Long-duration Venus Lander for Seismic and Atmospheric Science

Tibor Kremic[1], Richard Ghail, Martha Gilmore, Gary Hunter, Walter Kiefer, Sanjay Limaye, Michael Pauken, Colin Wilson. [1]Correpsonding author contact info: Tibor.Kremic@nasa.gov

National Aeronautics and Space Administration, Glenn Research Center, Cleveland, Ohio 44135

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Abstract

An exciting and novel science mission concept called Seismic and Atmospheric Exploration of Venus (SAEVe) has been developed which enables a three-order magnitude increase in expected surface life (120 Earth days) over what has been achieved to date. This concept, if implemented, has the potential to enable significant new science investigations such as studying the seismicity of Venus and characterizing Venus near surface weather, energy balance and atmospheric chemical composition over time.

In addition to these important science contributions, SAEVe may be used as a critical pathfinder for more sophisticated landers in the future. For example, first order seismic measurements by SAEVe will allow future missions to deliver better seismometers and systems to support the yet unknown frequency and magnitude of Venus seismic events.

SAEVe is focused on science that can be realized with low data volume instruments that can operate at Venus temperatures over timescales of days to months. The envisioned mission architecture and operations maximize science while minimizing energy usage and physical size and mass. The entire SAEVe system, including its protective entry system and communication to

orbiter elements, is estimated to be around 45 kg and approximately 0.6 m diameter at the widest point of the aersohell. These features allow SAEVe to be relatively cost effective and be easily integrated onto a Venus orbiter mission.

The technologies needed to implement SAEVe are currently in development by several funded activities. Some component level work is ongoing under NASA's HOTTech program and both component and system level work that will enable the SAEVe concept is under development by the LLISSE project (Kremic, et al., 2017). LLISSE, which stands for Long Lived In situ Solar System Explorer, is a NASA project to develop a small Venus lander that will operate on the surface of Venus for 60 days and measure variations in meteorology, radiance, and atmospheric chemistry. LLISSE is developing a full-function engineering model of a Venus lander that contains essentially all the core capabilities of SAEVe thus greatly reducing the technology risk to its completion.

The SAEVe long duration Venus lander promises exciting new science and is an ideal complimentary element to many future Venus orbiter missions being proposed or planned today.

1 Introduction

A mission concept has been developed to address long standing science data needs related to Venus, and specifically at its surface. The mission concept, called Seismic and Atmospheric Exploration of Venus (SAEVe) is to deliver two landers to the surface of Venus, and have them return high value science for 120 days, which is over three orders magnitude longer than anything previously achieved (Williams, 2019). The science focus of SAEVe is seismometry and meteorology, long standing gaps in our data of Venus and measurements that are enabled only by long duration operations. The remarkable operating life of SAEVe is enabled by three key elements, 1) high temperature electronics and systems that operate without cooling at Venus surface conditions, 2) use of simple instrumentation and supporting avionics which can accomplish science goals with low volume of data, and 3) minimizing energy utilization through a novel operations approach.

The lander payload of the SAEVe mission concept is supported by a unique and innovative platform designed to operate at Venus surface conditions where temperatures are 460°C, pressure is over 90 bar, and reactive atmospheric chemistry is primarily composed of supercritical CO_2 with contains sulphur species and other reactive elements. Delivery to Venus is assumed to be by a Venus mission which includes an orbiter that serves as a data relay. The current SAEVe mission concept architecture focuses solely on the entry, descent and landed elements and assumes a nominal 24 h elliptical orbit for the orbiter (see Section 5.2).

We present an overview of the development of the SAEVe descent and landed mission concept, beginning with a review of the science objectives and traceability to overarching science goals defined by the Planetary Decadal survey (NRC, 2011), with specific measurements identified by the SAEVe science team. This is followed by discussion of the prioritized measurements and the instruments that can capture those measurements. We provide details of the entry and landing system concepts for the SAEVe mission. We also provide an assessment of the state of the art for technologies relevant to the SAEVe payload, entry, descent and landed elements, relative to readiness of each element. Finally, we provide a summary of ongoing funded work, and expected costs based on both internal and independent estimates. The orbiter architecture is not included in these studies, beyond costs for integration of the SAEVe delivery vessel to the orbiter vessel.

2 Science Objectives and Traceability

Due to its long life, the SAEVe mission concept is able to make two measurements that have not yet been made for Venus, and cannot be made with a short-lived (hours) lander: measurement of the seismicity of the planet and the composition and dynamics of the lower atmosphere *over time*. These measurements directly address some of the fundamental goals outlined in the National Research Council's Planetary Decadal Survey (for 2013-2022) (NRC, 2011), namely to "Understand the origin and diversity of the terrestrial planets," and "Understand the processes that control climate on Earth-like planets". SAEVe objectives also trace to specific scientific goals and objectives identified by the Venus Exploration Analysis Group (VEXAG) in their Goals, Objectives and Investigations Document, for example: III.A.Geologic Activity and III.A.Crust (VEXAF, Goals, Objectives and Investigations, 2019) . SAEVe focuses on unanswered questions in three areas, 1) crust and interior, 2) atmosphere, and 3) surface processes.

2.1 Crust and Interior Questions Targeted

Key open crust/interior questions that SAEVe will address include: How thick is the Venus crust and lithosphere? What is the composition of its crust? Is the heat loss from the interior by conduction through the crust, through volcanism or tectonism? Is there now, or has there ever been plate tectonics? There is mounting evidence for current volcanism (Smrekar, et al., 2010, Shalygin et al., 2015), but its frequency, scale, and magnitude are not known. Magellan data reveal signs of tectonic activity such as extensional fractures and wrinkle ridges and the presence of highlands. These features are indicative of a convecting mantle, yet the current level of tectonism is unknown. The Planetary Decadal Survey (NRC, 2011) question of "What are the major heat loss mechanisms associated dynamics of the cores and mantles?" is an example of an interior question that will be targeted by SAEVe.

2.2 Atmosphere Questions Targeted

Investigation of atmospheric dynamics and chemistry at the surface addresses the Planetary Decadal Survey (NRC, 2011) questions of: "Determine how solar energy drives atmospheric circulation, cloud formation and chemical cycles that define the current climate on the terrestrial planets," and "What are the key processes, reaction and chemical cycles controlling the chemistry of the middle, upper and lower atmosphere of Venus?"

One of the major mysteries about Venus is its rotation, both its direction and rate. The atmosphere is expected to influence the rotation rate on the short and long term through the exchange of momentum with the surface which changes the instantaneous rotation rate (Navarro et al., 2018). SAEVe will make regular pressure and temperature measurements to inform us about near surface heat fluxes due to local circulations such as slope or katabatic winds. While Venera 9,10 landers measured the wind speed with cup anemometers

(Avduevskii et al., 1977) and Venera 13,14 with acoustic anemometers (Ksanfomality et al., 1982), SAEVet will provide the first temporal data related to the possible momentum exchange between the atmosphere and the surface.

Surface rocks are a major sink for atmospheric species, yet we have only thermodynamic predictions for the species, style and kinetics of these reaction because of limited direct measurements of atmospheric and surface chemistry. To address this problem, SAEVe includes a range of chemical sensors (SO_x, H_2O, OCS, HCl, HF, NO, O_2 and HCN) that will provide new information about surface-atmosphere exchange. Variations in atmospheric chemistry may indicate transient inputs, such as volcanic gases.

2.3 Surface Process Questions Targeted

Venera lander images reveal Venus surfaces dominated by layered rocks and mobile sediment, but the origin of these materials is still open (e.g., Garvin et al., 1984). Major unresolved questions include: what is the distribution and particle sizes at the landing sites? Are salts and cements present on the surface that might indicate surface-atmosphere interactions? Are there any structures (e.g., faults) observable in the scene that may correlate with larger scale deformation? Are there landforms in the scene (e.g., dunes) that might indicate presence and transport of sediments? Investigation of the surface of Venus can address one of the fundamental objectives associated with the goal of understanding the origin and diversity of terrestrial planets listed in the Planetary Decadal Survey (NRC, 2011), to "Characterize planetary surfaces to understand how they are modified by geologic processes."

2.4 Outline of Science and Technology Objectives

The SAEVe team converted the fundamental science questions into mission objectives. These objectives and their traceability to Planetary Decadal Survey Report (NRC, 2011), are presented in Table 1.

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

Table 1. SAEVe Science Objectives and Traceability

3 Science Measurements Requirements and Instrument / Sensor Capabilities

To address the objectives described in Table 1, SAEVe will operate and take measurements in four modes: 1) Descent operations, 2) Short-term (~60 min) campaign directly after landing, 3) Long-term mode where measurements are taken at regular intervals of 2 min every 8 h for the life of the mission, and 4) 'Trigger mode' where SAEVe takes additional data when triggered by a seismic event. The measurements and science rationale for each mode are discussed below and summarized in Table 2 and Table 6.

3.1 Seismic Activity and Crustal Structure Measurements

The Mode 2 and Mode 3 seismic observations will provide 780 minutes of observations to characterize the background seismic noise level of Venus. Because the measurements are carried out throughout the course of the 120 day mission, the data will also provide engineering data on how the ambient Venus environment affects the seismometer over time. These precursor observations would be useful for planning a longer duration Venus seismic experiment. If sufficient battery power is available to transmit data from the vertical component of the seismometer continuously for a few weeks, then it might be possible to use ambient noise seismology techniques to determine the Rayleigh wave phase velocity spectrum and thus constrain both the thickness and composition of the crust in the region between the two landers (Shapiro et al., 2005).

As with the InSight Mission to Mars (Lognonné et al., 2019), the seismometer will be decoupled from the lander and covered with a wind screen to minimize any thermal or wind driven interactions. The optimum design for this mission is the adaptation of the short period 3-axis Micro-ElectroMechanic Sensor (MEMS) microseismometer provided by the Imperial College of London to the NASA InSight mission (Lognonné, 2018). The MEMS sensor must be adapted for the high temperature environment of Venus, and will have to be coupled with the high temperature electronics from NASA/GRC. The SAEVe seismometer has a detection threshold goal below 1 nano g on Venus. Although 10-100s of events are predicted to occur on Venus in an Earth year (Lorenz, 2012), the frequency of seismic activity on Venus is unknown. Due to this uncertainty, there is a possibility that more power will be needed to capture and transmit events. This may impact the 120 day life goal. This risk can be addressed by considering more conservative trigger thresholds, and/or varying trigger sensitivity over the lifetime of the mission. Increasing battery capacity is another straightforward approach.

3.2 Heat Flux Measurements

The geophysical heat flow at the Venus surface will be measured by a heat flux sensor that will be placed on the surface. Because the sensor will require at least 2 h to reach initial equilibrium, it would only be used during Mode 3. Therefore, heat flow measurements will be made every 8 h for the duration of the mission. This enables capturing the diurnal and atmosphere driven heat flow as well as the geothermal heat flow. Supporting meteorological sensor data will be used to distinguish between these two-flow variables. The instrument will measure heat flow with a magnitude between 10 mW to 1 W/m^2 at a resolution of 5 mW/m^2.

The heat flow sensor is a thermopile-based instrument (Figure 1) that generates a voltage proportional to the heat flux into it. This obviates the need for drilling and burial that traditional temperature gradient-based instruments require (Pauken et al., 2017), which allows for simple deployment. The instrument will be exposed to the full diurnal variation in heat flux caused by solar irradiance which is estimated to be ~ 3K (Lebonnois et al., 2018). Characterizing the diurnal variation to extract the internal flux requires at least six measurements covering more than half the diurnal period, with a precision of at least 5 mW m^{-2}. Over the 120 day operations of SAEVe, 360 heat flux measurements are expected which will be well beyond that minimum, and therefore, analysis suggests the diurnal effects can be accounted for allowing determination of the desired geothermal flux.

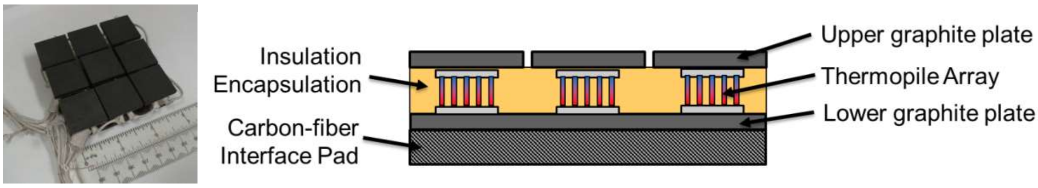

Figure 1. Heat Flow Sensor

The heat flux instrument will include supporting measurements such as surface skin temperature, and additional components and techniques will be used to help ascertain the thermal connection to the surface.

3.3 Meteorology and Chemical Chemistry Variability Measurements

SAEVe will capture meteorological data not only for the direct science it offers, but to support the seismic and heat flux measurements. Objectives include making measurements over a diurnal cycle (116 days) and capturing other possible variations in temperature, incident radiance, pressure, and wind speed/direction. To accomplish this, SAEVe requires the measurements of variations in air temperature at greater than 50 cm height above the surface and with resolution of 0.15K. Meteorology data, which includes solar radiance, is taken and returned during all measurement times except for seismic triggered operations. Some of the parameters, such as wind, are measured in seismic triggered mode (Mode 4) to support seismic measurements.

Table 2 provides some details on planned sensors. Temperature can be measured using a PtPt/Rh thermocouple sensitive up to 1500°C or by other approaches (Wrbanek and Fralick, 2006; Wrbanek et al., 2012), using inherent characteristics of the electronics themselves. Pressure and wind are measured using strain sensors using a silicon carbide (SiC) diaphragm and thin film sensors respectively (Okojie et al., 2014; Hunter, 2016). Radiance is measured using high temperature bolometers. The atmospheric chemistry multisensor array is based on resistors, electrochemical cells, and Schottky diodes as required to detect each of the species Hunter (2016). These are miniaturized and microfabricated (Figure 2) into arrays, typically 4-sides per array Chemical species sensors are designed to limit cross-sampling interference.

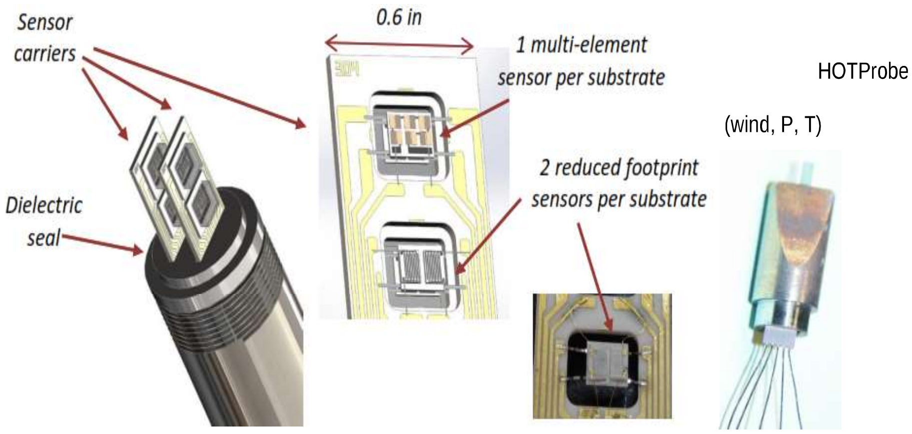

Figure 2. Atmospheric Chemistry Multisensor

3.4 Surface Morphology of the Landing Site

Each SAEVe station can carry two short duration cameras that operate at 800 nm wavelength. These cameras are commercial off the shelf (COTS) systems selected to achieve the morphology-science objectives described in Section 2. They are housed in temperature/pressure vessels to allow operation during descent operations and the short-term campaign of approximately 60 minutes after landing. One camera will look down to image the surface during descent and the second will be oriented off nadir to capture images of the seismic instrument and local morphology.

To assess landing site morphology, an image of the surface will be taken at ~5 km above the surface during descent and another image is taken at 400 m. The final landing site location will be visible in both these images assuming horizontal winds are ~ 1 m/s, which is consistent with prior data from Soviet landers (e.g., Ksanfomality et al., 1982)

In addition, two near field images will be taken at the surface. The first of these images of the surface serves two purposes: to examine the detailed morphology of the surface to look at rock, sediment type, and distribution as well as cements, and to examine the surface upon which the seismometer will be deployed in order to help assess surface contact. A second image of the same field will be taken after deployment of the seismometer so that it captures the seismometer and how it is resting on the surface.

The last (fifth) image to be taken will capture both the near field and the local horizon to look at morphology and topography of surface materials as well as landforms and structures in the scene.

The SAEVe imaging system is designed to consist of two COTS cube sat cameras. Each is located in its own thermally protected camera pod. Each pod/camera system weighs about 2.5 kg. Even considering the limited life of the camera systems, the most significant technical challenge is the data volume that will need to be transmitted. The communication system bandwidth (Section 4) limits the speed the images can be sent to the orbiter before the camera electronics fail. However, by limiting the resolution to 256×256 pixels at 8 bits greyscale, the five desired images can to be returned in the available time.

One concept for a camera pod and its contents is shown in Figure 3.

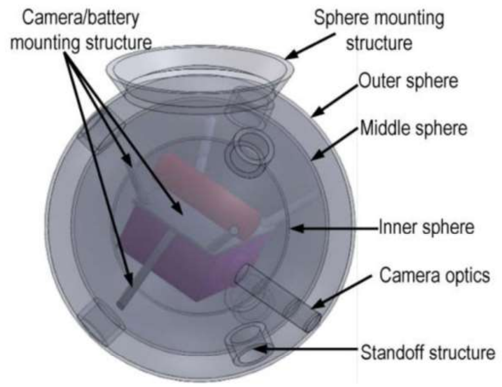

Figure 3. Camera Pod Concept

3.5 Measurements Summary

One additional instrument set is planned, although not described in detail because the concept and technology are at an early stage of development. This instrument is a set of sensors arranged in a certain pattern and tuned to maximize opportunity to “see” the sun. The objective is to determine if such an instrument could, over time, determine the sun’s path in the sky to provide lander orientation information. There is debate whether sun position can be determined. This instrument would allow answering that question with in-situ data, and allows for updating our models of the deep Venus atmosphere optical properties

Table 2 presents a summary of the characteristics of the various sensors and instruments planned for SAEVe that were described in this section. The technologies needed to implement the SAEVe concept are currently in development by several funded activities. Component level work is ongoing under NASA’s HOTTech program but most directly SAEVe relevant technologies are “under development” by the LLISSE project (Kremic, et al, 2017). LLISSE, which stands for Long Lived In situ Solar System Explorer, is a NASA project to develop a small Venus lander that will operate on the surface of Venus for 60 days capturing meteorology, radiance, and atmospheric chemistry variability. LLISSE is developing a full-function engineering model of a Venus lander with slightly fewer instruments and 60 day life goal, but otherwise is essentially all the core capabilities of SAEVe thus greatly reducing the technology risk to its completion. Table 2 reflects the development and targeted specifications ongoing in projects such as LLISSE.

Instrument/ Sensor	Description	Number of sensors used	Sensor input	Sensor output	Requirements				Notes
					Target n	Target max /frequency	Target accuracy ±	Target resolution	
Seismometer	Insight based MEMS sensor - 3 axis	1	Capacitance	Voltage	0.1 s period	100 s period	1 ng/rtHz	2 ng/rtHz	Vertical axis used for monitoring
Wind Sensor	Strain gage based	3	Voltage	Voltage	0.25 m/s	2.5 m/s	0.1 m/s	0.05 m/s	
Atmospheric Chemical Species	MEMS based Specie Abundance	1	Various	Voltage	Varies	Varies	Varies	Varies	Chemical species abundance measurement technique varies by specie.
Camera Pod	Thermally managed vessel with	2	Photons	Image Data	5 images, 1 radian FOV for descent	As time allows	1 mm spacial resolutio	256 x 256 image resolution	To minimize data volume, cameras will be monochromatic (~800nm)

Instrument/ Sensor	Description	Number of sensors used	Sensor input	Sensor output	Requirements				Notes
					Target n	Target max /frequency	Target accuracy ±	Target resolution	
	COTS cube-sat cameras						n at surface		
Heat Flux	Thermopile(s)	1	Thermal gradient	Voltage	10 mW/m2	1 W/m2	± 8 mW/m2	5 mW/m2	Also includes ability to ascertain thermal contact to surface and measure surface skin temp
Bolometer	Radiometer	2	Radiance	Voltage	4 W/m2	25 W/m2	2 W/m2	1 W/m2	Upward and downward
Sun Position	Solar radiance	4	Solar radiance	Voltage	TBD W/m2	TBD W/m2	TBD W/m2	TBD W/m2	Sun position locator to get coarse orientation info
Temperature Sensor	RTD in electronics	2	Current	Voltage	450 °C	492 °C	0.2 °C	0.15 °C	In body and on mast
Pressure	Resistive Capacitive	1	Voltage Capacitance	Voltage Voltage	80 bar	92 bar	1% full scale	0.6% Full scale	Only 1 of 2 versions will be used

Table 2. SAEVe Sensor/Instrument Summary Specifications

4 SAEVe Lander and Mission Design--a Simple Architecture

The SAEVe approach is to return important science via low-power instruments that generate low volumes of data. This philosophy is carried to the platform itself. A functional depiction and basic dimensions of the SAEVe lander concept was generated by the NASA Glenn COMPASS team and is shown in Figure 4.

With the exception of the contents within the camera pods all components for the lander utilize high temperature materials and electronics suitable for the expected temperature, pressure, and chemical conditions in transit, entry, and while operating on the surface. There is no cooling required anywhere on the lander. The instruments/sensing elements are located as needed around the lander as shown in Figure 5; their current technology readiness is listed later in Table 6.

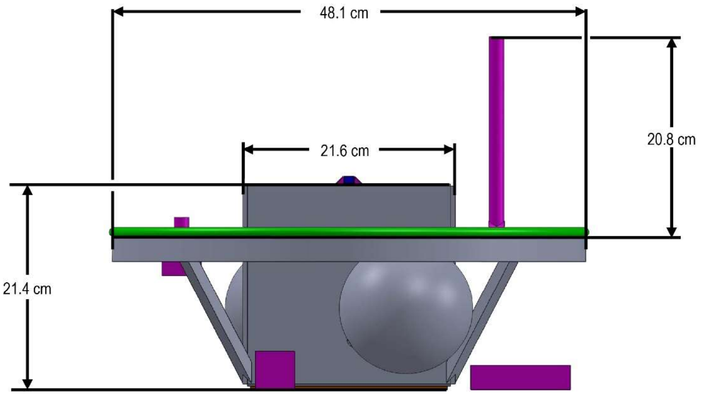

Figure 4. Basic Physical Dimensions

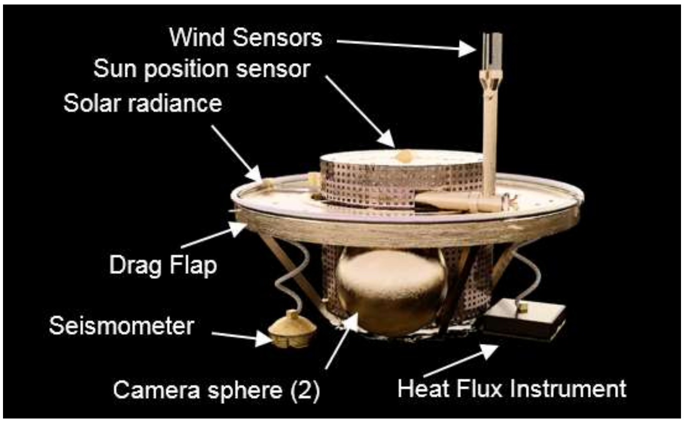

Figure 5. SAEVe Concept and Instrument Locations

There are only three simple moving parts associated with the lander, one of these is the wind sensor arm, and the other is the pin release mechanisms for the seismometer and heat flux instruments. At the appropriate time, the wind sensor arm hold-down releases, and the arm goes to its instrument's natural vertical position, and the other two drop the instruments the short distance between the drag flap and surface by the release pins that hold them in position.

Communication is handled via a VHF system operating at between 100 and 150 MHz, similar to what was done on previous Venus landers. Data rates will be 200 bps or higher. SAEVe has a transmit-only capability given its primary mission to provide unique, extended duration science data for the first time in a simple, low power platform that aims to maximize battery life. All operations to be conducted are predetermined before launch. Future iterations may consider some form of responsive interaction with the orbiter. An overall system diagram of SAEVe, its entry shell and the interface elements on the orbiter is shown in Figure 6. Only one camera sphere is shown for simplicity.

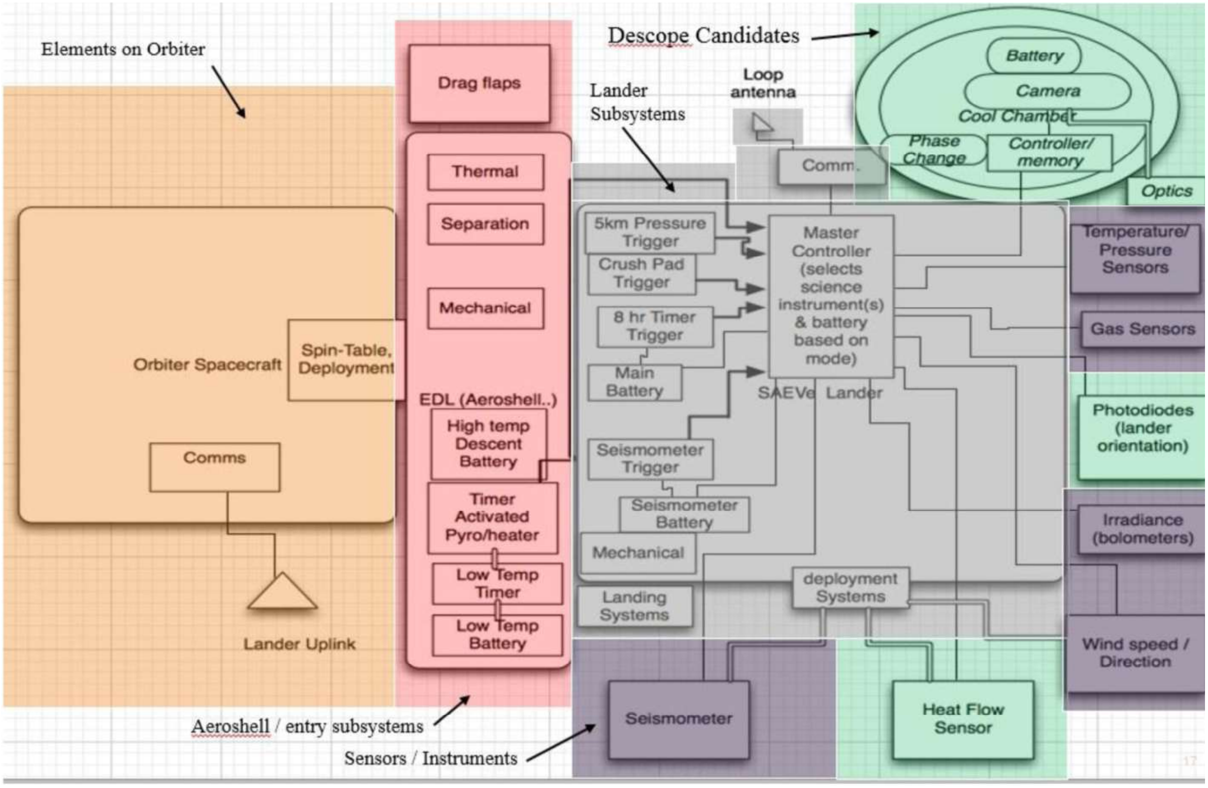

Figure 6. SAEVe's System Schematic

A high temperature battery [Landis, 2010, Burk, 1980] is assumed to power the lander for the desired life of SAEVe on Venus. The battery is not currently planned to be recharged, but has the energy required to execute the mission as shown in the energy usage summary in Table 3. There are promising capabilities being developed by NASA's HOTTech program that may have applicability for recharging a battery on Venus. These capabilities will be monitored, and resulting power availability and usage is shown in Table 3.

Energy Available	716 Wh	
Usage	**Energy**	
Descent from 5 km until Touchdown Energy	3 Wh (< 1%)	
Touchdown Energy:	5 Wh (< 1%)	
Science and Communication Energy	157 Wh (22%)	
Seismic Monitoring Energy	465 Wh (66%)	
Seismic Event Energy	81 Wh (11%)	
Total Power Available	716 Wh	

Table 3. Estimated battery energy available and its usage:

Cost estimates were developed for building and implementing the SAEVe mission as described. This was done via the COMPASS concurrent engineering design team. In addition, the resulting design, minus the cost estimate, was provided to The Aerospace Corporation to develop an independent cost estimate. The two estimates were assessed for differences, and a combined estimate was established. Integration costs and liens for the orbiter hardware are included, but development to get to Technical Readiness Level (TRL) 6 is not. The cost for implementing SAEVe with two stations outfitted as described is estimated to be approximately \$106M in FY17 dollars. Table 4 compares estimates for descope options, such as a single station or dual stations with descoped payloads that eliminate camera-pod and heat flux sensors. These estimates are based on both internal and independent estimates.

Estimates	Full Payload, 2 landers	Full Payload - Single Lander	Reduced Payload - Single Lander
Combined	\$106	\$87	\$71
Notes:	-In \$M dollars -Development to TRL-6 not included -Includes both subsystem growth margins and system margin wraps		

Table 4. Combined Cost Estimate

4.1 Mass Summary

Mass summary by subsystem and growth allowances are shown in Table 5. The mass budgets include subsystem growth as shown. An additional growth of 5 percent is carried at the system level. The total predicted mass of the base SAEVe concept with growth is 28.5 kg. The total predicted mass the orbiter would release would be approximately 45 kg.

SAEVe Master Equipment List (MEL)	Mass (kg)	Growth Allowance (%)	Growth Allowance (kg)	Mass plus Growth Allowance (kg)
Lander	18.08	25.0%	4.52	**22.59**
Science	1.21	30.0%	0.36	1.58
Attitude and Determine Control	0.00	0.0%	0.00	0.00
Command and Data Handling	0.38	30.0%	0.11	0.49
Communications and Tracking	0.51	30.0%	0.15	0.66
Electrical Power Subsystem	6.94	32.6%	2.26	9.20
Structures and Mechanisms	9.04	18.0%	1.63	10.67
EDL	13.68	18.5%	2.53	**16.21**
Electrical Power Subsystem	0.40	35.0%	0.14	0.54
Thermal Control (Non-Propellant)	13.3	18.0%	2.40	15.70
Camera-Sphere MEL (for 2 copies)	**Mass (kg)**	**Growth (%)**	**Growth (kg)**	**Mass with growth (kg)**
Cameras (2 pods)	5.02	17.7%	0.9	**5.91**
Science	0.18	30.0%	0.1	0.23
Thermal Control (Non-Propellant)	3.00	18.0%	0.5	3.6
Electrical Power Subsystem	0.05	36.7%	0.0	0.07
Structures and Mechanisms	1.80	15.6%	0.3	2.00

Table 5. Lander: SAEVE Total System, Including EDL

4.2 Mission design/architecture for delivery, entry, and landing

In the SAEVe Mission concept study we assume the landers would “ride along” with a Venus orbiter mission that would, along with its own science, provide relay capability for the 120 days that SAEVe would operate. The deployment, entry, and landing of SAEVe onto the Venus surface uses simple flight proven techniques and systems. The carrier spacecraft/orbiter will carry the SAEVe entry capsules (Figure 7) on spin tables. Using the spin tables, at the appropriate times, the carrier spacecraft will spin up and release the capsules. No other interactions/control is required from the carrier vehicle during launch, transit, and release (approximately 3 weeks before orbit entry). As the capsules enter the Venus orbit, the aeroshells will provide all entry functions, and communicate entry events via their own battery and avionics. The release of the capsules by the orbiter would be executed and timed to allow the orbiter to be in view of the landers and track/relay all the critical events associated with release and entry.

After successful entry of the 0.6 m diameter capsules, each will descend intact to approximately 6 km, at which time, the front and back shells separate. After the front shell is safely out of the way, the lander is then dropped from the back shell, and they naturally separate as they fall due to their mass and shape properties. There is no need for a parachute or other deceleration device on the landers. The thickening atmosphere, lander mass, and drag plate work together to safely bring the landers to the surface with a touchdown velocity of approximately 6 m/s. The lander commences science during the last phase of descent as described earlier. The total time for descent from entry is approximately 62 min (Figure 8). Section 5.2 describes the lander operations once it reaches the surface.

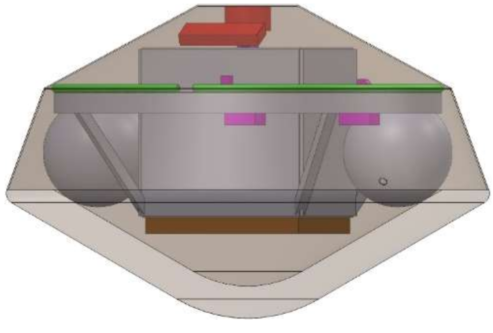

Figure 7. SAEVe Entry Capsule System

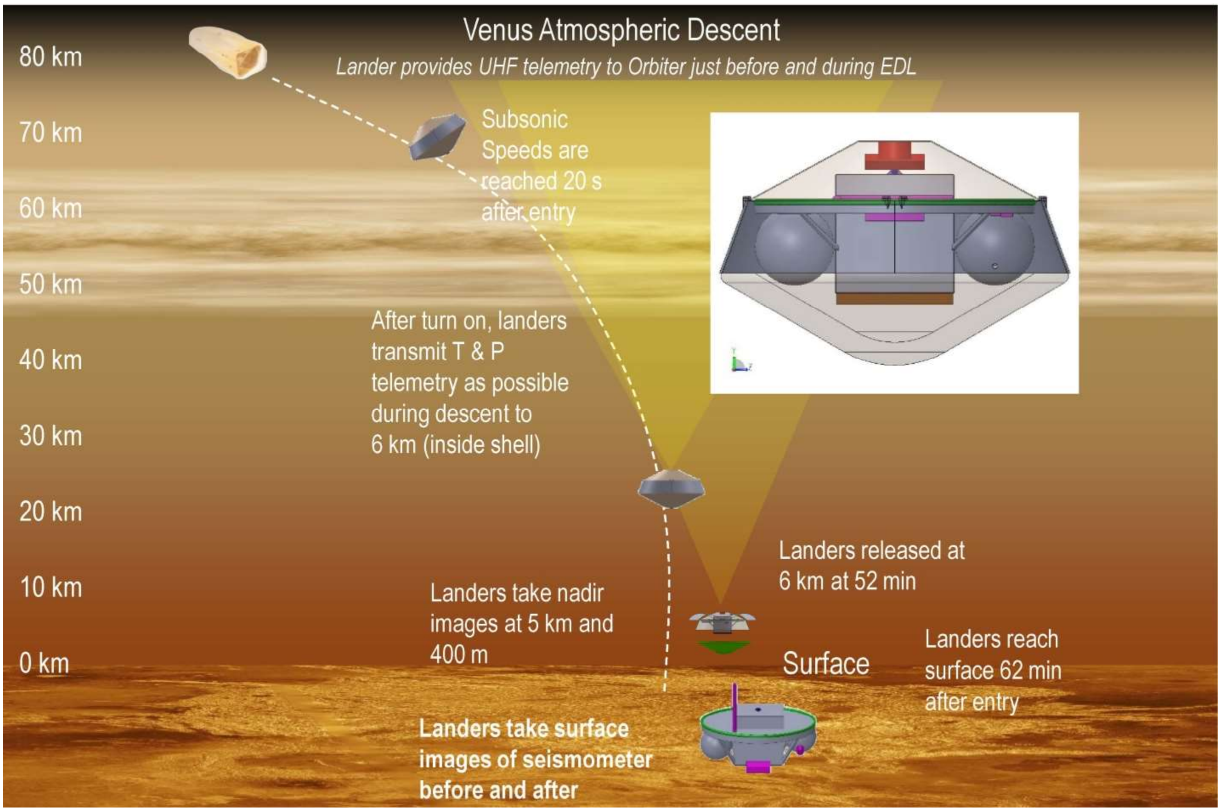

Figure 8. SAEVe Entry Sequence

5 Potential landing sites and rationale

Because SAEVe would be the first long-lived lander on the Venus surface, virtually any location on the surface would be an attractive science target. Among the instruments in the SAEVe payload, the seismometer would most benefit from a specifically targeted landing site. Geophysical observations suggest that the Beta Regio/Devana Chasma/Phoebe Regio and the Atla Regio regions are strongly supported by upwelling mantle plumes (Smrekar et al., 1997; Kiefer and Peterson, 2003; Kiefer and Swafford, 2006). This enhances the likelihood of current seismic activity in this region, which makes them high priority targets for a first Venus seismic mission. Because smooth landing sites are desired for safety, reasonable targets would be in the regional plains near Beta and Atla. Possible volcanic outgassing in either Beta or Atla could potentially be detected by the SAEVe atmospheric chemistry sensors. The high, mountainous plateau of Ishtar Terra has a crust that is relatively thick and possibly different in composition (more silica rich) than most of Venus's crust. This makes Ishtar an attractive target for seismic exploration, and the flat Lakshmi Planum plateau would provide a safe landing zone. It is recognized that if SAEVe is a ride-along secondary payload on another mission, then the SAEVe landing zone will be constrained by the orbital mechanics requirements of the primary payload. For this reason, we emphasize that landing sites anywhere on Venus would be scientifically valuable.

5.1 Assumptions on the Orbiter

Because SAEVe relies on a yet undefined orbiter to provide relay communications, some assumptions have been made. One assumption is the orbiter will be in a 24 h elliptical orbit (500 by 66,409 km) as seen with Venus Express (Venus Express Mission, 2009). This is a reasonable orbit assumption because of prior missions and future missions under consideration. If the orbit/landing is chosen such that the orbiter is over the lander at day 60 of the mission, a maximum possible communication link time of 23.5 h is available during each orbit (Figure 9).

The amount of contact time between the orbiter and lander will be determined by the actual orbit selected by the host mission and lander locations on the planet. Given the significant science SAEVe will contribute (as indicated in Table 1), it is expected that for a mission focused on advancing studies of Venus' seismicity and near-surface meteorology, the orbit will be chosen in part to help maximize the science return from SAEVe.

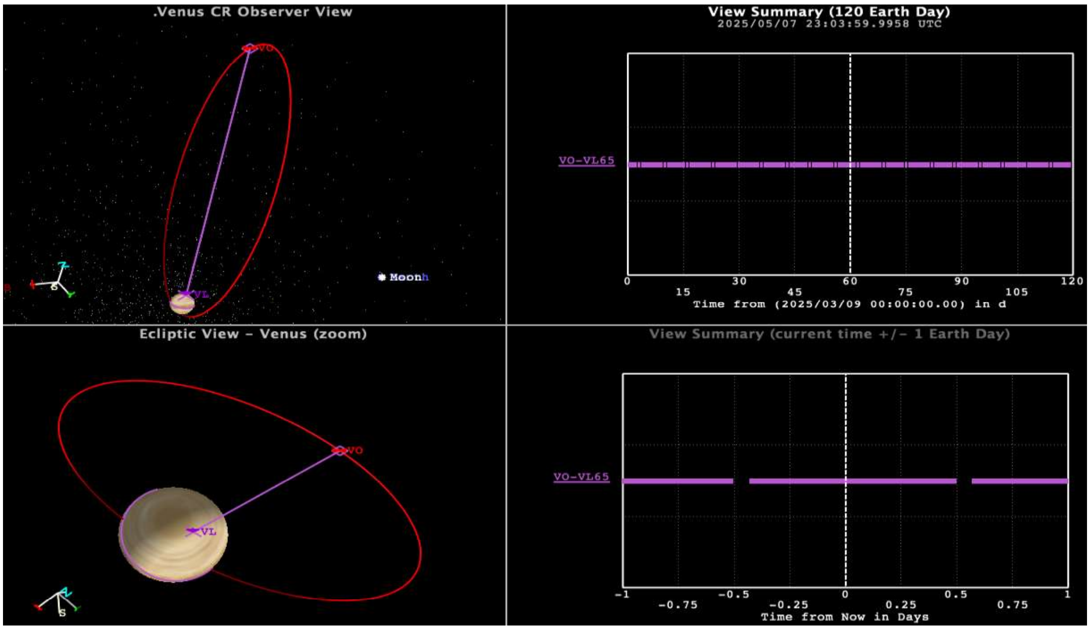

Figure 9. Assumed Orbit and Resulting Contact Times Between Lander and Orbiter

Because SAEVe relies on a simple periodic schedule to transmit data, the orbiter will know when to listen for the transmissions. This keeps operational uncertainty low so orbiter operations can be planned well ahead of time and any negative impacts to orbiter science minimized. It is understood that seismic events are transmitted as they occur and are unpredicted. Some events will not be captured by the orbiter, but given the number of events expected over 120 days earth orbits from models (Lorenz, 2012) and the potential for significant communication coverage, there is strong expectation that data from most of the detectable events can be returned.

5.2 Concept of Surface Operations

The surface operations plan is designed to achieve the science goals summarized in section 2.1 while optimizing resource usage. The most restrictive resource is energy stored in the battery. As soon as the lander is released from the aeroshell, it begins taking and transmitting images and the descent temperature, pressure, and chemistry measurements. A high priority is returning the five images that will be taken with the short duration cameras, see Figure 10. Five minutes will be allotted after touchdown for any dust to settle before the three images at the surface are taken. At the resolution planned, each image takes no more than 17 min to transmit.

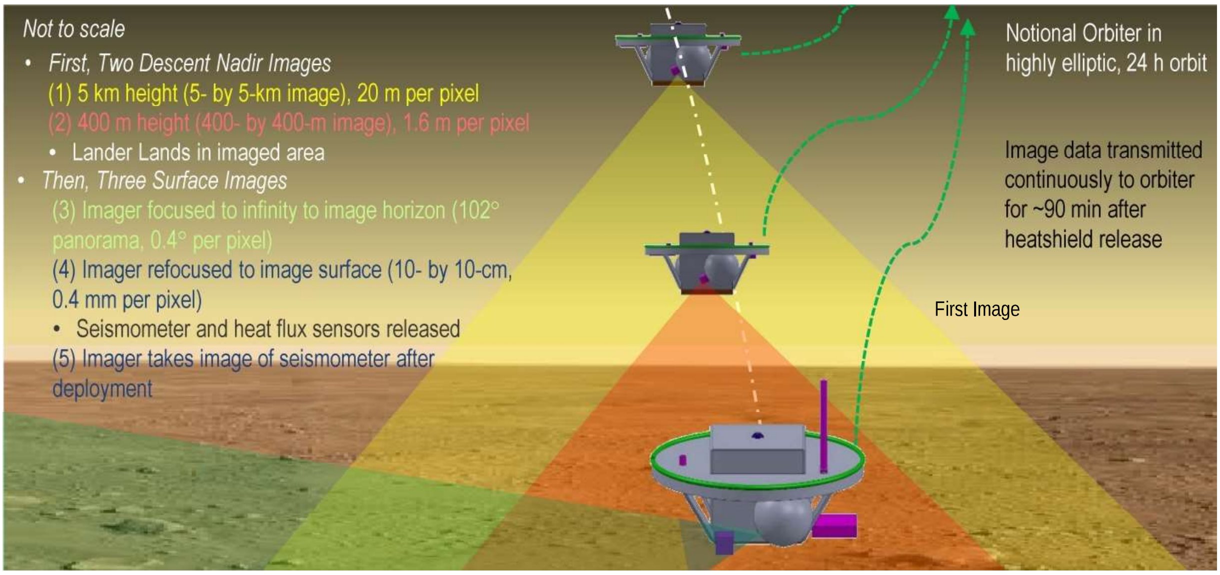

Figure 10. Summary of SAEVe Imaging Plan

The image data are written to onboard camera memory in the camera "pods," but these memory modules will stop operating once the temperature exceeds their operational range. This is predicted to happen 90 min after landing. By this time all images would have been transmitted.

Figure 11 portrays a notional timeline of science operations. All the payloads not already active (the seismometer, wind sensors, and heat flux sensor) are deployed shortly after landing. Once deployed, all instruments will be ready to start continuous transmitting (Mode 2), which begins as soon as the last image is transmitted. In this mode, all three seismometer axis and meteorological and atmospheric composition sensors acquire and transmit measurements for a 60 min period. This initial period allows first-order meteorological and seismic characterization of the landing site. All data are transmitted in near-real time. Heat flux measurement will not be taken at this time to ensure enough time elapses for all hardware to reach equilibrium conditions.

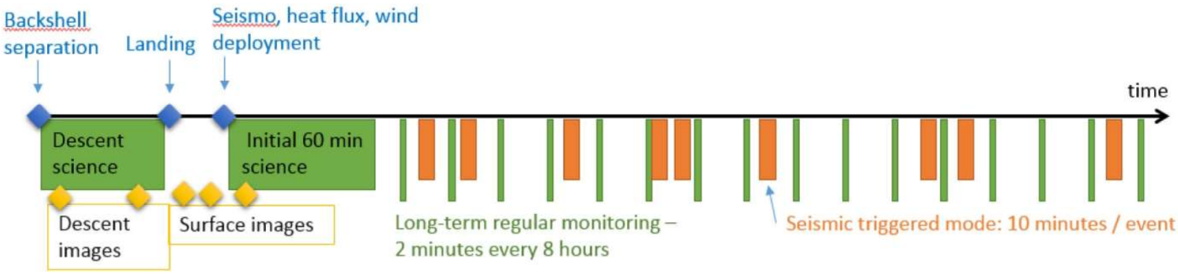

Figure 11. Notional Science Operations Timeline – Not To Scale

Operating Mode	Instruments Active
1 (Descent)	Cameras, Temperature, Pressure
2 (Short-term)	Cameras, Seismometer, Temperature, Pressure, Bolometer, Wind Sensors, Atmospheric Chemical Species Sensor
3 (Long-term)	Cameras, Seismometer, Temperature, Pressure, Bolometer, Wind Sensors, Atmospheric Chemical Species Sensor, Heat Flux, Sun Position
4 (Trigger)	Seismometer, Wind Sensors

Table 6. Operating Modes/Active Instruments

To characterize the variation of parameters over one solar day (118 Earth days), after mode 2 is complete, SAEVe enters a low power normal operations mode (Mode 3). In this mode, the probe wakes up once every 8 h and acquires 2 min of data. The data obtained in this mode are timed to enable the extended operating life and to meet science requirements for the nature of the measurements taken. Data are, again, transmitted in near-real time.

In normal long duration operations mode, the seismometer will be continuously on and “listening” for an event. As described earlier, in this mode the vertical-axis seismometer is monitored by a low power circuit; if a threshold criterion is exceeded, then the lander will start acquiring and transmitting seismic data.

The threshold criterion used to trigger seismic data collection will be carefully defined, so as to avoid too frequent or too infrequent triggers. The energy budget allows for 50 seismic events to be recorded during the 120-day nominal mission. As shown in Figure 6, there is a separate battery for seismometer operations. The purpose of this is to ensure that an unexpected large number of events, due to high levels of seismic activity or undetected wind triggers, do not impact the 120 day meteorology and heat flux related science objectives of the mission.

6 Technical Readiness

The SAEVe lander concept takes advantage of ongoing technology and system developments. Most notably, many of the capabilities SAEVe requires to realize its science goals are being developed and or proven through the ongoing Long-Lived In-situ Solar System Explorer (LLISSE) project (Kremic et al., 2017). The basic aspects of the SAEVe lander are similar to LLISSE and key capabilities (e.g., battery, most sensors, and communication system) will be developed and demonstrated in Venus simulated environments as part of LLISSE development. In order to understand the technical readiness of many of SAEVe subsystems and instruments, progress on the LLISSE project can be assessed. One then needs to assess the technical readiness of the remaining specific technology components used on SAEVe that are not a part of LLISSE. Table 7 provides a summary of the key technologies on SAEVe, and reflects where (LLISSE or another project) work is ongoing, if at all.

Technology	Current TRL	Estimated to be at TRL 6	Funding Source: Ongoing (O) (to TRL 6) and Potential (P)
Electronic circuits (SiC): sensors and data handling	4-5	2021	LLISSE (O)
Electronic circuits (SiC): power management	3-4	2021	LLISSE (O)
Communications (100 MHz)	3-4	2021	LLISSE (O)
Wind Sensor	4	2021	LLISSE (O)
Temperature Sensor	6	2021	LLISSE (O)
Pressure Sensor	4-5	2021	LLISSE (O)
Chemical Sensors	5	2021	LLISSE/HOTTech (O)
LLISSE Bolometer	3-4	2021	LLISSE (O)
Seismometer	3	TBD	LLISSE (O) and possibly Maturation of Instruments for Solar System Exploration (MaTISSE) (P)

Technology	Current TRL	Estimated to be at TRL 6	Funding Source: Ongoing (O) (to TRL 6) and Potential (P)
Heat Flux Sensor	3-4	TBD	Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) (O)—MaTISSE
Camera / imaging System	3-4	TBD	Rocket University (O)--MaTISSE if needed
Solar Radiance	4	2021	LLISSE (O)
High-Temperature Battery	3-4	2021	LLISSE (O) and HOTTech (O)
Entry Shell	6	Complete	Heatshield for Extreme Entry Environment Technology (HEEET)--Will need specific mission design

Table 7. Technology Readiness for Instrument and Critical Subsystems

The TRLs and dates are estimates and meant to provide a relative measure of the maturity of the overall SAEVe system. As with all estimates of future events, they are subject to funding and technical progress. Because specific mission or launch details are not available, one cannot determine certain parameters (e.g., vibration levels) necessary to demonstrate complete readiness to TRL 6. Therefore, for purposes of this assessment, TRL 6 is based on ability to meet goals of mission life at Venus surface temperature, pressure and atmospheric chemistry. These objectives are the drivers for a Venus surface mission, and therefore, is a reasonable metric for this paper.

7 Conclusions

SAEVe capitalizes on 1) the latest developments in high temperature sensors and electronics; 2) carefully selected and focused science objectives that follow a theme of temporal based science achievable with low volumes of data and 3) a novel operations approach to achieve its objectives. The innovative combination of these three elements will allow SAEVe to operate on the surface of Venus for a full solar day (~120 days, as opposed to ~ 2 h, as has been done to date). It will return science that helps us start tackling important science questions including: 1) seismic activity 2) crust thickness and composition, 3) meteorology and its potential local solar time variability, 4) momentum exchange between the atmosphere and planet, which helps get at superrotation, 5) chemical variability (relative to local solar time or otherwise), 6) energy balance at the surface, and 7) morphology.

This baseline mission can be realized with the two landers deployed 300 to 800 km apart. The two independent cost estimates for this novel mission architecture and concept predict that SAEVe will cost $106M.

As with any mission concept there are risks. The most significant is that we have little knowledge of Venus' seismic activity. The frequency and magnitude may be far different than anticipated. This would impact how long seismic measurements can be taken, or may result in not capturing events. This risk will be true for any mission. In many ways, SAEVe is an ideal mission to resolve this environmental issue. SAEVe will provide the data needed to design and plan future missions

One of the factors that support the possibility of a future SAEVe mission is that almost all the technology developments that are needed to realize SAEVe science objectives are in work. For example, the power, electronics, communication systems, and structure required by SAEVe are already in development with plans to demonstrate some level of performance at Venus conditions. The same is true for most of the sensors. The heat flux and seismometer have had some development, although for these two instruments, their current funding does not cover development to TRL 6.

SAEVe is an exciting mission that offers the potential for addressing long-standing science questions in a unique and innovative way. Benefits are: low relative cost, ease of integration onto a Venus orbiter mission, novel science, and serving as a pathfinder for understanding the Venus surface and interior. This will allow even more sophisticated future landers to be successful with their objectives.

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