Roadmap for Venus Exploration

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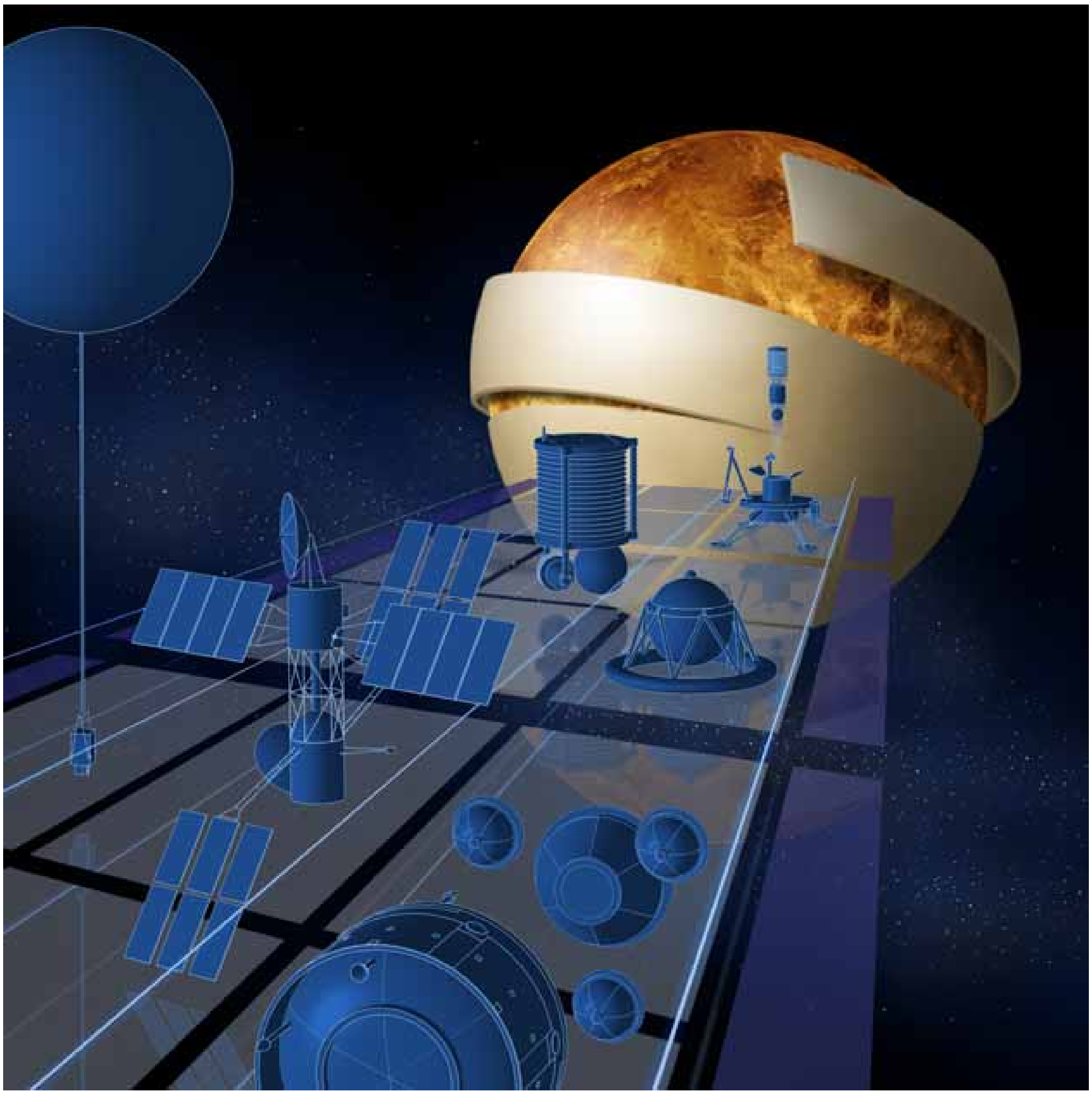

At the VEXAG meeting in November 2013, it was resolved to update the scientific priorities and strategies for Venus exploration. To achieve this goal, three major tasks were defined: (1) update the document prioritizing *Goals, Objectives and Investigations for Venus Exploration* (*GOI*), (2) develop a Roadmap for Venus exploration that is consistent with VEXAG priorities as well as Planetary Decadal Survey priorities, and (3) develop a *Venus Technology Plan* for technologies to be used by future Venus missions. Here, we present the *Roadmap for Venus Exploration*.

Developed by Venus Exploration Roadmap Topical Analysis Group: Doug Stetson and Martha Gilmore (co-chairs), Sushil Atreya, Bruce Campbell, Gordon Chin, Lori Glaze, David Grinspoon, Sanjay Limaye, Ralph Lorenz, and Sue Smrekar

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VEXAG Charter. The Venus Exploration Analysis Group is NASA's community-based forum designed to provide scientific input and technology development plans for planning and prioritizing the exploration of Venus over the next several decades. VEXAG is chartered by NASA's Solar System Exploration Division and reports its findings to NASA. Open to all interested scientists, VEXAG regularly evaluates Venus exploration goals, scientific objectives, investigations, and critical measurement requirements, including especially recommendations in the *NRC Decadal Survey* and the *Solar System Exploration Strategic Roadmap*.

ROADMAP FOR VENUS EXPLORATION

1. Introduction

Venus is so similar to Earth in size, composition, and distance from the Sun that it is frequently referred to as “Earth’s twin.” Despite these similarities, however, Venus has gone down a very different evolutionary path. Venus today is dominated by a greenhouse climate “gone wild” that resulted from a complex interplay of the same atmospheric, surface, and interior processes at work on Earth. Yet there is strong evidence that the planet was not always so inhospitable, and Venus may even have possessed significant water in the distant past. Thus, the study of Venus provides unique and important opportunities to understand not only the general processes that govern the inner planets, but it also serves as a comparison case to suggest how those processes affected Earth, and in particular why and how Venus and Earth diverged. Exploration of Venus is one of the great remaining challenges and opportunities of Solar System science. It will provide valuable insight into planetary processes, the past and future of the terrestrial planets, and the likelihood of habitable planets in other planetary systems around other stars.

This *Venus Exploration Roadmap* lays out a framework for the future exploration of Venus, encompassing observations of the atmosphere, surface, and interior using a variety of mission modes ranging from orbiters and probes to aerial platforms, landers, and eventually sample return. It was developed for the space science community by the Venus Exploration Analysis Group (VEXAG) to provide a context for strategic planning and to facilitate future investigations and mission and technology proposals. Proposals that address the measurement goals expressed in this *Exploration Roadmap* should be recognized by NASA review panels as being consistent with VEXAG’s recommended Venus exploration strategy. This *Exploration Roadmap* is also consistent with and amplifies the *Planetary Decadal Survey, Visions and Voyages for Planetary Science in the Decade 2013–2022* (also referred to as the *Decadal Survey*).

This *Exploration Roadmap* is based on the *Venus Goals, Objectives, and Investigations* (*GOI*) document, which establishes the scientific foundation and priorities for future Venus exploration. To facilitate the identification of specific mission concepts, the *Exploration Roadmap* is divided into four “exploration domains”—Atmospheric Composition, Surface Composition and Morphology, Atmospheric Structure and Circulation, and Interior Structure and Dynamics—within which measurements and missions can be structured in a logical progression of scientific discovery and engineering capability. The relative priority of the missions within each domain is based primarily on the scientific priorities of the *GOI* document, modulated by assessment of each mission’s technical feasibility and its compatibility with current budgetary and programmatic realities. Thus, the *Exploration Roadmap* represents a practical guide to future Venus missions that can achieve the highest priority science objectives in the most expeditious manner. For the discussion that follows, as shown in Table 1, near-term is this decade, mid-term is the next decade, and far-term is 2025 and beyond.

The representative mission sets described in this *Venus Exploration Roadmap* were derived based on assessment of their scientific potential, technology readiness, and programmatic considerations including feed-forward of science and capability in a logical fashion. Table 1 below summarizes the mission concepts binned by near-term (feasible this decade), mid-term (next decade), and far-term (likely to be beyond 2025). All the near-term missions are feasible within Discovery with the exception of the short-duration lander, which is a candidate for the next New Frontiers opportunity (e.g., VISE). The mid-term missions should also be feasible within future New Frontiers opportunities, provided that certain key technologies are developed and validated. All of the far-term missions are likely to be flagship-class, depending on technology progress. Multi-disciplinary missions (such as VCM) that aggregate several mission objectives are clearly also in the flagship class due to their cost, although from a technology perspective they may be feasible in the near- or mid-term.

Table 1. Venus Exploration Roadmap Mission Timeframes

Near-Term (This Decade)	Mid-Term (Next Decade)	Far-Term (2025 and beyond)
Active remote sensing orbiter (radar, topography, emissivity, gravity)	Deep multi-probes	Surface (or near-surface) platform with regional mobility
Sustained aerial platform	Short-duration tessera lander	Long-lived lander network for seismic studies
Deep probe	Long-lived geophysical lander	Venus surface sample return
Short-duration lander		
Multiple probes/dropsondes		
Passive remote sensing orbiter or multi-flybys		

2. Venus Exploration in NASA's Science Program

Important Venus science can be accomplished within all of the mission programs sponsored by the NASA Solar System Exploration Directorate. The diversity of compelling Venus science questions means that even highly focused measurements can be extremely productive, so even relatively low-cost missions can make major contributions. Conversely, the complex inter-relationships and variability of Venus' major systems make it an ideal candidate for larger multi-disciplinary missions. Missions to the lower atmosphere or surface that must contend with the harsh environmental conditions for extended periods of time will tend to fall in the higher cost classes. A far-term Venus exploration strategy comprising missions from all classes, coupled with strategic technology investments, will enable a comprehensive understanding of the key scientific issues with efficient feed-forward of knowledge and capability. This "virtual" Venus program, drawing its missions from the existing funded Solar System program lines, and with international collaboration, provides an opportunity to make progress in Venus exploration in a manner consistent with NASA's current budget constraints and other priorities.

2.1. Discovery Missions

The Discovery Program consists of Principal Investigator (PI)-led smaller missions that provide opportunities for targeted investigations with relatively rapid flight missions. The Discovery program is ideally suited for missions to Venus. The planet's relative proximity means that flight times are short, and power and communications bandwidth are plentiful for orbital missions. The dense atmosphere can be used for aerobraking or aerocapture to reduce propellant requirements, and Venus also provides an attractive and scientifically rich environment for probes or airborne science platforms. Important surface compositional and topographic measurements, including change detection, can be made from orbit using radar, altimetry, and emissivity techniques already proven at Venus. Discovery missions (including orbiters, probes, and aerial platforms) will represent critical steps toward understanding Venus and its scientific relationship to Earth, and they will serve as pathfinders for more complex multi-disciplinary missions.

2.2. New Frontiers Missions

The New Frontiers Program consists of PI-led medium-class missions addressing specific strategic scientific investigations endorsed by the *Decadal Survey*. The *Decadal Survey* recommended a single Venus New Frontiers mission, the Venus In Situ Explorer (VISE). This *Exploration Roadmap* reaffirms the importance of the VISE science goal of detailed characterization of the surface and deep atmosphere and their interactions. Clearly the challenge of landing a sophisticated science platform on Venus, even for focused short-term measurements, requires resources of at least the New Frontiers level. The technology for VISE is ready today (with the exception of entry technology that is under development and will be at technology readiness level (TRL) 5 before the next New Frontiers announcement of opportunity (AO), and it does not require a precursor Discovery mission, although some of the VISE atmospheric science objectives may also be achievable with Discovery-class missions. VISE itself represents an important precursor to more ambitious surface missions and a step toward the eventual long-term goal of Venus sample return.

The next *Decadal Survey* (or an update if NASA conducts one) may establish new or additional priorities for Venus New Frontiers missions. This *Exploration Roadmap* identifies several representative missions that should be considered future New Frontiers candidates. These missions include deep multi-probes, a short-duration lander to the more challenging tessera regions, and (perhaps) a single long-duration lander focused on geophysical measurements. Technology investments in these missions should begin now to ensure they are ready for a future New Frontiers call. Other mission modes could also be considered, building on the results of Venus Discovery missions that may have occurred in the interim. Such modes should be identified in the next Decadal Survey.

2.3. Flagship Mission Concepts

Flagship missions address those high-priority investigations that are so challenging that they cannot be achieved within the resources allocated to the Discovery and New Frontiers Programs. The *Decadal Survey* recommended a single small Venus flagship mission concept, the Venus Climate Mission (VCM), which would require no new technology, for the period 2013–2022. The VCM would make synergistic observations from multiple platforms (orbiter, balloon, mini-probe, and dropsondes) to enable global three-dimensional characterization of the atmosphere. This *Exploration Roadmap* reaffirms the value and high priority of the VCM.

This multi-disciplinary investigation of Venus' greenhouse effect will have important implications for understanding the stability of climate and our ability to predict and model climate change on Earth and extra-solar planets. Some elements of VCM science may be addressed by individual Discovery or New Frontiers-class missions, which can provide valuable data on portions of the scientific goals even without the contemporaneous supporting measurements. As awareness of climate change on Earth increases, the imperative to fly VCM along with related lower-cost Venus missions will also increase.

In the longer term, a Venus Surface Sample Return (VSSR) would provide the most definitive insight into Venus' geological and climatic history and biological potential. VSSR is a top scientific priority, but the technological challenges are extreme, and such a mission cannot realistically be contemplated until the late 2020s or later. A number of precursor science/technology missions, including the surface or near-surface mobile platform described later in this report, may be required prior to actually returning a Venus sample. Thus, VSSR represents a far-term campaign in itself and can serve to organize and motivate earlier missions.

2.4. Missions of Opportunity

As the pressure on space science budgets grows more severe, it is important that NASA consider alternative mission modes that may be able to make contributions to Venus science at lower cost—perhaps less than half the cost of a Discovery mission. For example, future missions to destinations other than Venus that use flybys of Venus for gravity assist could make observations relevant to the composition or dynamics of the upper atmosphere, or perhaps even deploy small entry probes. In such cases, small investments could provide valuable data at minimal cost. Earth-based telescopic observations, such as from high-altitude balloons, could provide valuable data on Venus' cloud dynamics. In addition, NASA should consider sponsoring micro-missions or CubeSats that could be launched as secondary payloads on other planetary missions and travel independently to Venus for highly focused observations. As such small spacecraft become increasingly capable, they could potentially conduct important short-duration scientific observations at very low cost, and in the process help to refine the goals of future larger missions.

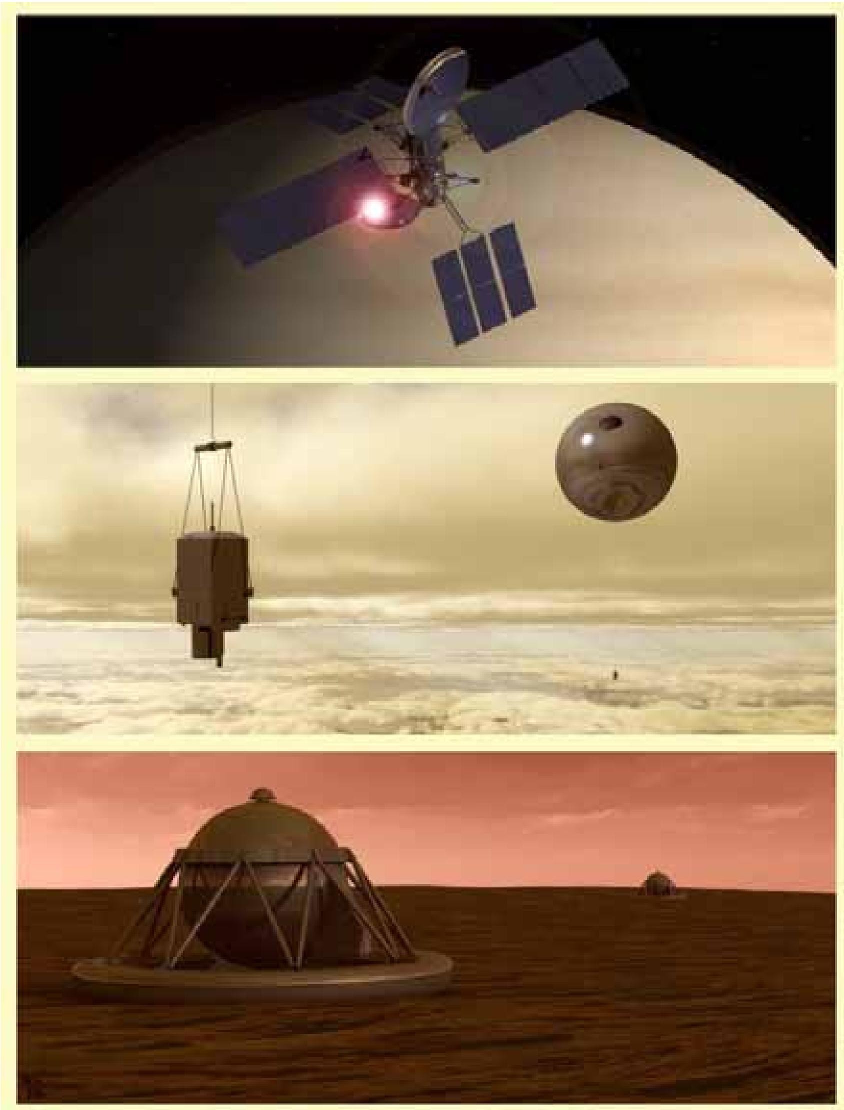
2.5. International Opportunities

The international community has demonstrated a strong interest in Venus, and future exploration of Venus can be greatly enhanced through international cooperation. The European Space Agency's Venus Express has benefited from involvement of other agencies including NASA. Likewise, the Japanese Space Agency's Akatsuki, if it succeeds in entering Venus orbit, will also involve other agencies. Russia's Roscosmos and Space Research Institute have recently entered into a collaboration with NASA's Planetary Science Division on Venera D, a highly capable mission with both landed and orbital elements, which is planned for launch early in the 2020s. Missions such as Cassini-Huygens exemplify how scientific return increases when multiple partners collaborate on a single mission, and this could serve as a model for future Venus missions such as VCM. Furthermore, given the large number of focused science objectives that comprise this *Venus Exploration Roadmap*, coordination at the program level could result in significant cost savings as international partners each undertake separate but coordinated missions. The International Venus Exploration Focus Group is working with VEXAG and identifying pathways for Venus Exploration. A preliminary report was given at the VEXAG meeting of November 2013.

2.6. Technology Readiness

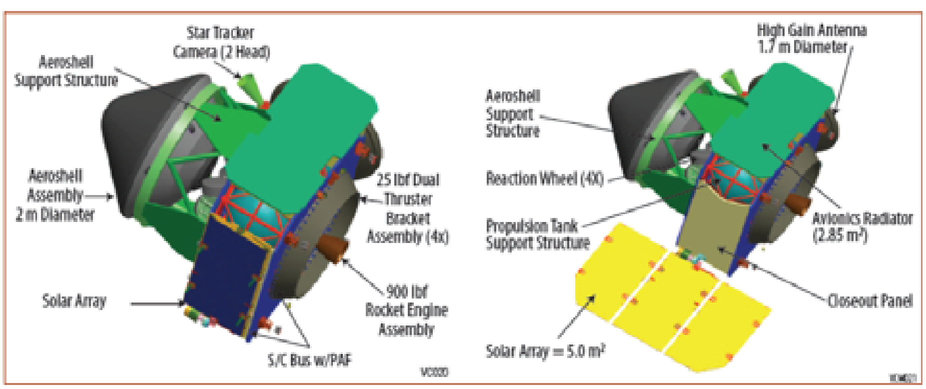
The key challenges facing future Venus orbital missions center on the obvious temperature extremes and the stresses they place on spacecraft subsystems, lightweight entry systems optimized for the Venus atmosphere, active and passive remote sensing techniques, and high-bandwidth communications and data handling to accommodate the large data volumes of investigations such as imaging radar. The majority of high-priority Venus orbital missions can be conducted with technologies that are ready today or that can be brought to TRL 6 between project selection and mission preliminary design review (within roughly 2 years). Atmospheric probes and airborne platforms may benefit from improvements in instrument technologies as well as advances in power, communications, and other supporting capabilities required by their specific mission architecture, but they are also generally at an advanced state of readiness.

Conversely, the surface of Venus is one of the most difficult places in the Solar System to explore. In addition to the obvious extreme thermal conditions, these missions must also contend with a corrosive chemical environment, lack of sunlight, uncertain terrain, and atmospheric limitations on communication and other spacecraft operations. While short-duration, scientifically significant missions to the surface or lower atmosphere are possible with current technology, longer duration missions will require substantial investments and a strategic approach to technology development and testing. The *Venus Technology Plan* developed as a companion to this *Exploration Roadmap* describes the challenges and priorities for Venus exploration and recommends an investment approach that can support all mission classes.



Artist's concept of Venus flagship orbiter, balloons, and landers.

Elements of the Venus Flagship Design Reference Mission, developed by the Venus Science and Technology Definition Team in 2008–2009.



Artist's Concept of the VCM Carrier Spacecraft with solar array stowed and deployed.

3. Exploration Domains and Representative Mission Concepts

This *Venus Exploration Roadmap* comprises four exploration domains that allow definition of mission concept sets with common scientific objectives and/or implementation modes. This provides a foundation for establishment of priorities based on feasibility and technology readiness as well as scientific potential. The three VEXAG Goals for Venus Exploration were not prioritized because developing an understanding of Venus as a system requires making progress in the science areas covered by all three goals. For the same reason, this *Roadmap* does not attempt to prioritize among the four exploration domains discussed below. However, within each exploration domain, the mission concepts are listed in priority order based on the priority given to science objectives and investigations in the *Goals, Objectives and Investigations for Venus Exploration* (*GOI*) and on technical readiness. The roadmaps for these individual domains comprise a prioritized sequence of mission objectives, each of which is further defined by specific measurement goals and a recommended mission mode. It is important to note that the missions cited here are illustrative and should not be interpreted as the only acceptable means of addressing a given scientific objective. As always, alternative or innovative approaches may be developed and proposed, and such approaches should be considered by NASA, provided they meet the measurement goals with acceptable cost and risk. In addition, there may be cost-effective means of addressing multiple investigations within a single mission (e.g., inclusion of atmospheric measurements during the descent phase of a surface lander), and these should be encouraged as a means to accelerate progress in Venus exploration.

3.1. Atmospheric Composition

A comprehensive understanding of Venus' atmospheric composition is central to determining how the planet's climate has evolved and how and when the runaway greenhouse effect took over. Past probe missions have determined the bulk composition of the atmosphere, but abundances and isotope ratios of noble gases and stable isotopes were poorly constrained or entirely lacking in some cases. Major questions remain regarding:

- Abundances and ratios of noble gases and stable isotopes;
- Altitude profiles of key minor species and how they vary throughout the major atmospheric regimes;
- Processes that form and sustain the clouds, and how their compositions vary; and
- Composition and characteristics of Venus' ubiquitous haze.

Orbital measurements to date (e.g., Venus Express) give only partial information about some constituents at high altitudes. In-situ instrumentation is generally needed beneath the cloud tops to investigate those chemical constituents and their isotopes for which abundance is too low, remote sensing signatures are too weak, or vertically variability is too great to effectively study remotely. New orbital measurements can expand the knowledge of space-time variability of certain constituents mainly above the cloud tops; a probe/lander making a single parachute descent could determine the critical vertical profiles but would lack the spatial/longitudinal coverage at altitude to address some compositional questions.

Measurements and Representative Atmospheric Composition Mission Concepts

The missions below are in priority order, based on the priority of the relevant *GOI* investigations as well as technical and programmatic feasibility.

1. **Mission Objective:** Determine the abundances and height profiles of gases and isotopic ratios to constrain atmospheric evolution and stability as well as possible biosignatures. Measurements include:

    a. Abundances and isotope ratios of noble gases

b. Isotopic ratios of hydrogen/deuterium (H/D), $^{15}N/^{14}N$, $^{17}O/^{16}O$, $^{18}O/^{16}O$, and $^{13}C/^{12}C$

c. Sulfur species (e.g., SO_2, OCS, SO, SO_3, H_2S, and H_2SO_4) and key isotope ratios

d. Abundances of halogen species (e.g., HCl, HF, and ClOO), and ^{12}C

e. Abundances of greenhouse gases, H_2O, and other condensables

f. Nature of the atmospheric haze

g. Search for and characterization of biogenic elements

Mission Mode: One or more probes equipped for chemical measurements and capable of making measurements at prescribed altitudes all the way down to the surface. Any other properly instrumented vehicle (e.g., a lander) that descends through the atmosphere could make the same measurements in conjunction with other objectives.

2. **Mission Objective:** Study the cloud region in situ to understand chemical processes, atmospheric structure and evolution, atmospheric stability, and to constrain biosignatures. Measurements include:

a. Atmospheric gas sulfur species abundance and isotopic ratios

b. Isotopic ratios of H/D, $^{15}N/^{14}N$, $^{17}O/^{16}O$, $^{18}O/^{16}O$, and $^{13}C/^{12}C$

c. Abundances and isotope ratios of noble gases

d. Properties of the UV absorber

e. Abundances of halogen species (e.g., HCl, HF, and ClOO) and ^{12}C)

f. Composition of aerosol and cloud particles

g. Frequency and strength of lightning

h. Presence and nature of biogenic elements

Mission Mode: A sustained aerial platform (e.g., balloon) enabling study of spatial and temporal atmospheric variability. Specific performance parameters (e.g., lifetime, mobility) are a science vs. cost tradeoff to be established by proposal.

3. **Mission Objective:** Determine abundances and height profiles down to the cloud tops. Measurements include:

a. Atmospheric gas sulfur species (e.g. SO_2, OCS, SO, SO_3, H_2S, H_2SO_4)

b. Variability of H_2O, SO_2, and other condensables

Mission Mode: An orbiter instrumented for atmospheric remote sensing, possibly in conjunction with other objectives. A multi-flyby mission could perform similar measurements with reduced science return but at potentially lower cost.

Mission Sequence Determination

All of the recommended missions are feasible with current technology and should be considered viable near-term missions. The complete vertical profile of a well-instrumented probe (or lander) can address key questions of atmospheric evolution and amplify on results of past missions. A sustained atmospheric platform can perform equally important science albeit with a more complex implementation. A remote-sensing orbiter or multi-flybys may be lower cost but cannot access the middle or lower atmosphere where critical chemical processes are occurring.

3.2. Atmospheric Structure and Circulation

The dense, super-rotating atmosphere of Venus presents a challenge to understanding the formation and evolution of planetary atmospheres. Our knowledge to date is derived from tracking entry probes and floating platforms and from near-surface anemometers, as well as tracking small-scale cloud features, Earth-based Doppler spectroscopic measurements from visible to sub-millimeter, and inferences from the global distribution of airglow measurements. These have provided a global view of the super-rotation of the atmosphere below ~75 km, an incomplete picture of highly spatially and temporally variable subsolar-antisolar circulation above 95 km, and only a vague idea of the near-surface magnitude of the winds at two locations. Key questions remain regarding the three-dimensional structure of the global atmospheric circulation from the surface to ~120 km, the processes (such as solar thermal tides, convection, and planetary and smaller scale gravity waves) that maintain the circulation, the characteristic temporal variation of the circulation and exchange of momentum with surface and vertical transport of trace species, and the nature and temporal variability of the circulation above the cloud tops up to ~120 km where it transitions from super-rotation to subsolar-antisolar circulation.

Future missions should be capable of elucidating the processes important in maintaining the Venus atmospheric circulation from surface to 120 km. Also desired is good knowledge of length-of-day variations to elucidate momentum exchange between the solid planet and the atmosphere; that can come from space- or Earth-based measurements. The detailed global circulation is important in understanding the global distribution of trace species, evolution of the spin state of the planet through exchange of angular momentum with the surface, and guidance for rocky exoplanet atmospheric circulations.

Measurements and Representative Atmospheric Structure and Circulation Mission Concepts

The missions below are in priority order, based on the priority of the relevant *GOI* investigations as well as technical and programmatic feasibility.

1. **Mission Objective:** Conduct an in-situ study of global atmospheric circulation. Measurements include:

   a. Small-scale waves and turbulence by frequent measurements of ambient horizontal wind during day and night

   b. Magnitude and direction of the vertical motion

   c. Turbulence/convection as a function of local time

   d. Simultaneous meteorological properties including pressure and temperature, and abundances of trace gaseous species and aerosols

   Mission Mode: One or more sustained atmospheric platforms capable of accessing multiple vertical levels in the cloud layers. The focus here is on atmospheric physical rather than chemical parameters. Lifetime and degree of mobility are a science vs. cost trade.

2. **Mission Objective:** Determine how atmospheric circulation patterns vary with altitude. Measurements include:

   a. Horizontal and vertical winds from the upper atmosphere down to the surface

   b. Standard meteorological parameters at a range of altitudes

   c. Abundances of aerosols and vertically variable major trace species

   Mission Mode: One or more entry/descent vehicles capable of measuring vertical circulation profiles. These could be probes that enter from orbit or from approach, or they could be dropsondes deployed from another atmospheric platform.

3. **Mission Objective:** Understand global atmospheric circulation at the surface.
   a. Near-surface wind speed and direction and pressure at a range of latitudes from pole to pole and at a range of local solar times

   Mission Mode: Multiple entry probes or dropsondes that survive to the surface. Number and distribution of vehicles and specific measurement profile are a science vs. cost trade.

4. **Mission Objective:** Understand global circulation of the upper atmosphere. Measurements include:
   a. Ambient wind velocities in the cloud layer and above to at least 120 km
   b. Simultaneous zonal and meridional components to enable estimates of meridional angular momentum transport

   Mission Mode: Orbiter with passive and/or active remote sensing, possibly in conjunction with other objectives.

Mission Sequence Determination

An extended study from an aerial platform would allow the most comprehensive understanding of Venus' atmospheric structure, circulation, and meteorology. Multiple simple entry probes or dropsondes would sample a greater vertical range at potentially lower cost but would not provide the time variability of an aerial platform. Both an aerial platform and simple dropsondes are top near-term priorities. Deep multi-probes (or dropsondes) that would extend the study down to the surface are considered mid-term due to the likely higher cost class and more extensive technology requirements. Orbital observations of the upper atmosphere can be done in the near term but would miss the deeper layers; however, coupling such remote sensing with simple probes might represent an attractive mission concept if it can be shown to be affordable.

3.3. Surface Composition and Morphology

The compositions of terrestrial planets reveal much about their evolutionary history from accretion to the present. The major element composition of the Venus surface measured at three sites by Venera and Vega landers and the morphology of plains observed by synthetic aperture radar (SAR) are consistent with a basaltic crust for Venus. The mean crater age for the surface is on the order of ~1 Ga or less, but it can be modeled by a number of resurfacing mechanisms operating over a range of temporal and spatial scales. Assumptions of broadly similar thermal budgets for Earth and Venus suggest that resurfacing processes, such as volcanism, continue on Venus today. Recent analyses of Venus Express Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) data have indicated possible evolved compositions for the (potentially ancient) tesserae, and also support relatively recent volcanism at hotspots. The characteristic rates and mechanisms of surface processes and weathering, particularly at the <100 m spatial scale, are poorly understood. Major questions remain regarding Venus' geologic history and the nature and range of morphological units, the range of crustal compositions and evidence of silica-rich crust, the extent and location of any geological activity, the history of volatiles, and active surface modification and weathering processes. These questions require improved measurements of the composition, morphology, stratigraphy, and ongoing resurfacing of the crust of Venus.

Measurements and Representative Surface Composition and Morphology Mission Concepts

The mission concepts below are in priority order, based on the priority of the relevant *GOI* investigations as well as technical and programmatic feasibility.

1. **Mission Objective:** Study Venus' surface morphology, topography, and composition. Measurements include:

a. Radar imaging, with polarimetry, at finer than Magellan horizontal spatial resolution (e.g., 5–25 m)

b. Topography at finer than Magellan horizontal spatial resolution (e.g., 0.1–1 km)

c. Global emissivity at ~1 micron (0.001 mm) wavelength

d. Interferometry/repeated orbital imaging for surface change detection

Mission Mode: Orbiter with active/passive remote sensing capable of detailed surface observations. Altitude, duration, and other mission parameters are science vs. cost trades. Could be combined with other orbital science objectives or delivery of entry vehicles. Visible imaging may be an important additional objective to aid in-site selection for future missions.

2. **Mission Objective:** Study surface geochemistry and mineralogy on the plains or a hotspot. Measurements include:

   a. Bulk composition of weathered and unweathered surface materials, major elements, and trace elements

   b. Surface mineralogy and petrography

   c. Panoramic to millimeter-resolution images of the surface

   Mission Mode: Short-duration surface mission (e.g., the *Decadal Survey* VISE) at any accessible location. This could be a dedicated lander or an atmospheric vehicle capable of surviving down to and operating on the surface.

3. **Mission Objective:** Study surface geochemistry and mineralogy on a tesserae highland. Measurements include:

   a. Bulk composition of weathered and unweathered surface materials, major elements, and trace elements

   b. Surface mineralogy and petrography

   c. Panoramic to millimeter-resolution images of the surface

Mission Mode: Short-duration lander to the tessera regions. The more challenging location will likely require precision landing capability and possibly precursor observations (radar and/or imaging) for site selection.

4. **Mission Objective:** Analyze surface compositional variations on a regional scale. Measurements include:

   a. Geochemistry and mineralogy measurements at multiple sites

   b. Remote sensing of the surface from low altitudes (down to 1 km), including visible–near infrared

   c. Panoramic and high-resolution surface imaging correlated with composition

Mission Mode: Mobile platform on the surface or in the lower atmosphere, mobility tens to hundreds of kilometers. This could be a surface rover or a balloon capable of repeated descents or continuous low-altitude operation.

Mission Sequence Determination

An orbiter to extend Magellan observations, detect any present-day surface activity, and serve as a pathfinder for future surface exploration is a top science priority and is feasible within Discovery. A New Frontiers-class short-duration lander can accomplish the VISE science identified in the *Decadal Survey* and is also considered a near-term mission. An advanced lander capable of accessing more challenging highland terrain is scientifically compelling but may require improved knowledge of surface characteristics and potential landing sites, and should be considered for the mid-term (next decade). A mobile platform for extended regional exploration of the surface and lower atmosphere will require substantial technology development and is a top priority for the far-term (2025 and beyond) and would be a step towards an ultimate Venus Surface Sample Return.

3.4. Interior Structure and Activity

Key to understanding why Venus and Earth went down such different evolutionary paths is characterizing the current state and evolution of the Venus interior. Major outstanding questions include understanding:

- How Venus formed and initially evolved;
- How its interior dynamics may have differed in the past and whether it ever had plate tectonics;
- The nature and rate of current and past volcanic and tectonic activity and what roles volcanism, tectonics, and volatiles play in current/past heat loss and volatile evolution;
- Whether there is extensive silica-rich crust, implying substantial crustal water in the past; and
- The planet's spin state (rotation and polar wander) and how it correlates to models of the interior and its evolution.

Radar altimetry, SAR imaging, and gravity data indicate that, contrary to predictions, Venus lacks plate tectonics—a system that on Earth, provides an efficient means of cooling the planet and, most importantly, recycling water into the interior, lubricating the plates. The presence or absence of past and present internal activity and its interplay with other mechanisms of heat loss is therefore of fundamental importance to understanding the planet's history and the evolution of its volatiles. Understanding the processes of differentiation and the existence of an extensive silica-rich crust would allow insight into the history of water on Venus.

Investigations and Representative Interior Structure and Activity Mission Concepts

The missions below are in priority order, based on the priority of the relevant *GOI* investigations as well as technical and programmatic feasibility.

1. **Mission Objective:** Study Venus' surface morphology, topography, composition, and gravity. Measurements include:

    a. Topography at finer than Magellan spatial resolution (e.g., 0.1–1 km)

    b. Radar imaging, with polarimetry, at finer than Magellan spatial resolution (e.g., 5–25 m)

    c. Global gravity with resolution finer than Magellan (e.g., to degree and order 180)

    d. Emissivity of the global surface in the 1 micron (0.001 mm) wavelength range

    Mission Mode: Orbiter with active/passive remote sensing. The gravity experiment may require special design considerations such as minimizing spacecraft disturbances and carrying an ultra-stable oscillator or other high-precision reference.

2. **Mission Objective:** Investigate the structure of Venus' interior and the nature of current activity. Measurements include:

    a. Seismology over a large frequency range to constrain interior structure

    b. Heat flow to discriminate between models of current heat loss

    c. Geodesy to determine core size and state

d. Electromagnetic (EM) sounding to constrain gross interior layering

Mission Mode: Geophysical lander with a life time of ~1 Venusian year. Survivability will require high-temperature electronics and/or some type of active cooling technology.

3. **Mission Objective:** Develop a comprehensive understanding of the history and present state of Venus' interior with a focus on determining the nature and extent of tectonic processes. Measurements include:

   a. All of the previously described geophysical measurements to higher fidelity

   b. Constrain rate of seismicity and regional crustal thickness variations

   c. Study local structure of specific targets (e.g., tesserae, hotspots, rifts, and Ishtar Terra)

   Mission Mode: Lander network with a lifetime > 1 Venusian year. Number and distribution of landers is to be determined based on further mission definition.

Mission Sequence Determination

An orbital study to extend Magellan observations and include gravity studies can link models of the surface and interior, and such a study represents an important near-term mission opportunity. Seismic landers or networks would provide the most complete understanding of Venus' interior and current/past activity but would require significant technology development. It is possible that a single lander of sufficient duration (~1 Venus year) could be considered in the mid-term, but a full network is considered a far-term mission. Given the challenges of long-duration Venus surface missions, other innovative approaches to achieving similar science objectives should be explored (e.g., possible detection of seismic activity derived from atmospheric observations).

4. Mission Concepts Summary and Mapping to *Venus GOI* Investigations

As noted in Section 1 and Table 1, the representative mission sets described in this *Venus Exploration Roadmap* were derived based on assessment of their scientific potential, technology readiness, and programmatic considerations including feed-forward of science and capability in a logical fashion. All the near-term missions are feasible within Discovery with the exception of the short-duration lander, which is a candidate for the next New Frontiers opportunity (e.g., VISE). The mid-term missions should also be feasible within future New Frontiers opportunities, provided that certain key technologies are developed and validated. All of the far-term missions are likely to be flagship-class, depending on technology progress. Multi-disciplinary missions (such as VCM) that aggregate several mission objectives are clearly also in the flagship class due to their cost, although from a technology perspective they may be feasible in the near- or mid-term.

Table 2 is a mapping of the *Exploration Roadmap* mission concepts into the 27 investigations identified by the *Venus GOI* document. Missions are listed on the vertical axis, and *GOI* investigations are listed along the top. Note that the GOI goals are not prioritized, but the objectives within each goal are in priority order from left to right, as are the investigations within each objective. The table shows that the recommended Roadmap missions will address all GOI investigations, and that the majority of the top science priorities can be addressed in the near term. It also shows that all *Exploration Roadmap* missions can address multiple *GOI* investigations. Together, the *Venus GOI* document and the *Exploration Roadmap* represent a robust strategy for Venus exploration that can address the key Venus science priorities in a cost-effective and technically feasible manner.

Acronyms and Abbreviations

AO	announcement of opportunity
EM	electromagnetic
GOI	*(Venus) Goals, Objectives, and Investigations*
H/D	hydrogen/deuterium
PDR	preliminary design review
SAR	synthetic aperture radar
TRL	technology readiness level
VCM	Venus Climate Mission
VEXAG	Venus Exploration Analysis Group
VIRTIS	(Venus Express) Visible and Infrared Thermal Imaging Spectrometer
VISE	Venus In Situ Explorer
VSSR	Venus Surface Sample Return

Bibliography

Visions and Voyages for Planetary Science in the Decade 2013 - 2022, Washington, DC: The National Academies Press, 2011 (also referred to as the *Decadal Survey*). The *Decadal Survey* was sponsored by the United States National Research Council and NASA. This document identifies key questions facing planetary science and outlines plans for space and ground based exploration ten years into the future. Missions to gather the data to answer these questions are described and prioritized.

Goals, Objectives and Investigations for Venus Exploration (*GOI*), developed by VEXAG as companion to this *Roadmap for Venus Exploration*, as a follow-up to a recommendation from the VEXAG meeting in November 2013.

Venus Technology Plan, developed by VEXAG as companion to this *Roadmap for Venus Exploration*, as a follow-up to a recommendation from the VEXAG meeting in November 2013.

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Table 2. Mapping of the Roadmap Mission Concepts into the 27 Investigations in the *Goals, Objectives, and Investigations for Venus Exploration* document

	Roadmap Missions / GOI Investigations	Relative abundances of Ne, O isotopes, bulk Xe, Kr, other noble gases	Isotopes of noble gases; D/H, $^{15}N/^{14}N$, O and H escape rates	Atmospheric super-rotation and global circulation	Atmospheric radiative balance and temperature profile, surface to 140 km	Small-scale atmospheric vertical motion	Meteorology/chemistry of middle cloud layer; aerosols, particles, vertical motion	Greenhouse aerosols and gases: composition, production, loss	Lightning/discharge strength, frequency, variation	Biologically-relevant cloud/gas chemistry, including $^{13}C/^{12}C$ and complex organics	Stratigraphy and deformation of surface units through imaging and topography	Radiogenic ^{4}HE, ^{40}AR, Xe isotopic mixing ratios	Structure, dynamics, history of interior and effects on surface geology	Rates of volcanic and tectonic activity	Absolute rock ages at locations that constrain global resurfacing rates	Composition, mineralogy, petrography of samples at key geologic sites, e.g. tesserae	Rock composition at regional scales through remote sensing	Structure of crust and spatial/depth variation	Size and state of core and mantle structure	Radiogenic element content of crust	Subsurface layering and geologic contacts to depths of several km	Isotopic D/H in atmosphere, and key isotope ratios of N, O, S, C	Hydrous minerals and greenhouse gases trapped in surface rocks	Identify/characterize areas that exhibit different formation epochs; role of water in tesserae	Noble gas elemental composition and isotopic ratios in atmosphere and solid samples	Characterize rock weathering at outcrop and regional scales	Abundance/altitude profile reactive species, greenhouse gases, condensibles	Stable isotopes of H,C,N,S,C in solid samples and aerosol composition
		Obj. A		Objective B			Objective C				Objective A					Objective B						Objective A			Objective B			
Near-Term	Orbiter: Radar, topo, emissivity										●		●	●		○	●	●	○	○				○		○		
Near-Term	Sustained aerial platform	●	●	○	○	●	●	●	○	●		●	○					○	○		○	●			○		○	○
Near-Term	Deep probe or lander (single)	●	●		●		○	○		●		●										●					●	●
Near-Term	Short-duration lander												●		○	●							○		●	○		
Near-Term	Drop-sondes or multi-probes			●	●	●	○		○			●										●					○	●
Near-Term	Remote sensing orbiter or multi flybys			●	○		○	○	●	○	●		●	●		●	○					●					●	
Mid-Term	Deep multi-probes/landers	●	●		●		●		○	●		●										●	○	○	●		●	
Mid-Term	Short-duration tessera lander												○		○	●							○	●	●	○		
Mid-Term	Long-lived geophysical lander												●	●				●	●	●	●							
Far-Term	Surface or near-surface platform with regional mobility									○	○		●	○	○	○	●	○		○			○	●		○		
Far-Term	Long-lived lander network												●	●				●	●	○	●							
Far-Term	Surface sample return	○	○									●	○	○	●	●			○	●		○	●	●	●	●		
		Goal 1: Atmospheric Processes and Climate History									*Goal 2: Evolution of the Surface and Interior*											*Goal 3: Interior-Surface-Atmosphere Interactions*						

● = Mission should strongly address investigation

○ = Mission should address investigation