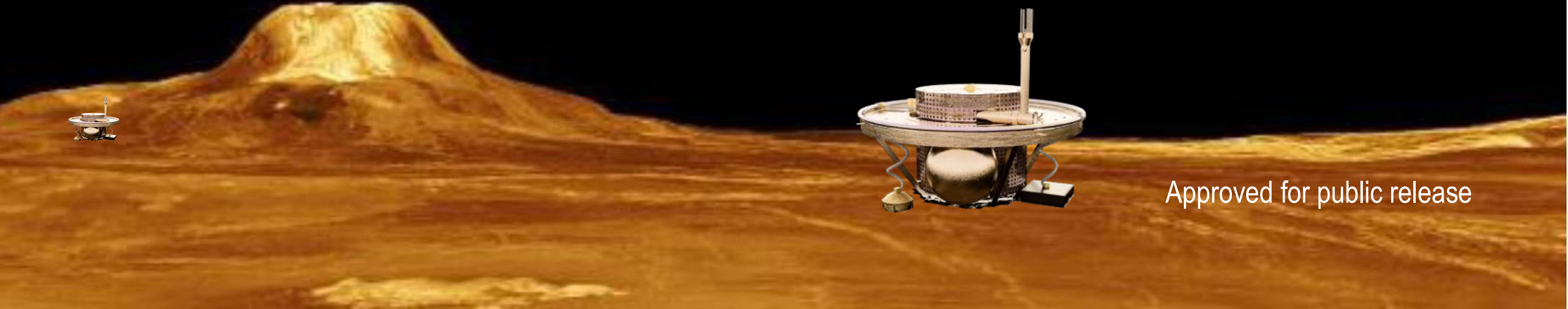
Seismic and Atmospheric Exploration of Venus (SAEVe) Final Report

June 25, 2018



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Seismic and Atmospheric Exploration of Venus (SAEVe)
Final Report

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1.0 EXECUTIVE SUMMARY

The Seismic and Atmospheric Exploration of Venus (SAEVe) is a mission concept 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*. The science implemented by SAEVe is focused on seismometry and temporal meteorology, long standing gaps in our data on Venus and measurements enabled only by long duration operations. Table 1 presents the science objectives targeted by SAEVe. Figure 1 illustrates the SAEVe lander concept and basic dimensions.

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 with emphasis on low data volume instruments and sensors, and 3) minimizing energy utilization through a novel operations approach. Integrating these elements into an innovative mission concept allows SAEVe to return high-value science while meeting study objectives.

Each SAEVe lander will weigh approximately 25 kg (~ 40 kg together with aeroshell, Figure 2) and will carry a suite of synergistic instruments and sensors. **The instruments in priority order are: seismometer, meteorology suite (which includes temperature, pressure, 2 or 3 dimension wind speed and direction, atmospheric chemical species abundances, and incident and reflected solar radiance sensors), a heat flux instrument, and finally an imaging package consisting of two cube sat cameras which will operate a short time at the beginning of the mission.** A sun position sensor set is also included as a demonstration of a potential simple technique to determine orientation of the lander relative to the surface.

Table 1. SAEVe Science Traceability

Decadal Survey Goals	SAEVe Science Objectives	Measurements	Instrument Requirements
A) Characterize planetary interiors	1) Determine if Venus is currently active, characterize the rate and style of seismic activity	Measure seismic waveform of seismic waves Concurrent wind data at time of seismic measurement	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

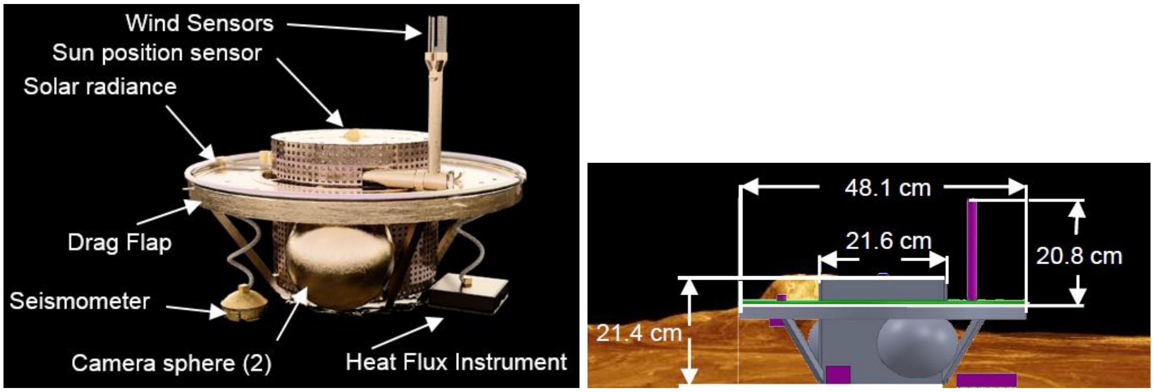


Figure 1. SAEVe Lander Concept with Subset of Instruments and Basic Dimensions

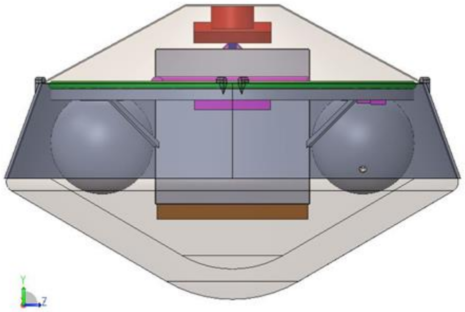


Figure 2. SAEVe in its aeroshell

SAEVe is assumed to be delivered to Venus as a secondary payload on a Venus orbiting mission. Since a specific orbiter and orbit is not available at this time, the team relied on some assumptions which are consistent with prior or proposed Venus missions. Basic assumptions are that we will be transmitting to an orbiter that is in a 24 h or shorter orbit period and that the orbiter has an enough space to carry the SAEVe entry shell / lander on a spin table and will release it as it approaches Venus. SAEVe will rely on the orbiter to capture transmitted data and relay it to Earth. Science and engineering data from the lander will be transmitted periodically at data rates of 200 bps or better between 100 and 150 MHz so the orbiter would need to carry the appropriate receiving antenna / hardware.

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

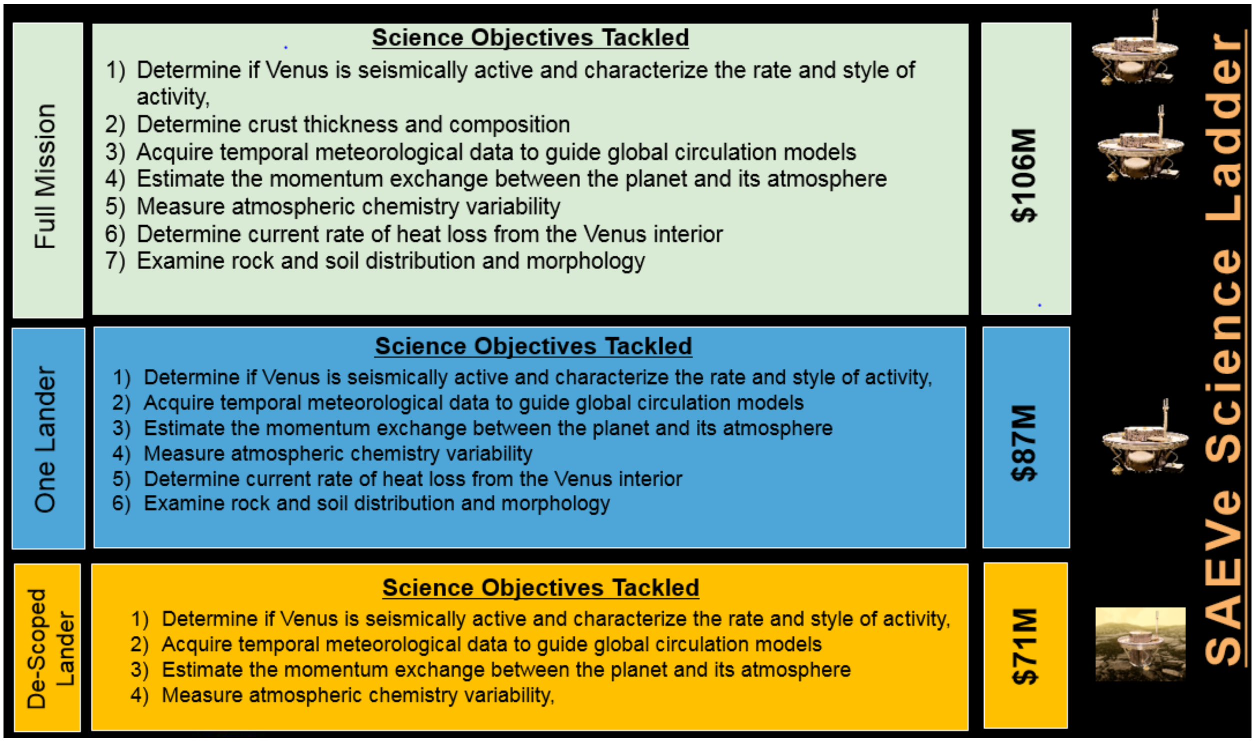
After touchdown an image supporting morphology and seismometer coupling is taken. The seismometer and heat flux instruments are dropped to the surface and the remaining images are taken and transmitted. Once all images are returned, all the other instruments begin operating and SAEVe transmits data for up to 1 h continually. After this initial period SAEVe goes into its nominal operating mode where it turns on and collects / transmits all instrument data for 2 min every 8 h. At all times, SAEVe will be monitoring the vertical axis of the seismometer. This will serves as a fast trigger so if an event of certain magnitude is detected, it turns on within 100 ms and begins transmitting data from all three axis of the seismometer, as well as wind and pressure data, continually for 10 min.

The particulars of the orbit influence the amount of contact time and therefore how many events are expected to be captured but, in ideal conditions the orbiter could be in view around 90% of the time. Undoubtedly, contact time will not be that high so some transmissions and seismic events may be missed but a significant fraction will be returned successfully over the 120 Earth days of operations.

SAEVe allows for easy scaling to address cost, mass, or other constraints. The mission including two copies of landers/aeroshells is estimated to cost $106M not including reserves and development of technologies to Technology Readiness Level (TRL) 6. Figure 3 shows that the second identical copy of SAEVe is expected to cost ~$19M. If desired, this can easily be descoped from the mission although this would reduce any potential insight into seismic event location and interior structure. A further descope could be the removal of the short-lived camera spheres. This saves some costs and mass for a lander. Figure 3 summarizes cost estimates based on mission architecture.

SAEVe leverages recent technology developments. The team explored the current technology state of all relevant elements. The results of that assessment are presented in Table 2. A notable take away from Table 2 is that most technologies are in development and funded to a level that could allow SAEVe to be picked up by a mission in the early to mid-2020s and launch in the mid to late 2020s, depending on the instrument suite desired. Since specific mission needs are not known, TRL 6 in Table 2 refers to only to demonstration of performance and life in Venus surface conditions.

SAEVe is an exciting mission that will return unique compelling science from the surface of Venus. It will operate over three orders of magnitude longer than anything previously for a fraction of the cost. It will not only provide valuable new data on our nearest planet but also serve as technology pathfinder for larger and more capable Venus surface missions in the future.



Science Objectives Tackled

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

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Figure 3. SAEVe Cost vs Science Ladder

Table 2. Technology Readiness Assessment Summary

Technology	Current TRL	Estimated to be at TRL 6	Funding Source: Ongoing (O to TRL 5-6) and Potential (P)
Electronic circuits (SiC): sensors and data handling	4-5	Aug. 2019	LLISSE (O)
Electronic circuits (SiC): power management	3-4	Sept. 2021	LLISSE (O)
Communications (100 MHz)	3-4	Sept. 2021	LLISSE (O)
Wind Sensor	4	Aug. 2019	LLISSE (O)
Temperature Sensor	4-5	Aug. 2019	LLISSE (O)
Pressure Sensor	4-5	Aug. 2019	LLISSE (O)
Chemical Sensors	5	Aug. 2019	LLISSE/HOTTech (O)
Bolometers	3-4	Sept. 2021	LLISSE (O)
Seismometer	3	TBD	LISSE (O) and possibly MaTISSE (P)
Heat Flux Sensor	3-4	TBD	PICASSO (O) - MaTISSE
Camera / imaging System	3-4	Sept. 2020	Rocket University (O) – MaTISSE if needed
Solar Radiance	3-4	TBD	MaTISSE (P)
High-Temp Battery	3	Aug. 2019	LLISSE and HOTTech (O)
Entry Shell	4-5	TBD	HEET – need specific SAEVe design

2.0 LEVEL 1 SCIENCE OBJECTIVES AND TRACEABILITY

2.1 SCIENCE QUESTIONS

Venus and Earth are of similar size, but have diverged dramatically in terms of their geologic and atmospheric evolution. Due to its long life, the SAEVe mission 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 Planetary Decadal Survey, namely to “Understand the origin and diversity of the terrestrial planets” and “Understand the processes that control climate on Earth-like planets”.

2.1.1 Status and Major Unanswered Question About the Interior

Venus has a similar size, mass and location in the solar system to Earth but almost nothing is known about its interior, other than that it has a very slow rotation (close to its orbital period around the Sun) and no magnetic field. Key remaining questions 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 [1,2], but its frequency, scale, and severity it is not known. Magellan data reveal signs of tectonic activity such as extension fractures and wrinkle ridges and the presence of highlands. These features are indicative of a convecting mantle yet currently Venus does not have a magnetic field. Another consequence of the similarity in size of Venus and Earth is that, if the amount of heat producing elements are similar, Venus would have the same heat flow as Earth. However, different tectonic styles may lead to divergence, e.g., a thicker lithosphere at Venus would reduce the heat flow and may indicate a more stagnant lid state. Investigation of the interior of Venus can address the Decadal Survey question of “What are the major heat loss mechanisms associated dynamics of the cores and mantles?”

2.1.2 Status and Major Unanswered Questions About the Atmosphere

Investigation of atmospheric dynamics and chemistry at the surface addresses the Decadal Survey 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 short and long term through the exchange of momentum with the surface which changes the instantaneous rotation rate [3]. SAEVe can address the rotation rate by measuring the near surface wind speed and direction over the duration of its mission that will provide the first indication of the sense of possible momentum exchange between the atmosphere and the surface one or two locations on Venus. For a global measure, such measurements need to be made at all latitudes for an estimate of the net exchange and its variations. The wind measurements are also needed to filter out the wind influenced noise in the seismometer data.

SAEVe will also make pressure and temperature measurements to inform us about near surface heat fluxes due to local circulations such as slope or katabatic winds. The chemical sensors (SOx, H_2O, OCS, HCl, HF, NO, O_2 and HCN) will provide new information about surface-atmosphere exchange and chemical changes if any.

2.1.3 Status and Major Unanswered Questions About Surface Processes

The four Venera landers that recorded panoramas reveal surfaces dominated by clastic rocks and mobile sediment; reprocessed Magellan data suggest that sedimentary rocks may cover almost half the Venus surface, primarily in the plains [4]. 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 the Decadal Survey question of "Characterize planetary surfaces to understand how they are modified by geologic processes."

2.2 SCIENCE OBJECTIVES

The SAEVe long-lived *in situ* architecture provides a novel and unique opportunity to address fundamental questions about Venus.

1. Determine if Venus is currently active, characterize the rate and style of seismic activity
2. Determine the thickness and composition of the crust and lithosphere
3. Acquire temporal data to update global circulation models from near surface measurements
4. Estimate momentum exchange between the surface and the atmosphere
5. Determine the key atmospheric species at the surface over time
6. Determine the current rate of energy loss at the Venus surface
7. Determine the morphology of the local landing site(s)

2.3 SCIENCE REQUIREMENTS

To address these science objectives, SAEVe will operate in four modes: 1) Descent operations which includes imaging, 2) Upon landing there will be a short-term campaign where the remaining images will be captured and returned. After the images are returned all the high temperature instruments will be turned on and operate continually for approximately 60 min, 3) After the short term campaign, the lander will operation in a long-term mode where measurements are taken at regular intervals. The current plan is to operate and transmit for 2 min every 8 h. In between those intervals the seismometer operates in 'trigger mode' where it takes data when triggered by a seismic event. The measurements and rationale for each mode are offered below.

2.3.1 Seismic Activity and Crustal Structure

The baseline measurement assumes two stations each with a 3-axis seismometer measuring a period range from 0.1 to 100 s. This allows the determination of the azimuth of the epicenter and the determination of source position and of crustal structure (seismic velocity vs. depth). The stations will be between 300 and 800 km apart. During the short-term campaign, the seismometer(s) would be on continuously transmitting any seismic events and measuring the ambient noise of the planet. In normal operations all instruments are operated periodically, every 2 min every 8 h. In between these operating periods SAEVe will be monitoring the vertical axis of the seismometer. At some to be defined threshold, perhaps around a magnitude 5 event, the trigger is activated and within 100 ms, all three axis begin transmitting data. Wind speed data are also transmitted at the same sampling frequency. Data capture and transmission continues for 10 min.

There are opportunities to extend lander life or conserve power with the seismometer. For example, a single axis seismometer could be used as a science floor. This would still address the presence and rate of seismic events and serve as a starting point for future missions.

Measurements by the Viking Lander have shown that it is critical to decouple wind noise from the seismic signal. To this end, we will measure the 2-D horizontal wind velocity at the same sampling rate as the seismometer. The seismometer will be decoupled from the lander and covered with a wind screen to minimize any thermal or wind driven interactions.

2.3.2 Meteorology, Global Circulation Models and Atmospheric Superrotation

SAEVe will capture meteorological data not only for the direct science it offers but also to support the seismic heat flux measurements. Objectives include understanding diurnal and other variations in temperature, incident radiance, pressure, and wind speed/direction. To accomplish this SAEVe requires measurements of variations in air temperature at greater than 50 cm above the surface and with resolution of 0.15 K. In summary, meteorology data, which includes radiance, is returned for 60 min during the short campaign and for 2 min every 8 h. The general sampling frequency is 1 Hz. For the first 60 min and when supporting seismometer measurements, the wind speeds are sampled at higher rates to characterize atmospheric turbulence.

The meteorology suite will also take measurements the last 5 km during the initial descent.

2.3.3 Atmospheric Chemistry

Measurements of spatial and temporal variation in trace gases will be taken in order to constrain active volcanism and/or active surface/atmosphere exchange. Trace gases including H_2O, SO_2, SOx, CO, HF, HCl, and HCN are all species known to be associated with active volcanism. SAEVe will measure trace gases including H_2O, OCS, SO_x, CO, NO, O_2, which are possibly important players in surface-atmosphere buffering reactions. At the surface, data will be collected continuously for 60 min during the short-term campaign and for 2 min every 8 h consistent with the other sensors and instruments.

SAEVe will also return temperature, pressure and atmospheric chemistry data starting at approximately 5 km above the surface with vertical sampling occurring every 100 m. Measurement requirements for the atmospheric instruments can be found in Table 3.

2.3.4 Heat Flux

The geophysical heat flow at the Venus surface will be measured by a heat flux sensor that will be dropped to contact the surface. The sensor requires at least 2 h to reach initial equilibrium with the environment prior to the first heat flow measurement so it would not operate during the short term campaign. Heat flow measurements will be made every 8 h for the duration of the mission to capture the diurnal and atmosphere driven heat flow and the geothermal heat flow. Supporting meteorological sensor data will be used to distinguish between the variables. The instrument will measure heat flow with a magnitude between 10 mW to 1 W/m^2 and at a resolution of 5 mW/m^2.

2.3.5 Surface Morphology

SAEVe requires that the camera operate at 800 nm wavelength as this maximizes the detection of upwelling radiation from the surface [5]. To assess landing site morphology, a measurement of the surface during descent will be taken at ~5 km above the surface where it is calculated that the surface becomes visible. Another image is taken at 400 m where the surface should be clear to the imager. The landing site will be visible in both images assuming horizontal winds are consistent with prior data from Soviet landers.

At the surface, two images are required beneath the spacecraft. The first image from the surface serves two purposes. The first is to examine the detailed morphology of the surface to look at rock and sediment type and distribution as well as cements. A second purpose is to examine the surface upon which the seismometer will be deployed in order to help assess surface contact. A second image from the surface will repeat the first but this time that seismometer would have been deployed so it will capture the seismometer and how it is resting on the surface.

The last image is of the near surface and the horizon to look at morphology and topography of surface materials as well as landforms and structures in the scene.

All images can be accommodated by a 256×256 pixel camera system. The view of one camera pod is nadir and the other uses a wide angle lens and pointed of to the side to allow both the surface and the horizon to be captured.

3.0 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 likely 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 likely strongly supported by upwelling mantle plumes [6,7,8]. 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 rather than on the summits of these volcanic rises (Figure 4, black triangles). Possible volcanic outgassing in either Beta or Atla could also potentially be detected by the SAEVe atmospheric chemistry sensors. The high, mountainous plateau of Ishtar Terra likely has a crust that is relatively thick and possibly different in composition (more silica rich) than most of Venus's crust. This also makes Ishtar an attractive target for seismic exploration, and the flat Lakshmi Planum plateau would provide a safe landing zone (Figure 4, white triangle). We recognize, however, that if SAEVe is a ride-along secondary payload on another mission, then the SAEVe landing zone may be constrained by the orbital mechanics requirements of the primary payload. For this reason, we emphasize that a landing site anywhere on Venus would be scientifically valuable for the first long-duration landed mission.

Having two landers, each with a seismometer operating simultaneously would enhance SAEVe's ability both to localize the source regions of seismic events and to use the seismic data to probe the structure of the crust, lithosphere, and mantle. The two landers would ideally be placed 300 to 800 km apart to create a regional seismic array. One lander and seismometer will not be able to detect the source of activity but information on the rate and style of events would be still be possible.

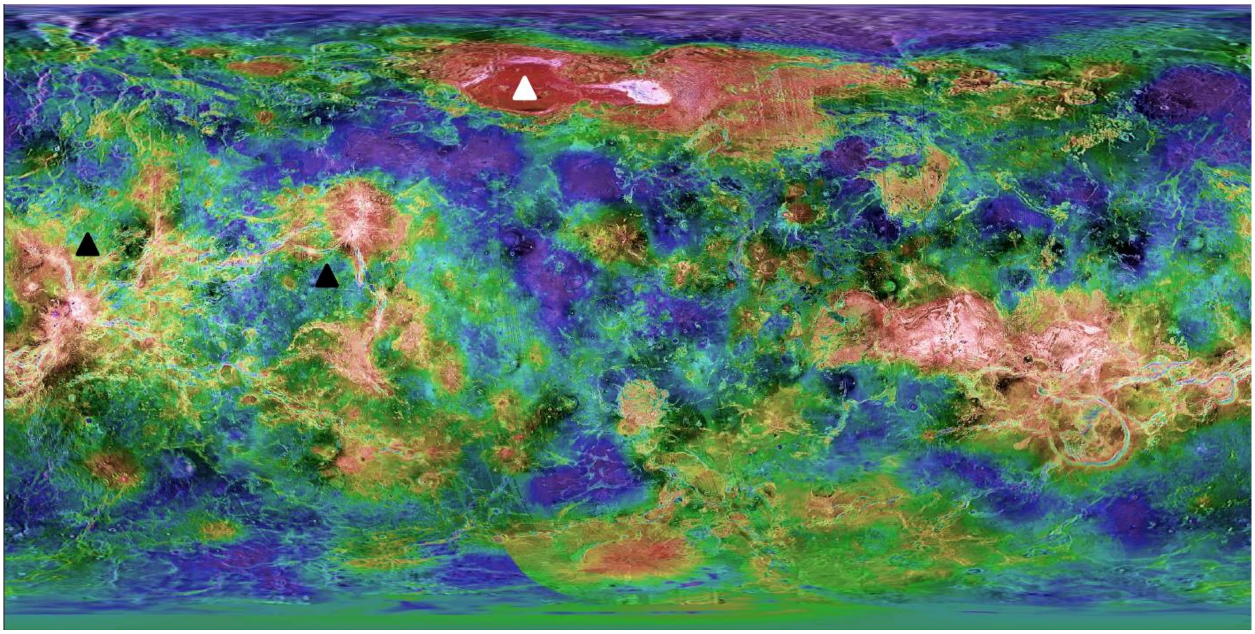

Figure 4. Candidate landing sites for SAEVe, with Atla Regio and Beta Regio as black triangles and Lakshmi Planum as a white triangle. The background image is a topography map of Venus, with low regions in blue and purple and high regions in red and white.

4.0 INSTRUMENT COMPLEMENT/RATIONALE AND DETAILS

4.1 INSTRUMENT COMPLEMENT AND RATIONALE

The SAEVe science payload is focused on geophysical and climatological measurements that can only be provided by a long-duration stationary platform. The science payload therefore consists of three suites of instruments:

- **Geophysics** – comprising a seismometer and heat flow sensor
- **Meteorology** – measuring atmospheric pressure, temperature, wind, radiance, and chemistry
- **Imaging** – landing site and instrument context images

These instruments address SAEVe's science goals to determine the rate and style of seismic activity on Venus and how variable the atmosphere is through the course of a solar day. With two landers there is the potential to get insight on Venus' internal structure and crustal composition.

The seismometer is the primary instrument and must operate continuously for a minimum of 120 days. In order to achieve this each seismometer will primarily be in its long duration standby mode operated with one axis with 3-axis measurements triggered by moderate seismic events. Wind data will be collected simulateously to correct for any wind noise. Supporting this goal is the heat flow sensor, which will provide the first direct measure of the rate of heat loss. Although only a single point measurement, in conjunction with the seismicity and the wider geological context, this value will provide a useful indicator of how active Venus is at the present day. Both these sensors must have good ground contact and be structurally separate from the lander body and the seismometer must also be shielded from surface winds.

These instruments therefore require good knowledge of the atmospheric conditions and contextual imaging, both to determine the quality of their connection with the surface and the wider geological context of the lander location, e.g., heat flow and seismicity might be expected to be higher near a volcano than in a featureless plain. At a minimum, the meteorological suite must therefore measure pressure, wind and temperate over the full lifetime of the seismicity and heat flow measurements; how these vary over the course of a solar day is as yet unknown and important to understand. Venera data imply frequent winds of ~1 m/s, and modelling results indicate a diurnal temperature variability of several K. Atmospheric chemistry may also vary, either in response to diurnal changes or through volcanic activity, particularly with respect to H_2O, SO_2, CO and OCS.

Ideally, four contextual images are required, two on descent and two on the surface. The two descent images provide for a wider area context that can be correlated with Magellan radar images, and provide a detailed landing site contextual image. Once landed, pre- and post-deployment images are required to understand the contact between the geophysical instruments and the ground.

Together, these requirements provide the rationale for the definition of the instrument suite: a seismometer, heat flow sensor and meteorological package able to operate for >120 days under ambient conditions (90 bar, 450 °C), and an imaging system only required to operate until deployment of the geophysical package, and therefore able to use cheaper and more capable low temperature electronics. The specification and technological readiness of these instruments are detailed below.

4.2 GEOPHYSICS

4.2.1 Seismometer

High temperature seismometry has been employed by the oil industry so a number of possible solutions are available. The optimum design for this mission, and what is assumed in this study, is the adoption of the short period 3-axis Micro-Electro-Mechanic Sensor (MEMS) microseismometer provided by the Imperial College of London to the NASA Insight mission. The MEMS sensor must be adapted for high temperature environment of Venus and will have to be coupled with high temperature electronics from NASA Glenn. A detection threshold below 1 ng and a performance goal of 0.1 to 100 sec . With the innovative 1 axis trigger scheme, battery power is sufficient for the ~50 detectable events (recording for 10 min per event) that are expected to occur within the 120 day mission [9,10]. Because of the high degree of uncertainty in Venus surface activity, a real driver for this seismic pathfinder mission, there is a chance that Venus is much more active than expected. This would the result in more power needed to capture and transmit events and thus may impact the 120 day life goal. There are ways to address this risk including starting with more conservative trigger thresholds and increasing trigger sensitive later in the mission life, carrying more battery, and other options.

The MEMS based seismometer (Figure 5) has the advantage of being small and light (< 300 grams) but robust (withstand >1000g loads) and is self-levelling, up to 7° off-axis, making a full 3-axis seismometer achievable on a small deployable platform [11]. The performance of the sensor and electronics in Venus conditions will need to be characterized. The main risk is the uncertainty of nature of Venus seismic activity and challenges associated with ensuring good ground connection, eliminating wind noise, and the impacts of the trigger threshold.

The trigger threshold is critical: too low and winds may trigger an event; too high and no events may be recorded.

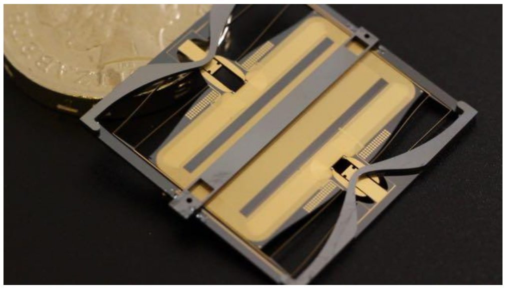

Figure 5. MEMS microseismometer

4.2.2 Heat Flow Sensor

The heat flow sensor is a thermopile instrument that generates a voltage proportional to the heat flux into it, obviating the need for drilling and burial that traditional temperature gradient based instruments require. This allows for simple deployment and integration and is an ideal candidate for use on the small SAEVe mission. The disadvantage is that the instrument will be exposed to the full diurnal variation in heat flux caused by solar irradiance. Although damped by the dense atmosphere, this variation is still ~3 K, generating a positive or negative flux (depending on the time of day) of ~1 W m^{-2}, more than 10 times larger than the expected geothermal flux, which is expected to vary between 10 and 90 mW m^{-2}, depending on the thickness of the Venusian lithosphere. Characterizing the diurnal variation to extract the internal flux requires at least 6 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, the number of heat flux measurements to ascertain diurnal influences will be well beyond the minimum required.

The sensor uses the thermoelectric effect of specific semiconductor materials to measure the heat flow across a set of thermopiles arranged vertically between two graphite plates (Figure 6). The Seebeck coefficient of the skutterrudite elements is 340 mV K^{-1} at 750K, producing 0.12 mV per element pair, sufficient for the required 5 mW m^{-2} heat flow resolution [12-13]. A carbon fiber comb pad is attached to the underside of the lower graphite plate to ensure a good connection with the ground. The heat flux instrument will include supporting surface skin temperature, components and technique to help ascertain thermal connection to the surface and other sensors to help characterize its thermal environment and remove environmental effects.

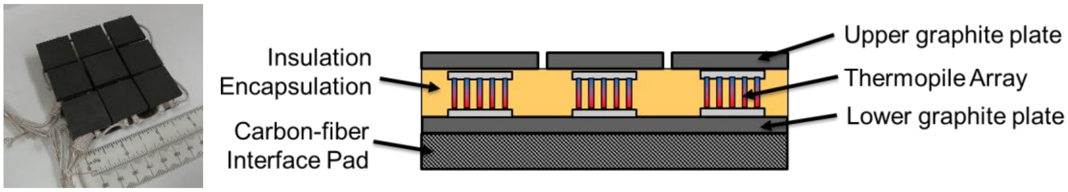

Figure 6. Heat Flow Sensor

4.3 METEOROLOGICAL PACKAGE

The meteorology package consists of a suite of sensors measuring temperature, pressure, wind, radiance, and a number of key atmospheric species. Table 3 includes details on sensors, some of which may not be required for the final sensor set. Temperature can be measured using a Pt-Pt/Rh thermocouple sensitive up to 1500 °C or other high temperature approaches [14-15] or by 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 [16,14]. The atmospheric chemistry multisensory array is based on resistors, electrochemical cells and Schottky diodes, as required to detect each of the species [17]. These are miniaturized and microfabricated (Figure 7) into a single array unit that includes temperature, pressure and wind sensors. Chemical species sensors are deigned to limit cross-sampling interference.

Table 3. Atmospheric Chemistry Sensor Types

Species	Sensor technology	Acid filter	Reactive filter for improved selectivity	Operating temperature, °C	Range, ppm
CO	TiO_2	TBD	Not needed	500	0-50
SOx	Ag-based or alkaline-earth-ion electrolytes	Yes	Yes for total sulfur measurement	500	0-200
OCS	TiO_2	Yes	Alumina filter for thermal decomp of CO	500	0-50
H_2	SiC diode	Yes	Yes to differentiate from HF	400	0-30
HF	SiC diode	No	NO	500	0-50
HCl	Potentiometric zeolite	No	TBD	500	0-5
NO	PtY and/or WO_3 YSZ	Yes	Reduce CO impact	500	0-30
NO	CrO_3/WO_3 on p-n junction	TBD	No	500	0-30
O_2	ZrO_2	Yes	Not needed	500	0-50
H_2O	Differential bias ZrO_2	Yes	Not needed	500	0-100
HCN	Potentiometric zeolite	No	TBD	400	TBD

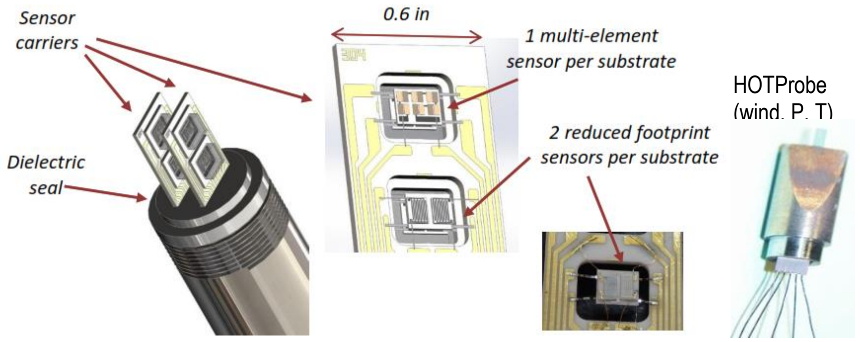

Figure 7. Atmospheric Chemistry Multisensor

4.4 IMAGING SYSTEM

Current solid state (CCD or similar) imaging systems typically fail at ~50 °C, although one new system can function at up to 115 °C. Because there is no near-term identifiable development pathway to high temperature cameras, the SAEVe imaging system is designed to consist of two COTS cube sat cameras, each located in its own thermally protected camera pod, where each pod / camera system weighs about 2.5 kg. One camera points nadir for descent context imagery, and the second is pointed to observe the geophysical instruments and the horizon. Given the limited life, the most significant constraint on camera system design is the data volume produced. The communication system bandwidth limits how quickly 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 number of images to five, and utilizing the high temperature communications system, the cameras can capture and return the data in the available time.

Minimizing openings into the pods lowers the heat loss but requires a carefully designed optics path. The nominal design adopted for this study (Figure 8) uses a sapphire collimator to pass light through the pod structure; its 62° field of view ensures sufficient aerial coverage on the descent camera and the ability to image both instruments and the horizon on the landed camera. A fisheye might be used to increase the field of view.

The internal temperature in the pods will be below 35 °C until all the phase change material changes state. This process is expected to allow for 90 plus minutes of camera operations.

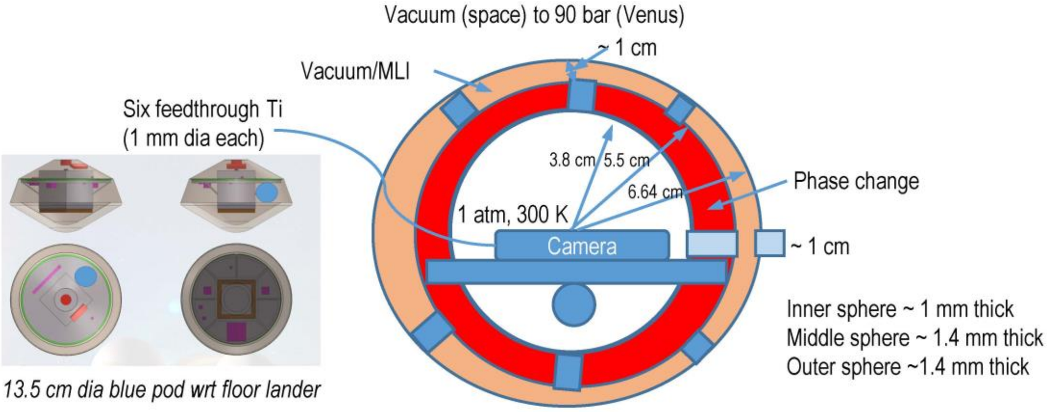

Figure 8. Notional Camera Pod Design

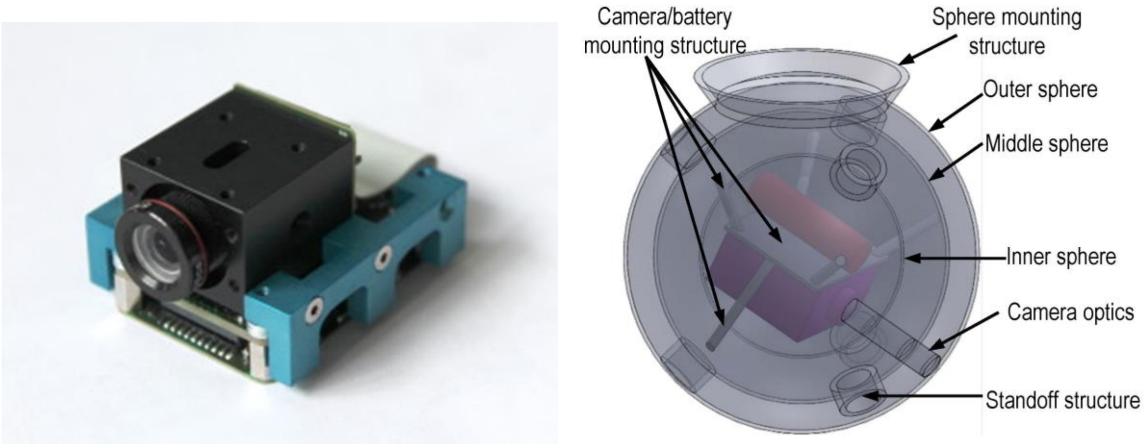

Figure 9. Camera sphere and example of flight proven CubeSat camera (Crystalspace CAM1U)

4.4.1 Sun Position Sensor

High temperature photodiodes are available that may enable the determination of the sun’s position [18-20] and this allow inference of the orientation of the lander relative to the surface In particular, GaAs-based photodiode with an optical filter to select the 1.0 to 1.1 μm wavelength band may provide measurements of solar intensity which can be tracked over time. Although signal to noise ratio will be high due to dark current at 450 °C, the photocurrent may still be measured with good accuracy. Only relative (not absolute) photometric calibration is required for Sun sensing. Measurements over time will give motion of Sun in the sky and on Venus providing a way to simply determine orientation.

A summary of instrument / sensor performance targets are provided in Table 4.

Table 4. SAEVe Instrument Summary Specifications

(a) Instrument and Sensor Summary

Instrument/ Sensor	Description	Number	Sensor input	Sensor output	Requirements				Notes
					Target min	Target max / frequency	Target accuracy, ±	Target resolution	Cameras to return 5 clear images with 256×256 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	
Heat Flux	Thermopile(s)	1	Thermal gradient	Voltage	10 mW/m^2	1 W/m^2	± 8 mW/m^2	5 mW/m^2	Includes ability to ascertain thermal contact to surface and measure surface skin temp
Bolometer	Radiometer	2	Radiance	Voltage	4 W/m^2	25 W/m^2	2 W/m^2	1 W/m^2	Upward and downward
Solar Radiance	Broad solar radiance	4	Solar radiance	Voltage	TBD W/m^2	TBD W/m^2	TBD W/m^2	TBD W/m^2	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	1	Voltage	Voltage	80 bar	92 bar	1% full scale	0.6% full scale	Only 1 of 2 versions will be used
	Capacitive		Capacitance	Voltage					

(b) Specie Sensor Performance Targets

Chemical Species	Number	Sensor input	Sensor output	Target min	Target max	Target accuracy (±)	Target resolution
SOx	1	Voltage	Voltage	0	400 ppm	0.3 ppm	10 ppb
H$_2$O	1	Voltage	Voltage	0	100 ppm	1 ppm	50 ppb
OCS	1	Voltage	Resistance	0	50 ppm	1 ppm	10 ppb
CO	1	Voltage	Resistance	0	50 ppm	1 ppm	10 ppb
HCl	1	Voltage	Voltage	0	5 ppm	0.5 ppm	10 ppb
HF	1	Voltage	Voltage	0	5 ppm	0.5 ppm	0.5 ppb
NO	1	Voltage	Voltage	0	10 ppm	2 ppm	0.1 ppb
H$_2$	TBD	Voltage	Voltage	0	30 ppm	1 ppm	1 ppm
O$_2$	TBD	Voltage	Voltage	0	50 ppm	1 ppm	1 ppm
HCN	TBD	Voltage	Voltage	1	50 ppm	1 ppm	1 ppm

5.0 LANDER CONCEPT

5.1 SAEVE IS BASED ON A SIMPLE ARCHITECTURE

The SAEVe theme is to return important science via simple instruments with low data volume. This theme relies on sensors, instruments, systems, that are simple in terms of complexity but also simple to integrate and operate. A mission concept that meets study goals was identified through an iterative balancing process of refining science objectives, assessing technical risk, and designing of spacecraft concept. Thanks to support by the science team and NASA Glenn's COMPASS the SAEVe mission can offer significant science enhancements with little impact if added to a Venus orbiter mission.

5.2 LANDER OVERVIEW

The functional depiction of the SAEVe lander concept was generated by the NASA Glenn COMPASS team and is shown in Figure 10. The basic physical dimensions of the SAEVe lander is shown in Figure 11.

Except for the camera spheres, which are described in Section 4.4, 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. Avionics and batteries for the lander are housed in the central compartment and packaged such that the center of mass is near the bottom of the lander to facilitate the uncontrolled descent. An appropriately sized crush pad is at the base of the lander. The sensing elements are located as needed around the exterior of the lander as shown in Figure 12 and summarized in Table 4.

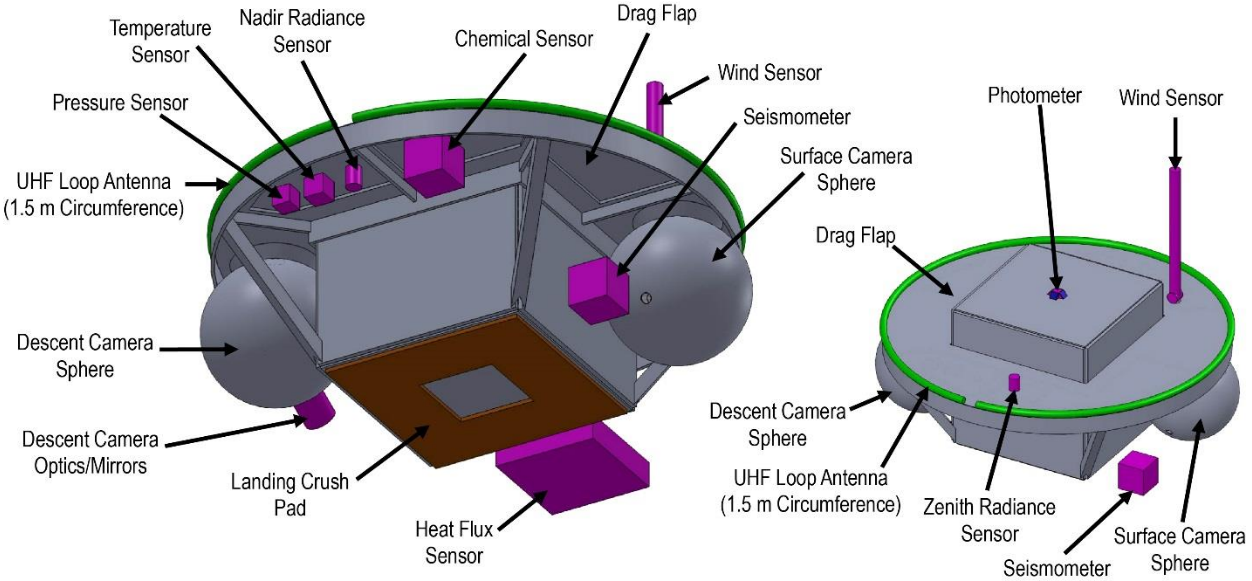

Figure 10. Function model of SAEVe concept

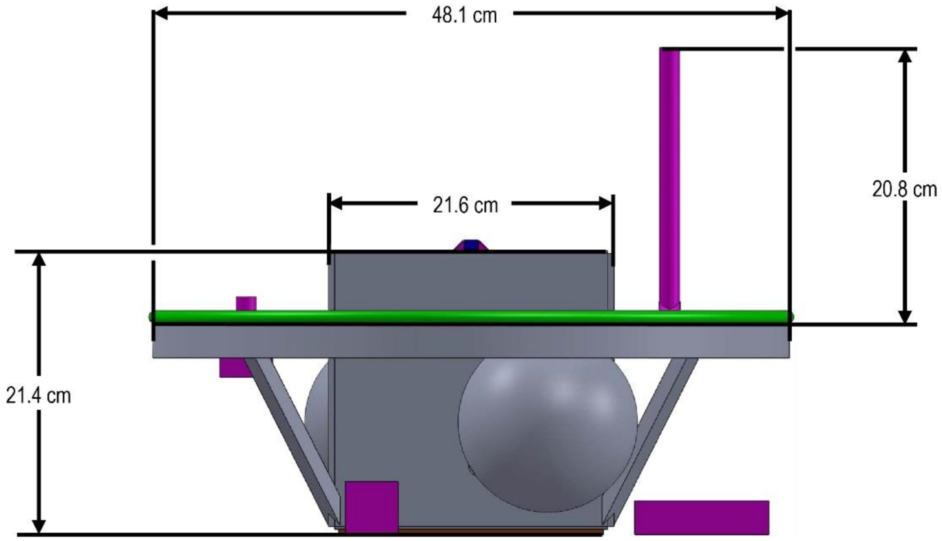

Figure 11. Basic Physical Dimensions

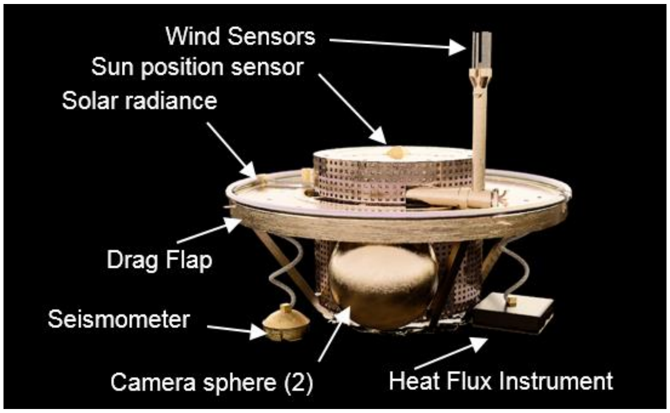

Figure 12. SAEVe Concept and Instrument Locations

There are only three simple moving parts associated with the lander, one of these is the wind sensor arm. The arm essentially folds up to a vertical orientation to position the wind speed sensors above the lander to minimize any potential lander and surface feature influences on the wind measurements. The other moving parts are the pin release mechanisms for the seismometer and heat flux instruments. At the appropriate time the instruments are dropped 5 in. or so from the drag flap by the release pins that hold them in position.

Communication (Figure 13) is handled via a UHF 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. With ½ W transmitted power, ½ wave loop antenna and an orbiter assumed to be at a distance of 80,000 km, this still leaves a link margin in excess of 2 dB.

To facilitate data return the orbiter will need to be able to receive the data transmitted at the lander frequency. It is assumed at this point that the orbiter would utilize a Yagi antenna (approximately 3 m) pointed toward the surface when receiving data from SAEVe. An overall system diagram of SAEVe, its entry shell and the interface elements on the orbiter is shown in Figure 14. Only one camera sphere is shown for simplicity.

Potential static and dynamic loads that may affect the lander have been assessed and results used to develop the concept design, sizes of the structural elements (Figure 15). For example, the drag flap that supports the sensors, communication antenna, and camera and instruments is sized to support the needed components at launch and landing but also to withstand the nearly 300g worst case entry load that may be seen when the capsule hits the Venus atmosphere.

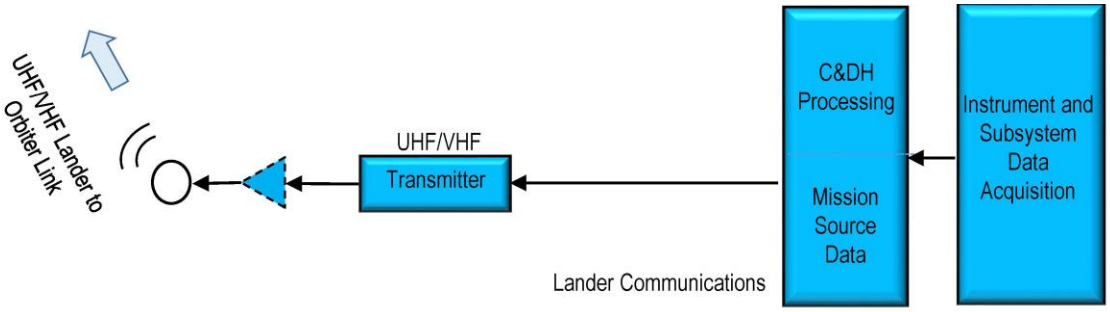

Figure 13. SAEVe's Simple Communication System

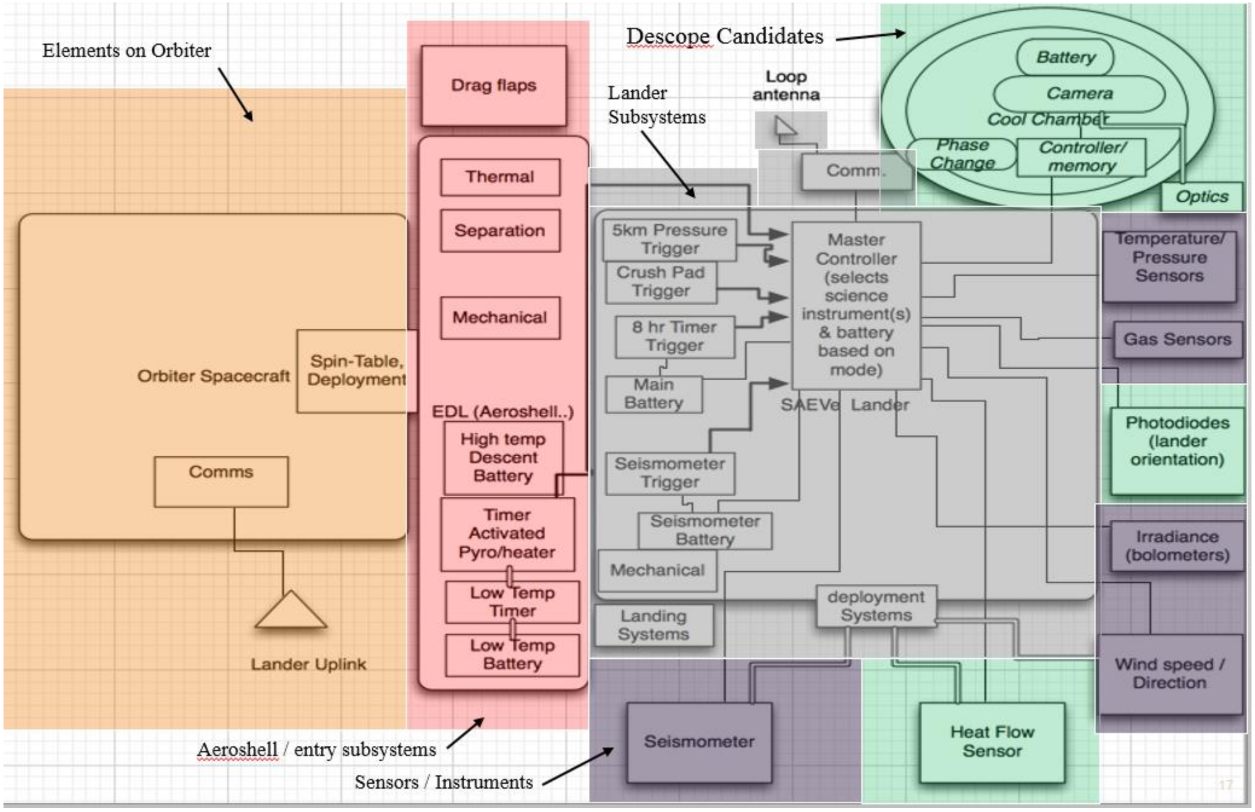

Figure 14. SAEVe's System Schematic

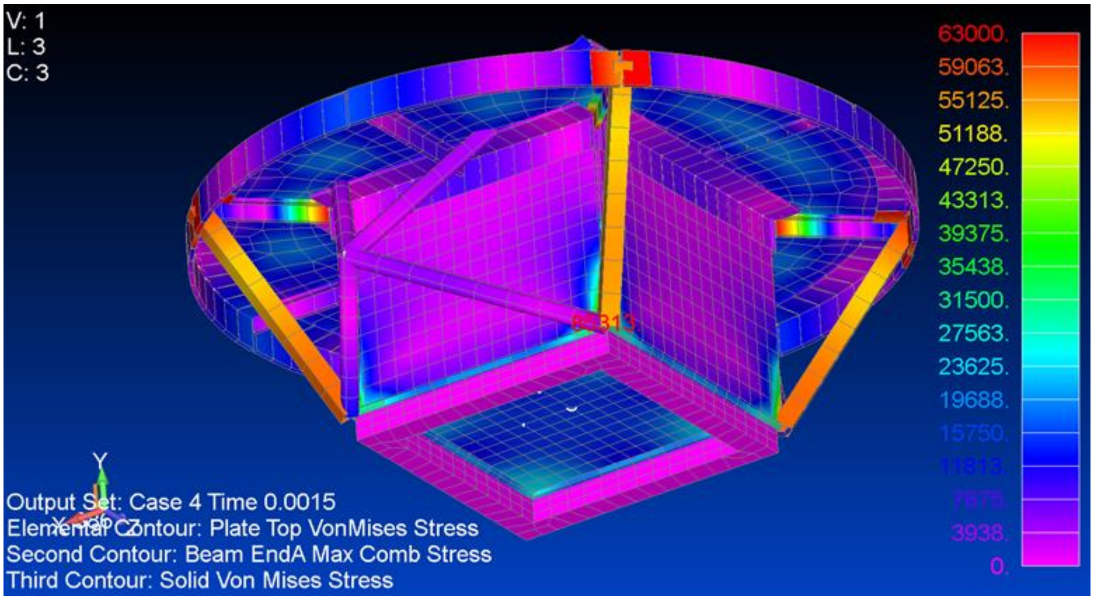

Figure 15. Worst Case Dynamic Load Analyses (Occurs During Entry)

5.3 MASS AND POWER SUMMARIES

Mass summary by subsystem and growth allowances are shown in Table 5. The mass budgets include subsystem growth as shown in these table. An additional growth of 5% is carried at the system level so the total predicted mass of the base SAEVe concept with growth (not including the camera and spheres or the heat flux sensor) is 22.6 plus 5.9 kg or 28.5 kg. The total predicted mass the orbiter would release would be approximately 45 kg.

Power and energy modes and durations are shown on

Table 6. The power mode / energy allocation summary includes 30% margins for all elements.

SAEVe is a small and innovative lander that returns high value science but also helps better understand the environment and what it will take for future mission to successfully return the most science for their dollar.

Table 5. Lander: SAEVe Total System, Including EDL—Mass Estimates

SAEVe Master Equipment List (MEL)	Mass (kg)	Growth (%)	Growth (kg)	Mass with growth (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)**
Camera	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 6. Power Mode and Duration Summary for the SAEVe Lander

Power mode	Descent from 5 km until touchdown	Touchdown	*Continuous initial monitoring*	Science/ ConOps	Seismic monitoring	Seismic event
Power, W	9.3	13.8	*13.8*	13.1	0.2	9.7
Duration	17.5 min	134 min after landing	*60 min*	2 min	8 h	10 min
Science & Comm Frequency	Continuous	Continuous	*Continuous*	357 cycles	None	50 events
Total Duration	17.5 min	134 min	*60 min*	11.9 h	2858 h	8.3 h

6.0 MISSION DESIGN/ARCHITECTURE (ENTRY, LANDER(S), ASSUMPTIONS, ETC.)

This study assumes that SAEVe would be a ride along with a Venus orbiter mission that would, along with its own science, provide relay capability for the 120 days that SAEVe will transmit its science data. While this assumption has its limitations, it allowed this team to focus time and resources on the unique and innovative aspects, challenges, and contributions of the lander rather than on the general transit to, capture, and orbit considerations that been demonstrated numerous times at Venus. Therefore, this report, and specifically this chapter, focuses on the lander entry system, and liens on the host orbiter.

6.1 SAEVE ENTRY DESCENT AND LANDING SUMMARY

The deployment, entry, and landing of SAEVe onto the Venus surface uses simple and flight proven techniques and systems. The carrier spacecraft/orbiter will carry the SAEVe entry capsules on a spin table. At the appropriate times the carrier spacecraft will spin up (7 rpm) and release the capsules. No other interactions / control is required from the carrier vehicle during launch, transit, and release before orbit entry. As the capsules enters the Venus orbit, the aeroshells will control and communicate entry events via their own battery and avionics. The release of the capsules and maneuvers by the orbiter would have been 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 (based HEET thermal protection system), capsules, each will descend intact to approximately 6 km, at which time the front and back shells separate. The separation of the two pieces is assisted by the use of simple drag flaps or other technique (Figure 16). 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 that surface with a touchdown velocity of approximately 6 m/s. The lander commences science during this last phase of descent. The imaging package takes a context image of the landing site from 5 km. It continues to descend and takes another picture around 400 m. Temperature, pressure and chemical species abundances are transmitted in this phase of descent as well. The total time from for descent from entry is approximately 62 min (Figure 17). Section 7.0 describes the lander operations once it reaches the surface.

The entry shell will have its own avionics but will utilize the lander communication system to transmit entry events. The entry capsule power summary is shown in Table 7.

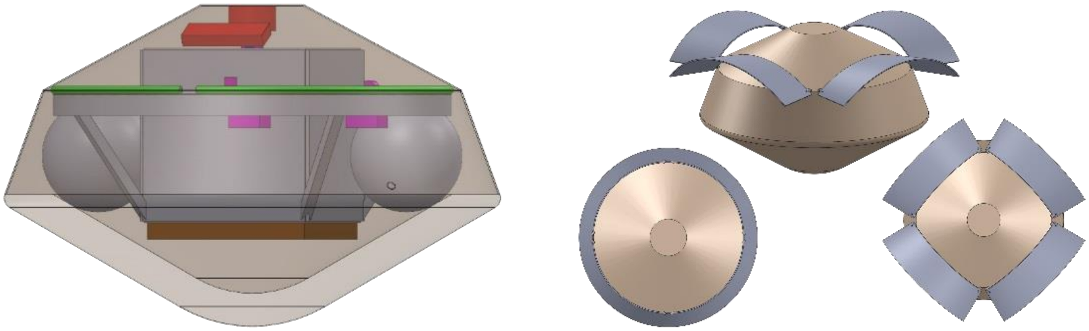

Figure 16. SAEVe Entry Capsule System and Separation Assist Flaps

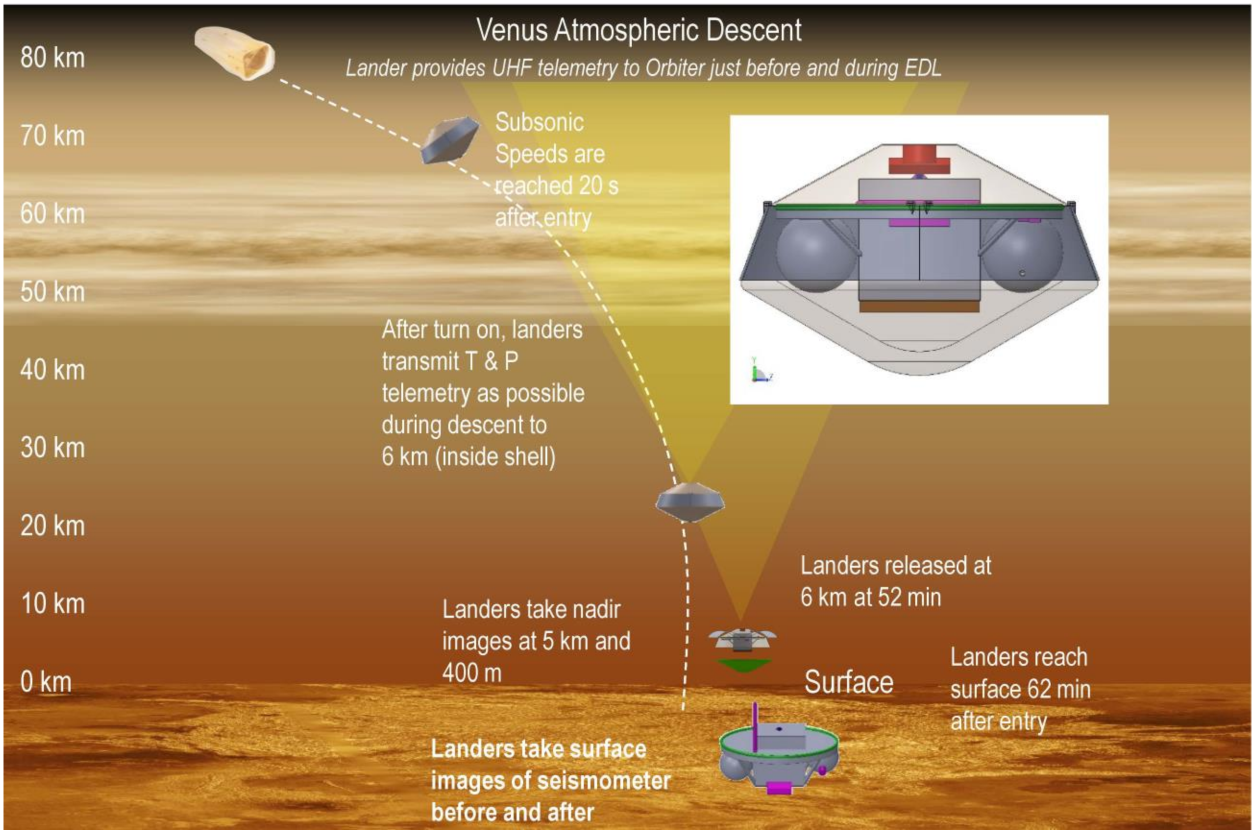

Figure 17. SAEVe Entry Sequence

Table 7. Power Mode and Duration Summary for the SAEVe Entry Capsule

Power mode	Aeroshell coasting	30 min Prior to Entry Until 5 km
Power	32.5 mW	5.8 W
Science and Comm Frequency	None	Continuous
Duration	720 h	95 min

6.2 MISSION / ORBIT ASSUMPTIONS

Since SAEVe relies on the orbiter to provide relay communications some assumptions have been made in this study. One assumption is the orbiter will be in a 24 h elliptical orbit (500 by 66409 km). This is a reasonable orbit assumption in light 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, there is a large fraction of every day, over the lander life, where contact is available between the lander/orbiter as shown in Figure 18. In fact, in this scenario, the orbiter can be in communication link with the lander over 23.5 h of a 24 h day.

Clearly the amount of contact time between the orbiter and lander will be determined by the actual orbit selected by the host mission. Given the significant science SAEVe will contribute, it is expected that the orbit will be chosen in part to help maximize return from SAEVe.

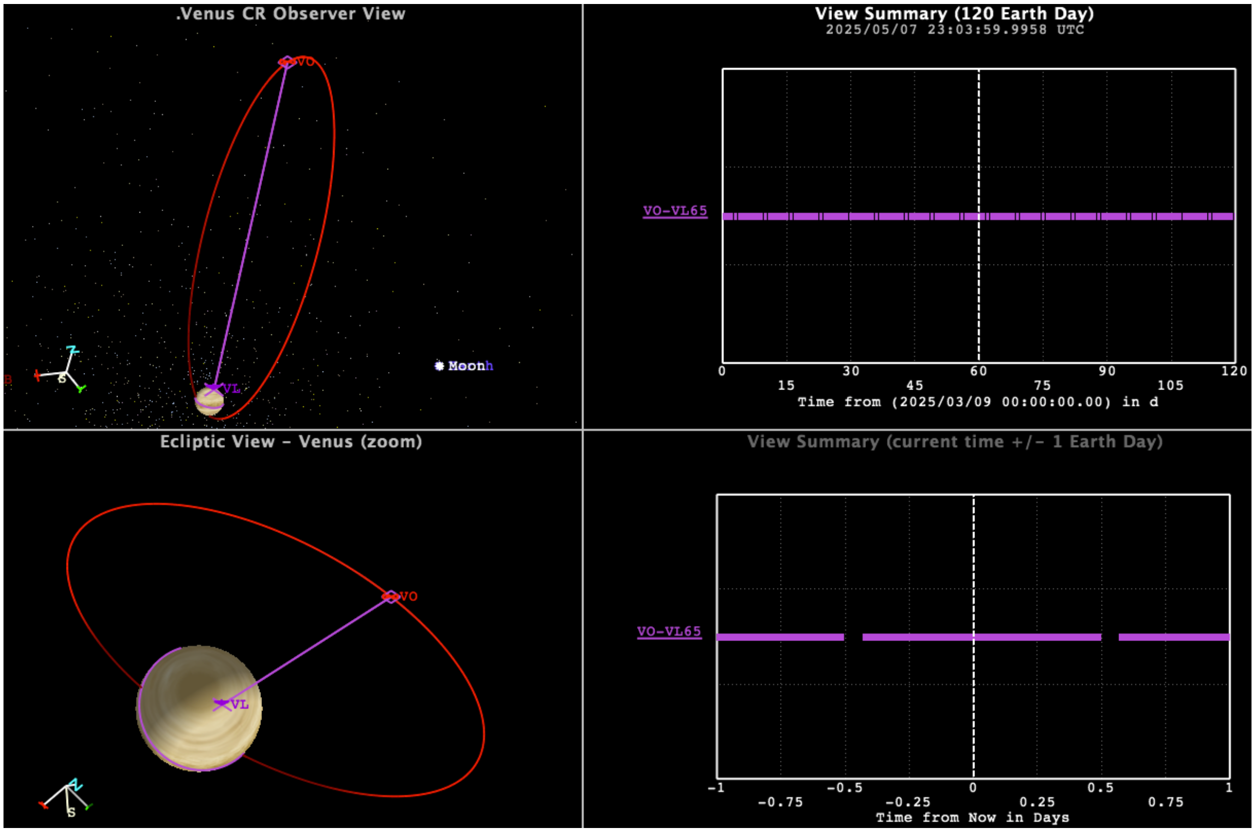

Figure 18. Assumed Orbit and Resulting Contact Times Between Lander and Orbiter

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 extremely low so orbiter operations can be well planned long ahead of time and any negative impacts to orbiter science minimized. Seismic events are transmitted as they occur and given the number of events expected from models and the potential for significant communication coverage there is strong expectation that data from many if not most of the events can be returned.

7.0 CONCEPT OF SURFACE OPERATIONS

The surface operations plan is designed to achieve the science goals summarized in Table 1, while optimizing resource usage, the most stringent of which is energy stored in the battery.

7.1 SURFACE OPERATIONS

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 19. Two images are taken during descent and three after touchdown. Five minutes will be allotted after touchdown for any dust to settle before the final three images are taken. The third image to be taken is a close-up image showing the seismometer deployment area before deployment and the fourth image is of the same site after seismometer is deployed. The last image to be taken is the distant-focus image showing the local horizon. At the resolution assumed each image takes no more than 17 min to transmit.

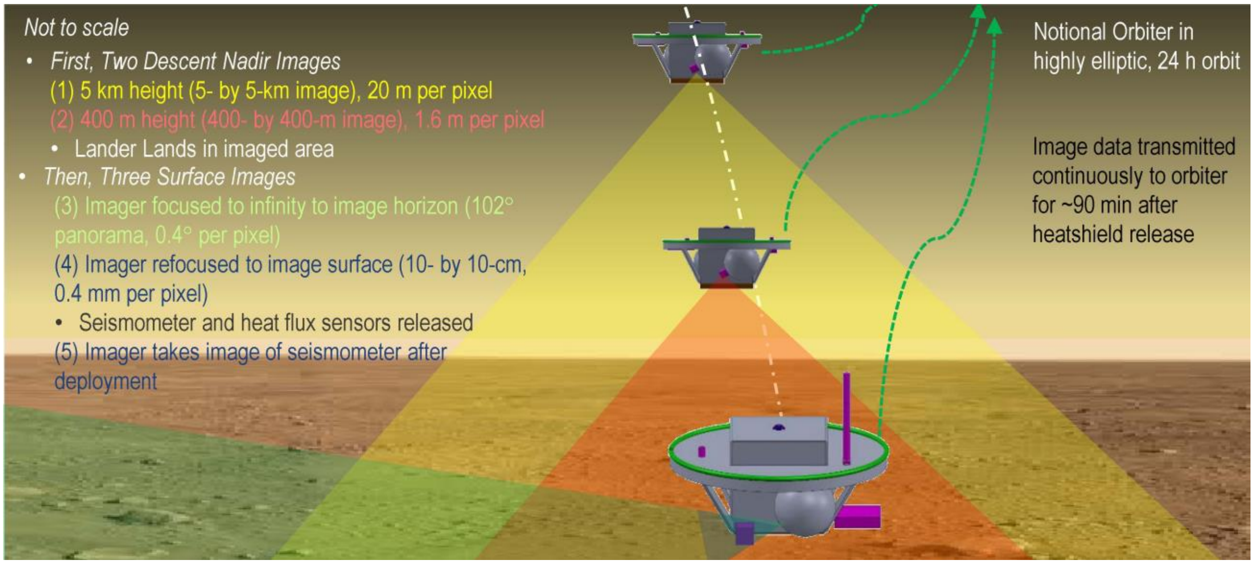

Figure 19. Summary of SAEVe Imaging Plan

The image data are written to onboard camera memory in the imager "pods" – but these memory modules will stop operating once their temperature exceeds their operational range, which is predicted to happen 90 min after landing. By this time all images will have been transmitted. To ensure this, the image data are continuously uplinked via UHF to the orbiter from the heatshield deployment until transmission of the final image has completed.

All the payloads not already active (the seismometer, wind sensors and heat flux sensor) are deployed shortly after landing and the predeployment image is acquired. Figure 20 portrays a notional timeline of science operations. One deployed, all instruments will be ready to start continuous transmitting as soon as the last image is transmitted. All three seismometer axes and meteorological and atmospheric composition sensors acquire measurements for an initial 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 be not be taken at this time to ensure enough time for all hardware to reach equilibrium conditions. Heat flux measurements will the occur during the 2 min of every 8 h science operations cycle.

To characterize the variation of atmospheric parameters over one solar day (118 Earth days), SAEVe enters a low power mode in which the probe wakes up once every 8 h and acquires 2 min of data. Data are, again, transmitted in near-real time.

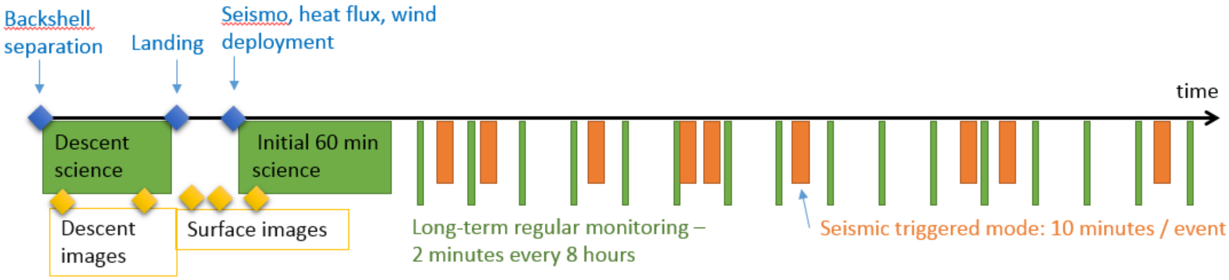

Figure 20. Notional Science Operations Timeline – Not To Scale

Between these 2-min operations, the seismometer will be continuously on in a listening mode. In this mode, the test mass position in 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 data transmitted will be 3 axes of seismometer data and 2 axes of wind data. The wind data are essential, in order to permit characterization of the wind-induced noise on the seismic measurements. Other atmospheric sensor data (temperature, pressure, composition) are not transmitted, in order to minimize requirements on the data link.

The threshold criterion used to trigger seismic data collection will have to 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 14, 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 wind events, do not impact the 120 day meteorology and heat flux related science objectives of the mission.

The 2 min every 8 h pattern continues until the battery is no longer able to drive the onboard electronics.

8.0 ASSUMPTIONS ON LAUNCH/CRUISE, DEPLOYMENT FROM ORBITER, AND ORBITER SUPPORT

This study focused on the Venus lander making the assumption that it would be delivered to by a Venus orbiter mission. Therefore, launch, transfer, and capture details of the orbiter are not applicable, other than to note that the launch vehicle and mission architecture must support the mass and volume needs of the of the small landers and their aeroshells.

There are a limited set of requirements that would be levied on an orbiter to support deployment and operations of SAEVe landers on the Venus surface. One of the main assumptions and requirements is that the orbit will carry a spin table for each SAEVe lander/ entry vehicle, where each aeroshell/lander system will be approximately 0.6 m in diameter and weigh about 45 kg. Another main assumption is that the orbiter will carry an antenna and receiver that will be able to capture the 100 to 150 MHz signals sent by the SAEVe landers. The final assumption is that the orbiter will serve as a data relay for the lander science data over the entire mission lifetime. Thus lander locations and contact times would be factors that the orbiter team would consider in their mission orbit planning.

From a sequence perspective, the orbiter will initiate the deployment sequence as it approaches Venus during cruise. At the appropriate time, the orbiter would spin up the landers and release them so they ballistically enter the Venus atmosphere in the expected locations. After release, the entry system will protect the lander inside and help it quickly descend until it is released at about 6 km above the Venus as described earlier. This approach builds on experience gained from the prior Venera, Vega, and Pioneer Venus (PV) missions. From the time of entry into the atmosphere till touchdown is expected to take approximately 60 min. From deployment by the orbiter to release of the lander the aeroshell/entry vehicle communicates critical event health and status to the orbiter.

Once the landers are sent toward Venus, the orbiter executes a divert maneuver to establish a trajectory to ensure telecommunication contact with the entry vehicle and the SAEVe landers during EDL operations, and of course also to avoid becoming a lander itself. The divert maneuver would require slewing the vehicle to orient the main thruster in the forward velocity direction and firing the main engine to decelerate the spacecraft to bring it into a captured orbit. The orbiter must have the at least 4 h of contact time during entry and landing with the SAEVe landers to receive initial science data including images. Once the landers go into long duration operations mode the orbiter periodically receives the science data and relays it back to Earth. While SAEVe is functioning, the orbiter would continually listen and capture, to the extent possible, any data that may transmitted due to a seismic event, which may occur at any time.

9.0 COSTS ESTIMATES

Two independent cost estimates were prepared for this study. One was a parametric estimate generated by the COMPASS team based on the conceptual design they developed and using the PRICE True Planning estimating tool. The second was a hybrid estimate (parametric and comparative) generated by The Aerospace Corporation (TAC). This later estimate took the COMPASS lander design and estimated their own cost to build and implement the mission as described in this report. Both COMPASS and TAC estimates assumed that required technologies were already at TRL 6 and therefore costs to reach that level of technical maturity are not in the estimates.

Since the focus of this study was a Venus lander and an assumption was that SAEVe would be a ride along with a Venus orbiter, no costs were included for launch or transfer to Venus. Costs were included for SAEVe specific orbiter hardware like the appropriate antenna and receiver and the spin table(s). All other costs to implement SAEVe (Phases A to F) are captured including operations related to SAEVe and resources for science analysis and publications.

The best estimate was developed by the SAEVe team based on the two independent data sets. Table 8 is a summary of the team's best combined estimate.

Table 8. Combined Cost Estimate

Estimates	Full Payload, 2 Landers (point)	Full Payload, 2 Landers (with 25% reserves)	Full Payload - Single Lander (point)	Full Payload - Single Lander (reserves)	Baseline Payload - Single Lander (point)	Baseline Payload - Single Lander (reserves)	Notes / Comments
Combined	**$106**	**$131**	**$87**	**$109**	**$71**	**$89**	Estimate is combination of independent COMPASS and TAC estimates
Notes:	1) All costs in $M						

10.0 TECHNICAL READINESS

The SAEVE lander concept takes advatage of ongoing technology and system developments. Most notably, many of the capbilities SAEVe requires to realze its science goals are being developed and or proven through the ogoing Long-Lived In situ Solar Sytem Explorer (LLISSE) project. Although the specific design of SAEVE diverges in aspects from the LLISSE design due to its different targeted application and funtionality, the basic aspects of the SAEVE lander are similar to LLISSE and key capabilities (e.g., battery and communication system) will be demonstrated by LLISSE. Thus, in order to understand the technical readiness of many of SAEVe subsytems and insruments, one needs to assess progress on the LLISSE project. Beyond that, one then needs to understand the technical readiness of the specific technology components used on SAEVE that are not in LLISSE. Table 9 provides a summary of the key technologies on SAEVe and reflects where (LLISSE or another project) work is ongoing, if at all.

Table 9. Technology Readiness for Instrument and Critical Subsystems

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	Aug 2019	LLISSE (O)
Electronic circuits (SiC): power management	3-4	Sept 2021	LLISSE (O)
Communications (100 MHz)	3-4	Sept 2021	LLISSE (O)
Wind Sensor	4	Aug 2019	LLISSE (O)
Temperature Sensor	4-5	Aug 2019	LLISSE (O)
Pressure Sensor	4-5	Aug 2019	LLISSE (O)
Chemical Sensors	5	Aug 2019	LLISSE/HOTTech (O)
LLISSE Bolometer	3-4	Sept 2021	LLISSE (O)
Seismometer	3	TBD	LISSE (O) and possibly MaTISSE (P)
Heat Flux Sensor	3-4	TBD	PICASSO (O) – MaTISSE
Camera / imaging System	3-4	Sept 2020	Rocket University (O) – MaTISSE if needed
Solar Radiance	4	TBD	MaTISSE (P)
High-Temperature Battery	3	Aug 2019	LLISSE and HOTTech (O)
Entry Shell	4-5	TBD	HEET – need Venus specific design

The TRLs and dates are estimates and meant to provide a relative measure of the maturity of the overall SAEVe system and, as with all estimates of future events, are subject to funding and technical progress. Since specific mission or launch details are not available one cannot deterime certain parameters (e.g., EMI, Vibe) necessary to demonstrate complete readiness to TRL-6. Therefore, for purposes of this assessment TRL-6 is absed on ability to meet goals of mission life at Venus surface temperature, pressure and chemisrty. These objectives are the drivers for a Venus surface mission and thus is a reasonable metric for this study. Discusson of the maturity of the various SAEVe components and the various technical challenges is below.

10.1 TECHNICAL READINESS OF COMPONENTS—LLISSE RELATED

LLISSE has a goal of developing and demonstrating proof of concept probes that will function in Venus surface conditions for weeks to months. These prototype probes will be designed, fabricated, and demonstrated by test to operate in Venus conditions. To accomplish these goals, LLISSE leverages GRC high-temperature electronics, sensors, power, and communications collect and transmit science data for 60 Earth days or longer in Venus conditions. The LLISE development plan assumes a two phase approach: a battery only version to be demonstrated in 2019 followed by a wind powered version to be demonstrated in 2021. While the battery powered version of LLISSE is the most relevant to SAEVE and will provide the core of the SAEVE functionality, some aspects of LLISSE, such as a higher frequency communication system and aspects of power management, are scheduled to be developed and demonstrated as part of the wind powered version of LLISSE. This is highlighted in Table 9.

A core to SAEVe operation is high temperature electronics for sensors, data handling, communications, and power management. These electronics are based on the world’s first microcircuits of moderate complexity that have shown extended operation in Venus relevant conditions [21-22]. These circuits have been recently up scaled in complexity to over 100’s of transistors per chip with two metal interconnect layers, and have now demonstrated operation for thousands of hours at 500 °C in Earth air ovens [22], and very recently for 60 days in the Glenn Extreme Environments Rig (GEER) simulated Venus surface conditions without any cooling or environmental protection [23-24]. This integrated circuit capability enables a wide range of very compact onboard mission electronics, including sensor signal amplification, digitization, and wireless transmission integrated circuits, to operate for months without any environmental sheltering from the harsh atmosphere found on the surface of Venus. Another important finding of the high-fidelity reproduction of Venus atmospheric conditions provided by GEER tests is necessary to qualify parts for prolonged surface missions [21-22]. It is envisioned that prototype demonstration circuits specifically designed for most core aspects of operation will be fabricated and preliminarily evaluated in 2018.

As part of this recent GEER testing, core components of sensor technology were tested in simulated Venus conditions. These include first generation sensor systems for surface wind speed, temperature and pressure, as well as specific sensors for atmospheric chemical composition (SO_2, HF, CO, OCS). Analysis of the results of this testing for both the sensors and electronics is on-going. Overall, valuable knowledge on the operability of the sensing approaches was gained combined with further characterization of candidate sensor materials stability to Venus conditions. To varying degrees, preliminary viability of each chosen core sensor approach was supported. For example, the SO_2 sensor [23,25] responded to the intentional injections of SO_2 into the GEER chamber during the 60-day test in a manner suggesting real-time monitoring of the simulated Venus ambient conditions. However, further improvement of Venus-durable integrated circuit and sensor capabilities overall is planned and remains to be done.

The development of other components is also progressing. Communication system designs including antennas are being investigated, coupled with modeling and limited component/materials testing. The LLISSE plan includes demonstration of communications at ~10 MHz in 2019, with further development, including appropriate circuits, for ~100 MHz communication capabilities by 2021. The development of the communications system will be closely coupled with the electronics development to enable higher frequencies transmissions at adequate power levels.

The battery system assumed in this study is based on sodium sulfur (NaS) chemistry. The NaS battery has a long history of development for applications on Earth and has been space qualified. This includes demonstration test of the NaS battery in space on space shuttle flight STS-87 in November 1997 [26,27].

An energy density of 120 Whr/kg was assumed for this study, but higher power densities may be viable. The LLISSE project is assessing several options and is maturing a non-rechargeable battery that will also be suitable for SAEVe. A contract [28] has been awarded to an industry partner for battery development leading to functional demonstration in GEER.

10.2 SAEVE SPECIFIC TECHNOLOGIES

In order to achieve the science objectives of SAEVE some specific technologies and corresponding designs are required, these are described in the sections below.

10.2.1 Seismometer

The Venus seismometer system envisioned in this study would combine the core Insight Mars mission MEMS seismometer sensors and adapt them to Venus surface operations. This would include combining the sensors with high temperature electronics tailored for the capacitance response range of the seismometer sensors. Technical challenges with this complete Venus seismometer system include: 1) Ruggedization of the MEMS seismometer sensor for Venus surface operations; 2) Circuit development and integration of high temperature electronics with the MEMS seismometer to provide the required response; and 3) Packaging of the MEMS seismometer and electronics for deployment in the SAEVe lander system.

In addition to the seismometer hardware, modeling, analysis and testing is required to understand how to address the seismometer trigger for various seismic events in order to understand and interpret the data that may be collected and understanding impacts and effectiveness of techniques to minimize wind effects

10.2.2 Heat Flow Sensor

The Heat Flow Sensor is in a development under a PICASSO award. Some aspects of its operation are to be demonstrated in the near future. Given the expected impact such an instrument would have for understanding Venus and the potential success of the PICASSO goals, it is anticipated that a MatISSE proposal would be submitted to mature the instrument to the needed TRL-6.

Technical challenges related to operation of the heat flux sensor include: 1) Demonstrate required sensitivity for Venus surface applications; 2) Develop and demonstrate techniques to assure integrity of the contact between the heat flow sensor and the Venus surface; 3) Circuit development and integration with high temperature electronics; and 4) Verify compatibility of the materials used for the heat flow sensor in Venus temperature, pressure, and chemistry.

10.2.3 Imaging System

Major technical challenges associated with this system include: 1) Integration of the camera system into a camera pod; 2) Optical interfaces to allow correct field of views and light levels and optical access to the Venus environment; and 3) Maintaining the temperature at levels which the camera can operate and store data long enough for the high temperature communications system to transmit the images. This is coupled with need to minimize the size and power consumption of the pressure vessel so as not to overly burden the lander system. Other challenges include the adequate vacuum or MLI insulation to maintain temperature of the camera system and electronics. As noted elsewhere, high temperature electronics are currently not as capable as standard conventional electronics so power consumption, data storage, and transmission rates are significant drivers for supporting the imaging system design.

10.2.4 Sun Position Sensor

The use of solar cells on the Venus surface is viable but technical challenges include:
1) Enhancement of solar cell technology for the ambient solar radiance on the Venus surface;
2) Demonstration of the durability of solar cell for long durations in Venus environments;
3) Integration of high temperature electronics with the solar cells; and 4) Modeling of the photodiode output to relative sun position in order to interpret resulting data.

10.3 POTENTIAL HIGH IMPACT FUTURE TECHNOLOGIES

A range of technologies are needed for SAEVe mission operation and success. As noted above, development of much of the technologies needed by SAEVe is on-going on the LLISSE project. The needed extensions to that platform and their technology readiness for baseline SAEVe operation have been noted above. This section highlights particular tall poles noted during the study that would augment the baseline operation of SAEVe-like missions. These include:

- Power sources, whether battery-based based or other methods, that provide increased power density at reduced weight than present battery systems. It was especially evident that restrictions in the power density of existing high temperature battery systems drove major aspects of the mission design, and thus the science achieved.

- High-temperature, low-power memory would enhance science. It would allow more flexibility in returning images, seismometer operations and could ensure significant data is not lost because an orbiter was not in view to "hear" the transmission of a seismic event.
- More capable communications systems would also enhance science. This would help provide broader frequency response to the instruments sensors, allow for return of better resolution and/or more images. Capability for direct contact with Earth without reliance on orbiter systems would allow simplification of overall mission architecture but this would need further analysis to understand all the ramifications.

11.0 TOP MISSION RISKS & KEY MISSION TRADES

SAEVe is dependent on a host mission for delivery to Venus and data return. We require a suitable 100 MHz receiver on the orbiter to relay data and we assume a 24-h elliptical orbit. There is considerable flexibility around this assumption but a significantly shorter, low circular orbit would reduce contact time and hence lead to a reduction in data returned. However, we note that such an orbit is likely to be achieved by aerobraking from an initial longer elliptical orbit over a period likely to be similar to or longer than the SAEVe mission lifespan and we therefore count this risk as low. The passive landing system, using atmospheric density to retard velocity, has been successfully demonstrated on many Venera landers and even unintentionally allowed the Pioneer Venus Day probe to survive impact. SAEVe is therefore a low risk (and high benefit) addition to any Venus orbiter mission.

The primary mission risks relate to deployment of the seismometer and heat flow sensor, battery power, and communications. These risks and their severity are outlined in Table 10.

Table 10. Risk Table

Risk	Impact	Severity	Possible Action
Rapid battery discharge	Insufficient instrument power	Severe	Mitigate via design than verify via demonstration (LLISSE)
	Reduction in mission life	Severe	
Seismometer not deployed correctly	Increased wind noise	Modest to Severe	Mitigate with terrestrial tests and design development
	Poor seismic signal detection	Modest to Severe	
	Increased battery drain	Severe	
Unfavorable host orbit	Intermittent loss of communications	Modest	Watch – Work with Orbiter team
Seismicity: Lower Higher	Below detection threshold / wind noise Early battery drain	Modest Modest	Analyze / modeling than accept remaining risk
Loss of Camera Pod vacuum	No context imagery	Modest	Mitigate via design than verify via test
Communication system performance not as good as anticipated	Loss of science return and shorter life	Modest to Severe	Mitigate via design than verify via test
Heat flux complexity impacts its ability to return anticipated science	Geophysical heat flux not definitively addressed	Modest	Mitigate via design than verify via extensive testing

The main uncertainty is that Venus may be significantly more seismically active than anticipated, frequently triggering the seismometer and draining the battery before the end of the 120 day mission. The power supply is arranged to allow this to occur in isolation so that the other instruments (heat flow and atmospheric package) and core lander systems, particularly communications, continue to operate for the full mission duration. Since such a situation would represent a major scientific discovery, the mission would still be regarded as highly successful. The converse, in which no seismic events are triggered, is less clear-cut since the possibilities of poor contact and instrument failure, or other reasons, would have to be eliminated before it could be regarded as implying a lack of seismicity on Venus and hence an important discovery. Both these situations underline the pathfinder aspects of SAEVe, providing the data necessary to design more capable missions in the future.

The most important mission trades are with respect to battery power and overall mass/cost. The mission is scaled for slightly more than one Venus solar day, but could include an initial three-week continuous campaign to characterize the seismic background noise that would reveal details of the planet's internal structure. Should additional mass margin become available, the trade between increased battery mass to allow such a campaign, and the option of an identical second lander – with or without cameras – should be explored to understand, for instance, whether two landers can be located with sufficient accuracy for coseismic analysis.

12.0 CORE SCIENCE TEAM EXPERTISE AND TRACEABILITY TO MISSION OBJECTIVES

The SAEVe team was well suited to implement the study and mission concept presented here (Table 11). The "theme" of SAEVe is focused science that is doable with low data volume instruments/ sensors and which will best capitalize on the long life it will have on the Venus surface. The science objectives of SAEVe are traceable to the unique long-life capability that is offered by the high temperature systems employed and the novel operations approach. The science team, in turn, aligns with this theme and the specific science objectives. Take for example seismology. One of the long standing and important Venus science questions is "How seismically active is Venus?" [29,30,31]. To answer this question one needs to take seismic measurements over a period of months or longer [32]). SAEVe will operate long enough to expect to capture scientifically sufficient seismic measurements and therefore this is a key science objective for SAEVe. The SAEVe team, through Drs. Kiefer, Ghail, Wilson, and Hunter and other study support members, have strengths specifically in the area of Venus geology, geophysics, seismicity and in seismometer development [33,34].

Table 11. SAEVe Team Roles and Responsibilities

Member/Experience	Role	Responsibilities
Dr. Tibor Kremic—Project/Technology Manager—work within science communities and leading technology development.	PI	Study quality / direction and use of funds. Lead science and technology teams.
Dr. Richard Ghail—Planetary geologist / scientist, lead proposer ESA Venus mission.	Co-I	Geology, science objectives, and requirements.
Dr. Martha Gilmore—Geomorphology and spectroscopy of planetary surfaces, Venus science community leader.	Co-I	Morphology and minerology objectives and requirements. Weigh risk/merit for camera package.
Dr. Gary Hunter—High-temperature electronics and seismometers, chemical sensors, and heat flux sensors.	Co-I	Core high-temperature electronics, seismometer and sensors. Lead technologist.
Dr. Walter Kiefer—Geophysicist. Interior modeling and dynamics expert—geophysical evolution of Venus.	Co-I	Geophysical science, seismometry objectives and requirements.
Dr. Sanjay Limaye—Venus atmospheric scientist, Venus science community leader, Venus mission experience.	Co-I	Surface/atmosphere interactions; ties to super rotation, and deep Venus atmosphere.
Dr. Michael Pauken—High-temperature heat flux sensor, instruments.	Co-I	Heat flux sensor details and applications. Instrument concepts.
Dr. Colin Wilson—Interdisciplinary scientist with broad science and mission background	Co-I	Maximize size via synergies innovative concepts, integrating science objectives and measurements.

A similar case exists for the meteorology oriented science. Currently, near surface meteorology data is extremely limited and no data has been acquired over the terminator, a likely time when significant meteorological events may occur. SAEVe seeks to change that with periodic meteorological data over an entire solar day, likely covering both day to night and night to day transitions. In the persons of Drs. Limaye, Wilson, Hunter, and Kremic the SAEVe science team is well aligned to define science and instruments requirements and represent Venus atmospheric science interests. Limaye and Wilson have published extensively on Venus atmosphere science [35]. Both are members of various mission teams such as the Venera-D science definition team, lead role on the ESA M-5 Envision proposal team, members of several other proposals, and Dr. Limaye is also participating scientist in residence for the Akatsuki mission which is focusing on the Venus atmosphere. Dr. Hunter has long standing expertise in developing high temperature sensors for harsh environments and is supporting Venus community as VEXAG Executive Committee member and well as being lead for one of the two Venus focused small sat mission studies under Venus Bridge. Dr. Kremic is PI on the LLISSE development project which is developing and testing, meteorological sensors as well as other systems and sensors for Venus surface applications. He also has extensive roles and experience in Venus science communities and teams such as the VEXAG, including Executive Committee member for several years, member of the Venus Flagship study, member of the joint US – Russian Venera-D science definition team where is the technology lead, and has been lead for several Venus workshops and interchange meetings.

SAEVe also seeks to perform long duration monitoring of key chemical species for variability over solar time and also potentially capture any outgassing or other events. This will help understand planet / atmosphere interactions and help identify potential sources for chemical species in the Venus atmosphere. Drs. Limaye, Wilson, and Hunter support these science objectives having extensive publications and experience in atmospheric chemistry and, for Dr. Hunter, developing and applying high temperature chemical species measurements, particularly in harsh environments [36].

A heat flux instrument is included on SAEVe. This instrument, along with the complementary measurements of the solar radiance sensors and the supporting atmosphere and surface temperature and wind measurements, will help address surface energy balance questions. Given the expected diurnal and local wind / cloud dynamics, frequent heat flux and supporting measurements must be made to tease out the geophysical heat flux from these other environmental variables. The heat flux instrument is well suited to the SAEVe theme and the instrument has strong support in the science team primarily through Dr. Pauken. Dr. Pauken is the PI for the development of a Venus heat flux sensor currently funded under a NASA PICASSO award. In addition to his extensive experience in developing this instrument he also has additional science support in the persons of Dr. Sue Smrekar of JPL and Dr. Paul Morgan of the U.S. Geological survey in Colorado, both with extensive geophysical science experience. While Drs. Smrekar and Morgan were not officially on the science team, they did provide support to Dr. Pauken and also participated with the SAEVe science team in discussions specific to measuring heat flux on Venus using the SAEVe concept.

The imager(s) are desired for a number of reasons described in earlier sections but because there are no known or expected systems that can function at Venus surface conditions, the imager would be a temporary, short lived package that survives just long enough to take and transmit key images of context, coupling, and morphology. Geologists and morphology experts on the science team include Drs. Gilmore and Ghail. Dr. Gilmore has extensive experience in geology and morphology, has mission planning, implementing, and proposing experience [37,38] and is a current leader in the Venus science community, most notable perhaps as Deputy Chair of VEXAG. Dr. Ghail's expertise is described earlier.

Table 12 summarizes the science team expertise and traceability to the SAEVe concept and science goals. A number of other experts supported the SAEVe team and contributed to this concept, these include researchers, engineers, technologists, mission architects and planners, cost estimators, project managers, and others. The core SAEVe team is greatly appreciative of all the great work accomplished by these unnamed individuals, some of which are part the NASA GRC COMPASS team (NASA Glenn's' concurrent engineering mission design team).

Table 12. Science Team Member Traced to Science Objectives and Instruments

Science objectives	Instrument (s)	Science team champions
Determine if Venus is seismically active	Seismometer, wind speed sensors	Kiefer, Ghail, Wilson, Hunter, Kremic
Estimate location of seismic events	Seismometers on multiple stations	Kiefer, Ghail, Wilson, Hunter, Kremic
Determine current rate of heat loss from the interior	Heat flux, atmosphere and ground temperature, wind speed sensors	Pauken, Limaye, Wilson, Kremic
Estimate the moment exchange between the planet and its atmosphere	Wind speed sensors, wind direction, temperature, pressure	Limaye, Wilson, Ghail, Kiefer, Kremic
Acquire temporal meteorological data to update global circulation models	Wind sensors, temperature, pressure, chemical composition	Limaye, Wilson, Ghail, Hunter, Kremic
Quantify near-surface atmospheric chemistry variability	Chemical composition, wind speed, direction	Limaye, Wilson, Hunter, Ghail, Kremic
Examine local context and rock and soil distribution and morphology	Visible / NIR Camera packages	Gilmore, Ghail, Kiefer, Pauken, Kremic

13.0 CONCLUSIONS

This study confirms that a $100M class small sat mission is not only feasible but can return high-value science from Venus. Despite the nearness of Venus and the similarities the planet has with Earth there is much we don't understand about it, especially at or below its surface. The harsh environment coupled with the challenging atmosphere make both remote and surface in situ exploration very difficult, at least until SAEVe is realized.

SAEVe would take advantage of a future Venus orbiter for both transportation and release to the planet and also for a data relay back to Earth. Other than those functions, SAEVe place no liens on the host orbiter making it an "easy" secondary payload for consideration. Once released for entry by the host orbiter SAEVe uses proven techniques to enter and land.

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) and return science helping us start tackling important science questions including: 1) seismic activity 2) thickness and composition of the crust, 3) meteorology that can help get at superrotation, 4) momentum exchange between the atmosphere and planet, 5) chemical variability, 6) energy loss at the surface and 6) morphology.

This can be realized with the two landers deployed 300 to 800 km apart that make up the baselined mission. Two independent cost estimates were developed to get as good an estimate as possible for this novel mission architecture and concept. One was a parametric estimate by NASA GRC's COMPASS team, and the other was a bottom's-up cross-checked version of a hybrid estimate by The Aerospace Corporation. The study team combined these and predicts SAEVe will cost $106M not including reserves and a single lander version or descope single lander would cost $87 or $71M respectively, not including reserves.

As with any mission concept there are risks. Perhaps the most significant is that we have so little knowledge of Venus' level of seismic activity - we may find that the frequency and magnitude may be far different than anticipated which would impact how long seismic measurements can be taken o may result in not capturing events. This risk will be true for any mission and, in many ways, SAEVe is an ideal way to help us understand the environment so we can better design and plan future missions once SAEVe reveals this fundamental information.

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 are in work, either to the levels needed to implement SAEVe objectives, or at least a good way towards that. For example, the power, electronics, communication systems, and structure required by SAEVe are already in development with plans to demonstrate performance at Venus conditions by end of 2019. The same is true for all of the sensors. The heat flux and seismometer are in development as well, although for these two instruments their current funding does not cover development quite to TRL 6.

SAEVe is an exciting mission that offers the potential to begin addressing long standing science questions in a unique and innovative way. Benefits are low relative cost, ease of integration onto a Venus orbiter mission, great science, and serving as a pathfinder for understanding the Venus surface and interior better so that more sophisticated future landers can be successfull with their objectives.

APPENDIX A. TRACEABILITY MATRIX

Investigations	Decadal Survey Goals	SAEVe Science Objectives	Measurements	Instrument Requirements (descoped version)
Interior structure and dynamics	Characterize planetary interiors to understand how they differentiate and dynamically evolve form their initial state.	**Determine if Venus is seismically active and to what degree.**	**Measure seismic waveform of seismic wave at periods approaching a range of 0.1 to 100 sec.** **Concurrent wind data at same rate as seismic measurement.**	**3-axis MEMS seismograph, initial 60 min continuous campaign followed by triggered measurements (trigger uses 1 axis).** **Use 12-16 bit digitization of seismic amplitude.** **3 axis wind sensor, initial 60 min campaign followed by 2-D triggered measurements for 10 min after seismic event.**
		Determine the structure and composition of the crust and lithosphere.	**Same as above.**	**Two stations (one station) with instrumentation as above.**
		Determine the current rate of energy loss at the Venus surface.	**Measure heat flux at Venus surface and solar radiance**	**Two (1 or 0) heat flow and measurements at landing sites. Measure incident and reflected radiance**
Atmospheric Dynamics, composition and surface interaction	Understand the key processes, reaction and chemical cycles controlling the chemistry of the middle, upper and lower atmosphere of Venus.	**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 (as much as possible) and for 2 min every 8 h on surface.**
		Acquire temporal meteorological data	**Measurement of p, T, u, v (at 1 Hz) and light**	**3-axis wind sensor measurements for 60 min and then for 3 min every 8 hours.**
		Estimate moment of exchange between the surface and the atmosphere	**Same as above**	**Same as above during Venus day and night**
Surface properties	Characterize planetary surfaces to understand how they are modified by geologic processes	**Determine the morphology of the local landing site(s).**	**Quantify dimensions, structures and textures of surface materials on plains unit.**	**At least 5 (0) panchromatic (800 nm) images, 2 upon descent and 3 on the ground. Two images of seismometer/heat flow package deployment area.**

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