

Venus Exploration Themes

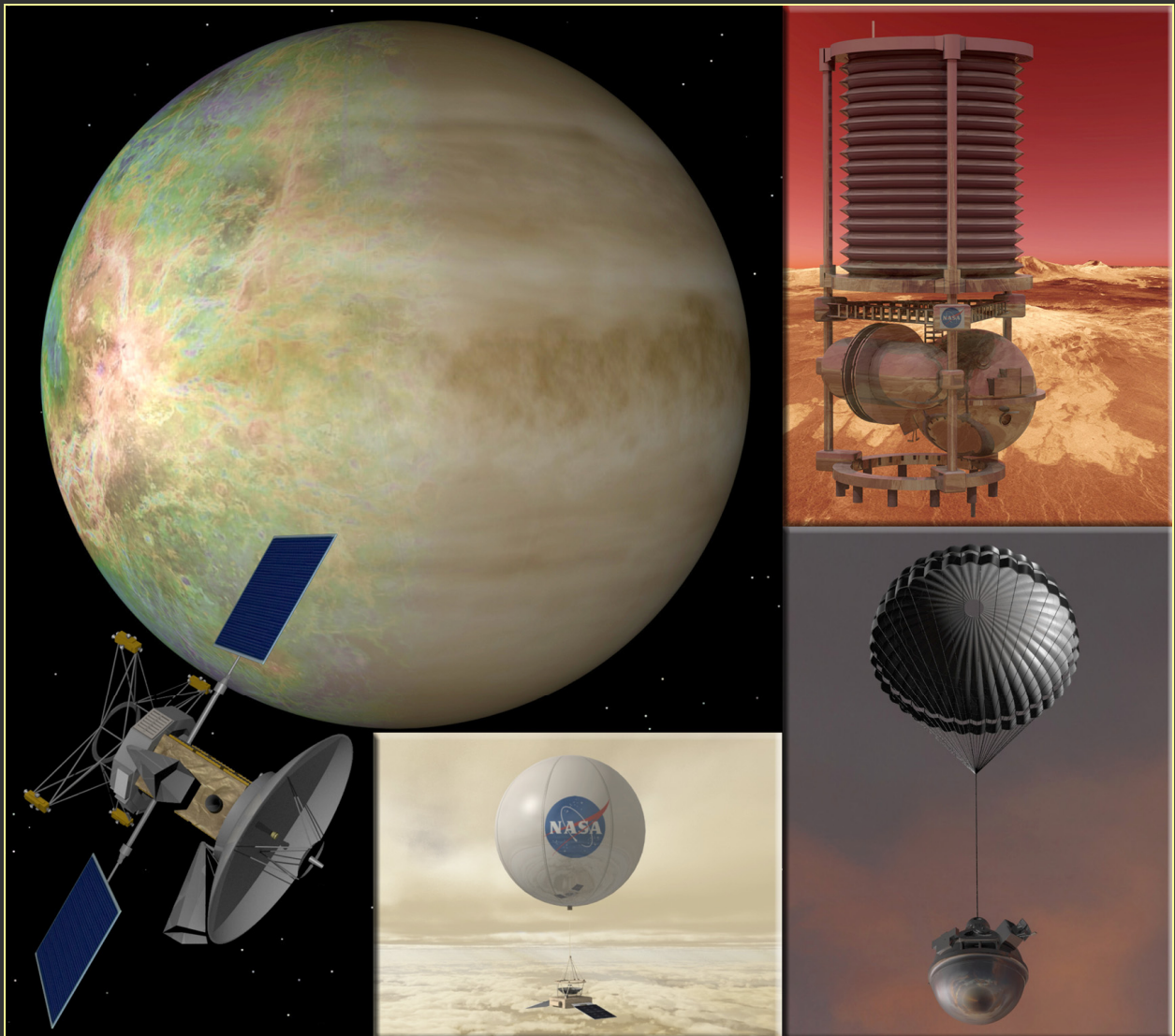
Adjunct to Venus Exploration Goals and Objectives 2011

September 2011

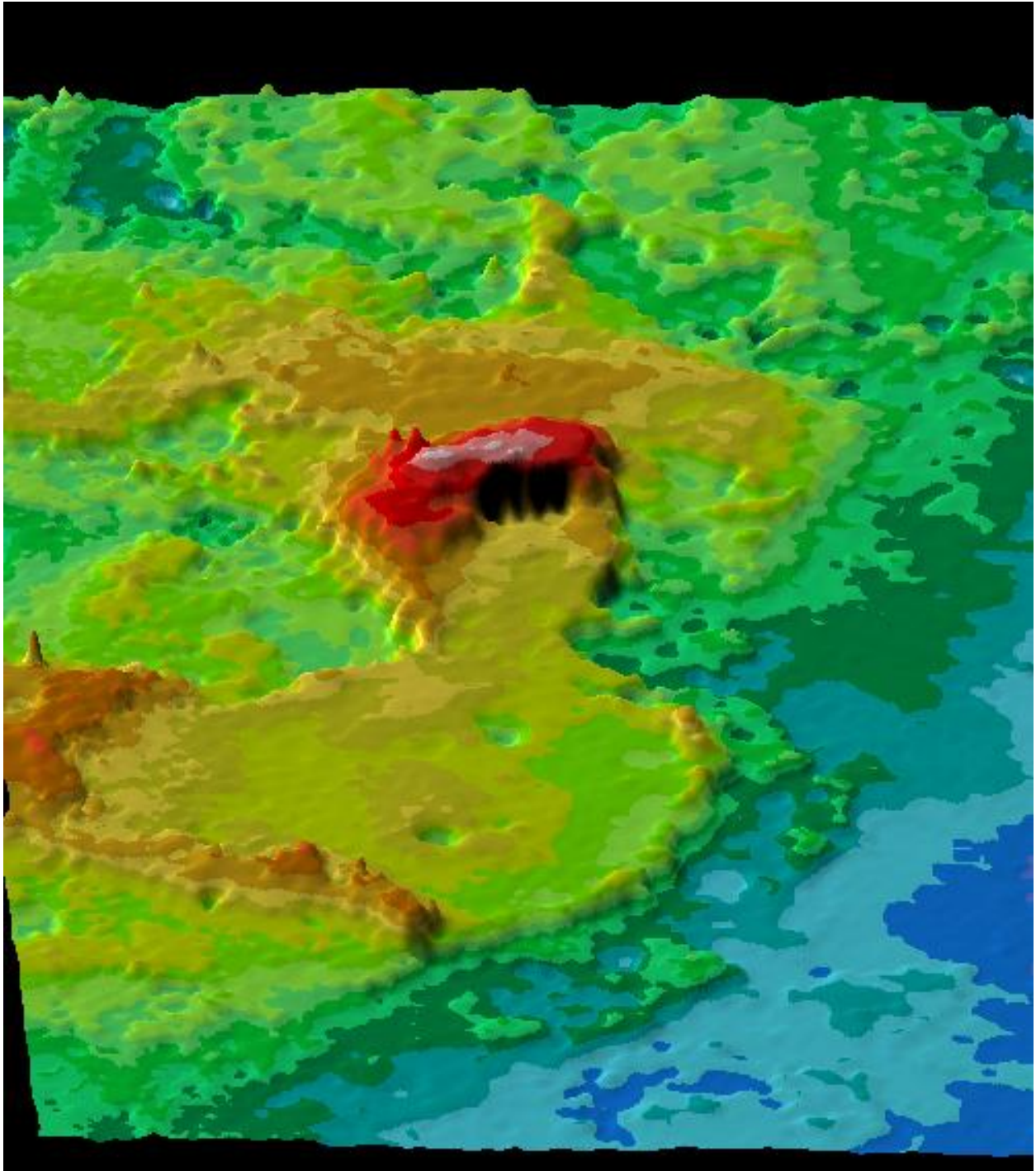
Fifty Years of Venus Missions

Venus Exploration Vignettes

Technologies for Venus Exploration



*Front cover is a collage showing Venus at radar wavelength, the Magellan spacecraft, and artists' concepts for a Venus Balloon, the Venus In Situ Explorer, and the Venus Mobile Explorer.
(Collage prepared by Tibor Balint)*



Perspective view of Ishtar Terra, one of two main highland regions on Venus. The smaller of the two, Ishtar Terra, is located near the north pole and rises over 11 km above the mean surface level. Courtesy NASA/JPL-Caltech.

Prepared as an adjunct to the Venus Exploration Goals and Objectives document to preserve extracts from the October 2009 Venus Exploration Pathways document.

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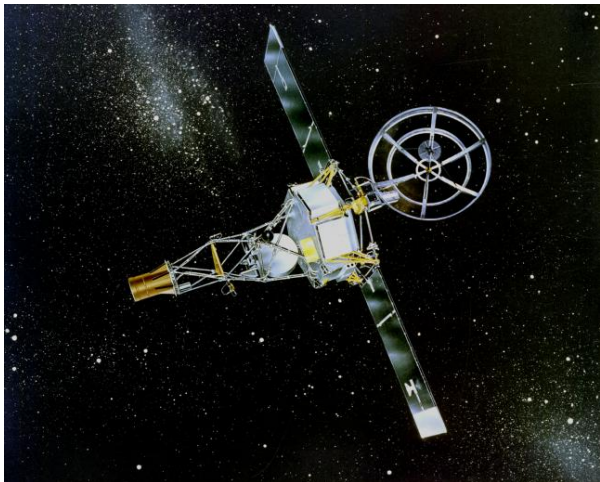
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Artist’s concept of Mariner 2, the first spacecraft to visit Venus (1962)



Artist’s concept of Magellan spacecraft (1990–1994)

ACKNOWLEDGMENTS

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FIFTY YEARS OF VENUS MISSIONS

To complete the context for future Venus exploration, Table 1 provides an overview of the past, current, and future Venus missions that have been carried out by the Russian, European, Japanese, and American space agencies. The Russian space program in 1961 initiated an extensive program for the exploration of Venus, which included atmospheric probes, landers, orbiters, and balloon missions. This produced many successful missions, which provided information on how to survive and conduct experiments in the Venus environment. The Venera 1 impactor was the first spacecraft to land on another planet. The Venera 13 lander survived on the surface for 127 minutes, which is still unmatched by any other spacecraft at Venus. The Vega balloons demonstrated the ability of balloons for aerial exploration. The Russians are now pursuing a Venera-D orbiter, balloon, and lander mission to be launched in 2016.

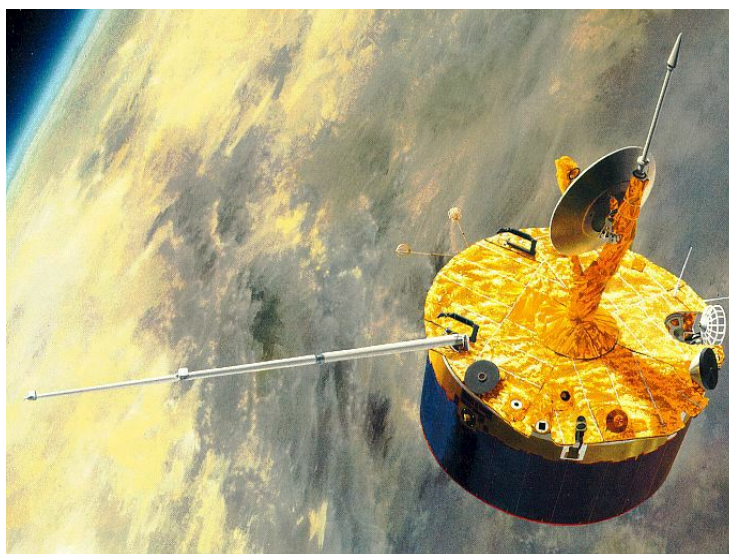
U.S. Venus exploration commenced in 1962 with the flyby of the Mariner 2 spacecraft. Following this, U.S. missions conducted an exploration of the atmosphere and the surface of Venus. In the late seventies, NASA conducted the orbiter/multiprobe Pioneer–Venus mission, with the objective of understanding the atmosphere of the planet. Magellan in the early 1990s mapped 98% of the surface of the planet, as described in Vignette 1.

Today, Europe’s Venus Express orbiter is providing significant science contributions to the understanding of Earth’s sister planet by measuring atmospheric dynamics and structure; composition and chemistry; cloud layers and hazes; radiative balance; the plasma environment and escape processes; and, to a certain extent, surface properties and geology through remote sensing, as described in vignettes 2 and 3. Another orbiter, Japan’s Akatsuki (Planet-C, Venus Climate Orbiter, VCO), failed to achieve orbit at Venus on December 7, 2010; and it is now in orbit around the Sun with an orbital period of about 200 days. At this orbital period, which is just 10% shorter than that of Venus, Akatsuki will encounter Venus again in 2016–2018, after 11 revolutions around the Sun.

Table 1. Summary of Past, Present, and Future Venus Missions.

Spacecraft	Launch Date	Type of Mission
Venera 1	1961	Flyby (intended); telemetry failed 7 days after launch
Mariner 2	1962	Flyby; first to fly by Venus (US)
Zond 1	1964	Probe and main bus; entry capsule designed to withstand 60 to 80°C / 2 to 5 bars
Venera 2 & 3	1965	Probe and main bus; entered the atmosphere of Venus; designed for 80 °C / 5 bar
Venera 4	1967	Stopped transmitting at 25 km; 93 minutes descent; first to descend through the atmosphere; designed for 300 °C / 20 bar (Russia)
Mariner 5	1967	Flyby (US)
Venera 5	1969	Lander; stopped transmitting at ~20 km (320 °C / 27 bar); 53 min descent (Russia)
Venera 6	1969	Lander; stopped transmitting at ~20 km (320 °C / 27 bar); 51 min descent (Russia)
Venera 7	1970	First to transmit data from the surface; parachute failure, rough landing, landed on the side; 55 min descent / 23 min on surface (Russia)
Venera 8	1972	Performed as designed; soft-lander; 55 min descent / 50 min on surface (Russia)
Mariner 10	1973	Flyby en route to Mercury (US)
Venera 9	1975	Orbiter and lander; first to return photos of surface; 20+55 min descent / 53 min on

Spacecraft	Launch Date	Type of Mission
		surface (Russia)
Venera 10	1975	Orbiter and lander; 20+55 min descent / 65 min on surface (Russia)
Pioneer-Venus 1	1978	Orbiter with radar altimeter; first detailed radar mapping of surface (US)
Pioneer-Venus 2	1978	Four hard-landers (US)
Venera 11	1978	Flyby, soft-lander; 60 min descent / 95 min on surface (Russia)
Venera 12	1978	Flyby, soft-lander; 60 min descent / 110 min on surface (Russia)
Venera 13	1981	Orbiter, soft-lander; first color images of surface; 55 min descent / 127 min on surface (Russia)
Venera 14	1981	Orbiter, soft-lander; 55 min descent / 57 min on surface (Russia)
Venera 15 & 16	1983	Orbiter with a suite of instruments, including radar mapper and thermal IR interferometer spectrometer (Russia)
Vega 1 & 2	1984	Flyby, atmospheric balloon probe (Russia / International)
Magellan	1989	Orbiter with radar mapper (mapped 98% of the surface); first high-resolution global map of Venus (US)
Venus Express	2005	Orbiter with a suite of instruments – ongoing mission (ESA)
Planet-C (VCO)	2010	Venus Climate Orbiter “Planet-C” – Venus orbit insertion failed in December 2010; a possible return to Venus in 2016 (JAXA)
Venera-D	2016	Orbiter with lander and balloons (Russia)



Artist's concept of Pioneer Venus Orbiter (1978–1992)

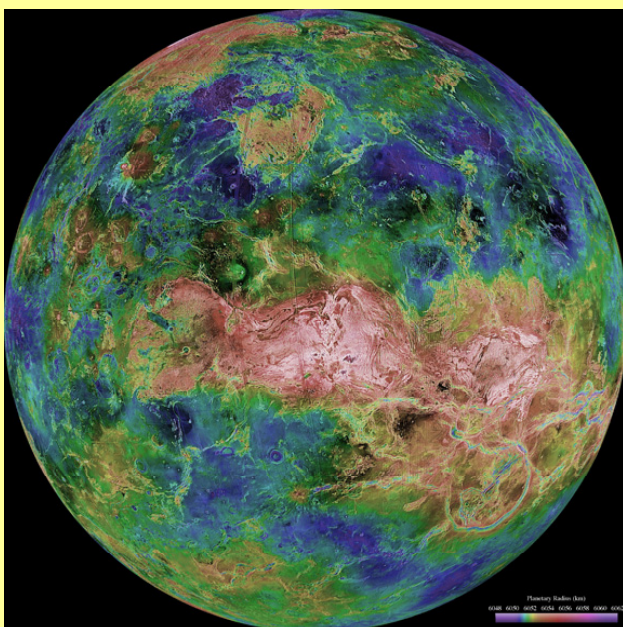
VENUS EXPLORATION VIGNETTES

Vignette 1: Magellan

The Magellan spacecraft was launched May 4, 1989, and arrived at Venus on August 10, 1990. The Magellan synthetic aperture radar (SAR) mapped 98% of the surface of Venus, with a resolution of about 100 m. Global altimetry and radiometry observations also measured surface topography and electrical properties. A global-gravity map was obtained after Magellan's aerobraking to a circular orbit. This aerobraking paved the way for several future missions. The Magellan mission ended in October 1994 with a controlled entry into the Venusian atmosphere.

Magellan SAR images confirmed that an Earth-like system of plate tectonics does not operate on Venus, most likely due to the lack of surface water. Volcanism characterizes the surface; more than 85% consists of volcanic plains. Two types of highland regions were identified: topographic rises with abundant volcanism interpreted to be the result of mantle plumes, and complexly deformed highland regions called tessera plateaus, hypothesized to have formed over mantle upwellings or downwellings. The gravity field is highly correlated with surface topography, with some highland regions apparently supported by isostatic compensation and others by mantle plumes. Erosion of the surface is not significant due to the lack of water, although some surface modification by wind streaks was seen.

The biggest surprise revealed by the Magellan mission was the crater population of Venus, which is randomly distributed and largely unmodified. Although resurfacing in the last 500 million to one billion years has obscured the impact history of Venus (particularly when compared to the Moon, Mars, and Mercury), the mean surface age is estimated to be ~500 million to one billion years. A debate has ensued over whether the entire surface was resurfaced in a catastrophic event approximately 500 million years ago, or if it was resurfaced more slowly over time. Understanding the history of the surface is not only important for constraining the interior evolution of Venus, but also the evolution of the atmosphere. While Magellan unveiled Venus, the data returned did not answer the question of why Venus and Earth have followed such different evolutionary paths. However, Magellan data provide a basis for a new set of specific scientific investigations, which will help constrain how habitable planets evolve.



Magellan Radar Mosaic. Blues and greens are the lower plains areas; whites are the rugged highlands.

Vignette 2: Experiencing Venus by Air: The Advantages of Balloon-Borne In Situ Exploration

Balloons provide unique, long-term platforms from which to address such fundamental issues as the origin, formation, evolution, chemistry, and dynamics of Venus and its dense atmosphere. As successfully and dramatically demonstrated by Russia's twin Vega balloons in 1985, such aerial vehicles can uniquely measure Venus' dynamic environment in three dimensions, as they ride the powerful, convective waves in Venus' clouds near the 55-km level. Also, by sampling over an extended period, balloons can measure the abundances of a plethora of tell-tale chemical and noble gases, key to understanding Venus' origin, evolution meteorology, and chemistry. While the Vega balloons successfully pioneered the use of aerial platforms to explore planets, weight restrictions prevented their measuring abundances of diagnostic chemicals or noble gases. The new, highly miniaturized instrument technologies of the 21st century allow such measurements to be made.

Our knowledge of the origin, formation, and evolution of all the planets—including Venus—relies primarily on knowledge of the bulk abundances and isotopic ratios of the noble gases—helium, neon, argon, krypton, and xenon—as well as on the isotopic distributions of light gases such as nitrogen. For example, xenon, with its nine tell-tale isotopes, along with krypton (Kr) and argon (Ar) and their isotopes, can together reveal a range of ancient cataclysms on Venus and other planets. These include the nature of (1) any global atmospheric blowoff by intense solar extreme ultraviolet radiation, and (2) any major impacts by large (>200-km diameter) comet-like planetesimals from the outer solar system. On the other terrestrial planets where xenon has been adequately measured—Earth and Mars—one or more such major cataclysmic events occurred early in their histories. Similar measurements for Venus would reveal whether cataclysmic events occurred on our sister planet as well. As these key tell-tale noble elements have no appreciable spectral signature, in situ sampling is the only means by which to measure them. Thus, to reach into the planet's past, one must sample Venus directly, with typical precisions of better than 5% for both isotopic ratios and bulk abundances.

Such detailed and precise isotopic measurements can be more than adequately achieved by today's lightweight balloon-borne instrumentation suspended for several days in the middle atmosphere near an altitude of 55 km. Riding the strong winds of Venus near the Earth-like 297-K, 0.5-bar pressure level, hundreds of high-precision, mass-spectroscopy measurements can be acquired and transmitted during the balloon's two-day transit across the face of Venus as viewed from Earth, thus achieving the requisite tight constraints on isotopic abundances of all the noble gases and many light elements. In addition, vertical profiles of chemically active species can be obtained as the balloon rides the planet's dynamic array of gravity waves, planetary waves, and convective motions, thus providing unique insights into photochemical and thermochemical processes. Additionally, the planet's sulfur-based meteorology can be explored, for example, by measuring over time and altitude both cloud particles and their parent cloud-forming gases, as well as lightning frequency and strength.

As was done by the Vega balloons, both local dynamics and planet-scale atmospheric circulation can be investigated via radio-tracking of the balloon from Earth. Today's improved interferometric and Doppler tracking together with well-calibrated onboard pressure sensors can yield knowledge of all three components of balloon velocity an order of magnitude more accurately than achieved by Vega, that is, better than 10 cm/s on time scales of a minute in the vertical and an hour in the horizontal. Such accuracies can provide fundamental measurements of the amplitude and power of gravity waves and the latitude/longitude characteristics of zonal and meridional winds at known pressure levels. All of these are key to understanding the processes powering Venus' super-rotating circulation.

Beyond providing unique insights into the origin/evolution, dynamics, and chemistry of Venus, exploring Venus by balloon provides valuable experience for flying the skies of other worlds. Experiencing Venus for days and perhaps weeks by the first airborne rovers could well lead to a new era of "aeroving" the distant skies of Titan and the many gas giants of the outer solar system.

Vignette 3: Lessons Learned from Pioneer Venus Orbiter and Huygens

Pioneer Venus Orbiter 1978–1992. Venus orbiter with comprehensive payload for remote sensing and in situ aeronomy.

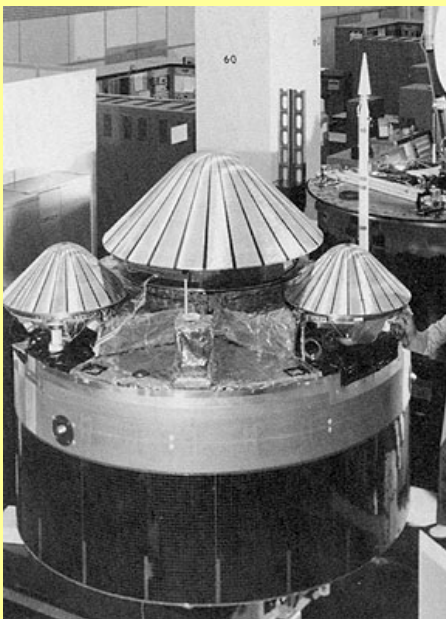
1. Showed that the greenhouse effect operates much more efficiently on Venus. Data from the four atmospheric probes led to a greenhouse model that closely matches the observed vertical temperature profile.
2. Measured long-term changes in atmospheric minor constituents above the clouds. These indicate forcings on decades-long timescales. Possible causes are volcanic activity and variable dynamics of the middle atmosphere.
3. Measured upper atmosphere's response to solar cycle.

Pioneer Venus demonstrated the need to examine the long-term stability of the current climate and to probe all altitudes during an entire solar cycle. In addition, the nature of the middle and deep atmosphere remains to be examined via remotely sensed spectral signatures or long-duration in situ probes.

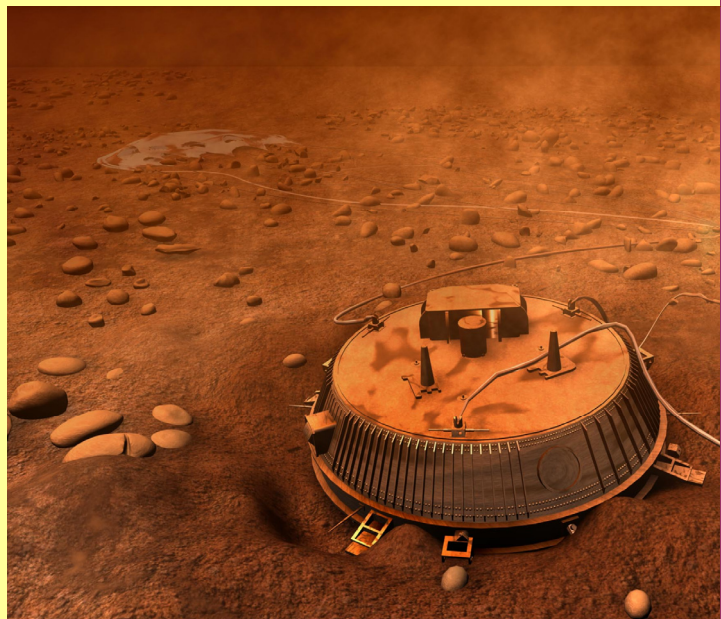
Huygens 2005. Titan lander with cameras, spectrometers, and in situ atmospheric and surface science instruments.

1. Huygens provided vertical resolution and sensitivity impossible from remote sensing by the Cassini orbiter, thus providing direct measurements of wind and chemical profiles from >200 km altitude down to the surface and measurement of volatiles entrained within surface materials.
2. Huygens descent images, when combined with other remote observations, allowed identification of dune fields by their distinctive color. This, in turn, yielded the exact lander location and ground truth for remote sensing as well as provided regional context for the landing-site measurements.

Also, radar identification of fields of linear dunes on Titan allowed comparisons to similar features on Earth, Venus, and Mars. Comparisons to Earth analogs in turn have increased understanding of surface processes on both bodies.



Pioneer Venus Orbiter and Probes



*Artist's concept of Huygens Probe.
Courtesy of ESA.*

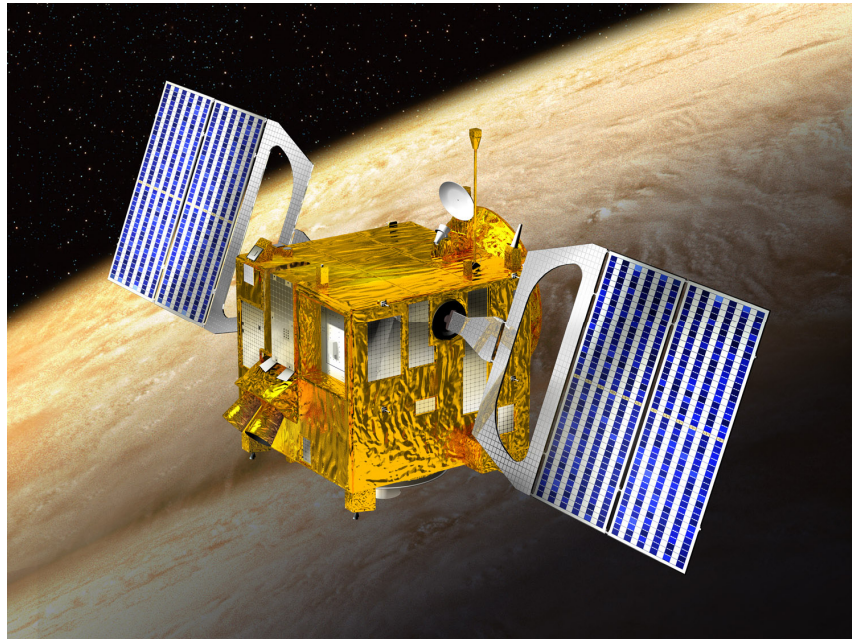
Vignette 4: Venus Express: Revealing the Mysteries of a Neighboring World

Circling the planet once per Earth day since arriving in April 2006, ESA's Venus Express is the first mission to comprehensively explore the entire globe of our sister world from the ground up through the mesosphere, thermosphere, ionosphere, and into space. In particular, Venus Express is the first Venus orbiter to utilize the new tool of nighttime near-infrared spectroscopic imaging to regularly map the structure and movement of clouds and gases in the hostile depths of Venus below the obscuring upper-level clouds, thereby obtaining new insights into the planet's enigmatic circulation, dynamic meteorology, and complex chemistry. This novel spectroscopic tool—embodied on Venus Express as the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS)—maps both (1) the structure and movement of clouds at three different levels (~50-km altitude on the nightside, and 59- and 70-km altitude on the dayside), and (2) the abundances of a plethora of chemically reactive species, including water (H₂O), sulfur dioxide (SO₂), carbon monoxide (CO), and OCS—at a variety of altitudes in the deep atmosphere below the clouds. It also observes the hot (~740 K) surface of Venus near 1-micron wavelength, mapping thermal emissions from the ground, which can be used to constrain 1-micron surface emissivity and composition as well as to search for and characterize active volcanic processes, as evidenced by locally elevated thermal temperatures and enhanced trace-gas abundances.

Further information from the surface comes from a bistatic-radar experiment that utilizes the spacecraft's communication-radio system to reflect signals off the surface toward Earth. As one facet of the Venus Radio experiment (VeRa), these echoes of Venus are then intercepted by NASA's Deep Space Network (DSN) to reveal characteristics of Venus' surface texture and emissivity at cm wavelengths. VeRa also utilizes radio-occultation techniques to measure the vertical profile of Venus' temperature, density, and pressure down to ~36-km altitude over a large range of latitudes, thereby providing detailed information on the planet's 3-D temperature structure, thermal winds, and vertical wave properties. The Venus Monitoring Camera (VMC) images the upper-level clouds in the UV and near-IR at 0.36 and 0.94 μm wavelength, thus providing high-spatial resolution imagery (better than 1-km resolution) of the wave and cell structures of Venus's clouds, as well as providing detailed movies of their motions. Long exposures by this experiment of Venus' night side can be used to search for lightning.

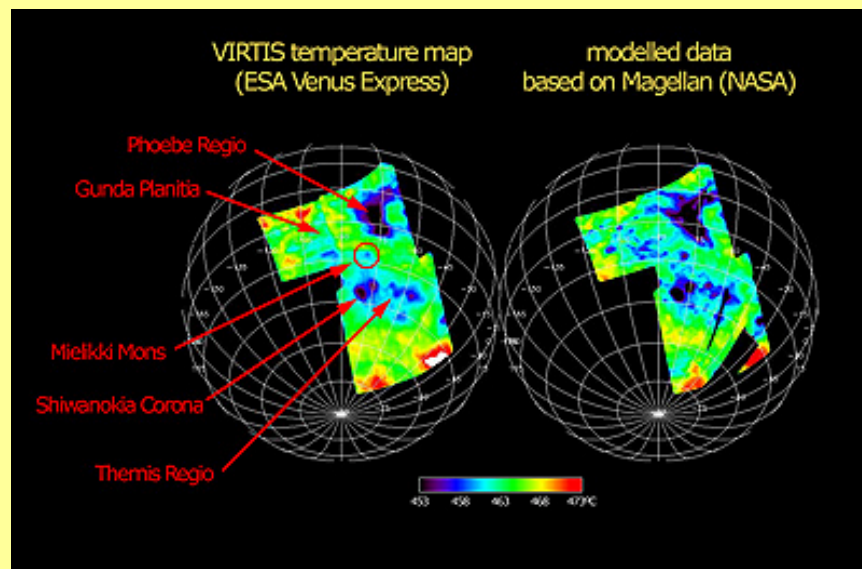
Venus Express also scrutinizes the upper atmosphere of Venus above the clouds. Dual UV and near-IR spectrometers, SPICAV and SOIR, regularly observe the limb of the planet in solar occultation from close range (typically less than 1000 km), thereby producing high-resolution (~5-km) vertical profiles of a variety of light-absorbing species, including H₂O, CO, and SO₂. VIRTIS observes nighttime emissions produced by the recombination of photochemically generated oxygen atoms into oxygen molecules, thereby revealing key day-to-night circulation flows near the 120-km level. Also, VIRTIS maps the nighttime temperatures of the atmosphere at 5-km vertical resolution from 60 to 90 km, providing constraints on the thermal winds in this region. Enigmatic polar features known as Polar Dipoles at the south and north poles, possible manifestations of the Hadley circulation, can also be mapped in detail and followed in time.

Venus Express also investigates the planet's ionosphere and near-space environment. ASPERA measures the solar wind as it streams around Venus, assessing the number density and speed of protons ejected from the Sun. A magnetometer experiment (MAG) measures the local magnetic field produced by ionization of Venus' upper atmosphere by both intense UV sunlight and solar wind. Joint measurements by ASPERA and MAG from a variety of positions around Venus then reveal how Venus interacts with the Sun's magnetosphere and solar wind. ASPERA also measures ionized atoms such as hydrogen and oxygen ejected from the planet's tenuous uppermost atmosphere by the solar wind, thus providing constraints on the loss of atmospheric elements responsible for the extremely dry state of Venus today. Venus Express has generated more than 1 Terabit of data to Earth in its first 500 days of operation. Recent Venus Express VIRTIS results are given in Vignette 3.



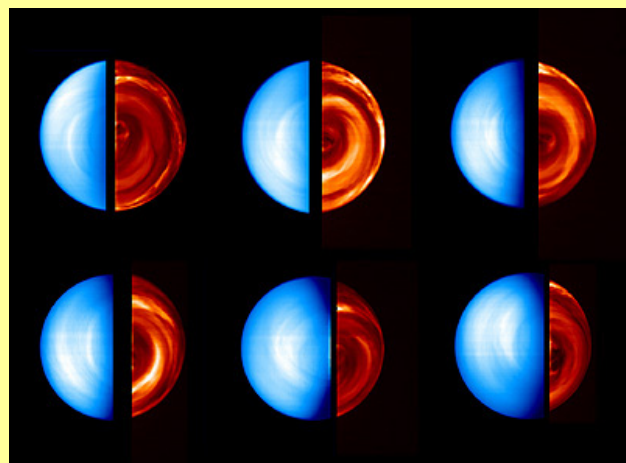
Artist's concept of Venus Express spacecraft operating at Venus since 2006. Courtesy of ESA.

Vignette 5: Venus Express VIRTIS Results



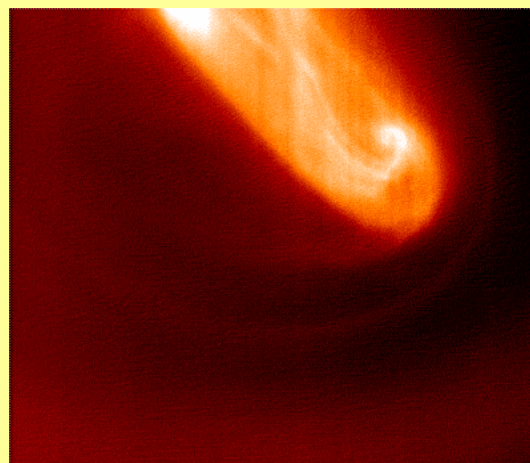
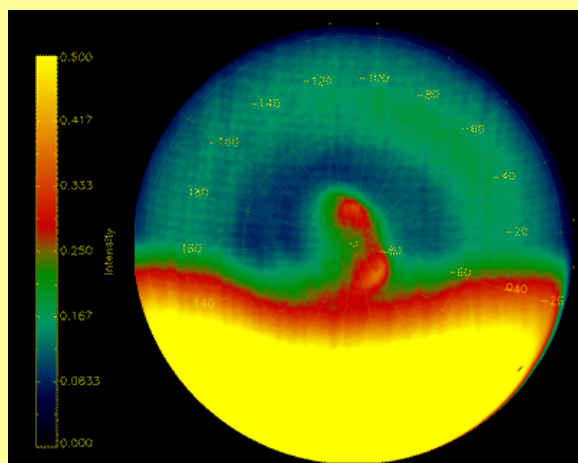
Surface Temperatures. (left) Black-body temperatures measured for the surface correlate well with topography (right), due to decreases of surface temperature with height. Slight variations in this correlation may indicate differences in the surface rock emissivities. Courtesy of ESA.

Vignette 5: Venus Express VIRTIS Results (continued)



Day and night images of the south pole of Venus.

Daytime images (left side of each image) show high-altitude clouds of small particles near the 70-km level. Night images (right side of each image) show thick clouds of relatively large particles near the 50-km level. Clouds at night are seen in silhouette against the glow of Venus' hot lower atmosphere, using near-infrared thermal radiation near 1.7- μm wavelength. Following the dark (cloudy) and bright (less cloudy) regions, as they move around the planet, yields measurements of Venus' winds near the 55-km level. Comparison with 70-km altitude winds as measured by the movements of dayside clouds yields wind shears, providing clues to the processes powering Venus' enigmatic system of super-rotating winds.



Polar Vortex Phenomena. Venus Express confirmed that the Venusian south pole has a complex and variable vortex-like feature, sometimes taking the shape of a dipole, but at other times morphing into tripolar, quadrupolar, and amorphous, indistinct shapes. Temperatures near the 60-km level are shown in the nighttime portions of 5- μm images, revealing the dipole to be notably hotter than its surroundings, likely due to compression of descending air. (Bottom left image, taken in daytime conditions, is overexposed by the Sun). Right-hand, close-up image shows filamentary nature of the dipole, which changes shape constantly in the dynamically active atmosphere. The dipole is offset from the pole by several degrees of latitude and rotates with a period of about 2.4 days.

TECHNOLOGIES FOR VENUS EXPLORATION

*Excerpts from Venus Technologies White Paper [a],
submitted to the NRC Decadal Survey Inner Planets Sub-panel–2009*

This appendix provides an overview of technologies required for future Venus exploration missions. These technologies will focus on mission-enabling and -enhancing capabilities for in situ missions, because most orbiter-related subsystems are considered heritage technologies. This appendix draws heavily on the 2008–2009 Venus Flagship Mission study [b] that identified key technologies required to implement its Design Reference Mission (DRM). These technologies include surface sample acquisition and handling; mechanical implementation of a rotating pressure vessel; and a rugged–terrain landing system. Also, a large-scale environmental test chamber is needed to validate these technologies under relevant Venus–like conditions. Other longer–term Venus flagship missions will require additional new capabilities; namely, a Venus–specific radioisotope power system, active refrigeration, high-temperature electronics, and advanced thermal insulation.

The chosen mission architectures —whether large flagship, medium New Frontiers, or small Discovery-class missions—are primary drivers for Venus technologies. The Venus Flagship Mission study [b] recommends a multi–element mission architecture of an orbiter, two cloud–level balloons, and two short–lived landers, which have been successfully used for past Venus exploration missions. In addition, the Venus flagship DRM used heritage technologies and, in turn, minimized the number of new technologies required for this mission’s implementation. This multi–element architecture also allows designers to utilize appropriate technologies for smaller (New Frontiers or Discovery-class) missions, which would use similar mission elements. However, NASA’s 2006 Solar System Exploration Roadmap identified other missions, including the near-surface Venus Mobile Explorer, a seismic network, a New Frontiers–class VISE, and Discovery-class balloon missions ultimately leading to a Venus Surface Sample Return mission. Discovery and New Frontiers missions are not expected to include a significant amount of new technologies and could be designed without them; although they could benefit from new technologies if they were made available as part of a technology development program for a future flagship mission.

Table 2 summarizes enabling and enhancing technologies for potential future Venus missions, with emphasis on in situ elements. Further information can be found in the “Technologies for Future Venus Exploration” White Paper [a] and in the Venus Flagship Mission study final report [b].

References

Balint, T., Cutts, J., et al., “Technologies for Future Venus Exploration,” VEXAG White Paper to the NRC Decadal Survey Inner Planets Sub-Panel, September 9, 2009.

Hall, J.L., Bullock, M., Senske, D.A., Cutts, J.A., Grammie, R., “Venus Flagship Mission Study: Report of the Venus Science and Technology Definition Team,” National Aeronautics and Space Administration, Jet Propulsion Laboratory, California Institute of Technology, Task Order NM0710851, April 17, 2009.

Table 2. Technologies for Future Venus Exploration

Legend:

<i>Bold italic</i>	The highest-priority technology items—those that would enable the mission to survive for 5 hours on the surface—as recommended by the Venus Science and Technology Definition Team
Bold	Technologies that would enhance the DRM by extending its lifetime up to a day are in italics with light red shading
<i>Italic</i>	New technologies that would extend the lifetime to up to several months are in regular text with light green shading
Roman	Technologies that would further enhance future Venus exploration missions

Capability	Current state of the art (TRL)	Technology development needs to enable Venus missions	Benefits to future Venus missions
<i>Surface sample acquisition and handling (VDRM)</i>	<i>TRL 2–3 Heritage Soviet–derived systems are not available off the shelf, but they demonstrate a feasible approach.</i>	<i>Surface sample acquisition system at high temperature and pressure conditions; Vacuum–driven sample transfer is demonstrated on Venera, but requires development for NASA.</i>	<i>Drilling, sample collection and sample handling are enabling for the Venus Flagship Mission.</i>
<i>Rotating pressure vessel (VDRM)</i>	<i>TRL 2 Rotating pressure vessel concept is powerful but technologically immature.</i>	<i>Full scale design and testing of a rotating pressure vessel with a driver motor and mounted sampling system.</i>	<i>It minimizes the external components, such as drill arms, actuators, motors, sampling systems; and the heat leakage from the outside through the number of windows required for panoramic imaging.</i>
<i>Rugged terrain landing (VDRM)</i>	<i>TRL 2 Russian landers provide proof of concept, however, these landed at benign surfaces and used a drag plate instead of parachutes.</i>	<i>Design and test a landing system that can account for a large variety of unknown landing hazards using parachutes.</i>	<i>Tessera and other rugged areas on Venus cannot be reliably accessed unless a properly engineered rugged terrain landing system is developed and tested.</i>
<i>Testing facility (VDRM)</i>	<i>TRL 2-6 Two small Venus environment test chambers are operational at JPL; A small Venus test chamber setup is under way at GSFC; Proof of concept from Russian test chamber (decommissioned).</i>	<i>Large test chamber doesn't exist; Develop large Venus test chamber for full scale in situ elements (probe/lander) testing; Simulate transient atmospheric conditions; composition.</i>	<i>The 12.5 km anomaly on the Pioneer–Venus mission demonstrates the critical need for an environmental chamber using relevant atmospheric composition and conditions; It can test spacecraft components; validate and calibrate science instruments; test operating scenarios under realistic conditions.</i>

Capability	Current state of the art (TRL)	Technology development needs to enable Venus missions	Benefits to future Venus missions
Advanced passive thermal control (enhancement to VDRM)	TRL 3–9 Venera and PV era insulation and phase change materials are mostly available.	Alternate insulation and phase change material technologies are needed to increase lander lifetimes beyond 2–5 hour operation.	Achievement of 12 to 24 hour lander lifetimes would enable humans-in-the-loop operation by ground controllers; Improved thermal insulation will decrease refrigeration requirements for truly long-term lander missions.
High-T and Medium-T components, sensors, and electronics (new capabilities)	TRL 2–4 Geophones could operate up to 260°C; High-temperature pressure, temperature, anemometers used on Venera/VEGA and Pioneer-Venus; Silicon based high-T components are designed for up to 350°C for the automotive and oil drilling industry; Limited number of components and integrated circuit capability demonstrated for SiC at 500°C; Limited electronics packaging at 500°C; Data storage, ADC, power converters, and other needed components never demonstrated.	High-temperature MEMS technology for seismometers could operate at surface temperatures; SiC and GaN high temperature sensors and electronics require development to operate at surface temperatures; Development of data acquisition, processing and storage capability, and packaging; Development of high-T power management; Demonstration of reliability and long life.	Long life on the surface is desirable (especially, for meteorology, seismometry); Sensors, actuators, instruments directly interfacing with the environment cannot be sufficiently protected, and therefore, high temperature components can enable operations and science measurements (e.g., long lived meteorology, seismometry) that otherwise cannot be achieved; High temperature data processing and storage, and power electronics results in a drastic reduction in refrigeration requirements, even at moderately high temperatures (>250°C); Low power dissipation at 300°C and long life reduces environmental tolerance requirements for components.
Power generation (new capabilities)	TRL 4 Demonstrated single Stirling convertor operation for 300 hours with a 850°C hot-side temperature and 90°C cold-side, 38% efficiency and 88 W power output with heat input equivalent to 1 GPHS module.	Cold side temperature must be raised from 90°C to 480°C with high conversion efficiency preserved (e.g., maintaining ΔT through increased hot end temperature, which would require materials or design development); Material testing, system development and validation for reliable operation in Venus surface environment.	Required for long life operation; Venus specific RPS with active cooling could enable long lived missions, operating for months; Low mass version could power near surface aerial mobility systems; It could power long lived seismometers and meteorology stations on the surface (117 days minimum).

Capability	Current state of the art (TRL)	Technology development needs to enable Venus missions	Benefits to future Venus missions
Active refrigeration (new capabilities)	TRL 4 Cryocoolers are space qualified, but high temperature operation is not demonstrated at the system level.	Adopt Stirling conversion based coolers for Venus surface conditions; High efficiency duplex Stirling system must be produced that integrates the heat engine and refrigerator functions into a high efficiency and high reliability device; Refrigeration system should be coupled with the power source; Low mass and low vibration is desirable.	Almost every long-duration (~25 hrs+) in situ platform will require some amount of refrigeration to survive; Focus should be on radioisotope-based duplex systems that produce both refrigeration and electrical power; Low mass version would allow for near surface aerial mobility (metallic bellows); Low vibration version would enable a seismic network (on multiple landers) (117 days minimum); Extended mission life allows humans in the loop.
Pressure control	TRL 4–9 Titanium pressure vessel is space qualified; New lightweight materials need development.	Advanced materials (e.g., beryllium, honeycomb structures) could reduce structural mass.	Mass saving translates to higher payload mass fraction for the same entry mass.
Thermal control (passive)	TRL 4–9 Aerogels, MLI, PCM are space qualified, but not for high g-load entries and high temperatures.	High performance thermal insulation for Venus environment is required for mission lifetimes beyond Venera demonstrated lifetimes.	Improvements in passive thermal control could extend mission lifetime from ~2 hours to 5 hours or maybe more. (Beyond that active refrigeration and a power source is required.)
Power storage	TRL 4 Demonstrated LiAl–FeS ₂ , Na–S, and Na–metal chloride secondary batteries with specific energy in the 100–200 Wh/kg range; Short lived missions could use high TRL primary batteries.	Adapt high temperature cell and battery designs for space applications; Address stability of seals and terminals; Minimize the corrosion of current collectors at high temperatures; Optimize the electrolyte composition to improve performance and reliability.	High temperature batteries operating at Venus surface temperatures would make it possible to keep the power storage outside of the pressure vessel, thus reducing volume and thermal requirements for the pressure vessel.

Capability	Current state of the art (TRL)	Technology development needs to enable Venus missions	Benefits to future Venus missions
Instruments (in situ) for the Venus Flagship Mission	TRL 2–9 Descent probe instrument heritage from Pioneer–Venus; New in situ contact instrument need development.	Several Venus Flagship Mission instruments, e.g., heat flux plate, XRD/XRF are at medium TRL; High–T seismometry and high–T meteorology are at low TRL; G–load tolerance during atmospheric entry should also be addressed.	In situ instruments are key drivers for Venus missions and are required for mission success.
Upper atmosphere Balloons	TRL 5–7 Russian VEGA balloons successfully operated for 48 hrs over 20 year ago; Large super–pressure balloon have been built and tested at JPL and at CNES; Development for a mid–altitude balloon is underway at JAXA.	Cloud level balloons are considered mature, but further development, testing, verification and validation are required to address lifetime and reliability issues for a 30–day mission; Materials must tolerate high temperatures, corrosive environment (sulfuric acid droplets in clouds).	The Venus Flagship Mission balloons are designed for 30–days operation; An ASRG powered balloon mission could operate for months, circumnavigating the planet and continuously measure dynamics and atmospheric composition.
Near surface balloons	TRL 2–3 Metallic bellows proof–of–concept was built at JPL and tested at high temperatures.	Development is needed to build and test a metallic bellows system and test it under Venus surface pressure and temperature conditions; Near surface operation must address altitude change and surface access.	A near surface mobile platform could traverse hundreds of kilometers over a 90–day mission, image the surface at high resolution and periodically access the surface for sampling.
Descent probes and sondes	TRL 2–9 Pioneer–Venus probe heritage for large probes Microprobes have been designed but not yet tested.	Develop small drop sondes that could be released from a balloon platform (also work as ballast).	Drop sondes can enhance science by providing vertical slice measurements to complement balloon constant altitude measurements of the atmosphere.
High–T Telecom	TRL 2 Demonstrated 2 GHz operation at 275°C using SiC; SiC and vacuum tube based oscillator demonstrated at ~500°C.	Development efforts should address SiC based RF components for transmitters; Miniaturized vacuum tube technology for power amplifiers; SiC based RF components for transmitters.	High temperature telecom on the surface would drastically reduce cooling requirements; It would enable long lifetime (117 days minimum); High data rate (~4.5 kbps) would support seismic operations; However, high temperature data storage at Venus surface temperature may represent a significant technology challenge.

Capability	Current state of the art (TRL)	Technology development needs to enable Venus missions	Benefits to future Venus missions
Orbiter instruments and telecom	TRL 3–9 Magellan, Venus Express, Pioneer–Venus heritage; Venus Flagship Mission InSAR needs development.	Development is required for InSAR; passive infrared and millimeter spectroscopic techniques; and cloud LIDAR	InSAR is a key instruments on the Venus Flagship Mission; Ultra-fine resolution radar mapping and cloud LIDAR could provide high resolution science data on the surface and clouds, and highly desirable by science.
Atmospheric entry	TRL 5-9 Carbon-Phenolic (CP) used on Pioneer–Venus and Galileo probe; Provides heritage for use in steep entry flight path angle (EFPA) missions; Special rayon needed to make heritage CP; This rayon is out of production; Current arc jet capabilities are limited; Mars and Titan TPS, lower density, could be useful for lower EFPA.	1. Re-establish test capabilities; 2. Periodic verification of Industry capability to remanufacture heritage CP; 3. Establish alternate to heritage CP TPS, since heritage rayon is not made anywhere, anymore and current supply in hand is limited; 4. Assessment of lower density TPS be performed for shallow EFPA missions.	TPS is essential and enabler; High entry flight path angle (EFPA) entries result in high heat flux, pressure and g-loads; Limited supply of heritage CP enables unrestricted access to the planet; Lower density TPS can provide significant mass savings, but constrain the EFPA and thus the mission architecture.
Autonomy	TRL 4–6 Autonomous operation have been tested in previous missions (e.g., Pioneer–Venus probes), but at a lower complexity than required for a Venus flagship mission.	Develop and test reliable autonomous operation for a Venus surface mission, including control of the rotating pressure vessel; drill site selection; sample acquisition; instrument operations; reliable telecom.	Short lived missions (up to 5 hours) does not support humans in the loop; Autonomous operation is required for all science measurements and subsystem control.
Cross cutting technologies	See above	TPS; pressure vessel materials; passive thermal control (insulation; phase change materials).	These technologies can benefit a number of planetary missions, e.g., probes to Venus and deep probes to the Giant Planets.