a higher fidelity and cadence of simultaneous upstream magnetospheric and in situ ionospheric measurements is achieved if the orbit satellite is placed at either L1 or L2.

The ideal two-point measurements for space physics science came from the necessity to separate the spatial and temporal variations. In case of Venus, the two-point measurement (satellite and subsatellite) configuration of satellite-subsatellite play different roles. A subsatellite in the same orbit as the main orbiter enables the study of the structure of the magnetosphere at small distances and the influence of the solar wind on the magnetosphere at large distances (though favorable configurations of satellite-subsatellite occur infrequently and efficiency of this configuration is low). Having the subsatellite at L1 would provide continuous monitoring of the solar wind, and thus allow for a thorough study of the solar wind influence on the planetary environment. A subsatellite at L2 is a version of two-point measurement that emphasizes the magnetospheric tail dynamics science. The choice is difficult, as each configuration has advantages and disadvantages.

Similarly, continuous, high-fidelity full-disk monitoring of Venus' day or night side atmosphere may be consistently obtained at near-zero phase if observations are made on a platform located at the Lagrangian points. This is a capability that is not possible with the main orbiter. Likewise, a high cadence of radio occultation observations may also be obtained over the lifetime of the mission. The radio occultation profiles provide almost synoptic coverage at two latitudes due to the geometry of the Venera-D orbiter in near-polar orbit and the path of the L1/L2 satellites over one Venus year (225 days). These types of observations, which are only possible if the main orbiter is supplemented by a subsatellite, would support indepth investigations of Venus' (i) radiative balance and (ii) thermal structure profiles at morning and evening terminators on both the northern and southern hemisphere as discussed below in Section 8.4.1.2.

8.4.1.1 Two-Point Investigation of Solar Wind Interaction with Venus

Investigations of the solar wind interaction on previous missions to Venus, including Venera-9 and -10, Pioneer Venus Orbiter, and VEX, led to the discovery of the comet-like planetary plasma tail, with its unique type of 'induced' magnetosphere and processes leading to atmospheric losses (see Section 3.1.1.6). Yet without the benefits of upstream measurements provided by two-point measurements, these previous studies provided only limited knowledge of atmospheric loss rates relative to solar and interplanetary conditions and their potential for producing significant changes to the chemical composition of the Venusian atmosphere over time.

Simultaneous measurements by two spacecraft, one within the Venusian magnetosphere and the other in the solar wind, are needed to take the next steps toward understanding the influence of the solar wind of Venus' atmospheric state. In particular, observing the influences of space weather 'storms' on ion escape processes and rates is essential for inferring the evolutionary impacts of solar activity and the solar wind interaction on Venus on short and long time scales.

To significantly advance our understanding of the solar wind-Venus interaction and Venus escape processes over recent and millennial time scales, several questions, which can only be adequately resolved from two-point observations, must be answered. These questions are

- What are the time scales on which the Venus-solar wind interaction responds to external changes? What are the consequences of those time scales? Does 'memory' of past conditions affect the solar wind interaction?

- What additional ion loss processes manifest themselves as time dependent features (e.g., plasma formation in the tail, transient 'tail rays', breaking K-H waves on the magneto sheath-ionosphere boundary)? How important are these from the total atmosphere escape perspective?
- How well do time-dependent global magnetohydrodynamic (MHD) and/or hybrid models coupled with the variable ionosphere describe what is observed at Venus? Can they be used to estimate behavior for exotic parameter ranges and long-term solar wind interaction effects?

8.4.1.1.1 Measurement Requirements

Table 8.9.—Key Measurements Needed from the Proposed Two-Point Measurement Strategy

Measurement Type	Observing Platform	
	Main orbiter	Subsatellite
Reliable mass separation C^+, N^+, O^+, O_2^+, CO_2^+, NO^+, CO^+, and N_2^+	Present	He^+ and H^+ ion mass measurement
Electron spectra	Present	Present
Magnetic field measurements	High frequency	Moderate frequency
Energetic particle measurements	Detailed	Simplified sensor
Upstream condition monitoring	Absent	Present
Energetic neutral atoms analyzer	Present	Simplified detector

8.4.1.2 Improved Dynamics, Albedo, and Thermal Structure Knowledge

From L1 and L2 points, the planet is seen to rotate at its slow rotation rate allowing continuous measurements of Venus' full disk (=12 hr of local time) on the day side (L1) and night (L2) sides, achieving near synoptic coverage of the disk in over a 225 Earth-day period equivalent to 1 Venus orbital year. This type of uninterrupted monitoring of the temporal evolution of the atmospheric properties relative to the underlying topography at a fixed LST and phase angle is not feasible from orbit around Venus or Earth. This is a tremendous advantage to investigate the temporal changes in the Venus atmosphere/cloud cover over time scales comparable to Venus solar day or Venus orbital period (year) without phase angle effect. The absence of phase angle variation increases the accuracy at which the radiance from the atmosphere may be measured on either the day or the night side. This will allow the first unambiguous studies of periodicities in Venus' atmospheric radiance relative to local time and topography, as well as the existence (and persistence) of perturbations to the hemispheric asymmetry of Venus' atmospheric radiance. Further, the main Venera-D orbiter (in near-polar 24-hr orbit) will be occulted two times per day over a major fraction of the Venus year (225 Earth days). Thus, atmospheric and ionospheric profiles can be extracted from the frequent occultations between the Venera-D orbiter and L1/L2 communications link (X and/or Ka band) at nearly constant local times but at different latitudes. This is very different from the traditional radio occultations obtained from previous Venus orbiters (Venera-9, -10, -11, and -12), Pioneer Venus, Magellan, VEX, and Akatsuki spacecraft, which have provided profiles at Venus locations that are biased in solar zenith angle. The improved frequency of thermal profiles and accuracy of radiance levels achievable when the Venera-D baseline mission is supplemented by a small subsatellite at L1 and L2 would lead to significant advances in the investigation of the evolution of Venus' cloud top albedo, atmospheric opacity, atmospheric circulation, and overall climate.

Table 8.10.—Atmospheric Payload Requirements for Subsatellite in Orbit at L1/L2

Measurement Technique	Spectral Range	Observable
Multispectral imaging	0.2 to 1.0 μm	Day side albedo
NIR imaging	0.9 to 2.3 μm	Night side cloud opacity
Thermal imaging	8 to 12 μm	Emitted radiation
Radio science	Radio communications with ultra-stable oscillator (USO) via X/S/Ka band	Radio occultations between Venera-D orbiter and subsatellite(s) around L1/L2 points

8.4.2 Orbit Options and Insertion Requirements

There are two options for the orbit of subsatellite. The subsatellite may be put on an orbit that is elongated but intersecting the orbit of the main satellite (Figure 8.6). This will place the subsatellite in the solar wind flow at the same time when the main spacecraft is within the magnetosphere and ionosphere; in this configuration, the two vessels provide periodic coverage of the solar wind properties. However, if the small satellite is placed at either L1 or L2, a higher cadence of simultaneous two-point observations may be obtained. Additionally, from this vantage point, separation of the temporal and spatial variations within the magnetosphere may be observed.

An additional small satellite can be transferred into an L1 orbit by the following scenario. Initially, the small satellite is joined with the main orbiter, and after separation from the LM, both items continue the trajectory of Venus flyby. Then, at the Venus pericenter, the main orbiter performs a burn for insertion into the operational orbit (polar highly elliptical orbit with the pericenter altitude of 400 km, a period of 24 hr, and consequently an apocenter altitude of 66,000 km) and simultaneously separates the small satellite and inserts it into a transfer trajectory towards L1.

The maneuver cost to inject a small satellite into a transfer trajectory towards L1 is about $V_1 = 450$ m/s (in opposite direction to the velocity vector), if performed at the pericenter of the arrival hyperbola with altitude of 400 km from Venus' surface. The required maneuver for the main orbiter for the elliptical orbit insertion is about $V_2 = 900$ m/s (see Table 4.16 and Table 4.17). Therefore, the satellite separates from the main orbiter when the required velocity is achieved, while the main orbiter continues burn until insertion into the operational elliptical orbit around Venus.

An advantage of such a scenario is that it enables one-impulse transfer of a small satellite into an L1 orbit, only by making use of the propulsion of the main orbiter. After separation from the orbiter, the small satellite requires only trajectory correction and station-keeping maneuvers. Station-keeping maneuvers are required in the vicinity of L1 but have a low cost. From the experience of Sun-Earth Lagrangian points missions, the station-keeping cost may be not more than 1 m/s per year. Another advantage is that a satellite can be transferred from L1 orbit into an orbit in the vicinity of L2 orbit, and this is so-called a 'free' transfer, namely it doesn't require a specific maneuver (Figure 8.7).

It should be noted that achievable L1 orbit depends on the choice of the operational orbit of the main orbiter. The Venera-D operational polar orbit, or with inclination of 90°±10°, and the constraint on the argument of the pericenter $\pi/2 < \omega < \pi$ or $3\pi/2 < \omega < 2\pi$ (in a reference frame laying in the Sun-Venus rotation plane), which guarantees to keep the required pericenter altitude, led to a large-amplitude orbit (see Figure 8.9). Another outcome of the Venera-D constraints is that from the arriving to Venus hyperbola from the interplanetary trajectory, only L1 orbit is achievable. Hence, the satellite can be transferred into the vicinity of L2 only through the L1 orbit.

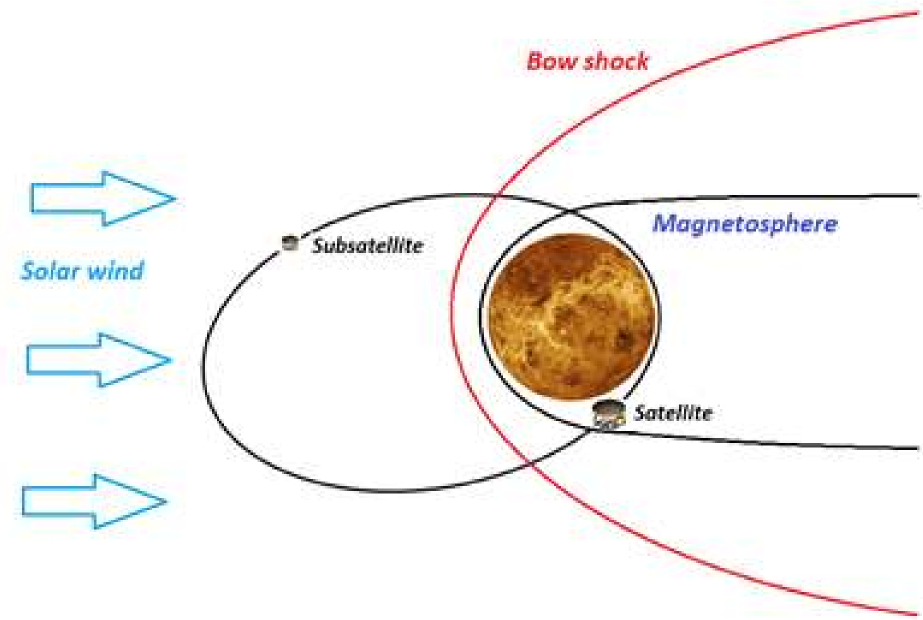


Figure 8.6.—Mutual arrangement of the orbiter and subsatellite in case of placing the subsatellite in orbit around Venus.

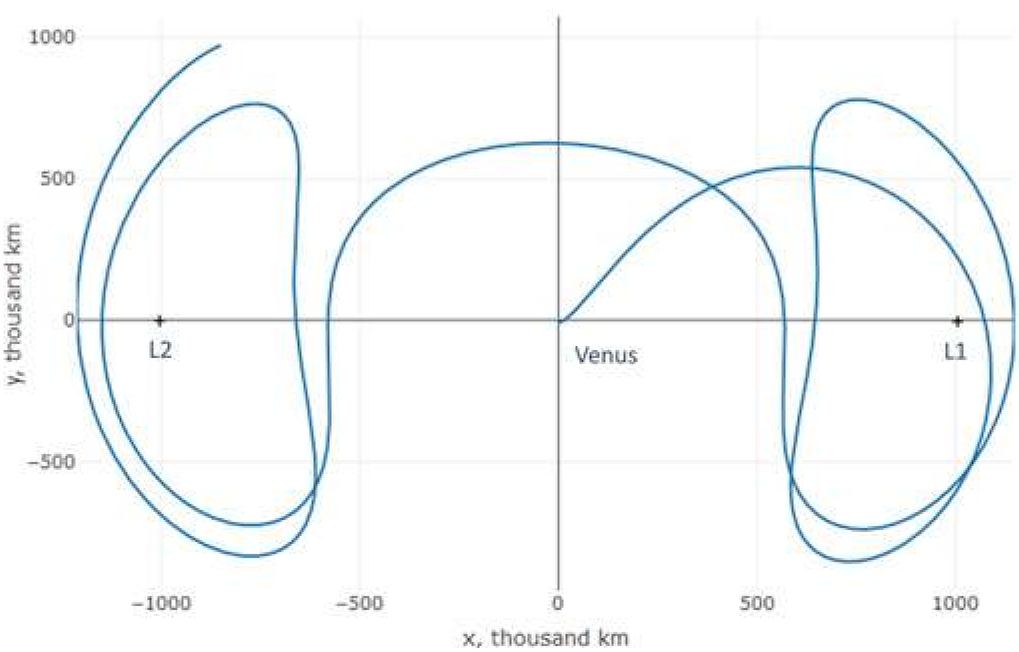


Figure 8.7.—Sun-Venus rotating frame. Ecliptic plane projection. Transfer trajectory from Venus to L1 orbit, then to an orbit near L2.

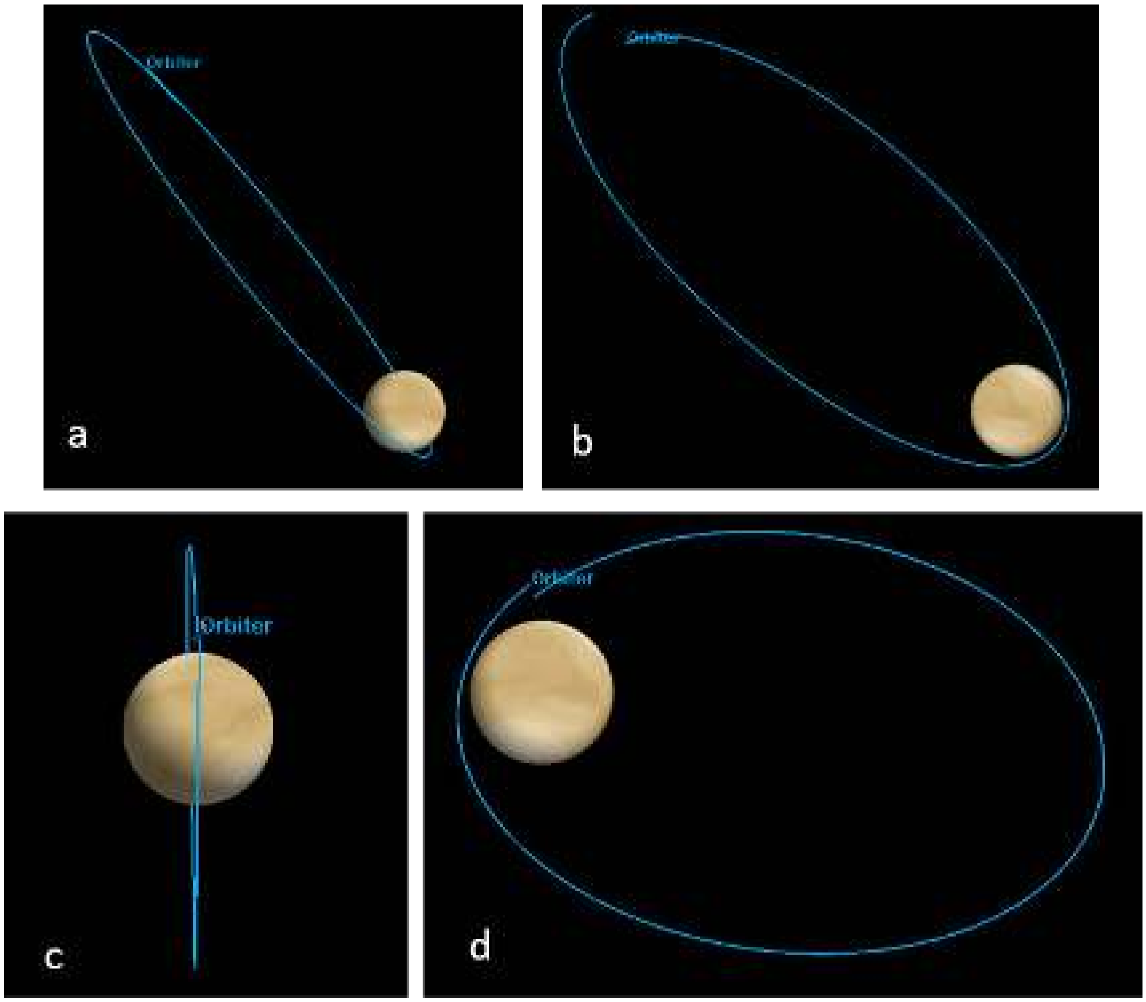


Figure 8.8.—Main orbiter's operational orbit around Venus (elliptical 24-hr period orbit with pericenter altitude of 400 km) as seen from subsatellite in an orbit near L1. Positions a to d of the subsatellite are shown for its trajectory in Figure 8.9 and Figure 8.10.

8.4.3 Additional Advantages of Small Satellites Around Lagrange Points 1 and 2 (L1 and L2)

8.4.3.1 Increased Occultation Opportunities

Occultation events between the main orbiter in a one-day elliptical orbit and a satellite in an L1 or L2 orbit will occur nearly every day and once (entry and exit) per revolution of the main orbiter around Venus, enabling retrieval of atmospheric and ionospheric profiles of temperature and electron density during entry and exit events. Figure 8.8 shows projections of the elliptical orbit of the main satellite onto the plane orthogonal to the line from a subsatellite in a libration point orbit to the center of Venus. In other words, it shows views of the main satellite's orbit as seen from the subsatellite. This example corresponds to a launch opportunity in 2026, with the main satellite inserted into a 24-hr period orbit around Venus and the pericenter altitude of 400 km above the surface, while a subsatellite is transferred into the vicinity of the L1 point orbit, as shown in Figure 8.8 and Figure 8.9. The average duration of occultation (Figure 8.8(a)) takes 30 min. The longest occultations might take about 4 hr and occur when the main orbiter is behind Venus as seen from the subsatellite, while the orbiter passes through the apocenter of its operational orbit (Figure 8.8(c)). It should be noted that in a specific relative positions of the main orbiter and the subsatellite in L1/L2 vicinity, occultation events might not occur over about 10 days (see Figure 8.8(b) and (d)). However, these no-occultation intervals are infrequent and would happen once per revolution of the subsatellite about either Lagrange point (112.5 days). The duration of this "no-occultation" period is much shorter than for Venus orbiter-Venus-Earth DSN occultations, so the mutual occultations between a satellite in orbit around L1 or L2 will provide four to five times the number of occultations between a Venus orbiter in a 24-hr orbit and Earth as shown by the experience with Pioneer Venus and VEX missions.

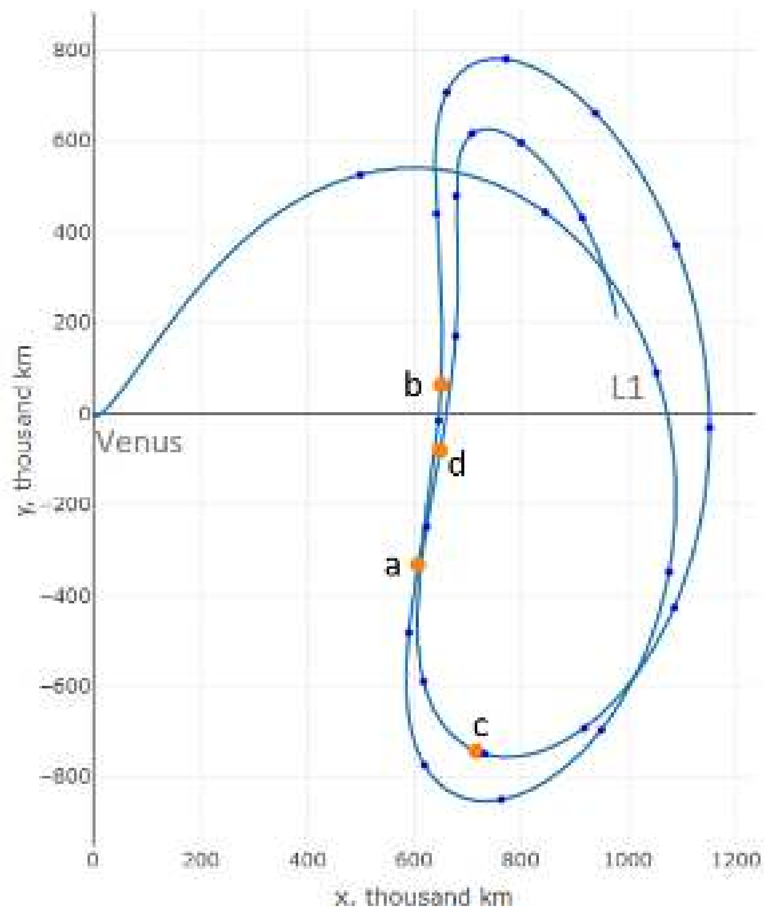


Figure 8.9.—Transfer trajectory from Venus arrival hyperbolic orbit to L1 orbit. Ecliptic plane projection, Sun-Venus rotating frame. Intervals between blue tick marks is 10 days. Orange marks correspond to positions of satellite in Figure 8.9.

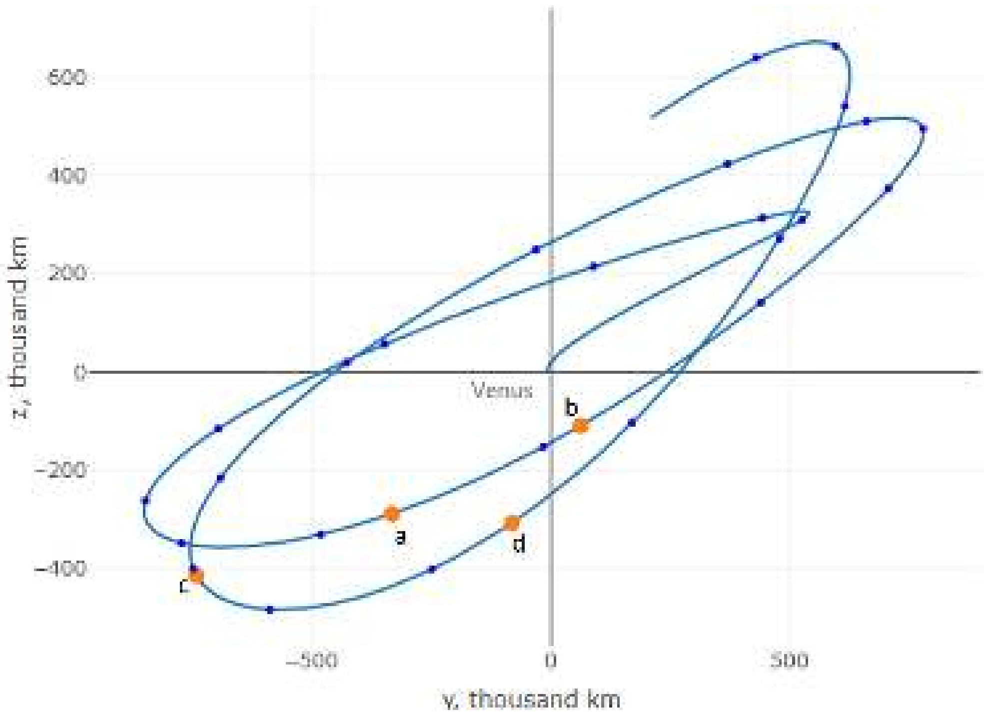


Figure 8.10.—Transfer trajectory from Venus arrival hyperbolic orbit to L1 orbit as seen from Venus. Sun-Venus rotating frame. Interval between blue tick marks is 10 days. Orange marks correspond to positions of satellite in Figure 8.9.

8.4.3.2 Increased Communication Opportunities and Support of Multiple Surface Stations

For the purposes of the spacecraft control, to send or receive service information and scientific data, it is supposed to use a number of Russian X-band ground stations with the main mirror diameter of 12 and 32 m. No less than two ground stations will be used at the same time to gain the needed reliability. Thus, almost full northern hemisphere coverage will be available.

Any entry or surface platforms deployed will need to communicate their data to the main orbiter or to a satellite in about around L1 or L2, as the direct link to Earth will be inefficient due to low transmitter power. The relative distance between the main orbiter and the subsatellite orbiter located about L1 is illustrated in Figure 8.11. The range to a satellite around L2 is expected to be comparable.

In the Phase III, the following considerations should be studied:

(1) The supposed ground stations fields of view and their sufficiency for the selected orbits and years;
(2) The needs and possibility of using a number of the Ka-band surface stations (in case of using a Ka-transmitter on the orbiter); and
(3) The possibility of using NASA's ground stations and foreign surface stations in the southern hemisphere in X- and Ka-bands for the extended transmission time and for the southern hemisphere coverage.

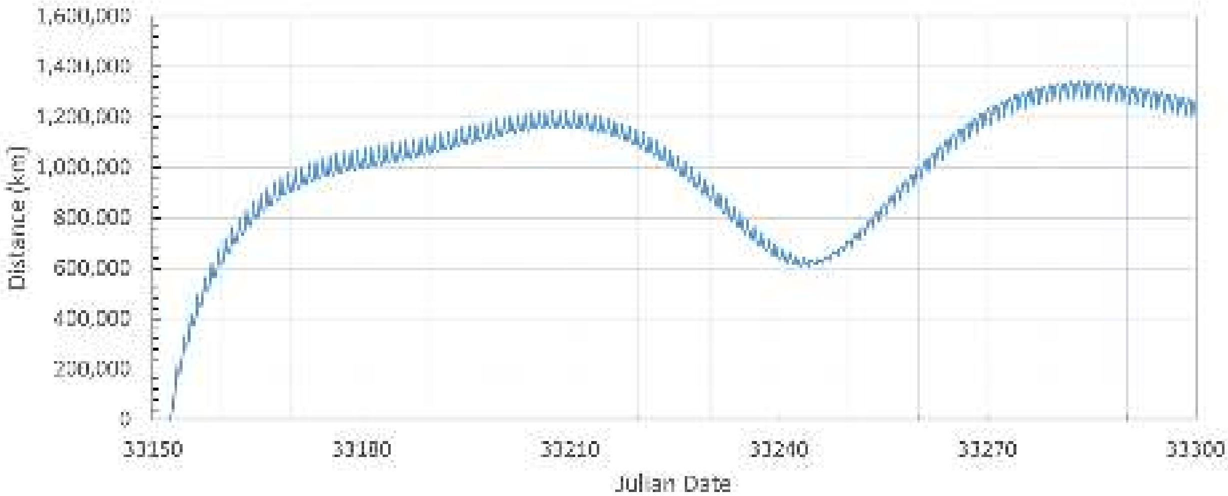


Figure 8.11.—Distance between the Venera-D orbiter in a 75° inclination orbit and a satellite around L1 as a function of time. The dates are post arrival at Venus in 2031.

9 Assessment of Risk Structure

The study team has performed a preliminary assessment of Venera-D mission risks. Table 9.1 shows the identified risks on a standard 5×5 matrix, and Table 9.2 provides a brief description of those risks. Specific mitigation strategies should be future work as part of a Phase III study.

Table 9.1.—Venera-D Risk Matrix

Likelihood					
5			**014**		**003**
4		**027**	**004, 024, 026**	**005, 006, 007, 008**	
3		**021**	**009, 010, 015, 017, 018, 019, 020**	**011, 022, 023**	
2				**012, 013, 016, 025**	
1			**001**	**002**	
	1	2	3	4	5

Consequences

Table 9.2.—Risk Descriptions

Risk Number	L×C	Risk Description
VD-RS-001	1×3	Angara-A5 with KVTK may not be ready for 2026, resulting in a possible delay or requiring a different launcher, which may impact Venera-D mass allocations and specifications (e.g., vibration).
VD-RS-002	1×4	Ka–band Russian ground stations may not be ready for 2026, potentially increasing need for additional storage, other ground stations outside Russia, or live with an impact to desired data return rates.
VD-RS-003	5×5	Lander's MGA may not be ready with other components of spacecraft. Further analysis study is needed to fully characterize the communication link between the lander and orbiter. If the MGA is not available, it increases the risk of not recovering all the lander's high-priority science measurements.
VD-RS-004	4×3	Composition, specifications (for example thermal, overload, vibration limits), and timeline of payload are not fully specified, increasing the risk for rework, additional testing, delays in delivery of payload, and increased risk to successful operations at Venus.
VD-RS-005	4×4	The operational condition of the required test facilities at NPOL are not confirmed and could impact development schedule and launch readiness or add additional risk of successful operations at Venus.
VD-RS-006	4×4	The details and characteristics of potential contributed elements are not specified, increasing the risk for rework, additional testing, delays in delivery of payload, and increased risk to successful operations at Venus.
VD-RS-007	4×4	Surface sampling system not yet designed. May require more MPV resources than expected. It also may not satisfy science requirements for depth of acquisition, number of samples, or adequate distribution to the measuring instruments.
VD-RS-008	4×4	LLISSE (long-lived surface station) technology development is not yet complete. May require more MPV resources than expected. May not achieve planned lifetime on the surface, and therefore, not achieve desired science.
VD-RS-009	3×3	Possible contributed AP is not yet designed or finished with technology development. May require more MPV resources than expected. May not achieve desired mission lifetime or altitude range, and therefore, not achieve desired science.
VD-RS-010	4×3	Addition of multiple windows and other penetrations to the lander pressure vessel may cause unacceptably high heating of the payload and prevent achievement of the required surface operational lifetime.
VD-RS-011	3×4	Mass growth of the lander and orbiter may exceed current margins and reduce the mass available for other contributed elements such as an AP.
VD-RS-012	2×4	Telecom relay design for LLISSE and AP to orbiter is not well developed. Do not have good estimates for achievable transmitted data volume; hence do not know if science objectives for those platforms can be achieved.
VD-RS-013	2×4	No design yet for arrangement of instruments, sampling system, and lander components inside the pressure vessel. Cannot verify that adequate volume exists to accommodate everything. May result in growth in size and mass of pressure vessel with possible ripple effects on landing ring, drag plate, and entry aeroshell, or it may require removal of instruments from the payload.
VD-RS-014	5×3	Current 7-yr project schedule with a 2026 launch is aggressive due to the need to successfully complete multiple technology developments, design development, and test of the many instruments and mission elements. Challenges in these areas may result in delay of mission or increased costs.
VD-RS-015	3×3	Most instruments for the lander have not been developed, tailored, or testing for Venus operations that will be seen. This may result in not meeting measurement goals/science objectives or growth in size, mass, and power.
VD-RS-016	2×4	The mission concept of operations (CONOPS) and sequence of operations, particularly for the lander and its communication with the orbiter, is not well defined. This may result is science objectives not being accomplished.
VD-RS-017	3×3	The challenges associated with interfaces across international boundaries and support needed from multiple governments may result in delays to complete mission development, which may impact launch readiness dates and possibly science objectives.
VD-RS-018	3×3	Desired payload for AP may exceed capability of platform. Competing science objectives may result in growth of the system or compromise of science goals.

10 Recommendations (Findings)—NPOL Architecture Concept

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 on additional direction received from both IKI and NASA, findings and recommendations are put forward regarding (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.

10.1 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; a single, highly capable lander; and an attached long-lived station (LLISSE). 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 NIR, 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 10.1.

Table 10.1.—Baseline Venera-D Mission

Mission Element	Science Goal	Anticipated Science
Orbiter (high-eccentricity polar orbit with periapsis ~400 km, 24-hr period)	Understanding atmospheric superrotation and global circulation	Validate different processes that maintain superrotation
	Radiative balance and driver for superrotation	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-hr descent to the surface, 1 hr of surface measurements and 1 hr 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 VIS 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
SAEVe: long-lived (120-day) stations	Temporal meteorological measurements at the surface (superrotation and global circulation) and atmospheric chemistry variability (surface atmosphere interactions); seismic activity; surface heat flux	Near-surface winds (pressure, temperature, wind speed and direction); seismic activity; heat flux at Venusian surface
LLISSE: long-lived (>60 days) station not attached to the lander	Temporal meteorological measurements at the surface (superrotation and global circulation) and atmospheric chemistry variability (surface atmosphere interactions)	Long-duration information about meteorology and interactions between the surface and atmosphere. Multiple LLISSEs would provide more information about surface winds

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 10.2). 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 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 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 subsatellite with a focus on solar wind and ionospheric processes was examined and found to provide an incremental advancement in the state of knowledge.

Table 10.2.—Potential Enhancements to the Venera-D Mission

Mission Element	Science Goal	Anticipated Science
≥2 SAEVe (60 days, battery 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
	Seismicity and internal structure	Measure active seismicity and heat flux from the Venus interior
	Technology development	First demonstration of long-lived station on the surface of Venus
Variable altitude maneuverable AP (>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, and solar thermal tides
	Nature of the UV absorber	Identity of the unknown UV 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 UV contrasts and NIR 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 UV 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 UV contrasts and NIR opacity and cloud chemistry/composition
Small satellite in orbit around L1 (day side) orbit	Day side cloud cover, cloud top temperatures, radio occultation temperature profiles Solar wind and magnetosphere and ionosphere interaction	Temporal evolution of day side albedo and thermal properties and upper mesospheric temperatures from limb data (LIR camera) Radio occultation profiles using Venera-D orbiter Communication relay for AP and LLISSE. Permanent solar wind and interplanetary magnetic field control
Small satellite in orbit around the L2 point (night side)	Cloud top temperatures, radio occultation temperature profiles Solar wind and magnetosphere and ionosphere interaction	Temporal evolution of night side cloud top thermal structure and upper mesospheric temperatures from limb data (LIR camera) Radio occultation profiles using Venera-D orbiter Communication relay for AP and LLISSE
Subsatellite in same orbit as Venera-D orbiter	Solar wind and magnetosphere and ionosphere interaction	Partial solar wind and interplanetary magnetic field control, separation of spatial from temporal variations, ionospheric/atmospheric radio occultations

10.2 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 yr) investments would need to be made to bring the mission concept to fruition. For an anticipated launch in the 2026 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; and
- Continued development regarding all potential contributions.

10.3 Assessment of Joint Science Definition Team (JSDT)–Chartered Tasks

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.

(2) Assess the Venera-D mission architecture, including possible modular options (e.g., subsystems) for collaboration opportunities and required instrumentation capabilities. Assess TRL 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 were evaluated and a rating of level of needed development was established to quantify the time to needed to reach flight readiness TRL.

(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 timeframe.

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

(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.

(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 GCMs would form the basis for devising engineering techniques to successfully launch samples from the surface for retrieval in space. Measurements of how active Venus is seismically would enable future missions to optimize future seismic investigations. 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.

11 Programmatics (Schedule, Plans for Cooperation, Etc.)

The study team assessed a range of plausible development schedules as summarized in Table 11.1. The total development time ranges from 7 to 10 yr and will be a function of speed with which partnering arrangements can be finalized and the rate at which new technology developments can be accomplished. As the label indicates, the 8.5-yr timeline was judged by the JSDT to be more realistic than the faster option. Table 11.1 shows a June 2019 start date to fix ideas; note that the 2026 launch opportunity that serves as the earliest date considered in this study can only be accomplished with a fast development timeline (7 yr) that begins on this June 2019 date. Any other circumstance will force the use of a later launch opportunity.

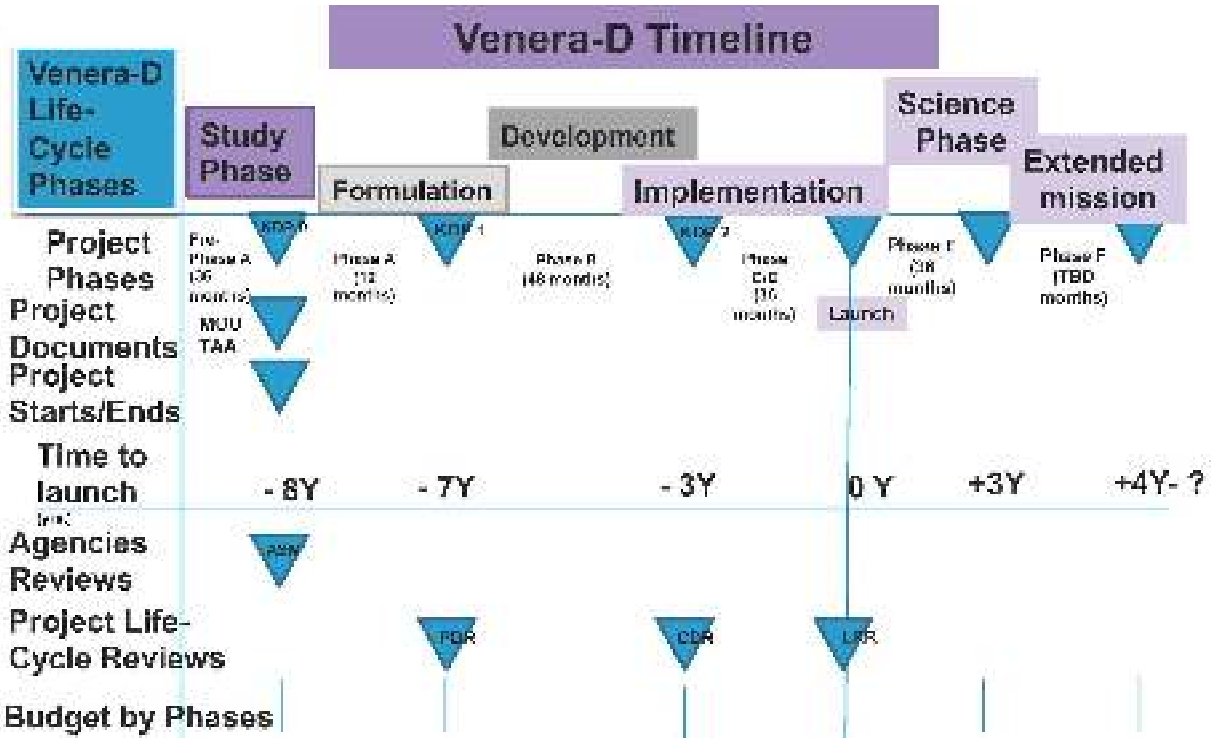
The suggested composition of cooperation during stages of R&D of the spacecraft is indicated in Table 11.2. During the R&D stage, the composition of cooperation may change.

IKI is the primary scientific organization in Russia responsible for the Venera-D mission. Together with NASA, it makes decisions on the spacecraft modules and instrument composition as well as reception, processing, and interpretation of the scientific information.

Technological interfaces, detailed schedule of works, and principles of cooperation between NASA and Roscosmos should be determined at the stage of Phase A.

Table 11.1.—Suggested Options for the R&D Schedule

Phase		Description	Period, yr		
Russian	**English**		**Fast**	**Realistic**	**Long**
Аванпроект	Phase A	Creation of general concept of the spacecraft, specification of requirements and characteristics, design development, modification analyses of the spacecraft, and selection of cooperation modes.	1,5 (June 2019 to January 2021)	1,5 (June 2019 to January 2021)	2 (June 2019 to January 2021)
Эскизный проект	Phase B	Detailed development of selected design, principal decisions, and verification of cooperation.	2 (January 2021 to January 2023)	3 (January 2021 to January 2024)	3 (June 2021 to June 2024)
Разработка конструкторской документации	Phase C	Final appearance development of the spacecraft and its assembly drawings and raw models.	1,5 (January 2023 to June 2024)	2 (January 2024 to January 2026)	2,5 (June 2024 to January 2027)
Наземная экспериментальна я отработка	Phase C/D	Modeling, testing, and assembly.	2 (June 2024 to June 2026)	2 (January 2026 to January 2028)	2,5 (January 2027 to June 2029)
Лётные испытания	Phase E	Launch and operations.	3 (June 2026 to June 2029)	3 (January 2028 to January 2031)	3 (November 2029 to November 2032)
		Total development time (yr):	**7**	**8.5**	**10**



Notes: MOU = Memorandum of Understanding; TAA = Technical Agreement; TBD = to be determined; ASM = Acquisition Strategy Meeting; FAD = Formulation Authorization Document; KDP = Key Decision Point; PCA = Program Commitment Agreement; PIR = Program Implementation Review; SDR = System Definition Review; SRB = Standing Review Board; SRR = System Requirements Review

Blue triangles represent life-cycle reviews that require SRB. The Agencies Decision Authority, Administrator, ADA, may request the SRB conduct other reviews. PDR = Preliminary Design Review; CDR = Critical Design Review; LRR = Launch Readiness Review

Figure 11.1.—Suggested time scale for a launch in year "0".

Table 11.2.—Suggested Composition of Cooperation during Stages of R&D of the Spacecraft

Segment	Integral Part (IP)	Cooperation
Earth	Ground control complex	NPOL Association, Russian Space Systems, Keldysh Institute of Applied Mathematics (Russian Academy of Sciences (RAS)), Special Design Bureau of Moscow Power Engineering Institute (SDB MPEI), and TsNIIMASH
	Ground science complex	NPOL Association, IKI, and NASA
	Launch facility	NPOL Association, Russian Space Systems, Khrunichev State Research And Production Space Center, and TsENKI
Space	Orbiter, lander	NPOL Association, Guskov Institute, Antares RC, Polus RC, Geofizika-Kosmos, VNIIEM Corp., Module RC, Russian Space Systems, TsNIIMASH, KBKhM, Saturn PJSC, IRZ, OKB Pyatoe Pokolenie, NIIFI, and NASA (LLISSE)
	Scientific instruments	IKI and NASA

12 Suggested Next Steps

Relative to the development life-cycle process provided by TsNIIMASH (Центральный научно-исследовательский институт машиностроения), the JSDT activity has completed the activities of defining the science goals, identifying a notional scientific payload, and participated in the preliminary assessment of the mission feasibility (Figure 12.1). The next phase of development would focus on a deeper examination of the science and instruments along with the definition of the spacecraft requirements. Within this context, the JSDT has identified specific areas that deserve immediate attention, including

(1) Development of capable facilities to test mission enabling instruments and the spacecraft at the component and system level in a simulated Venus environment;
(2) Definition of a comprehensive mission concept with core and prioritized science-enhancing elements (e.g., AP, long-lived stations, small satellites at L1 and L2 points);
(3) Formulation and prioritization of synergistic science goals for the mission architecture between instruments of the baseline elements and possible contributed elements;
(4) Definition of a concept of operations for the LLISSE+lander complex, including a timeline of science observations, strategy for sample acquisition, handling and analysis, data flow, and downlink;
(5) Refinement of baseline LLISSE+lander and orbiter instrument capability relative to the prevailing environmental conditions to confirm its ability to achieve the science goals;
(6) Refinement of the envelope (MPV) for the payload of the baseline elements;
(7) Maturation of the baseline small station interface, instrumentation, and concept for targeting and deployment of LLISSE+lander;
(8) Refinement of the AP accommodation deployment, requirements, optimization, and operations relative to science priorities and instrumentation;
(9) Refinement of the multiple additional contributed long-lived weather and seismic station accommodation and requirements;
(10) Refinement of the subsatellite platform accommodation, orbit parameters, instrument priorities, and requirements; and
(11) Assessment of data communications capability between
    (a) Up/down links between Venera-D orbiter and Earth stations at X and Ka bands
    (b) Downlink between from lander to Venera-D orbiter
    (c) Downlink between AP and
        (i) Venera-D orbiter
        (ii) Additional LLISSE (or SAEVe)
        (iii) Subsatellite in orbit around L1 location
        (iv) Subsatellite in orbit around L2 location
    (d) Up/down link between Venera-D orbiter and L1 and L2 satellites
    (e) Up/down link between L1/L2 satellites and Earth stations

(12) To accomplish several of these goals, we need to expand the team to include a preproject team that is composed of engineers to work with the present team of scientists, such as telecom engineering, structural and thermal engineering, system engineering, and so on.

To achieve a number of these items, a greater engagement of the broader Venus science and engineering community is also recommended. The development of the Phase II description of the Venera-D mission architecture and baseline component payload has benefited greatly from modeling workshops held in both the United States and Russia to understand the limitation and needs of current models. As a follow-on to these workshops, a Venera-D landing site selection workshop is needed to ensure the highest science potential from the lander+LLISSE observations. Likewise, the habitable zone in the Venus cloud layer is a critical topic for more comprehensive participation of the astrobiology community. Consequently, *the VDJSDT recommends holding an international workshop in 2019 to investigate (1) potential landing sites for the Venera-D lander and (2) habitability in the Venusian clouds and astrobiology*. This workshop would be held in the days prior to the 10th Moscow Solar System Symposium (10M-S^3). The dates for 10M-S^3 are October 7 to 11, 2019; the recommended Landing Site/Habitability workshop would be held at IKI October 2 to 5, 2019. We anticipate 2 days spent on landing site selection and 2 days on habitability/astrobiology.

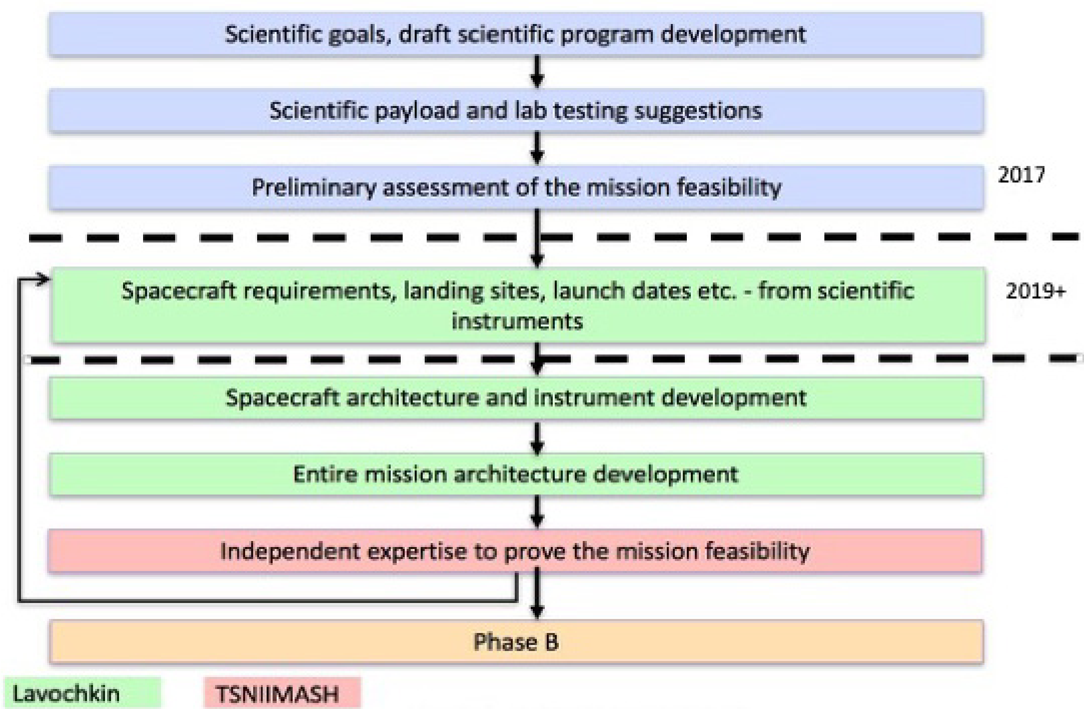


Figure 12.1.—Mission development cycle provided by TsNIIMASH.

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Appendix A.—Acronyms and Definitions

Acronym	Definition
3D	three-dimensional
ACS	Atmospheric Chemistry Suite
ADA	Agencies Decision Authority
ADRON	Active Detection of Radiation of Nuclei
AGNESSA	Active Gamma and Neutron Spectrometric Soil Analysis
AGS	Atmosphere Gas Sampling
AOTF	acoustic-optic tunable filter
AP (ВП)	aerial platform (Воздушная платформа)
APXS	alpha particle X-ray spectrometer
AS	antisolar
ASM	Acquisition Strategy Meeting
ASPERA-4	Analyzer of Space Plasmas and Energetic Atoms 4
aSPECT-V	neutron decay spectrometer
ATS-JV	Alcyon Technical Services Joint Venture
BAT	Beta-Alta-Themis
BMSV	fast solar wind monitor
CAP	chemical analyses package
CBE	current best estimate
CCSDS	Consulting Committee for Space Data Systems
CDR	Critical Design Review
CIA	collision-induced absorption
CIR	co-rotation interaction regions
CIRS	Compact Integrated Raman Spectrometer
CME	coronal mass ejection
CMET	Controlled Meteorological
CONOPS	concept of operations
CORONAS-Photon	Complex Orbital Observations Near-Earth of Activity of the Sun-Photon
D	Dolgozhivuschaya
DAN	Dynamic Albedo of Neutrons
DCU	data compression unit

DEM	digital elevation model
DFB	distributed feedback
DLR	German Aerospace Center
DLS	diode laser spectrometer
DME	dimethyl ether
DSN	Deep Space Network
ELSPEC	electron spectrometer
ESA	European Space Agency
ESTRACK	European antenna infrastructure control Center
EUV	extreme ultraviolet radiation
FAD	Formulation Authorization Document
FCB	Functional Cargo Block
FEC	forward error correction
FIRE	Federal Institute of Radio-engineering and Electronics
FM-V	Fluxgate Magnetometer for Venus
FNA	fast neutrals analyzer
FOV	field of view
FS	Fourier spectrometer
GB	gigabyte
Gb	gigabit
GC	gas chromatography
GCM	general circulation model
GC-MS	gas chromatograph-mass spectrometer
GEER	Glenn Extreme Environments Rig
GPI	General Physics Institute
GRC	NASA Glenn Research Center
gb	groove belts
H	high
HEEET	Heatshield for Extreme Entry Environment Technology
HGA	high-gain antenna
HIAD	Hypersonic Inflatable Aerodynamic Decelerator
HOTTech	Hot Operating Temperature Technology
HTTB	high-temperature tolerant battery

IAPS	Institute for Space Astrophysics and Planetology
IC (ПК)	instrument container (Приборный контейнер)
ICOS	integrated cavity output spectroscopy
IEF	International Engineering Fair
IFOV	instantaneous field of view
IKI RAN	Russian Space Research Institute
IKI	Institut Kosmicheskih Issledovanyi (Space Research Institute)
IMU	inertial measurement unit
INAF	National Institute for Astrophysics
IR	infrared
ISKRA-V	Investigation of Sulphurous Komponents of Rarefied Atmosphere of Venus
ISO	International Organization for Standardization
ISRO	Indian Space Research Organisation
ISS	International Space Station
IVOLGA	infrared heterodyne fiber analyzer
IZMIRAN	Space Weather Prediction Center
i	impact
J2000	astronomical reference frame
JAXA	Japan Aerospace Exploration Agency
JIRAM	Jovian Infrared Auroral Mapper
JPL	NASA Jet Propulsion Laboratory
JSDT	Joint Science Definition Team
Kb	kilobit
KB	kilobyte
KBKhM	Конструкторское бюро химического машиностроения имени А.М. Исаева
KDP	Key Decision Point
KVTK (*КВТК*)	Кислородно-водородный тяжёлого класса
L	low
L1	Lagrange point 1
L2	Lagrange point 2
LAC	Lightning and Airglow Camera
LaRC	Langley Research Center

LATMOS	IPSL Atmospheres Laboratory
LESIA	Laboratory of Space Studies and Instrumentation in Astrophysics
LGA	low-gain antenna
LIBS	laser-induced breakdown spectroscopy
LIDAR	Laser Imaging, Detection and Ranging
LIMS	laser-induced mass spectrometry
LIP	large igneous province
LIR	longwave infrared
LLB	long-lived balloon
LLISSE	Long-Lived In-Situ Solar System Explorer
LLISSE-W	Long-Lived In-Situ Solar System Explorer (wind-powered)
LM (ПМ)	landing module (Посадочный модуль)
LRR	Launch Readiness Review
LST	local solar time
LTE	local thermodynamic equilibrium
LVF	launch vehicle fairing
M	medium
M5	Mission-class 5
MatISSE	Maturation of Instruments for Solar System Exploration
Mb	megabit
MB	megabyte
MEMS	microelectromechanical systems
MER	Mars Exploration Rover
MESSENGER	MErcury Surface, Space ENvironment, GEochemistry and Ranging
METEO	meteorological
MEV	maneuverable entry vehicle
MEx	Mars Express
MGA	medium-gain antenna
MHD	magnetohydrodynamic
MIMOS-2A	miniaturized Mössbauer Spectrometer
MIPT	Moscow Institute of Physics and Technology
MIR	mid-infrared
MLAS	Multichannel Laser Absorption Spectrometer

MMW	millimeter wave
MOU	Memorandum of Understanding
MPV	mass, power, volume
MS	mass spectrometry
MSL	Mars Science Laboratory
MTDL	multichannel tunable diode laser
mb	mountain belts
NASA	National Aeronautics and Space Administration
NAV	navigation
NEδT	differential figure-of-merit
NII KP	НИИ КП (Russian Space Systems (RSS))
NIR	near infrared
NPD	neutral particle detector
NPOL	Lavochkin
NRC	National Research Council
NS	neutron spectrometer
NTO	dinitrogen tetroxide/nitrogen tetroxide
O	ongoing
OBC	onboard computer
OE	onboard avionics equipment
OIR	orbiter infrared radiometer
OM	Orbiter Module (Орбитальный модуль)
OMEGA	Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité
Ops	operations
PCA	Program Commitment Agreement
PCF	phase change fluid
pdl	densely lineated plains
PDR	Preliminary Design Review
PE	payload equipment
PEL	Planetary Emissivity Laboratory
PFS-VD	planetary Fourier spectrometer-Venera D
PI	Principal Investigator

PICASSO	Planetary Instrument Concepts for the Advancement of Solar System Observations
PIR	Program Implementation Review
PREM	preliminary reference model
PVLP	Pioneer Venus Large Probe
pl	lobate plains
pr/RB	ridged plains/ridge belts
ps	smooth plains
psh	shield plains
psi	smooth plains of impact origin
psv	smooth plains of volcanic origin
QCL	Quantum Cascade Laser
r	radius
R&D	Research and Development
RAS	Russian Academy of Sciences
RG	Roentgen-Gamma
RKPNI	Russian Complex for Receiving Scientific Information
RX	receive
rp1	regional plains, lower unit
rp2	regional plains, upper unit
rz	rift zones
S-VD	seismometer Venera-D
SAEVe	Seismic and Atmospheric Exploration of Venus
SAGE	Stratospheric Gas and Aerosol Experiment
SAR	synthetic aperture radar
SAS	small astronomy satellite
SC (KA)	spacecraft (Воздушная платформа)
SDB MPEI	Special Design Bureau of Moscow Power Engineering Institute
SDR	System Definition Review
SDT	Science Definition Team
SLE	Space Link Extension
SOIR	Solar Occultation at Infrared

SPICAM	Spectroscopy for Investigation of Characteristics of the Atmosphere of Mars
SPICAV	Spectroscopy for Investigation of Characteristics of the Atmosphere of Venus
SRB	Standing Review Board
SRR	System Requirements Review
SS	subsolar
SSB	Space Studies Board
SSOE	solar and star occultation spectrometer
sc	shield clusters
TAA	Technical Agreement
TBD	to be determined
TC	telecommand
TGO	Trace Gas Orbiter
TIRVIM	Thermal Infrared V-shape Interferometer Mounting
TM	telemetry
TPW	temperature, pressure, wind
TRL	technology readiness level
TsNIIMASH	(vЦентральный научно-исследовательский институт машиностроения) Central Research Institute for Machine Building
TIRVIM	thermal-infrared channel
TX	transmit
t	tessera
U.S.	United States
UDMH	unsymmetrical dimethylhydrazine
UH	University of Hawaii
UHF	ultrahigh frequency
ULF	ultra low frequency
USO	ultra-stable oscillator
UV	ultraviolet
UVI	ultraviolet imager
UVMAS	Venus Ultraviolet-visual Mapping Spectrometer
V	Venera

VAMP	Venus Atmospheric Maneuverable Platform
VAP	Venus Aerial Platform
VASI	Venus Atmospheric Structure Investigation
VDJSDT	Venera-D Joint Science Definition Team
VEM	Venus Emissivity Mapper
VenDI	Venus Descent Imager
VENIS	visible and near-infrared spectrometer
VeRa	Venus Radio Science Radio Occultation Experiment
VERBA	infrared radiometer for Venera-D
VEX	Venus Express
VEXAG	Venus Exploration Analysis Group
Vg	VEGA
VICI	Venus In situ Composition Investigations
VIRA	Venus International Reference Atmosphere
VIRTIS	Visible and Infrared Thermal Imaging Spectrometer (on Venus Express)
VIS	visible
VISAR	Venus Interferometric Synthetic Aperture Radar
VLBI	very long baseline interferometry
VMC	Venus Monitoring Camera (on Venus Express)
VTLS	Venus Tunable Laser Spectrometer
v	volcanic
XRD	X-ray diffraction
XRF	X-ray fluorescence

Symbols

0	present time
A	current mean age of the surface
$C_{32} = (V^{\infty})^2$	energy of arriving relative to the Venus trajectory, km^2/s^2
$C_{31} = (V^{\infty})^2$	energy of departing from Earth trajectory, km^2/s^2
E	up and down flux (visible and near infrared)
H	humidity
P	pressure or potential (Table 8.8 only)

T	temperature or time (

Table 4.13 to Table 4.15 only)

V_1^∞	modulus of departing velocity vector (at infinity), km/s
V_2^∞	modulus of arriving to Venus relative velocity at infinity (i.e., asymptotic), km/s
ν	wavenumber
W	speed of descent
W′	acceleration
α_1^∞	right ascension of same vector at J2000 equatorial coordinate system, degrees
α_2^∞	declination of the vector of arriving asymptotic velocity, degrees, degrees
ΔT	temperature gradient (atmosphere)
ΔV_1	delta velocity to start from Earth satellite initial circular low orbit with altitude of 200 km
ΔV_2	delta velocity to transfer onto Venus satellite high elliptic orbit with pericenter altitude of 500 km and period of orbit equal 24 hr
δ_1^∞	declination of the departing asymptotic velocity vector (at infinity), degrees
δ_2^∞	declination of the vector of arriving asymptotic velocity, degrees, degrees
λ	wavelength
τ	optical depth
ω	speed of angular rotation

Appendix B.—Comparison of Venera D to Recent Venus Missions

Table B.1.—Venera-D Comparison to Venus Express (VEX) and Akatsuki

Venera-D Baseline	VEX	Akatsuki
PFS-VD Fourier transform spectrometer, 250 to 2,000 cm^{-1} λ = 5 to 45 µm, $\Delta\nu$ = 1 cm^{-1} **Longwave infrared camera (LIR)** structure of upper clouds at altitude of τ = 1 at 10 µm (8 to 12 µm).	PFS didn't function	**Longwave infrared camera (LIR)** structure of upper clouds at altitude of τ = 1 at 10 µm (8 to 12 µm).
MM-radiometer; Ka, V, and W bands		
UV-IR imaging spectrometer, **VENIS** **2-µm camera (IR2**) (1.65 to 2.32 µm) radiation coming from low clouds and below the clouds	**VIRTIS**	**2-µm camera (IR2**) (1.65 to 2.32 µm) radiation coming from low clouds and below the clouds
UV-mapping spectrometer,190 to 490 nm, $\Delta\lambda$ = 0.3 nm		
VMC	**VMC**	**1-µm camera (IR1)** would image heat radiation emitted from (0.90 to 1.01 µm)
VEM maps surface emissivity in six spectral bands in five atmospheric windows through the clouds		
Solar and star occultation spectrometer (**SSOE)**	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.	**Venus Radio Science Radio Occultation Experiment (VeRa)** Venus Radio Science	**USO** for high precision measurement of distance and communication
Radio-science 2 Ground to orbiter two-frequency occultation in (L?), S-and X-bands		
Plasma instruments-Suite of 3 Panoramic energy mass-analyzer of ions Ares V, ELSPEC, FNA, Magnetometer, Langmuir Probe Energetic particle spectrometer	Analyzer of Space Plasmas and Energetic Atoms 4 (**ASPERA-4**)	

Appendix C.—Comparison of Venera-D to Future/Potential Venus Missions

Table C.1.—Venera-D Comparison to Veritas and EnVision

Venera-D Baseline	Veritas—Discovery Competed	EnVision	ISRO
PFS-VD Fourier transform spectrometer, 250 to 2000 cm^{-1} $\lambda = 5$ to 45 µm, $\Delta v = 1 cm^{-1}$			
Longwave infrared camera (LIR) structure of upper clouds at altitude of $\tau = 1$ at 10 µm (8 to 12 µm).			Venus Thermal Camera (8 to 12 µm), with instantaneous field of view (IFOV): 880×880 mrad, NEδT ~0.3 K at 230 K
MM-radiometer; Ka, V, and W bands			
UV-IR Imaging Spectrometer, **VENIS** **2-µm camera (IR2**) (1.65 to 2.32 µm) radiation coming from low clouds and below the clouds		**VEM**: Venus IR emission mapper, IR and UV spectrometer	Venus Atmospheric Spectropolarimeter (NIR Spectropolarimeter) 0.9 to 1.7 µm with $\delta\lambda = 2.5$ nm at 1.5 µm), FOV = 2°, 256-pixel linear detector
UV mapping spectrometer,190 to 490 nm, $\Delta\Lambda = 0.3$ nm			UV Imaging Spectroscopy Telescope 200 to 400 nm, δλ better than 0.5 nm
VMC	**VEM** maps surface emissivity using six spectral bands in five atmospheric windows that see through the clouds		Cloud Monitoring Camera (283 and 365 nm, 20 nm bandwidth), 11.4° FOV
VEM maps surface emissivity in six spectral bands in five atmospheric windows through the clouds			
SSOE Solar and star occultation spectrometer			
IVOLGA,Infrared heterodyne spectrometer			
		High-resolution (≤20 m/px) SAR; ground-penetrating radar	S-band SAR with 20- to 30-m spatial resolution
			Advanced Radar for Topside Ionosphere and Subsurface Sounding
Radio-science 1 Orbiter to ground, two-frequency occultation in (L?) S- and X-bands.			Radio Occultation Experiment (S and X band)
Radio-science 2 Ground to orbiter two-frequency occultation in (L?), S- and X-bands			

Venera-D Baseline	Veritas—Discovery Competed	EnVision	ISRO
Groza-SAS2-DFM-D, electromagnetic waves generated by lightning and other electric phenomena			Airglow photometer (667.7 and 630.0 nm with 0.8 nm bandwidth), 128×128 pixel array, 6° FOV
Plasma instruments-Suite of three Panoramic energy mass-analyzer of ions Ares V, ELSPEC, FNA, Magnetometer, Langmuir Probe Energetic particle spectrometer			
	Venus Interferometric Synthetic Aperture Radar (VISAR) generates a digital elevation model (DEM) with an accuracy of 250 m horizontal by 5 m height		
			Venus Ionospheric Electron Temperature Analyser
			Retarding potential analyzer (temperature: 1,000 to 5,000 K, ion drift velocity 0.01 to 2.0 km/s^{-1}, Total ion concentration 10 to 10^6 cm^{-3})
			Venus Neutral and Ion Mass Analyzer (1 to 200 amu)
			Venus Ionospheric Plasma Wave Detector

Table C.2.—Venera-D Comparison to Davinci

Venera-D	Davinci—Discovery Competed Venus Mission
MTDL spectromter (ISKRA-V) chemical composition of the atmosphere including abundancies of gases SO2, CO, COS, H2O, NO2, HCl, and HF, and their isotopologues and isotopic ratios D/H, $^{13}C/^{12}C$, $^{18}O/^{17}O/^{16}O$, and $^{34}S/^{33}S/^{32}S$ during descent from 65 km and after landing	**Venus Tunable Laser Spectrometer (VTLS**) first highly sensitive in situ measurements of targeted trace gases and associated isotope ratios at Venus, addressing key science questions about chemical processes in the upper clouds and the near-surface environment
TPW package—temperature, pressure, wind speed, temperature gradient, acceleration from 120 km altitude to the surface and at the surface 1) P,T,W,W', 2) ΔT, nephelometer, 3) accelerometer/altimeter, 4) photometer	**Venus Atmospheric Structure Investigation (VASI)** would provide measurements of the structure and dynamics of Venus' atmosphere during entry and descent, providing context for chemistry measurements and enabling reconstruction of the probe's descent
CAP (GC-MS)—chemical composition of the Venus atmosphere and clouds At the surface, the package measures chemical composition of rocky sample (which must be delivered inside the lander) and continues measurements of chemical composition of the atmosphere: abundance and isotopic ratio of noble gases in the atmosphere, M/ΔM = 1,100 at ^{84}Kr , and 300 at M = 2	**Venus Mass Spectrometer (VMS)** would provide the first comprehensive in situ survey of noble and trace gases on Venus, and has the capability to discover new gas species in the Venusian atmosphere. Heritage MSL
Panoramic cameras—surface imaging during the descent phase, landing and at the surface (optical properties of the atmosphere). Stereo imaging of the surface with FOV 30° to 45° and angular resolution ~0.0005 rad during the landing starting from the altitude of several kilometers. Panoramic stereo imaging of the surface. Detailed stereo imaging of surface with the spatial resolution better than 0.2 mm	**Venus Descent Imager (VenDI)** provides high-contrast images of the tessera terrain at the descent location
XRD/XRF spectra—element and mineral composition of surface materials; possible detection of bounded water in the surface minerals	
Gamma-spectrometer (AGNESSA)—gamma-ray spectrum of the surface induced by the flux of neutrons; elemental composition; radioactive isotopes of K, U, and Th.	
Mössbauer spectrometer. Mineral composition of iron-containing surface rocks. XRF spectra—main-element composition of the surface material	
Outdoor Combined Atmospheric LIDAR and Time-Resolved Raman Spectrometer Instrument (**Raman-LIDAR**)—vertical profiles and chemical composition of aerosols and polyatomic gases of Venus atmosphere above and below the clouds	
Infrared Radiometer and UV-VIR-NIR-spectrometer (VERBA)— infrared radiometer for atmospheric transparency windows. Up and down energy net fluxes. Spectrometer for vertical profiles of H_2O and other absorbers	
LLISSE—long-term measurements of METEO parameters, wind speed and direction, near surface atmosphere composition, incident, and reflected solar radiance	
Groza-SAS2-D—measure in range of 10 Hz to 100 kHz electromagnetic fields, electrical activity, and conductivity of the atmosphere	

Appendix D.—Sample Venera-D Technology Data Sheet

Table D.1.—Venera-D Technology Data Sheet

Venera-D Technology Data Sheet

Technology Item: Orbiter Instrument #1 - UV mapping spectrometer - UVMAS

Instrument: ☒ Spacecraft Subsystem: ☐ Mission Support: ☐ Other: ☐

Description: Imaging UV spectrometer

Technology Features/Contact Information

Principle Contact: Name G.Bellucci , Ignatiev Org: IAPS-INAF

Contact Information: Phone: 8-495-3331502 Email: Giancarlo.Bellucci@iaps.inaf.it

Volume: 150 × 150 × 200 mm - 0.005 m^3 Power: 4 W Mass: 3 kg Data Volume: 40 Kb/s, 60 MB/session (30 min)

Measurement/Use: Image and spectrum at λ = 0.19 to 0.49 µm, with $\Delta\lambda$ = 0.3 nm

Duration/Frequency: Continuous imaging whole mission, ~ 1 s/image

Does the technology fully meet the science measurement requirements for resolution, mission duration and all other requirements? Yes: ☒ No: ☐ If not, what are all the gaps?

Special Interface or Location/Placement Needs

Does the mass, power, volume (MPV) specified above include cabling and all support subsystems needed? Yes ☐

If not, where is that MPV allocation assumed to be?

Applications on Venera-D

Instructions: Check all that apply

Orbiter: ☒ Lander: ☐ Subsatellite: ☐ Mobile Aerial: ☐ Long-Lived Lander: ☐

Dropsonde: ☐ Launch Vehicle: ☐ Cruise: ☐ Entry: ☐

Technology Heritage

Has this technology ever flown? Yes: ☒ No: ☐

If Yes, last used? Where? OMEGA/MEx When? 2003 to present

What new upgrades, components, etc., are required?

Current Status of Technology

What is current TRL(s) for the intended Venus application? 7

If further development is required for Venera-D Application, describe what development is used.

Is that development currently funded/in process?

How long is development expected to take?

Other Information

Does this technology rely on other subsystems/technologies (e.g., sample collection system, avionics) shared with another instrument, etc.? Yes: ☐ No: ☒ If Yes, what is the relationship?

Any supporting Lab work needed to develop, test, or interpret results?

Any supporting Qualification/Test facilities needed to qualify and test hardware?

Are there other options/technology solutions if this technology isn't ready? What are they?

Science Contribution (if applicable): UV mesosphere studies at cloud tops (SO, SO_2, UV-absorber ; small and large scale dynamics) 65 to 75 km


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