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Potential Contributions to Solar System Exploration

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LONG-LIVED IN-SITU SOLAR SYSTEM EXPLORER (LLISSE), Potential Contributions to the next decade of Solar System Exploration. T. Kremic¹ and G W. Hunter¹, ¹NASA Glenn Research Center, 21000 Brookpark Rd., Cleveland, OH 44135 USA, tiber.kremic@nasa.gov, gary.w.hunter@nasa.gov

Introduction: Venus, while having similar size, mass, and location in the solar system to Earth, differs from Earth in key ways and holds many scientific mysteries despite the number of missions that have targeted it in the past. Primary known differences from Earth include climate, atmosphere, and perhaps most notably the extreme surface conditions. Remote sensing techniques to study Earth and other planets are not as effective at Venus. Global sulfuric acid clouds and the CO₂-dominated atmosphere make remote sensing difficult at Venus. In addition, Venus surface conditions present formidable engineering challenges to landers due to the high temperature, pressure, and reactive chemistry. To date, landed missions have not been able to last more than about 2 hours on the surface, limited in landing site options, and could deploy only one lander per mission [1]. Such short durations have resulted in significant knowledge gaps about the surface conditions of this important body in the solar system. The science community has effectively no in-situ *temporal* data even for basic measurements such as temperature, pressure or winds near the Venus surface. These data are critical for the development of a thorough understanding of Venus' weather, and the processes by which chemical species interact with each other and are transported throughout the atmospheric column.

Advances in technology, such as silicon carbide (SiC)-based electronics and high-temperature sensors, have matured to a state where a simple but long-life scientific lander is feasible for Venus. An entire self-contained lander is being developed under the current LLISSE project by integrating high-temperature power, avionics, and communication subsystems with an instrument/sensor payload capable of measuring temperature, pressure, wind speed/direction, radiance, and atmospheric specie abundances over time. Further, LLISSE is combining this system with a novel operations approach to create a game-changing paradigm for exploring the surface and deep atmosphere of Venus.

LLISSE is a small (~10 kg and <20 cm/side) yet completely independent lander that can be delivered to the surface of Venus via its own aeroshell, brought in with a large short-duration lander, or dropped from a balloon during float. The LLISSE project includes development of the lander and its instruments / sensors as listed in Table 2 [2]. An aeroshell design is not part of the LLISSE project but a LLISSE specific entry system design is being initiated under other NASA projects. As of early 2020 most of the systems are at Technology Readiness Level (TRL) of 4. Several items at TRL 5 or higher but there are a couple elements, that are transitioning from 3-4 due to being a late augment to the project (such as the radiance sensors) or are simply a more complex development effort like the high temperature transmitter. LLISSE platform, and its variants like Seismic and Atmospheric Exploration of Venus (SAEVe) or LLISSE-Tech Demo (LLISSE-TD), are a foundation for future mission concepts based on a core set of long-lived technologies that will demonstrate new capabilities and provide unique new science data by measuring key meteorological parameters on the Venus surface over 60 Earth days. After development, LLISSE has the potential to be a complementary element to Venus missions enhancing the science return possible with orbiters or short-duration landers alone.

Science: LLISSE focuses on science that 1) stands most to benefit from long-duration

surface operations (several Earth days or more) and 2) can be accomplished with a low energy (mW) and data budget (Mbit/day or less). LLISSE's science objectives and key measurements, listed in Table 1, leverage LLISSE technical capabilities. Meteorology data is relatively low in data volume both in terms of a single measurement and also in the required sampling rate. The same is true for radiance measurements which are made using high-temperature bolometers. By using micro-electro-mechanical sensors (MEMS)-based chemical sensors, atmospheric species abundances over time can also be measured in a way that leverages LLISSE's strengths and fits its science objectives.

Table 1 reflects LLISSE science objectives and traceability. All LLISSE goals can be traced to the current version of the Planetary Science Decadal Survey and VEXAG guiding documents. The key questions addressed by LLISSE include better knowledge of super-rotation of the atmosphere (Goal 1, Objective B), the climate and its evolution (Goal 1, Objective B), and surface-atmosphere interaction/weathering (Goal 3, Objective B).

Table 1: LLISSE Science Objectives

Decadal Survey Goals	LLISSE Science Objectives	Measurements	Instrument Requirements
A) Define the current climate on the terrestrial planets	1) Acquire temporal meteorological data	Measurement of pressure, temperature, wind speed and direction, and radiance	2-axis wind sensor measurements, radiance, measure temp. and press.
	2) Estimate momentum exchange between the surface and the atmosphere	Same as above	Same as above
B) Understand chemistry of the middle, upper and lower atmosphere	3) Determine key atmospheric species at the surface over time	Measure the abundance of gases H ₂ O, SO ₂ , CO, HF, HCl, HCN, OCS, NO, O ₂	Chemical sensor measurements
C) Determine how solar energy drives atmospheric circulation and chemical cycles	4) Determine the rate of solar energy deposition at the Venus surface	Measure incident and reflected solar energy	Measurements of radiance

Development Plan and Status: Development of LLISSE a flight-like hardware is ongoing. The product will have similar form, fit, and function as a spaceflight version but without all the flight materials, hardware rigor, process controls, or cost. The current development plan calls for the flight-like hardware to be built and tested for life and performance in Venus conditions by the middle of 2024. This version would be a primary battery-powered LLISSE with a life goal of 60 days and communicating at ~100 MHz at power levels that would support a communication link to an orbiter ~70,000 km above the Venus surface.

While the LLISSE project itself has been in existence for ~3 years, it should be noted that the background capability and some of LLISSE's components have been developed over many years by other aerospace projects like jet engine development diagnostics. In the last 3 years, however, tremendous progress has been made on several key fronts. For example, a key goal is to drive up electronics complexity to enable avionics that could control all LLISSE functions. Integration of the increasingly complex electronics into fewer integrated circuits (IC) allows for a

simpler system and lower power needs. Since project start, devices per IC has increased by ~2 orders of magnitude and is nearing the level required to execute the LLISSE mission as intended. At the sensor level, versions of all sensors that were part of the baseline sensor suite have been developed and tested up to the full 60 day life goal. Table 2 provides more details on development and testing status of the sensors.

High-temperature electronics are particularly enabling for LLISSE, and represent a primary development focus. Si-based electronics generally used on missions do not operate at Venus temperatures [3], which require the use of wide bandgap electronics, such as SiC. SiC-based electronics have been chosen for LLISSE due to the design choices available in a small package, their capability to withstand harsh environments for prolonged time periods, and their ability to support complex ICs. Recent work has notably expanded capabilities and produced the world's first microcircuits of moderate complexity (Medium Scale Integration). These microcircuits have been shown to operate for thousands of hours at 500°C [4-7] as well as operation in Venus simulated conditions for 60 days.

The communication system is the second critical subsystem, and many of its components are in development. Tests have been conducted on materials compatibility, and basic functionality for some of the components. The power driver components are in design, and fabrication and will be tested in the coming months. Designs for the non-power communication electronics have been designed and tested in Venus surface conditions. These electronics are not yet proven at 100 MHz, the minimum targeted transmission frequency, but feasibility and basic functionality of multiple aspects of the communications' system has been demonstrated [8].

The primary battery is third and final critical subsystem. Work to date has focused on refining cell chemistry to not only function properly at Venus surface conditions but to also minimize self-discharge in support of the 60-day operating goal. Development and life testing of battery chemistry has resulted in great improvement in expected life when following the LLISSE concept of operations profile. Over the last 2 years of development, cell life has increased from a couple hours to well over a month. Although that time frame is still a little short of the full 60-day goal, work continues on further promising improvement options. Work is also progressing toward packaging and multi-cell configurations to make progress toward a complete battery.

Structure, interconnections, and other aspects such as material selections also continue to progress. Figure 1 shows a recent setup in a simulation chamber at NASA Glenn known as GEER (Glenn Extreme Environment Rig). This activity was undertaken to test how the GEER system interacts with the various system components, and how those components interact with each other under simulated Venus surface conditions. Ongoing work is building up to a full breadboard system-level demonstration.

A near-term focus of the project is on completing the electronics and communications that support higher operating frequency, lowering power demand of the electronics, completing the work toward 60-day battery life and packaging,

Figure 1. Recent test setup of LLISSE components in GEER showing SiC circuit boards, high temp wiring, and a bus. A battery case is also in the picture.

and completing the balance of the sensor development. A full performance system demonstration is planned for late 2021/early 2022 to verify the ability to execute performance and life objectives at a system level.

Table 2 summarizes current Technology Readiness Levels (TRL) of the various LLISSE platform subsystems and sensors, and the funding source when applicable.

Table 2: Technology Readiness for LLISSE and Potential Augmentations

Technology ¹	Current TRL	Development / testing status as of summer 2020	Funding Source: Ongoing (O) (to TRL 6) and Potential (P)
Electronic circuits: sensors and data handling (L)	5	Progressively complex integrated circuits (SiC JFET ICs) developed and tested in GEER and laboratory setting including successful testing in Venus conditions up to 60 days. Circuit design completed for complexity needed to execute LLISSE goals and currently in fabrication.	LLISSE (O)
Electronic circuits: power management (L)	3-4	Circuits (SiC BJTs) in development for power switch/management based on demonstrated prior short-duration prototypes. Transitioning this to enable long-term Venus durability by leveraging durable IC processing knowledge. First generation SiC BJTs in fabrication.	LLISSE (O)
Communications (100 MHz) (L)	3-4	100 MHz RF/power management devices in concurrent development. SiC JFET based communication circuit demonstrated at lower frequency. Communications system/antenna design baselined. 100 MHz circuit integration, antenna characterization, and system testing planned	LLISSE (O)
Wind Sensor (L)	4-5	Prototype versions with high temperature electronics designed and tested in Venus conditions. Tracking measurement of environmental changes in Venus conditions demonstrated. Improvements to sensor and driving electronics towards meeting LLISSE specs designed and in fabrication. Integration and testing in a multi-axis system planned.	LLISSE (O)
Temperature Sensor (L)	5	Multiple initial tests of wide T-range sensors have been completed in Venus conditions including successful 60 day test. Stable measurements achieved consistent with other temperature measurements were achieved. Tailoring of design to meet LLISSE measurement specifications ongoing.	LLISSE (O)
Pressure Sensor (L)	4-5	Two wide pressure range sensor designs demonstrated in harsh conditions. Demonstrated integration with electronics, and 12 days of operation/ 60-day survival of sensor element in Venus conditions. Meeting LLISSE measurements specifications is next focus.	LLISSE (O)
Chemical Sensors (L)	5	Four chemical sensors successfully tested in Venus conditions for 60 days with SO ₂ sensor tracking concentration changes and consistent with gas chromatograph readings. HF sensor with SiC electronics responded to concentration changes in 12 day testing.	LLISSE/HOTTech (O)
Solar Radiance(L)	3-4	Baseline design approach established and prototype bolometer sensors fabricated. Relevant materials tested in Venus conditions, next generation design changes have been identified, and are being fabricated.	LLISSE (O)
Seismometer	3	MEMS approach based on flight ready seismometers baselined. High temperature electronics approach identified and trial electronics in fabrication. Evaluation of modified MEMS seismometer in Venus conditions and integration with electronics planned.	LLISSE (O) and possibly ROSES awards
Camera / imaging System (short lived)	4	System designed, fabricated, and tested. First iteration was successful in achieving nearly all the thermal / life objectives.	GRC (O) and possibly ROSES awards

1) Items designated with “(L)” are part of the baseline LLISSE project - otherwise it is a future augment

2) TRL 6, as used here, is toward the ability to meet performance and life objectives at Venus surface conditions.

The LLISSE concept/and its subsystems:

Figure 2 is a rendering of a conceptual version of LLISSE on Venus. The sensors will take measurements periodically (every 8 hours), however, for the final flight version, timing of measurements will be determined in coordination with the orbiter with which LLISSE communicates. LLISSE's surface life would cover the duration of a Venus daylight period (1/2 solar day), including the terminator at one or both ends of that period.

Figure 2. Concept of LLISSE on Venus.

Capabilities that enable LLISSE include: 1) high-temperature sensors, electronics, communications, and power generation; 2) Low power and data volume science measurements; 3) Creative operations approach, periodic data transfer coordinated with orbiter; and 4) High-fidelity test/validation capability, in particular the Glenn Extreme Environment Rig (GEER) [9].

As noted, the TRL levels shown in Table 2 are based on LLISSE's ability to meet performance and life objectives on the Venus surface. Since launch and orbit parameters are not yet known, verification against those requirements are not yet possible. However, LLISSE is being designed to meet those future requirements based on conservative estimates of those requirements.

Because LLISSE is a small lander it can serve as a platform, or on-ramp for future technology advances. For example, under NASA's HOTTech program technology investments have been made on high-temperature solar cells [10] [11], re-chargeable batteries [12], [13], and other components that show promise. A high-temperature solar cells coupled with a high-temperature re-chargeable battery may allow longer operating life. The LLISSE project is following these and other developments, and will leverage them as appropriate.

LLISSE Concept of Operations: A scientifically significant and programmatically exciting application of LLISSE could be to serve as the "long-lived station" complementing a Venus orbiter or short-duration lander. LLISSE is deliberately designed to be a supportive element on other missions to Venus, be they orbiters or landers. Its small size and mass, its self-contained approach (Figure 3 and 4), and its complementary and compelling contribution to temporal scientific measurements, make it a good candidate for a U.S. Venus flagship mission. It could be considered for inclusion to competed missions proposed to NASA Discovery or New Frontiers calls, or on missions led by other national space agencies. For example, LLISSE is part of the baseline Roscosmos Venera-D mission concept [14] and would be attached to, and support, the main lander science of that mission. If attached to a large lander LLISSE would leverage the entry and then implement its own objectives independent of the lander and the lander's operating life. This keeps lander interfaces relatively simple although the orbiter would need to receive both LLISSE and lander communication signals operating at different frequencies.

LLISSE could readily be inserted into a small entry shell like Pioneer Venus or, better yet, a new entry shell designed with the NASA developed HEEET Thermal Protection System (TPS). This would become a complementary element to an orbiter (Figure 4) and would serve as demonstration of the entry system, an objective for NASA Space Technology Mission Directorate. Under such a scenario, the interfaces with the orbiter would be very simple. Physical connection would be through an appropriate spin table and would require only a release function by the spacecraft during the cruise stage. The only other interface would for the orbiter to receive the RF signals from the entry system (i.e., critical events and entry system engineering data) and from

LLISSE (for science contribution and its engineering data), and relay those data to Earth.

One final aspect of LLISSE to highlight is that there are opportunities to vary the capability and purpose of LLISSE. A series of studies has shown the viability of using the core LLISSE technologies, but adapted to different platforms to meet specific science or technology objectives. Figures 3a–b) show illustration of battery and wind powered versions of LLISSE, respectively. Figure 3c) shows a modified and enhanced LLISSE, called the SAEVe lander [15], which targets interior and atmospheric studies by adding a seismometer, heat flux measurement, and short-lived cameras to the basic LLISSE payload. Figure 3d) shows the Venus Bridge Orbiter and Surface System (V-BOSS) concept [16, 17], which is targeted for coordination with an orbiter for even better science return, e.g., IR imaging coupled with IR bolometers for operation at the surface, as well as for localized chemistry and composition measurements.

Figure 3. Artist's conceptions of the LLISSE platform and its various embodiments: a) Early concept for a battery-powered LLISSE after deployment; b) Wind-powered LLISSE after deployment; c) SAEVe lander; d) V-BOSS lander; e) Notional comparison of the V-BOSS lander to a Venera lander; f) A version of LLISSE mounted on a traditional, larger lander.

Overall, the various versions of LLISSE platform envisioned span a wide gamut including: a tech demo version of LLISSE that would establish the basic capability to survive and communicate from the surface of Venus (Figure 4): the LLISSE version in development (60-day life with scientifically relevant measurements); more sophisticated versions as captured in the recent SMD-funded planetary SmallSat study like the SAEVe lander; or the Venus Bridge study lander/orbiter pair (V-BOSS) referenced above. The more sophisticated versions of LLISSE have larger mass and volume, but also increased life and more instruments such as seismometers, cameras, and other sensors or instruments.

Figure 4. Conceptual Technology Demonstration version of LLISSE

Conclusion: LLISSE is a novel and exciting small Venus lander that is in development through testing of EM-fidelity hardware. LLISSE will have the potential to provide the first ever long-duration science from the surface of Venus, enabling new prolonged investigations of climate/weather, energy balance, and surface–atmosphere interactions.

LLISSE is designed to be a complementary element for virtually any Venus orbiter and/or landed mission. It is relatively easy to integrate and has minimal impact to its partner mission. It can be scaled from a technology demonstration item to more a sophisticated scientific element that may address unique and compelling science—potentially even seismology and local morphology.

As planned, the life and performance capability of a scientifically useful LLISSE will be demonstrated by end of 2023. Flights of a technology demonstrator version of LLISSE is feasible starting as early as the mid-2020s.

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