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Venus Flagship Mission Concept: A Decadal Survey Study

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Abstract

More than any other known planet, Venus is essential to our understanding of the evolution and habitability of Earth-size planets throughout the galaxy. We address two critical questions for planetary science: 1) How, if at all, did Venus evolve through a habitable phase? 2) What circumstances affect how volatiles shape habitable worlds? Volatile elements have a strong influence on the evolutionary paths of rocky bodies and are critical to understanding solar system evolution. It is clear that Venus experienced a different volatile element history from the Earth and provides the only accessible example of one end-state of habitable Earth-size planets. Venus

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will allow us to identify the mechanisms that operate together to produce and maintain habitable worlds like our own.

The (VFM) concept architecture relies on five collaborative platforms: an Orbiter, Lander, variable-altitude Aerobot and two Small Satellites (SmallSats) delivered via a single launch on a Falcon 9 heavy expendable. The platforms would use multiple instruments to measure the exosphere, atmosphere and surface at multiple scales with high precision and over time. VFM would provide the first measurements of mineralogy and geochemistry of tessera terrain to examine rocks considered to be among the most likely to have formed in a habitable climate regime. Landed, descent, aerial and orbital platforms would work synergistically to measure the chemical composition of the atmosphere including the Aerobot operating for 60 days in the Venus clouds. Loss mechanisms would be constrained by the SmallSats in two key orbits. The baseline payload for VFM includes instruments to make the first measurements of seismicity and remanent magnetism, the first long-lived (60 day) surface platform and the first life detection instrument at Venus to interrogate what could be an inhabited world.

The VFM concept directly addresses each of the three Venus Exploration Analysis Group (VEXAG) goals as well as several of the strategic objectives of the 2020 NASA Science Plan, Planetary Science Division, Heliophysics and Astrophysics. The simultaneous, synergistic measurements of the solid body, surface, atmosphere and space environment provided by the VFM would allow us to target the most accessible Earth-size planet in our galaxy, and gain a profound new understanding of the evolution of our solar system and habitable worlds.

1 Introduction

Venus is the key for understanding terrestrial planets. It is the only other Earth-size planet in our solar system and the only accessible example of an Earth-size exoplanet. Careful study since Magellan indicates that it is likely that Venus possessed an ocean for a major part of its history and we now have the information to target the oldest rocks on Venus that are most likely to record that extinct regime. Multiple platforms are needed to interrogate the interrelated processes that control the movement of volatiles through the Venus system.

The Venus Flagship Mission (VFM) concept study arose out of a proposal submitted to the NASA Planetary Science Division (PSD) call for Planetary Mission Concept Studies (PMCS) to inform the now ongoing Planetary and Astrobiology Decadal Survey discussions. This study, completed in approximately eight months, involved a Science and Technology Definition Team (STDT) and an Engineering Study Team located at Goddard Space Flight Center (GSFC). The full report can be found at [1] and the depth of analysis for both the science and engineering is commensurate with available resources. Further work is needed to fully flesh out the concept.

For the study, we assumed no European or US Venus mission prior to VFM i.e. if VERITAS or DAVINCI+ should be selected in Discovery Step 2 or EnVision be selected in the M5 competition. VFM complements existing proposals/concepts: if VERITAS is selected it would be extremely advantageous for high resolution mapping and determining the VFM Lander site; if DAVINCI+ is selected, it would inform the descent profile at another location

and characterize tessera morphology. Either mission would reduce risk and thereby cost. If EnVision proceeds as ESA's M5 selection in the early 2030's it could provide radar imagery and emissivity measurements at the same time as VFM. Venera-D, with a desired landing site in the plains, is synergistic and complementary to the proposed concept since it would conduct similar investigations on a vastly different terrain type.

2 The Science Rationale for Venus

The importance of Venus to the understanding of habitable terrestrial planets cannot be overstated. It is well known that the size and orbit of Venus makes it a critical comparison to the evolution of the Earth and to Earth-size exoplanets. Modeling shows that Venus should have accreted from similar materials as the Earth [2], including refractory and volatile elements. Venus should have a similar amount of heat as the Earth, a planet with rigorous volcanic activity and plate recycling, and indeed the evidence for active volcanism on Venus is mounting [3][4][5]. The atmospheric D/H ratio of Venus demonstrates the loss of significant amounts of water at some point in its history (e.g., [6][7][8]), and recent calculations show that oceans may have persisted on Venus for several billion years [9][10]. Our knowledge of planetary processes, then, predicts that Venus was once a habitable planet as Earth is now. The presence of microbes, in the clouds of Earth (e.g., [11] and the recent discovery of phosphine in the Venus clouds forces us to reconsider the possibility that that they too may be inhabited today [12][13][14][15][16]. Venus provides the single most accessible example of an end-state of habitable Earth-size planets and it allows us to identify the mechanisms that operate together to produce and maintain habitable worlds like our own.

Venus data are also essential to advance our fundamental understanding of solar system evolution. For example, one of the major outstanding questions in solar system research is from where and how did the Earth acquire its volatiles? Is the Earth's water a product of nebular processes, the accretion of water-rich planetesimals, or does it depend on delivery from the outer solar system? How do magma oceans, oxidation state, plate recycling and loss mechanisms determine the water inventory of terrestrial planets over time? Each terrestrial planet provides additional insight into these questions, but because of its size and proximity, Venus, *more than any other world in our solar system*, allows us to control for some of the factors that contribute to the geologic evolution of the Earth, e.g., the role of surface gravity, heat budget, plate tectonics and potentially long-lived oceans. It is imperative to study Venus to understand the delivery of water to the inner solar system.

The key scientific importance of Venus is clearly stated across the scientific community and NASA. The VFM concept addresses parts of each of the three Venus Exploration Analysis Group (VEXAG) science goals [17] as well as several objectives from the 2020 NASA Science Plan across all three divisions. It informs two of the strategic objectives of the Planetary Science Division, to advance scientific knowledge of the origin and history of the solar system, and to determine the potential for life elsewhere. It also addresses the strategic objectives of the Heliophysics Division to understand the Sun and its interactions with Earth, the solar system and the interstellar medium, including space weather, and would provide data on how Venus can inform one of the Astrophysics Division's science themes: Exoplanet

Exploration. The current Planetary Decadal Survey report [18] and Midterm evaluation [19] documented the critical importance of Venus to understanding the origin of terrestrial planets and notes that Venus missions are necessary to address a "...lack of balance [that] undermines the compelling comparative planetology investigations recommended by the decadal survey, particularly for the terrestrial planets. The discovery of numerous Earth-size and Neptune-size exoplanets provides even greater urgency to initiate new missions to Venus and the ice giants.

3 Science Goals, Investigations, and Requirements

The specific goals of the Venus Flagship Mission (VFM) are to understand the:

1. history of volatiles and liquid water on Venus and determine if Venus has ever been habitable
2. composition and climatological history of the surface of Venus and the present-day couplings between the surface and atmosphere
3. geologic history of Venus and whether Venus is active today.

The Objectives of the VFM Science Traceability Matrix (STM) are shown in Table 1.

4 Mission Concept

4.1 Overview

Achieving the science goals presented in the STM requires interrogating Venus from the interior to the exosphere at multiple scales, which leads to performing collaborative and synergistic measurement of Venus as a system as shown in Figure 1. From this, the architecture of the mission concept was derived: a Lander, Aerobot, Orbiter, and two SmallSats, which would launch on a Falcon 9 Heavy Expendable (Figure 2). Each platform houses multiple instruments, many with heritage from prior missions, to elucidate the synergistic factors that control the distribution of volatiles from the interior to the exosphere: volatile inventory, volcanic activity, weathering, atmosphere dynamics, cloud formation and atmospheric loss. Instruments on these platforms would assess, at multiple scales with high precision, the volatile reservoirs, inventory, and cycles over Venus history, and use this to constrain the habitability of Venus. A strawman payload is shown in Table 2, and the Orbiter and SmallSats are also able to conduct radio science atmospheric experiments using their telecommunications systems. The Long-Lived In-situ Solar System Explorer (LLISSE) operates independently up to 60 days to demonstrate high-temperature electronics and sensor technologies.

4.2 Mission Design

The overall mission concept was derived from the three major science goals, the STM and two cost-driven requirements that were derived early in the study: 1) Launch all elements on a single rocket and 2) limit the g-load for Venus entry to 50g in order to maximize the use of state-of-the-art instruments that have high heritage or high technology levels. Both of these requirements were accomplished. Further key requirements that drove the mission design are landing when the Orbiter and SmallSats can communicate with Earth, providing

continuous coverage of the descent and landing of the Lander, providing communication coverage of descent, initial inflation and floating of the Aerobot, and providing daily access to the Aerobot and LLISSE.

The baseline trajectory for the VFM launches in June 2031 and places the five science platforms at Venus in 2034 with the Lander released in May 2035. A backup launch opportunity in June 2032 is also identified. A similar sequence of events occurs for both trajectory options (Figure 3).

A few hours after launch (1), two SmallSats detach from the other elements (2) and follow a low-thrust transfer to Venus, each using solar electric propulsion. Once at Venus, the SmallSats spiral down to their final orbits (5). In addition to their science requirements, the SmallSats provide essential communication with both the Aerobot and Lander. Both SmallSats would be in place, orbiting the planet, approximately 3 months prior to the arrival of the Orbiter, carrying the Aerobot and Lander, which utilizes chemical propulsion and performs a Venus flyby enroute (3). The Aerobot separates (4) from the Orbiter and Lander about 5 days prior to the Orbiter Venus Orbit Insertion (VOI) (7) maneuver directly from interplanetary space. After separation, the Aerobot enters the venusian atmosphere (6) and begins operations shortly after the balloon inflation. After VOI, the Orbiter is placed in an elliptical polar orbit for 6 months and then releases the Lander (8) after taking RADAR and emissivity measurements of tessera targets. This mission concept is flexible enough to provide the option to extend this mapping orbit to acquire additional coverage of tessera terrain as an input to landing site selection. The Lander takes approximately 3 days to reach the planet's atmosphere and 1 hour from entry (9) to begin surface operations. The Orbiter provides communication access to the Lander for a short duration prior to handing over the relay to the SmallSats. Subsequently, the Orbiter performs a sequence of aerobraking maneuvers (10) over the course of approximately 2 years to reach its final polar science orbit (11). The concept of operations is based on science, the trajectory and inter-platform communications requirements.

The mission architecture allows us to target ancient rocks, as done for Mars, to understand volatile history and whether Venus was once habitable. The Lander nominally touches down in tessera terrain in Western Ovda Regio, which has been covered by the highest-resolution Magellan topography and is thought to be representative of tessera terrain. The landing area would be selected upon examination of the **Synthetic Aperture Radar (SAR)** and emissivity data when the Orbiter is in its elliptical orbit phase in advance of the Lander release or, more optimally, from VERITAS, if selected. Safely landing in tessera terrain is absolutely necessary to satisfy our science objectives, so we developed a concept for a Landing Terrain Relative Navigation and Hazard Avoidance (TRN-LHA) system and self-adjusting landing struts that help the Lander to touchdown at a safe velocity on a slope 30° , which is the maximum expected slope at 1 km spatial scales, and to control its horizontal orientation by $\sim 10^\circ$.

Lander instruments measure the mineralogy and detailed chemistry of tessera terrain to ascertain rock type, and look for evidence of past water. A drill will provide materials to two instruments in the lander, while surface chemistry is interrogated by a gamma ray

instrument. A **Raman-Laser Induced Breakdown Spectrometer (R-LIBS)** will acquire mineralogy and chemistry of 10s – 100s of targets over the lander's 8-hour lifetime. The depth-profiling potential of the drill system and **R-LIBS** allow the lander to sample successive layers beneath the surface of the rocks to look for changes in weathering style over time, and identify any preserved record of the past climate. Such measurements also provide ground truth and calibration for orbital instruments e.g., surface composition measurements help calibrate orbital NIR emissivity maps, and optical images from the surface help interpret high resolution **SAR** images for tessera terrain of unknown origin. Note that VFM is *not* primarily a '**SAR** mission' and does not aim to return global **SAR** imagery. The **SAR** spatial resolution required to achieve the VFM science objectives includes context images at 30 m and 10 m images of critical targets (e.g., landing site), effectively Mars Orbiter Camera (MOC) at Venus.

Detailed cloud-level *in situ* investigations are required to characterize the volatile reservoir represented by the clouds, as well as astrobiological and other goals, which led to the inclusion of a cloud-level, balloon-borne Aerobot. The Aerobot has the capability to vary its altitude from 52–62 km as it circumnavigates Venus examining the aerosol and cloud composition as well as obtaining unprecedented magnetic and seismicity data. It executes multiple, controlled, vertical cycles over the altitude range to permit characterization of both the main convective cloud layer and the upper convectively stable clouds, where the UV absorber—of unknown, and possibly biological, composition—is known to be present (Figure 4).

Carried by Venus's super-rotating winds, the balloon circumnavigates the planet roughly once every five days, providing approximately 12 circumnavigations over the nominal 60-day balloon lifetime, enabling measurements of vertical and horizontal wind fields at cloud level, and their correlation with composition.

The Venus lower atmosphere is poorly known but provides critical information about the transfer of volatiles through the Venus system. The **Neutral Mass Spectrometer (NMS)** and **Tunable Laser Spectrometer (TLS)** on the Lander would measure chemical composition as it descends through the entire atmosphere, determining isotopic ratios and abundances of hydrogen, noble gases, oxygen, sulfur, nitrogen, and other elements in the atmosphere and from the mesosphere to the surface. Because these instruments are on the Lander, they continue to operate on the surface during the Lander lifetime to collect samples of the atmosphere that is in direct contact with the rocks measured by the Lander instruments. Above the clouds, the **Submillimeter Spectrometer (S-mm)** on the Orbiter obtains vertical profiles in the range of 70–140 km with 1.5–3 km vertical resolution of temperature, CO and H₂O isotopologues, ClO, HCl, H₂SO₄, O₂, O₃, NO, OCS, SO, and SO₂ and, for the first time, co-located wind speeds measured through Doppler velocimetry, which gives direct measurements of transport. These measurements would be complemented by radio science vertical absorption profiles of H₂SO₄ (S-band) & SO₂ (Ka-band) with vertical resolution ~100 m on the Orbiter and SmallSats.

VFM constrains the geophysical regime of Venus and its interior structure using a combination of gravity mapping from the Orbiter, measurement of seismicity through

balloon-borne infrasound detectors, and magnetometer investigations to characterize properties of the core and search for remanent surface magnetism. These complement the surface composition characterization from the Lander and from orbital NIR measurements, and noble gas isotope measurements of the atmosphere to form a much more comprehensive picture of Venus's volatile inventory and distribution. Again, this illustrates the scientific complementarity of measurements from different mission elements which cannot be achieved with one platform alone.

In the exosphere of Venus, the SmallSat instruments (similar to the instruments on MAVEN) would measure heavy ion escape (e.g., atomic and molecular oxygen, carbon dioxide) with full spatial, energy, angular, and mass coverage during varying phases of the solar cycle (Figure 5). The measurements cover the majority of solar cycle 26, including the predicted ascending and declining phases. Our approach is to deploy identical ion and magnetic field instrument suites on the SmallSats in two different orbits designed to obtain simultaneous information about both the upstream solar wind conditions in interplanetary space and escaping ion measurements in the magnetotail, ensuring accurate cause-and-effect interpretations of the observed escape rate variations. Based on these measurements and developing insights about the early solar wind and solar activity from observations of young Sun-like stars, VFM provides the necessary framework for a time-integration of the oxygen escape, establishing its now uncertain role in the historical loss of water.

5 Technical Overview

5.1 Flight System

The VFM concept flight system fits within the 5 m diameter of the Falcon 9 Heavy Expendable fairing. The operational order (Figure 3) that required the Aerobot be deployed before the Lander reduced the packaging options significantly. A custom Payload Attach Fitting (PAF) allows the placement of the Aerobot inside its aeroshell beneath the Orbiter using commercial off-the-shelf (COTS) separation rings. The Lander inside its aeroshell is attached to the top deck of the Orbiter using COTS separation rings and the SmallSats are tucked in between the Lander and the top deck of the Orbiter. Two SmallSats are attached via separation rings to a vertical bracket, similar in concept to a Moog's Evolved Secondary Payload Adapter (ESPA).

5.2 Orbiter

The VFM Orbiter (Figure 6) functions as a carrier and propulsion system for the Aerobot and Lander, as a communication relay for the Lander and Aerobot and as a science platform [1]. The 5 m antenna functions as both the **SAR** and the communication antenna for S-band, X-band and Ka-band systems and stows into a very compact package with enough clearance to mount on the -y panel. The antenna is a smaller version of the 6m antenna flown in 2015 on the Soil Moisture Active Passive (SMAP) mission. The Orbiter also has two X-band Omni antennas and a Medium Gain X-band antenna for commanding and backup. The Orbiter is three-axis stabilized with significant momentum and torque capabilities to account for the large inertia associated with the stacked configuration.

5.2.1 Orbiter Payload—The Orbiter serves as a platform for a set of instruments (Figure 6) that achieve their science goals best by operating from a constant altitude a few hundred kilometers above the surface in a near-polar orbit. Atmospheric scattering limits the NIR resolution to ~100 km; to meet the science requirements (high SNR, ~50 km spatial resolution), the orbiter must integrate data taken from multiple passes of a minimum of tens of percent of the globe, including the VFM landing site. A pushbroom, multi-band NIR camera with a wide FOV, similar to those on the BepiColombo and proposed on VERITAS and EnVision missions [20], can achieve the science goals with the planned orbit, and has suitable TRL, mass, and power requirements.

An **S-band SAR** was chosen to collect the nested high-resolution surface imaging needed to examine key geologic sites, including the landing site. S-band has minimal atmospheric loss, enables a **SAR** that meets TRL, mass, power, and resolution requirements and provides images that can be placed in context with and compared to those from the Magellan mission. We require only two modes of combined resolution/swath-width and a single viewing geometry (i.e., a phased array is not required), so our SMAP-based design [21] provides a light-weight, high TRL solution.

Mesospheric composition of the atmosphere can be characterized in time and space using a sub-mm sounding instrument on the Orbiter operating at 1200 and 600 GHz with a narrow IFOV (1–2 arc-min) with the ability to scan over several tens of degrees while pointed in either the nadir or limb directions. The Submillimeter Wave Instrument (SWI) for ESA's JUICE mission to the Jupiter system (scheduled launch in 2022) provides suitable scientific capability with acceptable Size, Weight, and Power (SWaP) requirements [22] and is used as the basis for the sub-mm sounder for VFM. Two **neutral mass spectrometers (NMS)** (facing opposite directions to enable access to the RAM direction as we rotate the spacecraft to keep radiators away from the sun) would be able to observe in situ isotope and neutral constituents in the atmosphere. Finally, a fluxgate magnetometer (on a 2-m boom), two electron electrostatic analyzers (**ESA-e**) and two ion electrostatic analyzers (**ESA-i**) are on the Orbiter to provide another spatial dataset contemporaneous with the identical instruments on the SmallSat payloads discussed below as well as additional altitude coverage. The latter two instruments measure full 3D velocity distribution functions in both the solar wind and venusian plasma environment, which are especially important for better understanding the heating and acceleration of plasma throughout the induced magnetosphere and inner heliosphere.

5.3 Aerobot

The Aerobot is a floating platform that incorporates a helium variable-altitude balloon system that can control its altitude to a commanded profile in the venusian atmosphere. The Aerobot includes a 15 m diameter pumped-helium balloon with a second 7.5 m diameter internal chamber (Figure 7). The outer chamber is at approximately equal pressure with the atmosphere (a zero-pressure balloon), while a second internal chamber is at elevated pressure with a structural, constant-volume envelope (a super-pressure balloon). Helium is pumped from the outer chamber to the inner chamber to lower the total volume and hence buoyancy and altitude, while helium is vented from the inner chamber to outer chamber to

raise the altitude. The balloon system remains a sealed system for the entirety of operation; no atmosphere would be ingested.

The Aerobot uses an IMU to provide disturbance data for correlation with science measurements. It does not have an attitude control system nor a propulsion system. Ranging between the Aerobot and SmallSats provides estimates of the altitude of the Aerobot to within the required ± 1 km. Avionics and electrical components all have extensive flight heritage with only minor qualification updates needed for the survivability at altitudes from 52 to 62 km.

5.3.1 Aerobot Payload—The Aerobot payload (Figure 7) is focused on three science areas: composition, meteorology, and geophysics. An **aerosol mass spectrometer (AMS)** measures both gas composition and aerosol/cloud composition, using dedicated inlets for each. Aerosols and cloud droplets entering the inlet pass through a **nephelometer**, a device which measures light scattered from the particles, so as to determine their shape, size, and refractive index (e.g., to distinguish sulfuric acid droplets from volcanic ash). Finally, astrobiological science is addressed by a dedicated **fluorimetric microscope (FM)**, which examines cloud droplets for minute traces of constituents associated with past or present life.

The Aerobot also carries a suite of **meteorological sensors (MET)**. These include **barometric pressure** and **air temperature** sensors, to examine the convective stability of the atmosphere and to provide context for other measurements. A **radiometer** measuring up- and downwelling fluxes in seven channels spanning the full solar and thermal spectral ranges assesses the role of radiative balance and its relation with cloud-level dynamics. The spectral channels of the Aerobot's radiometer overlap with those of the Lander and the LLISSE surface station's radiometer, enabling a coherent investigation of radiative processes throughout the Venus atmosphere. Vertical and horizontal **wind velocities** would be determined by tracking the trajectory of the Aerobot, utilizing the Aerobot's communication link with the Orbiter and SmallSats; tracking the Aerobot's position using ground-based telescopes (as was done for the Vega balloons) is another option to be studied. Accelerations and torques measured by an Inertial Measurement Unit (IMU) allow trajectory reconstruction between communications passes, and facilitate the study of turbulence and waves. Like the Vega balloons, the VFM Aerobot would carry a **wind sensor** in order to distinguish vertical winds from changes in balloon buoyancy; it allows characterization of turbulence down to temporal scales which are inaccessible just by tracking the Aerobot. The **MET** also includes a **radiation dosimeter** in order to quantify the ionizing radiation levels in the cloud layer. All the meteorological sensors share a common data handling unit, which enables low-rate continuous monitoring at 0.5 Hz and occasional scheduled and event-driven acquisition of high-rate data (triggered by events such as a strong updraft or a burst of turbulence).

Finally, the Aerobot carries payloads addressing the geophysics of the solid planet below. Tectonic and volcanic activity during the mission would be monitored by the **barometric pressure (infrasound) sensor**; the high density of the atmosphere at Venus's surface ensures efficient propagation of the ground motion from seismic waves created by venusquakes or other sources into the atmosphere, making Venus well-suited for infrasound

investigations of seismicity [23]. Finally, a **3-D fluxgate magnetometer (Mag)** would carry out a number of investigations, including a search for remanent crustal magnetism; constraints on core size and properties from magnetic field draping; and a search for magnetic emissions from lightning. To involve students in this mission, the **visible imager (VI)**, which has high heritage, takes images of the balloon, gondola and atmosphere every other day.

All instruments take data throughout the 60-day nominal mission except the **FM**, which takes seven discrete samples during that time.

5.4 Lander

The Lander (Figure 8) is designed to operate for at least 6 hours and up to 8 hours on the surface of Venus where the temperature of the atmosphere is $\sim 441^{\circ}\text{C}$ and the pressure is 76 bar at West Ovda. In order to land safely, the mechanical design needs to accommodate landing terrain uncertainty, thus the Lander is designed to land on a slope up to 30° and have clearance to accommodate a 0.5 m boulder beneath the sphere. Because landing is identified as the highest risk for the mission, the Lander includes a Terrain Relative Navigation (TRN) and a Hazard Avoidance (LHA) system. The system would be used to estimate the Lander's local relative position by comparing terrain maps from the initial VFM orbit and/or other prior missions, which would be loaded into memory prior to separation, with terrain measurements from navigation sensors (LIDAR, engineering camera, laser altimeter). The TRN-LHA assesses the hazards in the projected landing site and uses fans to move the Lander laterally to avoid landing on the hazard (e.g., a steep slope or large boulder).

5.4.1 Lander Payload—The Lander was designed to conduct scientific measurements both during descent through the atmosphere and on the surface. During descent a suite of instruments provides a profile of chemistry through measurements of gas and particles, and environmental conditions (see, e.g., Figure 1); these instruments would continue to operate on the surface providing data on the near-surface atmosphere. Additionally, the **Descent Imager (DI)** provides images of the landing region during approach to place the landing site in context, and would continue to operate on the surface to image the drill site. The LIDAR acts as part of the Terrain Relative Navigation and Landing Hazard Avoidance (TRN-LHA) system to help the lander land safely. The instrument suite for surface operation is designed to provide quantitative chemistry (major through trace elements), mineralogy, and images of the tessera surface. Data from this suite are ideal for making geologic interpretations of the landing site (rock type, weathering style, geologic context), and when paired with the orbital dataset, can place the landing site in a broad context. The instruments chosen for these operations are capable of providing quality data over a short timescale. The drill would acquire samples to be delivered internally to the **XFS** and **XRD** instruments. The **GRS** and **R-LIBS** instruments interrogate samples on the exterior of the Lander. The instrument suite used for measuring chemistry and mineralogy provides some level of redundancy in the event of an instrument failure (e.g., multiple instruments can measure major and minor elements) but still provides unique, complementary data when all instruments perform nominally (e.g., **GRS** provides a bulk analysis, while the **LIBS** instrument is able to sample the outer surface of rocks). The stand-alone **LLISSE** payload provides atmospheric data

over long durations at ambient Venus surface conditions and thus supplements observations made by instruments on other mission platforms.

5.5 SmallSats

The Venus Flagship Mission includes two SmallSats (Figure 9) that house the science instruments listed in Table 2 and communications coverage for the Aerobot and Lander. The twin satellite approach has heritage from numerous programs—MMS, THEMIS/ARTEMIS, Cluster, and Van Allen. All the instrumentation has a TRL of 6 or higher and has flight mission heritage—MAVEN, Parker Solar Probe, Juno, THEMIS, and STEREO. The SmallSats and a majority of their subsystems are expected to be procured commercially. The study focused on developing a concept that meets the data storage and communication requirements, including defining a feasible propulsion subsystem and has leveraged the ESCAPADE architecture and mission design with similar instruments that are on this SIMPLEX-II twinsat plasma mission to Mars.

5.5.1 SmallSat Payload—The two Venus Flagship Mission SmallSat payloads focus on understanding atmospheric evolution and dynamics via the interaction of the venusian atmosphere and the solar wind. To accomplish this science goal, the identical payloads consist of a suite of plasma and fields instrumentation (Figure 9), which furthers our understanding of the history of volatiles and liquid water on Venus, helping to determine if Venus was habitable and if Venus once hosted liquid water on its surface. A **Langmuir Probe (LP)** measures thermal ions and electrons, which helps characterize the spacecraft potential and wave activity. The **Ion Electrostatic Analyzer (ESA-i)** measures in situ suprathermal Venus atmospheric ions and solar wind ions to study how ions are accelerated from rest. ESA-i also measures minor species escape rates as well as precipitating ion flux (a proxy for sputtering). The **Electron Electrostatic Analyzer (ESA-e)** measures in situ solar wind electrons and photoelectrons with the goal of characterizing the solar wind and the magnetic field topology. The electron data aids in the search for evidence of a current or past magnetic field and assist in determining the atmospheric escape rates over a full solar cycle. The **Solar Energetic Particle Detector (SEPD)** measures the *in situ* solar energetic particles (protons and electrons) at high energies to characterize solar activity and solar transient events in the inner heliosphere. The **fluxgate magnetometer (Mag)** data would be used to characterize the magnetic field topology and strength as well as search for evidence of a past or current magnetic field. The plasma and fields data, in concert with other comparable instruments aboard the five assets, aids in understanding the history of the liquid water and volatiles on Venus, as well as the evolution of the solar wind interaction with Venus at 0.7 AU. The **Electric Fields Detector (E-FD)** can directly measure and map the electric fields that accelerate atmospheric plasma, contributing to wave activity, ionospheric dynamics and atmospheric escape. Finally, the **Extreme Ultraviolet (EUV)** detector aids in characterizing the solar wind conditions and determining the solar wind radiation in the ultraviolet. The suite of instruments aboard the two SmallSats provides the means to collect data simultaneously on both the day- and night-side as well as previously unsampled low altitude, southern latitudes over the course of their expected mission.

6 Technology Maturity

The majority of the VFM mission concept uses proven flight hardware. However, there are several areas where a technology maturity effort either enables the mission or significantly reduces mission risk. Both the Orbiter and SmallSats could be procured with little to no technology development. However, the Lander and Aerobot do require advances in specific technologies as well as some of the instruments. The main technology development is the landing Terrain Relative Navigation (TRN) and Landing Hazard Detection and Avoidance system (LHDA), which enables safe landing on the sloped tessera terrain. The three lowest TRL elements are:

1. **Lander – Integrated Terrain Relative Navigation (TRN) and Landing Hazard Detection and Avoidance (LHDA):** A high-level trade conducted as part of this study determined that the risk of landing safely could be significantly mitigated if a combination of a Terrain Relative Navigation and a Hazard Detection and Avoidance system was used with a divert system consisting of four fans. This system is estimated to be TRL 3. Development is needed for the motor and fans, terrain relative navigation and hazard avoidance algorithms.
2. **Aerobot – Balloon:** The variable-altitude Aerobot platform is currently TRL 4 but there is ongoing work at JPL to mature Venus variable-altitude balloons beyond TRL 4. Without the balloon inflating or operating as planned, the Aerobot would not float or circumnavigate Venus nor would it measure at multiple altitudes, and loss of scientific measurements would occur.
3. **Lander and Aerobot – Instruments and Sample Acquisition/Handling Systems:** Some instruments on these platforms are in need of TRL maturation for the appropriate environment they would encounter in either the constrained environment of the Lander pressure vessel or the clouds of Venus. Development is also needed for Lander and Aerobot sample ingestion systems that are at lower TRL. In some cases, field trials are needed to mature the techniques and concepts of operations. The effect on the mission if one of them is not developed in time varies, but much of the development is re-engineering heritage instruments rather than developing new ones.

7 Flight Mission Operations

Mission operations has three phases: 1) Launch and Cruise to Venus operations, 2) Venus Orbit, Atmosphere and Surface operations, 3) Aerobraking and Science Orbit operations. Venus Orbit, Atmosphere and Surface operations are divided into the operations performed by each element.

7.1 Launch and Cruise to Venus Operations

The VFM launches from Cape Canaveral, Florida, on a single Falcon 9 Heavy Expendable vehicle with 5m fairing on June 6, 2031. The launch window is 14 days long. There is a backup launch opportunity in June of 2032. The mission timeline is shown in Figure 3.

7.2 Venus Orbit, Atmosphere, and Surface Operations

7.2.1 Aerobot Operations—Five days after release by the Orbiter the Aerobot enters the venusian atmosphere on November 9, 2034, and begins the Entry, Descent, and Float (EDF) sequence shown in Figure 10. Once the Aerobot is fully deployed after atmospheric entry and descent, the Aerobot altitude is set to a nominal 56 km, where the temperature is $\sim 20^{\circ}\text{C}$. Carried by ambient winds, the Aerobot circumnavigates Venus every 5 days on average. During the first circumnavigation, the altitude control system would be used to maintain a near-constant altitude, and thus a near-constant temperature, for sensitive characterizations of atmospheric composition including the isotopic ratio of noble gases. In later circumnavigations, the Aerobot would be used to descend to 52 km, rise over 2 hours to 62 km altitude, and then descend again to the chosen float altitude, allowing quasi-vertical profiles of atmospheric parameters to be measured (Figure 4). One ascent is planned during each dayside pass and during nightside pass, for a total of 24 vertical profiles, distributed over all times of day and night, over the 60-day nominal mission duration. Altitude cycling can be stopped or reduced at night if desired to conserve power. The nominal mission lifetime for the Aerobot is 60 days. The Aerobot communicates with the SmallSats at least once a day to receive a new 4–5 day observation plan from the ground and to downlink science and health and safety data.

The aerobot's meteorological instrumentation (**MET**) would be powered on at all times, measuring continuously at sampling rates varying from 0.02 Hz (radiometer) to 60 Hz (infrasound sensor). A low-rate meteorological data set recorded at 0.2 Hz would be returned for the whole mission duration. To characterize turbulence, power spectra of meteorological parameters would be calculated onboard for each half hour interval. Onboard autonomous event detection would be performed to identify possible seismic, volcanic, lightning or other transient events; high-rate data from these candidate events would be downlinked to Earth. The **AMS-N** is powered on for seven minutes, once per hour on average (with a higher measurement cadence during vertical ascents). During each operational period after a 2-minute warm up period, the mass spectrometer measures composition of the atmosphere for five minutes, and then measures the composition of cloud/aerosol particles, which are separated from atmospheric gas using an aerodynamic aerosol separator. The incoming atmosphere passes through a **nephelometer** that optically interrogates cloud and aerosol particles entering the mass spectrometer to constrain their size, shape, and composition. The mass spectrometer data are integrated over 10 second periods in order to reduce data rate. After each operational period, the instrument remains in standby power until it is ready to ingest the next sample.

The **FM** characterizes 7 samples during the 60-day mission. Each time it is switched on, a pump draws atmosphere in and the sample is then pumped via a bypass line in the fluidic manifold to 1-of-7 particle-capture filter sets located on a rotatable sample-stage. A stepper-motor positions the stage and directs the sample to a set of particle-capture filters as it aligns each filter set beneath the microscope objective. The **MET** and **Mag** operate continuously during the day and night side of Venus. The meteorological suite is sampled at 0.2 Hz background, the radiometer at 0.02 Hz, including additional 20 high-rate events per day of 3 minutes each. Magnetometer data are down-sampled to 0.5 Hz, which is sufficient

for measurement of remanent magnetism and occasional high-rate data for investigations such as Schumann resonances characterization and the search for lightning. The **VI** takes 1 image for 1 minute every other day, on the day side, to show the balloon and cloudscapes, for student and public outreach purposes.

7.2.2 Lander Operations—On May 16, 2035, the Orbiter performs a Lander entry targeting maneuver, spins up to 3 rpm and deploys the lander with a separation velocity of 1 m/s. The Lander has two operational sub-phases: 1) Lander Entry, Descent, and Landing Operations and 2) Surface Operations.

7.2.2.1 Lander Entry, Descent, and Landing Operations: The Entry, Descent, and Landing sequence is shown in Figure 11. The Lander transmits data from entry through landing. Lander science operations commence upon entry into the Venus atmosphere and continue throughout descent to obtain a full meteorological and spectroscopic atmospheric profile. The **NMS** and **TLS** sample above the cloud tops, below the main cloud layers, in the lower atmosphere and just above the surface. The **Neph** and **AS** obtain samples at 100 m increments. The **GRS** records data continuously in passive mode throughout descent. Below 9 km the **DI** captures the landing area by virtue of the slow rotation (2–3 RPM) of the lander as it touches down. Safe landing is achieved through the use of TRN-LHA.

7.2.2.2 Lander Surface Operations: The **TLS** and **NMS** sample the atmosphere upon touchdown, at landing+1 hour and landing+2 hours. Passive **GRS** science continues on the surface for 30 minutes after landing, then the **Neutron Generator** turns onto begin active **GRS** measurements, which continue until the end of surface operations. The **AS** continues to take data after landing (see Figure 12). A full set of panoramic images is taken upon landing and at landing+60 minutes. Imaging is completed, and images uploaded, while the lander is in communication range of the Orbiter. The **R-LIBS** begins surface interrogation upon landing and continues until the end of surface science operations at landing+7 hours, although the sampling rate is reduced after landing+2 hours in order for the full lander data to be uploaded to a SmallSat.

Once on the surface and with the lander leveled, sample science can begin. The **DI** images the drill area prior to and post drilling. Drill deployment and sample acquisition to 5 cm depth commences after landing and takes approximately 15–20 minutes to acquire the 3 samples from three different depths. Each sample would be ingested into the Lander interior and placed in an individual cup for analyses by the **XFS** and **XRD**, which takes 20 and 15 minutes to do their respective analyses. The sample ingestion system facilitates direct interrogation by the **XFS** while in the sample ingestion cup. Once this analysis is complete, the sample drops into a hopper that feeds the **XRD**. While the diffractometer analyzes the first sample, the **XFS** analyzes the second. This parallel sample analysis continues until all 3 samples are analyzed by both X-Ray instruments. Full sample science operations are complete at landing+105 minutes.

LLISSE operates continuously on the surface for 60 days from landing, sending data at regular 6- hour intervals to the SmallSats to be received whenever they are overhead. Figure

12 illustrates the timeline established by using a set of specific instruments to represent the strawman payload.

7.2.3 SmallSat Operations—The SmallSats collect science data and serve as communication relays for the Aerobot and the Lander. They provide 8 hours of coverage for the Lander mission in combination with the Orbiter. In addition, they provide at least one contact daily to downlink LLISSE data during its 60-day mission. They also provide at least 1 contact per day to the Aerobot. Finally, the SmallSats themselves have a payload consisting of seven instruments (Table 2) that are powered on and collecting data continuously as downlink and support for the other VFM assets allow for their entire mission.

7.3 Orbiter Operations

7.3.1 Transitional Aerobraking Orbit—The Orbiter goes through a series of maneuvers to circularize the initial eccentric polar orbit after VOI into a circular polar orbit of 300 km altitude above the venusian surface (the science orbit). Circularization is achieved via aerobraking, where the periapsis is first lowered to ~130 km altitude so that the Venus atmosphere can dissipate orbital energy to facilitate lowering the apoapsis to an altitude of 300 km. During the actual mission, orbit determination is performed by the Mission Operations Center (MOC) as frequently as possible and the maneuver cadence is decided based on contact schedule and limitations on the allowable density corridor and maneuver plans are uploaded to the Orbiter. The aerobraking phase is expected to last ~2 years.

Most of the Orbiter instruments take advantage of the time spent in the aerobraking orbit to conduct valuable science operations and are continuously operating during the aerobraking process. However, in order to maintain the aerobraking drag profile, the **SAR** does not conduct science operations during aerobraking. The data generated by the payload in a typical aerobraking orbit, assuming 95% operational efficiency, is approximately 38 Gb, allowing for ample margin on data downlink capacity.

7.3.2 Circular Science Orbit—Once in the circular science orbit, the full Orbiter suite, excluding the **SAR**, continues to operate at 100% duty cycle (**NIR camera** only images the night side). The **S-mm** spectrometer is mounted on a rotation platform allowing for alternate views of the limb of the planet on successive orbits. The **SAR** surface coverage requirement of 5% at 30-m resolution and 0.5% at 10-m resolution results in a very low duty cycle, assuming wide-swath mode, yielding flexibility in the timing of the RADAR operations. At close Earth-Venus range, full data downlink can occur over several DSN passes; more data buffering is required if RADAR operations occur at longer ranges.

8 Summary

The exploration of Venus is long overdue. It has been over 40 years since the last US mission, Magellan. A reticence to study Venus comes from the perception that because of the high surface temperature it is uninhabitable, inactive and too difficult to explore. Yet the importance of Venus to the understanding of habitable terrestrial planets and the evolution of our solar system cannot be overstated. Due to its size and proximity, more

than any other known planet, Venus is essential to our understanding of the evolution and habitability of Earth-size planets throughout the galaxy. Over the past 60 years, more than 40 spacecraft have been launched to explore Venus with flybys, orbiters and in situ probes, balloons and landers, but none by the US since Magellan in 1989. Analysis of our current data underscore the critical role of Venus in planetary evolution. Our knowledge of planetary processes predicts that Venus, like Earth is now, was and may still be a habitable planet. Our limited knowledge of the inventory and history of volatiles recorded in the Venus atmosphere and surface represents a significant gap in our understanding of the acquisition of volatiles in the inner solar system. Studying Venus allows us to identify the mechanisms that operate together to produce and maintain habitable worlds like our own. As on Earth, the processes on Venus are dynamic and interrelated and their understanding requires multiple investigations throughout the Venus system. It is clearly time for Venus.

Habitability is at the heart of our Venus Flagship Mission (VFM) study, and we approach it through tracing the history of volatile elements on Venus. It is clear that Venus experienced a different volatile element history from the Earth, thus providing the only accessible example of one end-state of habitable Earth-size planets. Venus allows us to identify the mechanisms that operate together to produce and maintain habitable worlds like our own. This mission concept study successfully demonstrates the feasibility of a scientifically viable mission to explore the habitability of Venus using existing technologies and flight heritage from previous missions for the science payload and for the various mission elements. It should be noted, however, that many elements of this mission concept study have not been optimized, which likely results in an oversizing of various instruments and mission elements. Future studies and mission proposals could benefit from continuing development of instruments and Venus related technologies. Such development could increase the overall science return and improve confidence in the cost estimates.

Notably, VFM would provide many firsts (Table 3) and for the current concept, the estimated cost for Phases A-F was in the range of a flagship mission (\$3.7B, 2025 dollars). While technology maturation and engineering development of some subsystems is needed, no high-risk elements have been identified, and given the 50% margin provides a ~70% confidence level.

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Figure 1.
VFM scientific investigations on each platform illustrating scale and altitude coverage

Figure 2.

Illustration of the VFM flight system concept, which addresses the VFM goals, consists of an Orbiter, Aerobot, Lander and two SmallSats (not to scale)

Figure 3.
Overview of VFM mission design concept from launch to Lander entry and subsequent
Orbiter aerobraking

Figure 4.

The Aerobot has variable altitude capability, allowing characterization of different levels of the venusian cloud deck

Figure 5.
Illustration of the past and possible future solar cycles. The blue box is the nominal lifetime of the SmallSats.

Figure 6.
Illustration of the VFM Orbiter concept showing instrument complement

Figure 7.
Illustration of the Aerobot concept with instrument complement shown

Figure 8. Illustration of the VFM Lander concept (deployed) showing exterior features including instruments

Figure 9.
VFM SmallSat concept showing instrument complement

Figure 10.
Conceptual illustration of the Aerobot Entry, Descent, and Float Operational sequence

Figure 11.
Lander Entry, Descent and Landing Operations as a function of Time, t (in seconds).

Figure 12.
Lander Surface Operations of the Strawman Payload

Table 1.

Venus Flagship Mission Concept Science Objectives (condensed from [1])

VFM Science Objectives
Determine if Venus has ever hosted liquid water at the surface.
Identify and characterize the origins and reservoirs of Venus's volatiles today.
Place constraints on whether there are habitable environments on Venus today & search for organic materials.
Constrain the composition of the surface and chemical markers of past and present climate.
Determine if Venus shows evidence of a current or past plate tectonic regime.
Determine whether Venus is tectonically and volcanically active today.

Table 2.
Instruments on each of the VFM Platforms with color groupings showing their scientific focus

Lander	Aerobot	Orbiter	SmallSats
Neutral Mass Spectrometer (NMS)	Aerosol Mass Spectrometer with Nephelometer (AMS-N)	Synthetic Aperture Radar (SAR)	Magnetometer (Mag)
Tunable Laser Spectrometer (TLS)	Fluorimetric Microscope (FM)	Near IR Imager (NIR-I)	Electron electrostatic analyzer (ESA-e)
Atmospheric Structure Suite [P, T, Radiometer] (AS)	Meteorological suite (P, T, Radiometer, 3-d Wind Sensor Dosimeter) (MET)	Sub-mm Spectrometer (5-mm)	Ion electrostatic analyzer (ESA-i)
Descent NIR Imager (DI)	Visible Imager (student experiment) (VI)	Magnetometer (Mag)	Langmuir Probe (LP)
Nephelometer (Neph)	Magnetometer (Mag)	Ion Electrostatic Analyzer (ESA-i)	Electric Fields Detector (E-FD)
Neutron Generator/Gamma Ray Spectrometer (GRS)		Electron Electrostatic Analyzer (ESA-e)	Solar Energetic Particle Detector (SEPD)
X-Ray Diffractometer (XRD)		2 each Neutral Mass Spectrometer (NMS)	EUV Sensor (EUV)
Raman-LIBS Instrument (R-LIBS)			
Panoramic Camera (PC)			
X-ray Fluorescence Spectrometer (XFS)			
Long-Lived In-Situ Solar System Explorer (LLISSE)			

Instrument Key

- Atmospheric
- Mineralogy and Geology
- Magnetic Fields
- Particles
- Aerosols

Table 3.

Venus Flagship Mission Concepts provides major, unprecedented advancements of the state of knowledge for Venus.

The Venus Flagship Mission will provide major, unprecedented advancements in our understanding of the formation, evolution and habitability of terrestrial planets.	
<i>First</i> mission to trace volatile inventory, phase, movement, reservoirs and loss over Venus history	
<i>First</i> landing in tesserae thought to represent the oldest rocks on Venus	<i>First</i> measurement of mineralogy and precise geochemistry of tessera terrain
<i>First</i> inventory of all major atmospheric noble gases and their isotopes	<i>First</i> simultaneous multipoint measurements in Venus exosphere and ionosphere
<i>First</i> measurement of global surface composition from orbit	<i>First</i> measurement of seismicity and remanent magnetism of Venus
<i>First</i> measurements of lower atmosphere composition with modern, high-accuracy, high-resolution instruments	<i>First</i> simultaneous measurement of ion loss rates from the exosphere and thermosphere reservoirs
<i>First</i> co-located mapping of winds and composition in the mesosphere and thermosphere	<i>First</i> deployment of uncooled ambient temperature electronics to enable long life operation at the Venus surface