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Exploring Venus with the long-duration lander mission concept 'KYTHERA'

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Abstract

Venus remains a high-priority target for unraveling the fundamental aspects of climate change and planetary evolution. A robotic lander mission to Venus has the potential of addressing the identified key outstanding scientific goals within the Venus exploration roadmap. Here, we present a new mission concept ('KYTHERA') for a long-duration lander system, where we present a new lander design, an entry-descent-landing sequence and corresponding landing site selection and timeline of scientific operations that can support a lander mission of up to 200 Earth days on the Venusian surface. To accommodate the long duration of the mission, the lander was designed with a vacuum-insulated core, cooled and powered by a set of radioisotope-powered Stirling generators. The identified landing site is the Lakshmi Planum region, indicated by a technical and scientific trade off. It was found that a long-duration robotic lander mission to Venus can address most outstanding key science goals outlined in the Venus exploration community. Finally, the results highlight the need for additional studies on the performance and feasibility of instrumentation and materials under Venus' harsh surface environment.

Keywords: Venus; Robotic lander; Mission concept; Planetary exploration; Atmosphere

1. Introduction

Venus remains a high-priority target for unravelling the fundamental mechanisms behind climate change and planetary evolution, as reflected in the science goals defined by the Planetary Decadal survey and other organizations (National Research Council, Vision and Voyages for Planetary Science in the Decade 2013–2022, 2011, VEXAG, 2019; Widemann et al., 2023). Due to the thick sulfuric acid-rich cloud deck present on Venus, most orbital observations and analyses can only be conducted to a limited extent, and primarily from the nightside (Widemann et al., 2023). For example, despite it being a significant feat, the optically transparent windows of the Venusian atmosphere enable only limited geochemical analyses, primarily measurements of relative FeO* contents of surface rocks and NIR spectral bands (Helbert et al., 2021). Previous successful short-duration landers within the Soviet Venera program conducted the first chemical analyses of the Venusian surface in the lowland regions of Beta-Phoebe (Venera 9,

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10, 13, 14), and the Navka Planitia terrain (Venera 8). Both the Venera and the Pioneer Venus Multiprobe missions also provided insights into the pressure, temperature, and compositional variation of Venus' lower atmosphere. Venus Express provided critical constraints on cloud motions and spatial distribution of key chemical species in the upper atmosphere (Wilson et al., 2022), potentially hinting at present-day volcanic activity (Marcq et al., 2013). However, many aspects of the surface and lower atmosphere composition and dynamics largely remain unknown. This prohibits a quantified understanding of long-term evolution of planetary atmospheres and the divergence between Earth and Venus. A long-lived robotic platform system is a key approach to exploring the Venusian surface and lowermost atmosphere (Kremic et al., 2020). Kremic et al. (2020) proposed an exciting long-duration (~120 Earth days) robotic lander mission to Venus (SAEVe or Seismic and Atmospheric Exploration of Venus) while incorporating several newly developed instrumentations suitable for the Venusian surface. This mission concept is heavily focused on seismic and atmosphere investigations, while maintaining a relatively low lander mass (~45 kg; Kremic et al., 2020). Given the low mass, specific instrumentation for analyzing rocky surface materials were not considered in that concept. However, analyses of Venus' enigmatic surface material are essential for providing geological contact to both past and future orbital observations. This study is therefore focused on a lander mission concept that enables chemical analysis of surface lithologies.

Here, we present an alternative mission concept called 'KYTHERA', which involves a single robotic lander specifically designed for a detailed and prolonged study of the Venusian (lower) atmosphere and surface, including geochemical analyses of surface lithologies. This mission concept was developed as part of the TU Delft DSE project, with 10 students working on the design. We present a lander design, EDL (Entry, Descent, Landing) procedure and an overall timeline of scientific operations, while incorporating power- and thermal management, prioritized scientific instrumentation, optimized lander materials, communications and landing sites of interest, obtained by various detailed trade-off procedures. Our results are also used to highlight potential research topics for future development of comparable mission concepts.

2. Methods

2.1. Science objectives

Venus is essential for understanding the evolution of planetary atmospheres and our solar system, which also extends to exoplanetary systems. The key outstanding science questions for an improved understanding of Venus were compiled by the Venus Exploration and Analysis Group (VEXAG, 2019). They relate to the early evolution of Venus, the degree of its potential (past) habitability, the dynamics of the past and present-day atmosphere, and the structure and composition from the interior to the surface (e.g. Kremic et al., 2020). We have extended, revised and/or clarified, where necessary, the various previously identified science goals that can be potentially addressed with a lander mission to Venus (Table 1). A long-term robotic lander mission to Venus has the potential to address most of the identified outstanding research questions. This includes a detailed assessment of the evolution of the water cycle, surface composition, interior structure, potential tectonics, degree of volcanic outgassing, and atmosphere-surface interactions. However, depending on the chosen landing site, the addressed research goals vary, depending for example on landing site elevation, proximity to potentially tectonic and/or volcanically active sites (e.g. Canali, impact craters, tesserae, coronae) and type of regional geological unit(s). Canali are among the longest volcanic channels in the solar system, and their origin remains enigmatic (e.g. Ghail et al., 2024; Trussell et al., 2025), whereas the composition and formation of the tesserae will shed key insights into the earliest evolution of Venus. Better constraints on the relative ages of impact craters will be important for understanding the nature and mechanisms behind (a) global resurfacing event(s), and therefore on climate evolution. Most notably, the possibility of direct chemical and mineralogical characterization is fundamental for understanding the geology of Venus, and therefore its evolution.

2.2. Requirements

For the mission concept to address the latter science objectives, the following requirements were considered, which can be subdivided into user requirements, mission requirements, and system requirements (Table 2).

Important user requirements are the location and predescent imagery of potential landing sites, which includes mapping of the landing ellipse with a 1-meter resolution. This resolution is required for identification of large potential boulders and minimizing the risks upon landing. A preferred landing within the Venusian volcanic plains is based on both minimizing risks during EDL while characterizing the most representative geological terrains of Venus. Landing site selection was done by considering a trade-off between expected terrain safety, geological terrain type, altitude, and proximity to potentially active geological sites, such as active coronae (e.g. Gülcher et al., 2020), as well as the communication window with the orbiter. Another important user requirement is the ability to monitor the chemical variability of the Venusian atmosphere over time, as the chemical short-term evolution and composition is poorly constrained. The chemical composition of the surface rocks at the landing site will be crucial for calibrating previous and upcoming (orbiter) mission results and, therefore, at least 20 individual chemical analyses need to be performed to explore the mineralogical diversity and to obtain a statistically meaningful surface

Table 1
Revised science goals for exploration of Venus (after VEXAG, 2019) and to what extent these can be addressed by a lander mission to Lakshmi Planum (top) and Lada Terra (bottom). Goals that can be addressed with reasonable certainty are indicated in dark gray and goals that may be addressed are indicated in light gray. Note that the science goals that are likely to be addressed are similar for both landing sites, except for science goals related to interior structure, tectonic features and origin of the Canali.

I. Early Evolution and Potential Habitability					
1. Did Venus have liquid water?	*Fate of early water?*	*Water recycling?*	*Atmospheric water loss?*	*Hydrous minerals?*	*Variability of D/H ratios?*
2. Is or was Venus habitable?	*Origin of volatiles & late veneer*	*Past habitability?*	*Organics in clouds?*	*Cloud habitability?*	–
II. Atmosphere Dynamics and Composition					
3. What drives global atmosphere dynamics?	*Origin & evolution of runaway greenhouse*	*Mechanisms of super-rotating atmosphere*	*Present-day deep atmosphere dynamics*	*Present-day upper atmosphere dynamics*	*Vertical coupling*
4. What governs composition & radiative balance?	*Atmosphere interactions*	*Aerosols & haze*	*Unknown UV absorber*	*Volcanic outgassing*	*Radiative balance*
III. Geologic structure, history and processes					
5. Structure and composition of interior	*Crustal thickness*	*Chemical & physical stratification of mantle*	*Size, composition & physical state of core*	*Thermal state & heat flow*	*Magnetism?*
6. What geological processes shape the surface?	*Global resurfacing?*	*Past geological activity?*	*Present geological activity?*	*Geochemistry & mineralogy*	*Crustal differentiation*
7. Impacts and tectonics	*Age of impact craters*	*Tesserae formation*	*Coronae formation*	*Mechanisms of interior heat escape*	*Present-day tectonically active?*
8. How do atmosphere and surface interact?	*Local weathering*	*Global weathering*	*Chemical interactions*	*Mineralogical evidence of past climate?*	*Evolution over time*
9. Regolith processes and morphology	*Physical properties of regolith*	*Effect of supercritical CO_2 on surface properties*	*Mass-wasting processes*	*Sedimentary processes*	*Origin of Canali*

Table 2
Assumed top-level requirements.

	User requirements
TLR-UR1	*The lander shall be deployed within a < 200 km landing ellipse within the volcanic plains of Venus*
TLR-UR2	*The lander shall map the expected landing ellipse with a resolution of 1 m/pixel*
TLR-UR3	*The lander shall conduct atmospheric chemistry analysis every 12 h throughout its operational lifetime*
TLR-UR4	*The lander shall conduct continuous seismic investigation throughout its lifetime*
TLR-UR5	*The lander shall conduct >20 chemical analyses of the surface throughout the mission's lifetime*
TLR-UR6	*Each instrument suite shall have an individual probability of successful analysis greater than 80%*
TLR-UR7	*Any terrestrial contamination shall remain within the limits established by COSPAR planetary-protection agreements*
	Mission requirements
TLR-MR1	*The operational life of the lander and its analytical packages shall exceed 200 Earth days*
TLR-MR2	*The total cost of the lander and analytical packages shall be less than 600 million EUR (2025 value)*
TLR-MR3	*The lander shall be delivered by another Venus mission that includes a data-relay orbiter*
TLR-MR4	*The data-relay orbiter shall operate in a 24-h elliptical orbit around Venus and achieve orbital insertion between 2035 and 2038*
	System requirements
TLR-SR1	*All subsystems and components shall have a TRL greater than 5*
TLR-SR2	*The power subsystem mass shall not exceed 25% of the total system mass*
TLR-SR3	*The individual probability of successful entry, descent, and landing shall be greater than 90%*
TLR-SR4	*The combined mass of the lander, including all analytical equipment, shall be less than 360 kg*

composition estimate for Venus globally. These measurements require the use of Raman LIBS (Laser-induced breakdown spectroscopy), as these techniques provide both constraints on mineralogy and absolute chemical composition (e.g. Clegg et al., 2014a), addressing many science goals outlined in Table 1.

A long-duration lander mission to Venus provides the unique opportunity to conduct detailed seismic analyses of the Venusian interior and to monitor the chemical composition and dynamics of the lower-most atmosphere over time. An important requirement is that the lander and its associated analytical and experimental packages shall survive for more than 200 Earth days (approximately one Venus day) on the Venusian surface. This is required for maximizing the likelihood of observing seismic activity (i.e. an open-ended observation strategy) and to monitor the lowermost atmosphere dynamics during almost a Venus day. The lander is expected to be delivered by another Venus mission that includes a data-relay orbiter which will be in a 24 h elliptical orbit (e.g. Venus Express; Kremic et al., 2020). For this mission concept study, an orbital insertion date of 2035–2037 was therefore assumed (Table 2). All system components were required to have a Technology Readiness Level (TRL) greater than 5 (or be capable of reaching TRL > 5 within a reasonable timeframe). The power subsystem mass was constrained to be less than 25% of the total system mass, and the combined lander mass was limited to under 350 kg (Table 2). Another important requirement is that potential forward contamination of the Venusian atmosphere and surface must be prevented at all costs. The proposed mission can be classified according to COSPAR (Committee on Space Research) to a Category II mission: there is significant interest in Venus' chemical evolution, but contamination by organic or biological materials is not considered a risk (COSPAR, 2024).

In terms of the mission requirements, a key requirement is the operational life of the lander and corresponding analytical packages of at least 200 Earth days. The proposed mission duration enables the observation of nearly two Venusian solar days (≈ 1.7), allowing the study of potential illumination-driven effects in the poorly constrained lower atmosphere. An extended operational period also increases the likelihood of detecting seismic activity and capturing chemical variability, enabling a more detailed characterization of near-surface atmospheric dynamics, including wind patterns, wind speeds, and temperature variations. Another key mission requirement is the total budget of the lander and analytical package of 600 million EUR (2025 value) – excluding operations and launch, which is close to or within the estimated range of other Venu lander mission concept budgets, including the VFM lander (Beauchamp et al., 2021) and the Venera-D mission concept.

3. Results

3.1. Landing site selection

The nature of the landing site region is of key importance for both science operations and engineering aspects. One key requirement is that the landing site should be situated ideally within a geologically representative terrain of Venus. Another important requirement is that the terrain type(s) considered must reasonably allow for the safe landing of the lander. This precludes consideration of mountainous terrains such as the enigmatic tesserae (Ivanov and Head, 1996). Nevertheless, a detailed assessment of the expected topography of the landing site remains highly speculative, given the relatively low resolution of available Magellan synthetic aperture radar data (i.e., >10–15 km with 100–250 m/pix for imaging, >50–100 vertical resolution; Saunders et al., 1990). However, the volcanic plains are relatively flat overall, with larger-scale topographic deviations of +/- 1 km relative to Venus' mean radius (Ghail et al., 2024). They also constitute up to 80% of the Venusian surface (Ivanov et al., 2015), depending on definition criteria, and therefore are representative of most of Venus' geologic evolution over time since the major resurfacing event(s) (e.g. Strom et al., 1994). From the Venusian basaltic volcanic plains, the unit identified as rp1 (regional plains, lower unit, Ivanov and Head, 2011; Appendix section A.1) is the most abundant, covering ~31% of Venus' surface. These plains are observed to be morphologically smooth and can be traced almost continuously around the globe (Ivanov and Head, 2011), making it an excellent unit for future exploration. Within the rp1 terrain, two potential landing sites were identified, after careful consideration of the VEXAG road map science objectives, engineering constraints and other trade-off criteria, as discussed in section 2.1 and Appendix section A1. The two potential landing sites are located within Lakshmi Planum and Lada Terra.

Lakshmi Planum is a large plateau in the western Ishtar Terra region bordered by Freyja Mons to the north and Akna Mons to the west, both intensely deformed terrains (Fig. 1). It has two large complex crater systems, Collette Patera (Ø = 149 km) and Sacajawea Patera (Ø = 233 km). The preferred 200 km diameter landing site within this region is located towards its northern-based region, centered at 69.6° N, 33.0° W. The area has an elevation of ~2900–3200 m, corresponding with an estimated surface temperature of 430°C and a pressure of 77 bar (Lebonnois et al., 2010, 2016; Martinez et al., 2023). To the south and south-west three coronae (Omosi-Mama, Beiwe and Xilonen) are situated, of which one is deemed to be inactive and two of ambiguous present-day activity (Gülcher et al., 2020). This may be problematic for coronae-proximal seismic work. However, given the elevation of the landing site, the *P-T* conditions and corresponding pressure-dependent chemical reactions may be less representative relative to Venus overall. On the other hand, the lower *P-T* conditions would provide larger lander design margins.

The other identified potential landing site is situated within the Lada Terra region as a 100 km radius circle centered at 68.8°S, 19.0°W (Fig. 1). This rp1 region is the southernmost of the three major continental regions of Venus and is characterized by many potentially active coronae. The most interesting of these is Quetzalpetlatl Corona, the largest corona on Venus. There are numerous

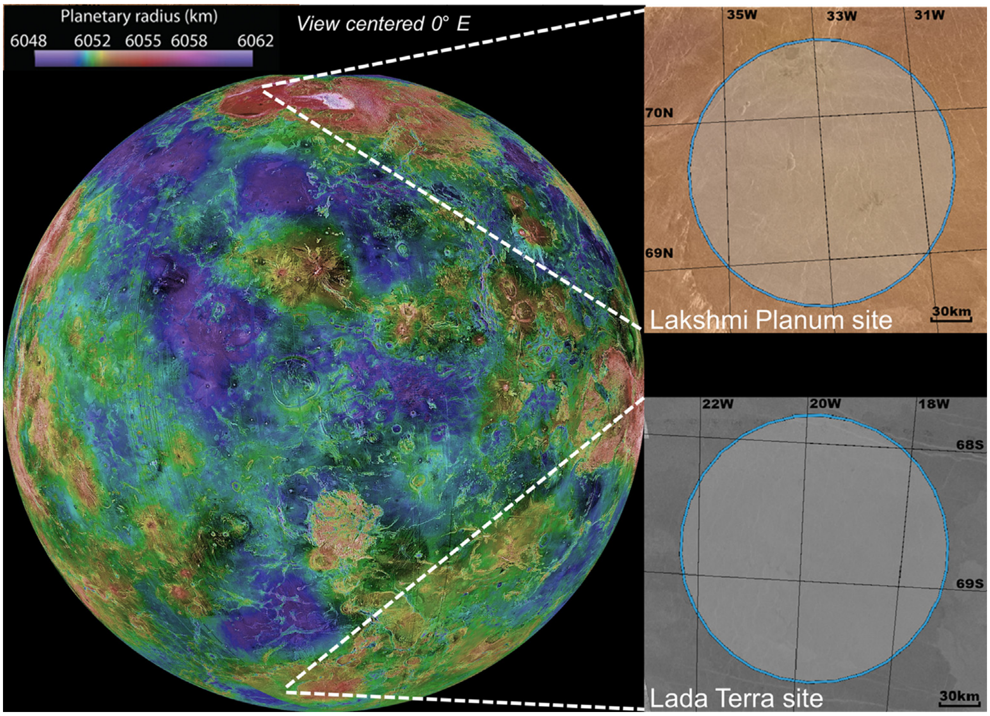

Fig. 1. Overview and position of both landing sites on Venus.

nearby potentially active geological features, including Quetzalpetlatl itself (Gülcher et al., 2020). These features make the Lada Terra landing site more interesting from a seismological point of view, as proximity to these features could provide more information about Venus's internal structure and tectonic activity (Table 1). In addition, the landing site is located within a topographically low area, yielding an estimated average pressure of 93 bar and a surface temperature of 464°C. This makes the surface conditions most representative of Venus globally, but technically more challenging. Finally, Venera data suggests the risk of rougher terrain for this landing site.

Several other landing sites and regions were considered but ultimately not selected due to expected terrain deformities, poor spatial coverage, or lack of distance to the most scientifically interesting features (Appendix section A.1). Ultimately, based on currently available information, it was deemed that both landing sites are approximately equal in potential scientific value and, as such, Lakshmi Planum was chosen given the less hostile *P*-*T* conditions, until a more thorough analysis can be done. Kremic et al. (2020) briefly discussed potential landing sites and proposed Lakshmi Planum plateau to be a landing site of major scientific interest, reinforcing this conclusion.

3.2. Lander design

Fig. 2 shows the designed lander with corresponding power, mass, and size budgets listed in Table 3, whereas Figs. 3 and 4 detail the deployable seismometer arm and EDL lander configuration, respectively. The main modules of the lander are the cold box (hidden within the hot box), the landing ring and struts, drag plate, legs, and two Stirling radioisotope generators (SRGs). The cold box contains most of the experimental and analytical equipment that requires cooling for optimal performance (Fig. 2). The overall structure is like the Venera landers, a result of the narrow structural design options for enduring the harsh Venusian surface environment. Details on the drag plate, and lander leg and/or impact ring structure are largely beyond the scope of this study, but a preliminary assessment can be found in Appendix section A.6. Here, we focus on the designed active cooling system and associated choice and placement experimental and analytical packages within the lander.

3.2.1. Power and thermal control

Given the harsh environment of Venus, active cooling methods are essential for the lander to survive longer time scales (i.e., hours). The Venera landers did not have active cooling units and the longest surviving mission at the Venus surface lasted <2 hrs. The main cooling function will thus be achieved by active coolers and passive thermal control methods, which are implemented to supplement cooling and reduce the workload of the active cooling system. Besides thermal control, the power subsystem is essential for powering instruments onboard. The main components of the power subsystem include primary power (i.e. generating electricity), secondary power (i.e. storing electricity, for use during high electricity demand), and distribution systems. A single Stirling cycle-based system can be used to provide both active thermal control and power

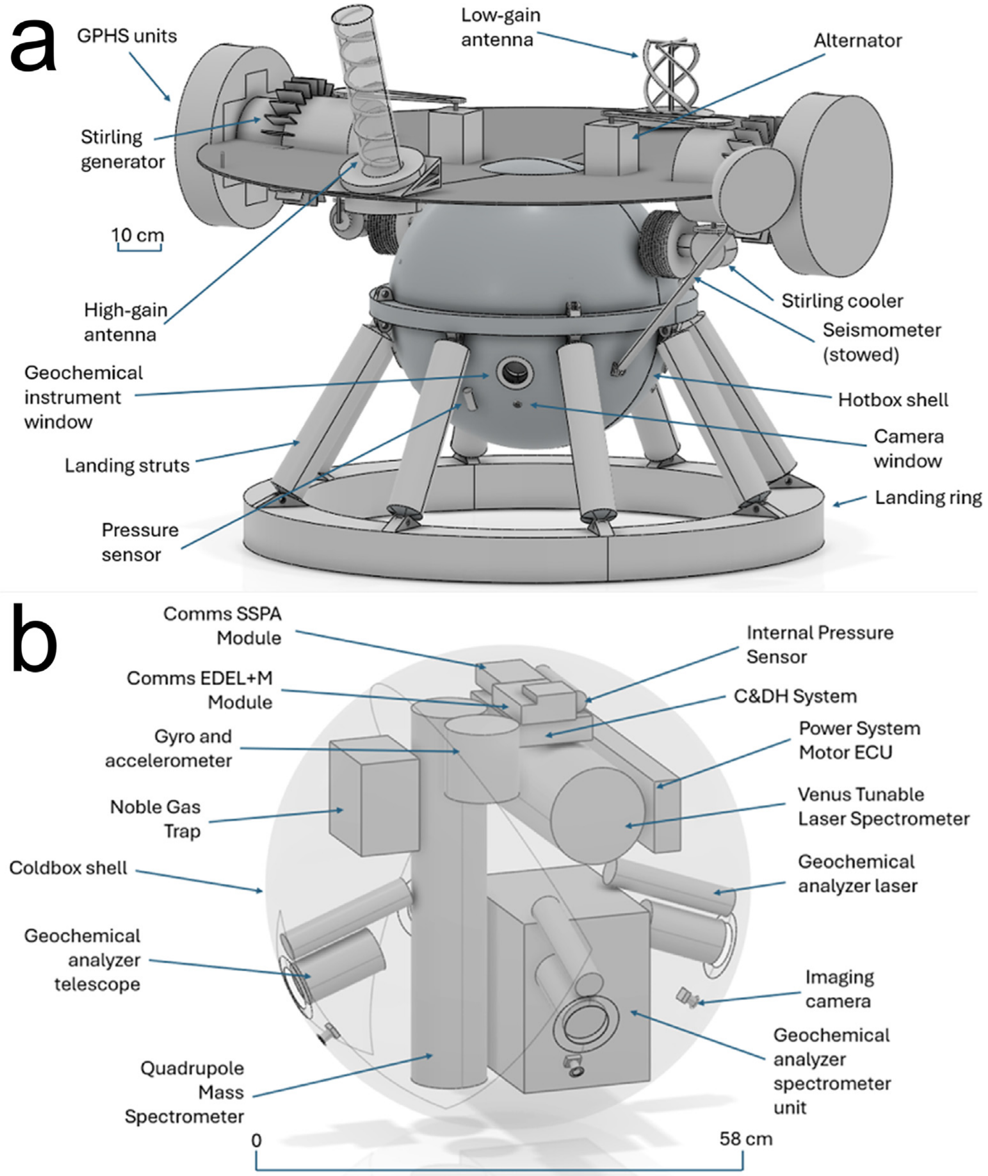

Fig. 2. Configuration of the KYTHERA lander (a) and cold box (b).

generation. Power and thermal control is therefore considered to be a single subsystem for the lander concept. It consists of seven general purpose heat source (GPHS) elements producing thermal energy from Pu-238 decay (Landis and Mellott, 2007; Landis, 2021), that is converted by the Stirling radioisotope generator (SRG) to mechanical energy. Due to the high working temperature of these elements, both SRGs are placed on the drag plate (Fig. 2). The authors understand the challenges and potential hazards through the launch and use of SRGs (e.g. Graves, 2016). However, our own trade-off study and other authors have shown previously that the use of an SRG power system is essential, now and in the foreseeable future for enabling a long duration Venus lander mission (Landis, 2021). This is mainly due to their potential capability of providing heat for very long periods (months to years) (Salazar et al., 2014).

During cruise, the internally generated heat and received solar radiation power will be transported out of the aeroshell by a two-phase loop heat pipe (LHP) system to the Cruise Heat Rejection System (CHRS). These LHP systems can provide transport powers up to 24 kW and start up on their own as soon as a threshold temperature gradient is built up, making them ideal for this application. Mishknis et al. (2008) tested an LHP setup intended for European Mars rovers of ∼254 g and a maximum power transfer of 80 W. The mass of the LHP aboard the lander's EDL subsystem is linearly extrapolated from this design, giving an LHP mass estimate of 17 kg, including a 50% margin. The LHP system is mechanically attached to the

Table 3
Lander configuration (power usage, mass, size; where available).

Component	Power (W)	Mass (kg)	Dimensions (cm)	Refs
Structural components				
Cold box	–	8	58 (OD)	–
Hot box	–	56.3	65 (OD)	–
Legs (8x)	–	65	8 (OD), 3.5 (ID), 25 (l)	–
Impact ring	–	51.9	70 (OD), 45 (ID), 10 (h)	–
Drag plate	–	37.5	144 (Ø)	–
Struts (4x)	–	20	8 (OD), 3.5 (ID), 53 (l)	–
Sum		***238.74***		
Power and thermal system				
Generator mechanism (2x)	–	43.2	–	–
Cooler mechanism (2x)	–	3.2	–	–
GPHS modules (14x)	–	20.2	–	–
Battery	–	2.0	–	–
Wiring and distribution (+15%)	–	10.0	–	–
Sum		***76.6***		
Experimentallanalytical packages				
Camera	2 [8]	0.0025 [9]	1.45 (l) × 1.81 (w) × 1.95 (h)	–
EDL LN-200S IMU [a]	12	0.748	8.89 (Ø), 8.51 (h)	–
NASA Glenn Seismometer	0.1	0.3	20 (Ø) × 20 (h)	K20
QMS	14.5 [72]	1.3 [72]	9.1 (Ø) × 46 (h)	T24
VTLS	27.1 [71]	3.7 [73]	12 (Ø) × 35 (h)	M12
LLISSE Radiometer	1	0.35	5 (l) × 5 (w) × 10 (h)	K17
NASA Glenn pressure sensor (external)	0.005	0.03	2 (Ø) × 5 (h)	–
Keller PAA-33X pressure sensor (internal)	0.28	0.25	27 (Ø) × 12 (h)	–
Thermometer	–	0.2	2 (Ø) × 20 (h)	–
Wind sensor (drag-force anemometer)	0.001	1	0.84 (Ø) × 4 (h)	W22
Geological analyzer suite				
4 Raman / LIBS lasers	40–70 [86]	14.7 [90,b]	3.5 (Ø) × 16.1 (l) (laser)	W21,M21
4 telescopes			5.5 (Ø) × 10 (l) (telescope)	–
Spectrometer unit			22 (l) × 16 (w) × 21 (h)	–
Sum		***22.6***		
Grand sum [d]		**356.4**		

***Refs:** K17 = Kremic et al. (2017), K20 = Kremic et al. (2020), M21 = Maurice et al. (2021), W21 = Wiens et al. (2021), W22 = Wrbanek (2022), Trainer et al. (2024) [a] IMU = Internal Measurement Unit (3 gyroscopes, 3 accelerometers) [b] The mass of the SuperCam telescope was assumed to be 1/3th of the SuperCam mast mass (Maurice et al., 2021). The laser length and telescope length were decreased by 30 and 50%, respectively, given volume considerations and would require a certain degree of re-engineering of performance and properties. [c] Required power depending on power transmission mode (50 W) or power science code (30 W). [D] Including communications and command and data handling systems (see Appendix section A.5).

aeroshell and is located on the drag plate above the heat exchangers (Fig. 2).

To absorb the heating power of the SRG heat source during entry while the aeroshell is attached but the CHRS is not available, a phase-change material is used. Paraffin waxes (e.g., n-Triacontane) are often used for this purpose because of their noncorrosive nature and high heat of fusion.

To provide cooling after landing without high electrical power demand, passive thermal control strategies also needed to be designed. The lander's two-shell design will be used to the advantage of thermal control. The hot box operates under ambient temperature, both during cruise and on the surface. During cruise, the cold box also operates under ambient temperature, where it may experience heating up to 60°C, based on the limits of the paraffin wax cooling. In the current configuration, the cold box will heat up to 30°C once the lander lands on the surface with active cooling engaged. The pressure within both the hot and the cold box is to be as close to a perfect vacuum as possible through the mission, eliminating most conductive or convective heat transfer. The only heat leaks of concern are those through radiation and through any mechanical connections between the two boxes. To maintain this vacuum, getters are implemented, which react with gases and turn them into solid materials or absorb them. Examples of potential getters for the cold and hot box are Zr-V-Fe alloys and alkali earth or rare earth metal alloys, respectively. The total heat leak, using this two-shell vacuum configuration, is estimated to be 174 W. To minimize radiative heat leak (i.e. minimize hotbox size) while still allowing a connection between both boxes, the hot box size was constrained to 64 cm in diameter, with a difference between the cold box and hot box radius of 3 cm.

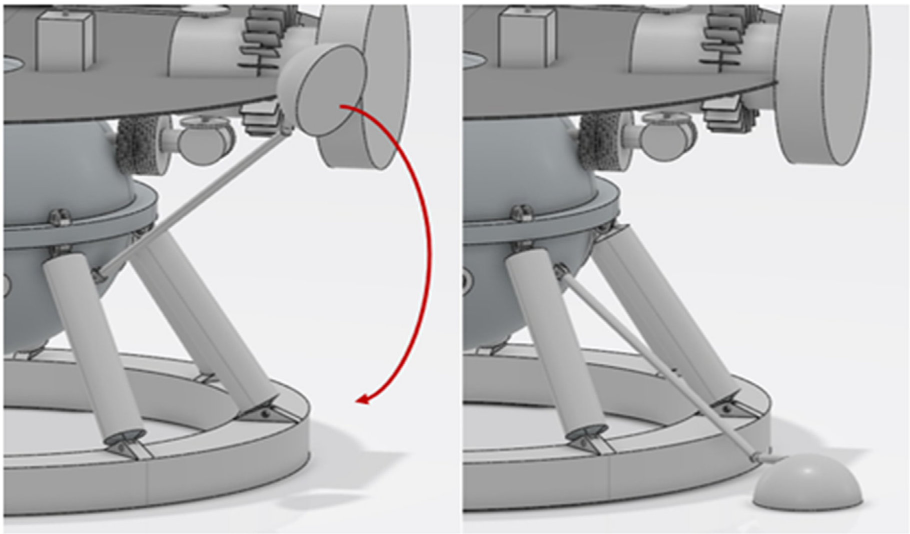

Fig. 3. Details of seismometer deployment arm.

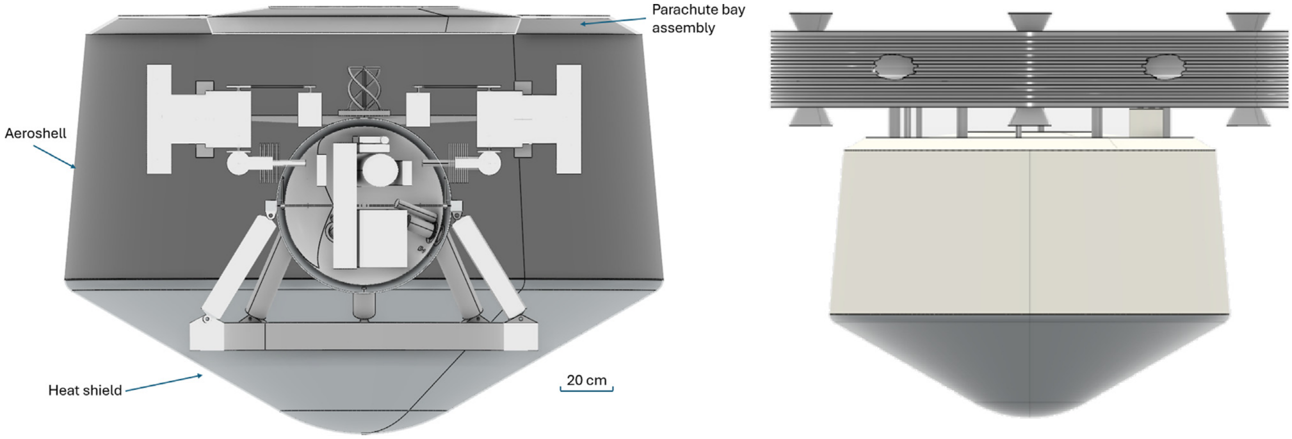

Fig. 4. EDL lander configuration (left) and entry capsule with coasting stage (right).

3.2.2. Experimental and analytical packages

The experimental and analytical packages were selected based on a trade-off, where the scientific return of each instrument was weighted against mass, power consumption, data handling, and durability (Appendix section A.3). Most instruments, except for a seismometer, were designed to be placed in an actively cooled compartment of the lander, the cold box. This cold box provides a structure for the delicate instruments to be mounted on and to maintain a stable, lower temperature for the electronics to function nominally. The cold box contains the following instruments, after a careful assessment of the identified science goals (section 2.2), listed with their masses and dimensions in Table 3. The design of the cold box was optimized by a best-fitting approach using the CATIA$^{(C)}$ software, while incorporating at least >1 cm distance between each instrument.

An important component is the Venus Mass Spectrometer suite (VMS), consisting of a Quadrupole Mass Spectrometer (QMS), VTLS (Venus Tunable Laser Spectrometer) and NGT (Noble Gas Trap), which have been developed for NASA's DAVINCI mission (e.g. Trainer et al., 2024). However, this set-up is tailored for rapid chemical analyses during DAVINCI's descent and not for prolonged exposure to the surface environment or repeated sampling cycles (Trainer et al., 2024). A revision of the design will therefore be needed, which includes enclosing the entire instrument with a thermally insulated, actively cooled and pressure-resistant compartment. Additional redesign includes lengthening the existing entry and exit capillaries to increase the pressure drop as well as required active cooling of the NGT instrument. It would also require merging of the VMS and VTLS instruments. However, after adaptation of the instrument suite it will be able to measure a wide range of atmosphere species, such as elemental abundances of Cl-, F-, S-bearing species with great precision, abundance and ratios of all noble gases as well as isotope ratios (e.g. D/H). Analyses obtained with these instruments directly address numerous identified science goals related to atmosphere composition and short- and long-term evolution (Table 1).

The cold box also contains the geological analyzer suite, which consists of a spectrometer linked to 4 telescopes with Raman LIBS laser pairs (Fig. 2). This instrument suite will be used to determine both the abundance of trace, minor, and major elements as well as mineralogical diversity, essential for characterizing surface geology, thereby directly addressing various key science goals (Table 1). The use of stepped motors will allow for deviation from the nominally designed 20° angle (i.e., 3 m distance) of the laser systems. These motors will allow for movement of the laser between 8° and 40° angle, corresponding to an effective analysis range of 1–7 m, within the analytical range of Raman LIBS spectroscopy. The lasers are designed to move 45° horizontally, so that the entire landing site can be effectively analyzed.

Given the necessity for deployment and functioning, a NASA Glenn HOTTech seismometer was selected and designed to be placed outside the lander (Dai et al., 2023). This seismometer incorporates a combination of highly durable materials, shock resistant structure, and high-temperature silicon carbide electronics. The seismometer will be directly deployed on the ground, to mitigate any noise transmitted from the lander's body. This results in a better coupling of the seismometer with the surface, shielded from lander-induced noise, allowing it to detect authentic seismic activity more reliably. The seismometer deployment mechanism is a spring-loaded passive mechanical arm (Fig. 3). In case of a lack of a suitable site, a secondary mechanism is activated that can rotate the arm by 30° for a more favorable placement site. A small explosion in a frangible nut will release the hatch and allow for careful placement of the seismometer, with the use of mechanical dampers. Finally, the lander contains a Venus-environment resistant wind-sensor, radiometer and *P-T* sensor (Appendix section A.3).

3.2.3. Communications and command & data handling system

A monofilar right-hand circularly polarized (RHCP) axial-mode helical antenna has been selected as the primary high-gain antenna (HGA) for the lander. LHCP could also be used, provided polarization is matched, but RHCP was chosen based on heritage and readily available components. To extend relay duration and improve reliability, a secondary low gain quadrifilar helical antenna (QHA) is also employed. Both antennas are mounted on the drag plate, directly exposed to Venusian surface conditions (Fig. 2). The antenna is mounted with a fixed offset of 20.4° and has a motor stage attached to the mounting that allows for antenna rotation on its vertical axis by ±180°. This mobility allows orientation of the antenna towards Venus's north pole, which is where the apoapsis of the orbit will ensure maximum relay window duration. The half-power beamwidth of the HGA is around 42.49° and enables a relay time of around 12.7 hrs per 24-hr full orbit. The QHA will also be mounted on the drag plate, opposite the HGA. It provides limited coverage but will still be able to transmit data to the orbiter for 1.9 hrs per orbit. Both antennas are connected to a shared transceiver capable of toggling between transmission and reception modes using a time-division duplexing scheme. Communications with the orbiter will operate on the L-Band wavelength at 1.2 GHz. This frequency experiences minimal atmospheric attenuation and scattering, ensuring robust signal propagation through the Venusian atmosphere while keeping antenna size within mission constraints. Additionally, the transceiver employs a Binary Phase Shift Keying (BPSK) modulation scheme in combination with Forward Error Correction (FEC) schemes to achieve a target bit error rate (BER) of 1E-06. The transceiver is housed within the actively cooled cold box and actively maintained at 30°C. The total uplink data volume per orbit is approximately 6 MB. The same antennas are used for downlinking, with the downlink data rate constrained to 400 bps to preserve a high link margin and ensure robust data delivery. The three main elements of the lander's Command and Data Handling system are the central processing unit (CPU), the volatile memory, and the non-volatile memory. Advanced compression algorithms are used by the lander to optimize the use of the limited amount of data that can be sent back.

Fig. 5 shows a relay simulation, with the primary antenna covering the apoapsis of the orbit where the orbiter has the slowest velocity to maximize the communication window. The secondary antenna provides additional relay time during science mode when the orbiter passes close to the lander and provides redundancy in the event of primary antenna failure.

3.3. Mission timeline

3.3.1. Entry – descent – landing (EDL) procedure

The atmospheric entry stage is one of the most structurally critical phases of the mission due to the high loads encountered within this phase. A primary and a backup interplanetary transfer window was selected with arrival dates of 28th June 2036 and 25th Jan 2038, respectively. On these dates, the landing site will be situated on the sunlit side of Venus, and coarse optical mapping of the landing ellipse is possible. Fig. 6 shows the EDL operation timeline. The time between the atmospheric direct entry and landing is estimated to be approximately 57 min, and the optimal flight entry angle was calculated to be between ~ –11 and –12.8°. The lander and entry capsule will be transported to Venus on a transfer stage. The lander will perform atmospheric entry directly from the interplanetary transfer trajectory. The transfer stage delivering the KYTHERA spacecraft will also act as the relay satellite. The spacecraft will be equipped with a Coasting Stage (CoS). To prevent overheating between launch and entry, a radiative cruise heat rejection system (CHRS) is integrated into the CoS

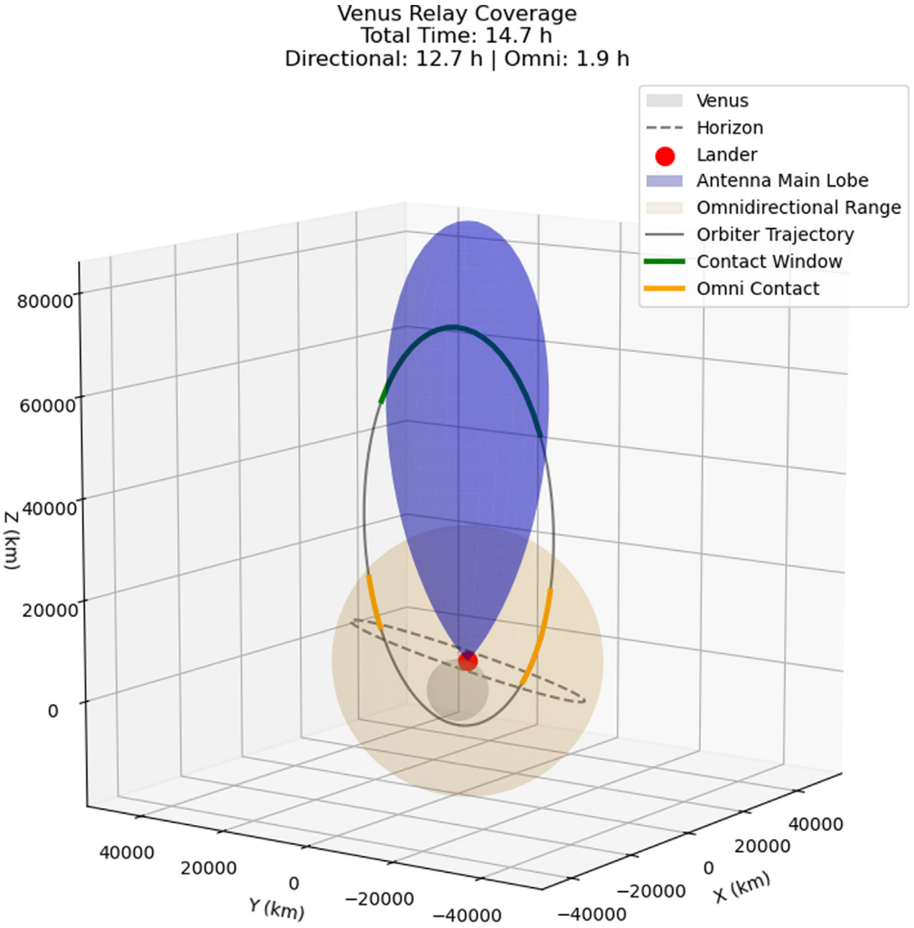

Fig. 5. Simulation of the communications relay model. The depicted horizon plane is directly affected by the lander location and can be optimized by increasing latitude or altitude when choosing landing sites. The omnidirectional coverage overlay shown is a preliminary approximation of the QHA radiation pattern – a more realistic model should be generated in more detailed design phases.

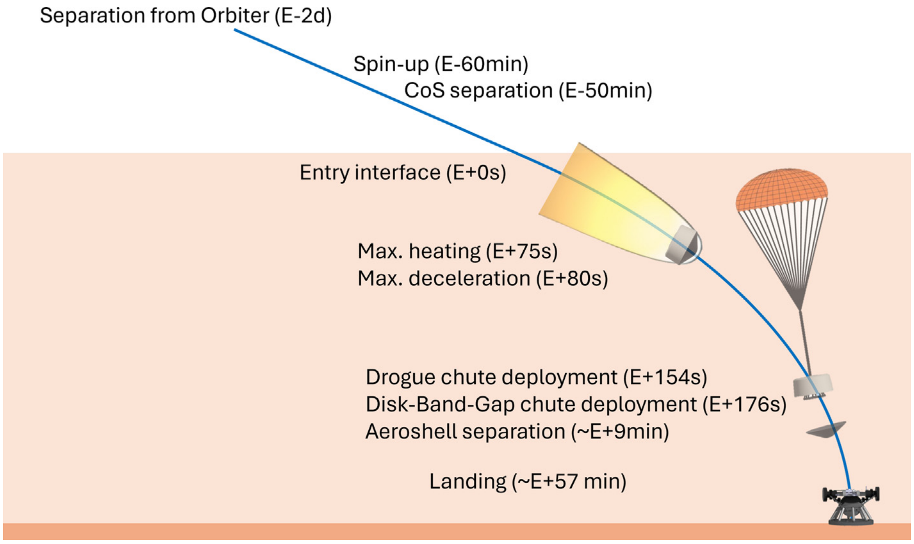

Fig. 6. **O**verview of the EDL timeline for an entry trajectory at –12.8° entry flight path and 12 km/s entry velocity.

to radiate heat into space and keep the internal lander temperature below 60°C. The EDL system will orientate the spacecraft with the main heat shield facing the flight direction. The spacecraft will be spun up to 13.5 RPM before entry, at an altitude of ~ 250 km, to provide the vehicle with gyroscopic stability during entry. An attitude determination and control system (ADCS) consisting of star trackers and gyros for determination, as well as a set of thrusters for control is incorporated into the CoS, performing the necessary course corrections and the spin-up. The CoS is not equipped with thermal protection and is detached 50 min prior to entering the atmosphere. The electrical and thermal interfaces are cut using pyro charges. The CoS is mechanically separated by a spring system, as these are better for applications than explosive solutions, when low tip-off rates are required. The drogue parachute will be deployed at 65 km altitude, between E + 154 s and E + 209 s (Mach 0.8). Once the vehicle has slowed down to approximately Mach 0.6 at an altitude of 61.5 km, a disk-band gap parachute system is employed to facilitate safe separation of the thermal protection system (Fig. 6). Initially, it will be reefed and then gradually unreefed over 10 s to minimize shock loads on the lander, parachute lining and mount. 20 s after the initial parachute deployment, the parachute state stabilizes and the heat shield is separated with pyrobolts. After heat shield separation, the EDL camera will take four photos throughout the descent to obtain an overview of the landing site region prior to landing. After 5 min of heat shield separation, the aeroshell is jettisoned as well, along with the parachute, leaving the lander in free fall. A drag plate is attached to the lander's body for stabilization and additional de-acceleration in the final stages of descent. The time of parachute deployment varies greatly with the trajectory chosen. Because of this, a g-switch, a timer and a pressure sensor will be used in combination to initiate the parachute deployment. The use of an AI-based hazard identification software in conjunction with the 1-meter resolution map of the landing ellipse of the final 1–2 km landing zone obtained during descent will conduct real-time hazard assessment, maximizing the chances of a successful landing, and post-landing contextualization.

3.3.2. Science operations

Fig. 7 lists the planned detailed payload operation times of the instrumentation discussed in section 2.2. Upon descent, science operations will start. The VMS instrument suite will conduct analyses every ~200 m, like the DAVINCI probe. Approximately 5 min after landing and settling of potential dust (Kremic et al., 2020), the camera will acquire one image per viewing port with a 3840 by 2160-pixels per view resolution of the landing site. This will provide fundamental context for interpreting subsequent chemical analyses of the landing site lithologies and is crucial for assessment of the terrain for the seismometer deployment. After identifying an optimal location, the seismometer is deployed (see section 3.2.2). From this moment onwards, the seismometer will continuously conduct seismic analyses of the Venusian subsurface (Fig. 7). The 200 Earth days mission duration is meant to maximize the potential detection of seismic activities. The wind sensor, radiometer, and *P*-*T* sensors will also be continuously operating from this point onwards.

The VMS suite will repeat an analysis cycle every ~12 h, yielding valuable insights into potential short-term variations in atmospheric composition, enabling detailed investigations of chemical gradients. This time window is based on the duration of each VTLS measurement (6 hr) and QMS analysis (1 hr), with a sufficient time margin for potential delays. A 200 Earth-day series of atmospheric analyses would yield unprecedented analyses of the chemical variability of the Venusian lowermost atmosphere. The required 20 geochemical analyses of surface materials using Raman LIBS is estimated to take 40 min for each individual analysis, with an initial LIBS (to remove dust) and subsequent Raman analyses at each site (Maurice et al., 2021). Depending on the first analytical results, additional target sites can be further optimized.

The thermal evolution of the lander is of key importance for the success of a prolonged duration lander mission to the Venusian surface. For this concept, a thermal evolution model was constructed (Appendix section A.4). Fig. 8 depicts the predicted thermal evolution of the lander during the first 12 h after landing. The preliminary modeling results show that the desired temperatures can be maintained by the proposed active cooling system. However, more detailed studies would have to be conducted for additional validation.

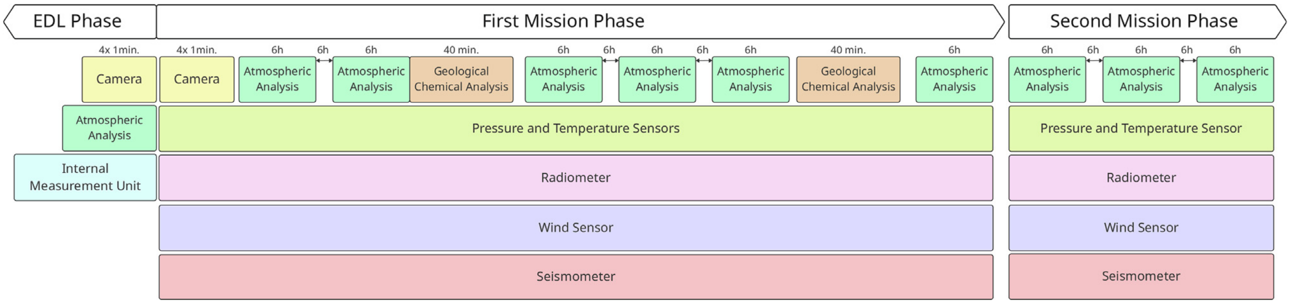

Fig. 7. Suggested payload operating timeline. Note that this is merely to demonstrate which instruments are continuously operating, and that the size of the boxes does not represent the operating time.

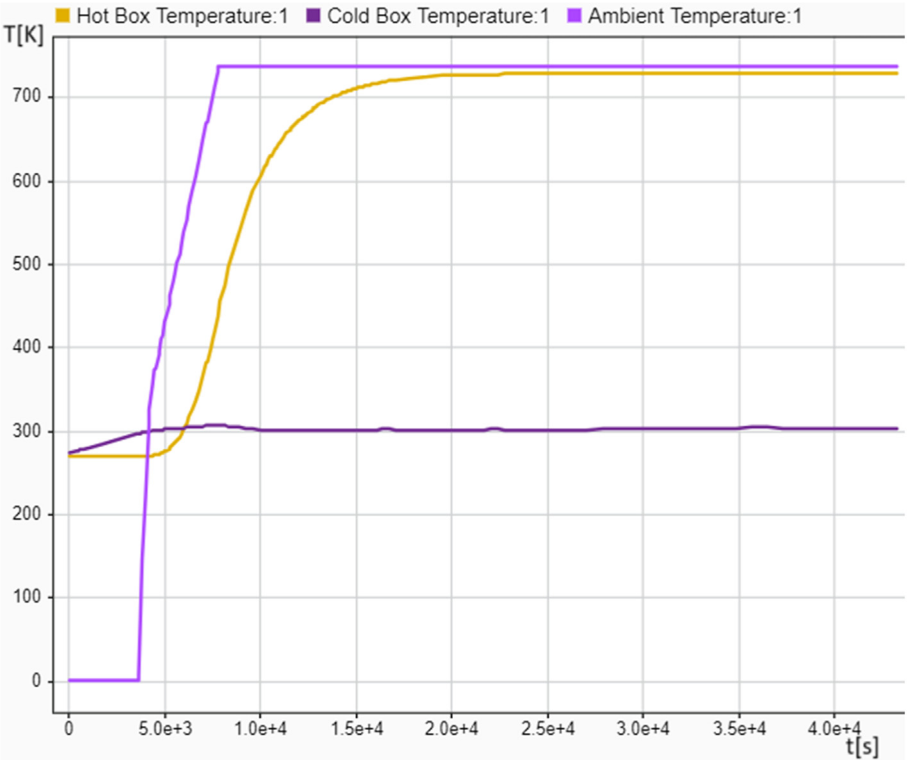

Fig. 8. Modeled hot box, cold box and ambient temperature during the first 12 h after coasting stage separation. Note that the temperatures remain constant shortly after landing while SRGs are used to actively cool the system.

4. Discussion & outlook

4.1. Required technical developments

A long-duration lander mission would revolutionize our understanding of Venus and would provide ground-truth calibration of decades of past and future orbital and remote observations. However, various technical aspects presented here require more detailed (experimental) assessment at the conditions directly relevant to the present-day Venusian surface (e.g. Kremic et al., 2020).

The mission feasibility largely relies on the availability of SRGs and therefore is associated with significant technological risks. One important required development is thus the adaptation of the proposed SRGs to the Venusian surface conditions and subsequent validation of thermal and electrical performance in relevant environments. For example, Venus' atmospheric super rotation wind may induce vibration or resonance to the SRGs that is not yet fully characterized. In 2021, Landis et al. concluded that the proposed SRGs can be considered at most TRL 4 (Mankins, 2009), because none of the technologies here have been tested on Venus. Further development and testing are clearly needed to qualify power generation and storage technology (Landis et al., 2021) and application of these systems to the Venusian environment. In-depth validation of the thermal evolution of the cold box needs to be conducted in more advanced lander design stages. This includes running detailed transient models with component-level heat dissipation, higher-fidelity 3D thermal fluid models with instrument thermal maps, radiative coupling networks, and associated uncertainty margins. For additional redundancy, a third SRG could be considered in future design steps. This might be close to or within the proposed mass budget and would allow one-out redundancy. Note that it would take approximately two days to reach 400 K and ten for 500 K with a single generator, so significant science could still be done. Finally, potential getters for the cold and/or hot boxes (e.g. Zr-V-Fe, alkali earth or rare earth metal alloys) should be explored under the relevant *P*-*T* conditions to determine reaction and absorption rates with gas that may leak into the system.

In terms of proposed seismic package, there is a potential risk of (a) smaller boulder(s) (<1 m) being present beneath the landing ring after touchdown, thereby preventing the seismometer from reaching the surface. An alternative, flexible, rope-based vertical deployment mechanism should be explored in more advanced design steps to ensure reliable surface contact. This alternative design would also likely mitigate any potential effects of the seismometer arm's joint stiffness on the quality of the seismic measurements. If it is decided to go forward with the proposed set-up here, the frangible nut and mechanical damper system proposed for the NASA Glenn HOTTech seismometer system will also need to be tested under Venus-relevant surface conditions.

The proposed sizing of the SuperCam laser and telescope system by 30 and 50%, respectively, because of volume limitations (Table 3), would also require reassessment of its spectral capabilities and quantification of the impact on the proposed scientific operations. The L-Band radio communications electronics will also need to be developed and tested for use under the Venus environment.

Lander structures and materials also require further detailed study. For example, the behavior and types of material selected for the lander's legs, such as potentially steel foam, and impact ring materials, require more detailed investigation, as well as the types of and preferred welding materials and approaches.

4.2. Uncertainties regarding scientific operations and analyses

In terms of scientific operations and analyses, several aspects remain uncertain. For example, seismic activity may be significantly different, in terms of magnitude and frequency than expected (Kremic et al., 2020), or unexpected poor ground coupling of the deployed seismometer. The considered individual probability of successful analysis greater than 80% for each instrument may also be optimistic. Serial-dependent instrument chains, for example during the proposed Raman-LIBS analyses, multiply failure rates and yield additional uncertainties that are now difficult to quantify. Ambient noise from potential wind or atmospheric pressure variations may also complicate seismic data interpretations.

The chemical composition of Venus' lowermost atmosphere could remain constant within the timescales of the proposed lander mission. The proposed landing site(s) may have significant smaller-scale topographical features or steep local slopes, which cannot be excluded based on currently available radar maps. Although Raman LIBS is an ideal instrument for a Venus lander mission based on instrument studies and trade off procedures, LIBS spectra do depend on atmospheric pressure, with a lower intensity under Venus conditions, relative to Mars and Earth (Arp et al., 2004; Clegg et al., 2014b; this study). Thus, some additional characterization of Venus analogs may be required under conditions directly relevant to the Venus surface. The proposed large pointing range of the lasers (approximately ±45°) corresponds with a relatively large window aperture. This will affect the optical transmission characteristics on LIBS performance and overall measurement quality. The application of anti-reflectance coating should greatly decrease any potential energy loss, but this should be tested in subsequent design stages. In terms of temperature, Raman spectra show a predictable shift of about 10 cm^{-1} at 1273 K, which is relatively well constrained (Sharma et al., 2007).

Finally, adapting the VMS suite for surface lander operations will require significant re-engineering. The VMS suite was originally designed for rapid descent and short exposure. The proposed 200-day surface exposure with ≤12-h atmospheric sampling cycles therefore requires mitigation strategies. Specific difficulties that must be addressed include the prevention of potential clogging of sampling inlets, as observed during the Pioneer Venus descent (Donahue et al., 1982), as well as the possible malfunction of sampling valves under Venus surface pressure–temperature conditions. Clogging may be mitigated through the use of heated inlet tubes, which can vaporize or thermally decompose sulfuric acid droplets before they accumulate within the inlet system. Sintered metal sphere filters may be employed to remove large aerosols. As implemented in the DAVINCI VMS suite, two separate sampling inlets are required, each optimized for different atmospheric regimes: one designed for operation in aerosol-rich cloud layers and another optimized for sampling the lower atmosphere below the cloud deck. In addition, careful optimization of capillary geometries and conductance, together with appropriate *in situ* calibration protocols, will be necessary to ensure stable gas flow and reliable compositional measurements under Venusian conditions for a 200 Earth-day mission.

A number of these topics can be addressed in the existing GEER (Glenn Extreme Environments Rig) or within the newly established Delft High-Pressure/Temperature Laboratory for Planetary materials (Steenstra et al., 2026), among others, where the exact pressure, temperature and atmosphere conditions of Venus surface can be simulated. Such facilities are essential for advancing the various proposed technical components to TRL-6.

5. Conclusions

In this study, we present a new long-duration lander mission concept to Venus. A new lander design was developed that can survive for up to 200 Earth days on the Venus surface, while conducting a wide variety of chemical analyses, using a set of Stirling radioisotope generators and a detailed cold/hot box design. The proposed mission concept can address most of the science goals outlined in the (revised) Venus Exploration Roadmap and the Visions and Voyages for Planetary Science in the Decade 2011 document. Many of these goals cannot be addressed by conventional orbiter missions, highlighting the necessity of a future long-duration lander mission to Venus to fully understand this enigmatic planet.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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