# An Overview of High Temperature Technologies for Venus Surface Applications

**Gary W. Hunter**
**NASA Glenn Research Center**
**Cleveland, OH**

International Conference and Exhibition on High Temperature Electronics Network (HiTEN 2022)

# Outline

- Introduction
- Venus Technology Plan
- Venus Surface Platform Study
- Long Lived Platform Development
    - Electronics
    - Sensors
    - Communication
    - Power
- Summary and Future Prospects

# Introduction

- Venus has a very hostile environment with an average surface temperature of 465°C and surface atmospheric pressure of 90 atm. in the presence of corrosive species
- Missions that have landed on the surface of Venus have typically lasted at most ~2 hours due to the high temperatures and harsh conditions
- Long term measurement of Venus planetary conditions has been limited by the lack of electronics, communications, power, sensors, instrument, and actuation systems operational in the harsh Venus environment
- Surface exploration of Venus for extended durations has notable science impact and is becoming more viable
- This presentation will provide a sampling of high temperature development and technologies that may have an impact on future Venus surface exploration

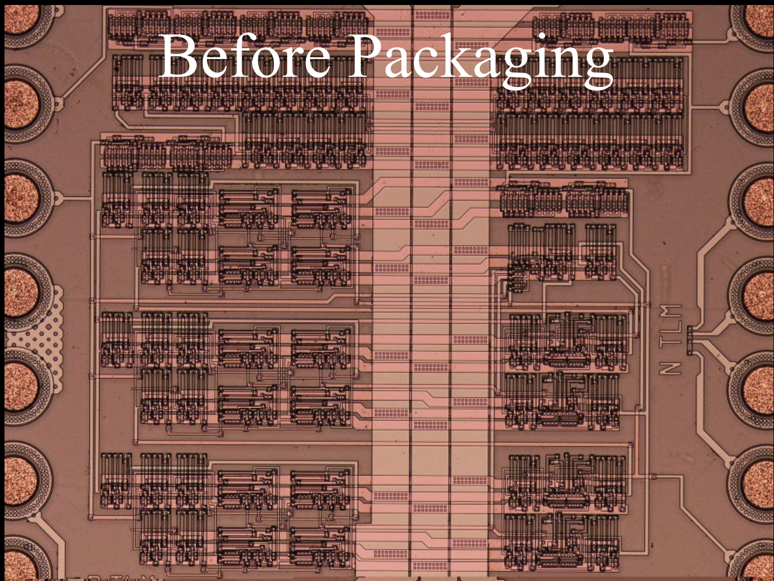
# Technology Development Overview

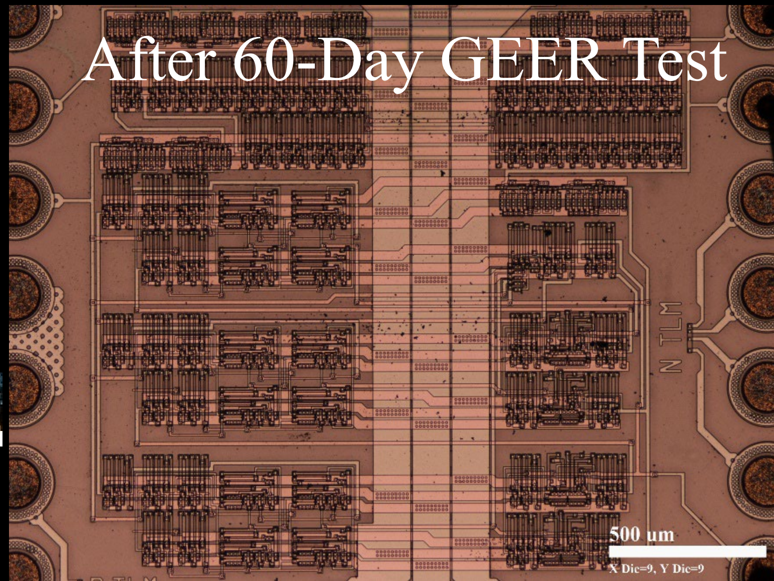
- Technologies relevant for Venus surface applications may often have their origin in other harsh environment applications e.g., aeronautics or industrial processing
- Material systems and engineering approaches standardly used for even harsh environment terrestrial applications may not be viable for Venus missions
- A major challenge is operation in Venus surface conditions without significant degradation and for extended periods of time
- Testing of proposed technologies in first at high temperature leading up to Venus simulated conditions include relevant chemistry, is core to technology advancement
- The status of Venus technology development is in some cases at the level of 1970's to 1980's technology; at these levels significant science can be accomplished.
- A mission needs a complete compliment of relevant technologies for success

GEER: 92 atm, 465 °C + chemical composition found at the surface of Venus ($CO_2$, $N_2$, $SO_2$, $H_20$, CO, OCS, HCl, HF, and $H_2S$)

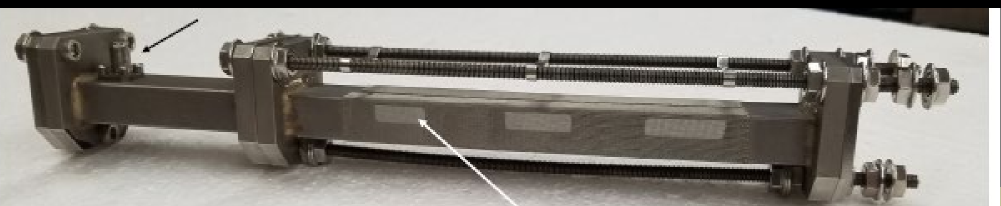
# Material Choice (and GEER Testing) Matters

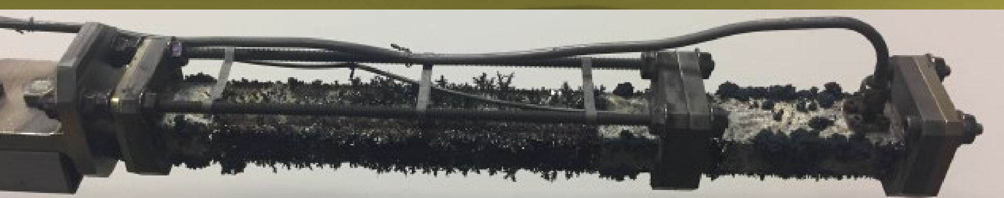
## SiC Clock IC Chip Optical Microscope Photos
## (These IC Materials Work - Chip operated for 60 days)




## Wave Guide Before and After 60 Days of GEER Testing
## (These materials react – grow crystals – will NOT work)





# Evolving "Handbook" of What Works in Venus Ambients

| Devices | Materials | Outcome |
|---|---|---|
| Electronics Packaging | Pb | PbS |
| | $Al_2O_3$ | No reaction |
| Insulation | CaO | $CaSO_3$, $CaSO_4$ |
| SiC Electronics | Pt | PtS; fibers when present as thin film |
| | Pt (in the presence of Au) | PtS spheres |
| | Au | No reaction, but mobile |
| | Ir | No reaction, but mobile |
| | SiC | No reaction |
| | $SiO_2$ | No reaction |
| Feedthrough Materials | Cu | $Cu_2S$ crystals |
| | Ni | NiS crystals |
| | CuBe | $Cu_2S$ crystals; Cl found on surface |
| SiC Pressure Sensor | Kovar (Ni-Co-Fe) | NiS, $Fe_xO_y$ |
| | AlN | No reaction |
| | Ag-Cu Braze | Segregation into $Cu_2S$ and Ag; Ag mobile |
| GEER Components | Inconel 625 (Ni-Cr-Mo-Fe) | NiS, $Cr_xO_y$ |
| | 304 SS | Mirror finish, low corrosion rate |
| | Al foil/Mg doped | MgO on surface, MgF inner layer, Al bulk no reaction |
| New Materials | Sputtered Aluminum | Reacts with HF to form $AlF_3$ |
| | Titanium | Oxide on surface decreasing into bulk |

https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2017EA000355

# VEXAG Venus Technology Plan
# 2019

# VEXAG Technology Plan 2019
# Generic Mission Descriptions

| Term | Mission Mode | Generic Description |
|---|---|---|
| Near-Term | Orbiters- Fixed | Orbiters for investigations including surface, interior, atmospheric, and ionosphere |
| Near-Term | Small Sat | A single small or cube sat conducting a focused science investigation |
| Near-Term | Deep Probe | A probe characterizing the environment down to the surface |
| Near-Term | Multiple Shallow Probes | Shallow probes or skimmers characterizing the upper-mid atmospheres |
| Near-Term | Short Lived Large Lander | A short lived lander comprised of a conventional electronics instrument suite |
| Near-Term | Aerial Platform Fixed | Aerial platforms with ability to operate in the atmosphere for sustained periods, but without flight control |
| Mid-Term | Advanced Orbiters | Highly complex orbiter systems with increasingly capable instrument array and limited ability to independently carry out and optimize investigations |
| Mid-Term | Multiple Deep Probes | Deep probes and sondes coordinated with aerial platform operations and each other |
| Mid-Term | Subsatellite/ Small Sat Platforms | Communication and observations systems able to provide a multiple scientific investigations as well as a communications and navigation infrastructure |
| Mid-Term | Aerial Platforms: Altitude Control Upper and Mid Cloud | Aerial platforms operating in mid and upper clouds with ability to control altitude |
| Mid-Term | Increased Duration Large Lander | A lander comprised of advanced thermal thermal protection extending life to 12 hours or more, and increasingly capable conventional electronics instrument suite |
| Far-term | Small Platform Lander- Long Duration | Small in situ platforms capable of operating at Venus ambient conditions to accomplish focused science investigations |
| Far-term | Advanced Orbiter /Smallsat Networks | An orbiter network composed of advanced orbiters and small sats providing coordinated science and mission communications support |
| Far-term | Aerial Platforms: Altitude Control All Cloud | Aerial platforms with ability to operate in the atmosphere for sustained periods throughout the various cloud altitudes |
| Far-term | Lander -Cooled Long Duration | A complex long-lived cooled landed systems with a suite of advanced earth-ambient temperature instruments |
| Far-term | Lander Network | A number of lander systems coordinated and linked in multiple scientific investigations, which are composed of a mixture of increasingly complex high temperature landers |
| Far-term | Mobile Surface | Mobile laboratory systems able to travel significant distances on the surface |
| Far-term | Sample Return Clouds | Sample recovery and return from the upper atmosphere |
| Far-term | Sample Return Surface | Sample recovery and return from the surface |

# VEXAG Technology Plan 2019
# Near-Term 2018 to 2022 : We Can Do A Lot Now

| | | Near-Term Missions | | | | | |
|---|---|---|---|---|---|---|---|
| | | Orbiters | Aerial Platform Sustained | Deep Probe | Multiple Shallow Probes | Multiple Shallow Sondes | Lander |
| System Technologies | Aerobraking | [green] | | | | | |
| | Entry ⬆ | | [green] | [green] | [green] | | [green] |
| | Descent and Deployment | | [green] | [green] | [green] | [green] | [green] |
| | Landing | | | | | | [green] |
| | Aerial Platforms | | [green] | [green] | [green] | [green] | [green] |
| | Landers - Short Durations ⬆ | | | | | [green] | [green] |
| Subsystem Technologies | Energy Storage- Batteries | [green] | [green] | [green] | [green] | [green] | [green] |
| | Energy Generation - Solar | [green] | [green] | | | | |
| | Thermal Control - Passive | | | | [green] | [green] | [green] |
| | High temperature mechanisms ⬆ | | [green] | [green] | [green] | [green] | [green] |
| | Medium temperature electronics ⬆ | | [green] | [green] | [green] | [green] | [green] |
| | Communications | [green] | [green] | [green] | [green] | [green] | [green] |
| | Guidance, Navigation and Control ⬆ | | MM | MM | | | MM |
| Instrument | Remote Sensing - Surface | | [green] | [green] | | | [green] |
| | Remote Sensing -Atmosphere | [green] | | | | | |
| | Probe - Aerial Platform | | [green] | [green] | [green] | [green] | |
| | In Situ Surface - Short Duration ⬆ | | | | | | [green] |

## Key

| | |
|---|---|
| (white) | Not applicable |
| [green] | Very High. Ready for flight. Same as TRL 6 |
| MM | Mix of Maturity. Some ready for flight but others at various maturity levels |
| ⬆ | Notable advancements since the last Plan |

# VEXAG Technology Plan 2019
# Evalutation Criteria

Key

| | | |
|---|---|---|
| | Not applicable | |
| (green) | Very High. Ready for flight in this timeframe. Same as TRL 6 | Established for flight. |
| (light green) | Moderate to High. Limited development and testing still needed | Defined transitioned to flight. |
| (yellow) | Moderate- Active on-going R&D effort needed for readiness in this given timeframe. | Presently understood technical pathway to achieve capability by this timeframe. |
| (orange) | Moderate to Low: Significant R&D effort needed for readiness in this timeframe | A viable foundation exists, but more than one technical pathway in consideration to achieve capability by this timeframe. |
| (red) | Low. Major R&D effort needed with notable technical challenges. | It not clear how to achieve the targeted capability and basic research activities in multiple fields may be needed to achieve this capability by this timeframe. |
| ⬆ | Notable advancements since the last | |

# VEXAG Technology Plan 2019
# Mid-Term 2023 to 2032: From This Baseline, New Missions and Science in Next Decadal Period

| | Mission Mode | Mid-Term Missions: Advanced Orbiters | Subsatellite/ Small Sat Platforms | Multiple Deep Probes and Sondes | Increased Duration Large Lander | Small Platform Lander-Long | Aerial Platforms Altitude. Control Upper and Mid Cloud |
|---|---|---|---|---|---|---|---|
| System Technologies | Aerocapture | | | | | | |
| System Technologies | Entry ↑ | | | | | | |
| System Technologies | Descent and Deployment ↑ | | | | | | |
| System Technologies | Landing | | | | | | |
| System Technologies | Flight ↑ | | | | | | |
| System Technologies | Landers ↑ | | | | | | |
| System Technologies | Mobility | | | | | | |
| System Technologies | Ascent Vehicle | | | | | | |
| System Technologies | Small Platforms ↑ | | | | | | |
| System Technologies | Automation and Autonomy ↑ | | | | | | |
| Subsystem Technologies | Energy Storage- Batteries ↑ | | | | | | |
| Subsystem Technologies | Energy Generation- Solar ↑ | | | | | | |
| Subsystem Technologies | Energy Generation - Radioisotope Power | | | | | | |
| Subsystem Technologies | Energy Generation-Alternative Sources | | | | | | |
| Subsystem Technologies | Thermal Control - Passive | | | | | | |
| Subsystem Technologies | Thermal Control - Active | | | | | | |
| Subsystem Technologies | High temperature mechanisms ↑ | | | | | | |
| Subsystem Technologies | Moderate temperature electronics ↑ | | | | | | |
| Subsystem Technologies | High temperature electronics ↑ | | | | | | |
| Subsystem Technologies | Communications | | | | | | |
| Subsystem Technologies | Guidance, Navigation, and Control | | | | | | |
| Instrument | Remote Sensing - Active | | | | | | |
| Instrument | Remote Sensing - Passive | | | | | | |
| Instrument | In-Situ Aerial Platform and Probe | | | | | | |
| Instrument | *In Situ* Surface - High Temperature Sensors | | | | | | |
| Instrument | *In Situ* Surface - Long Duration Mobile Lab | | | | | | |

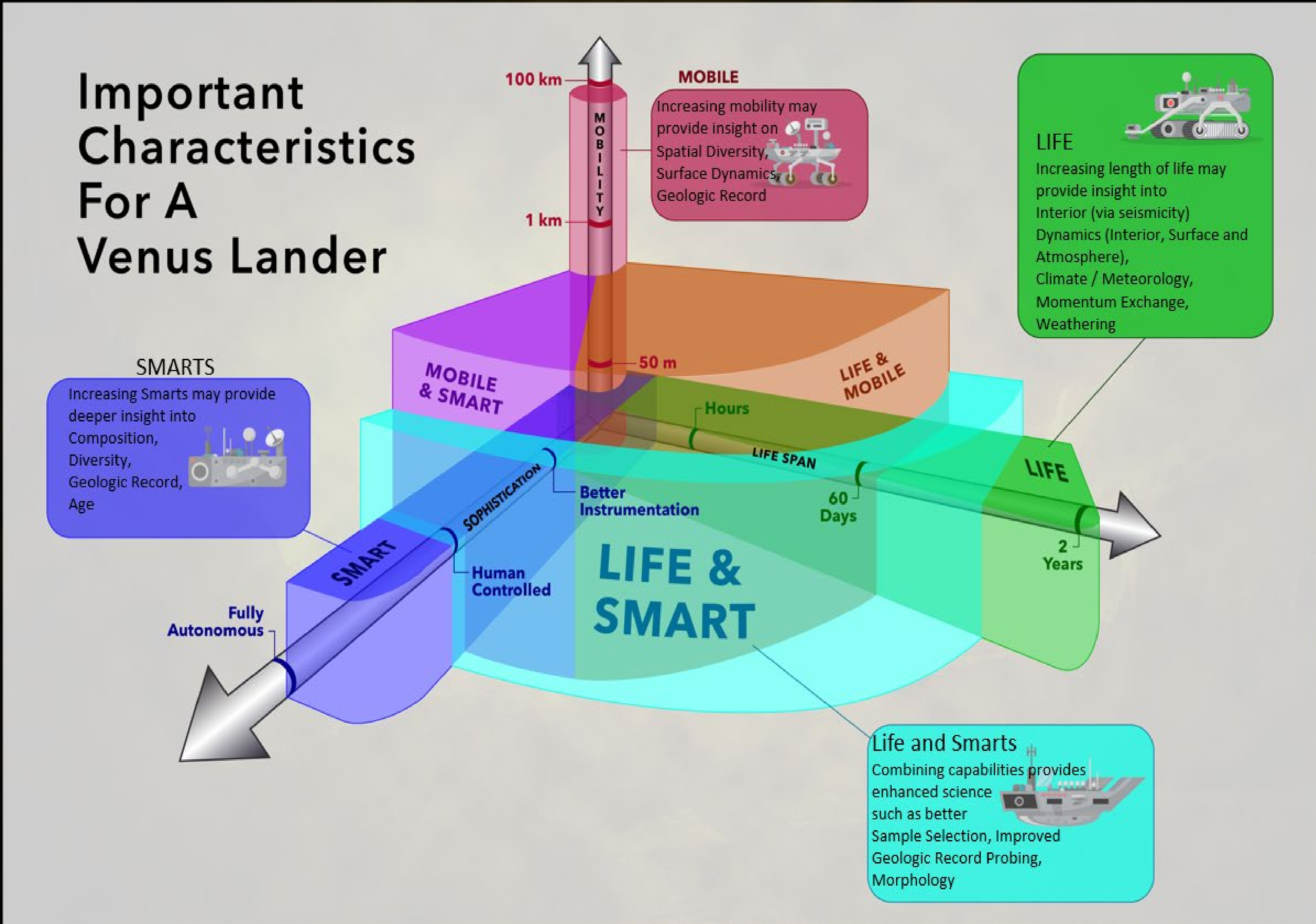
# VEXAG Technology Plan 2019

## Far-Term 2033 to 2042 : Venus Exploration More Like Other Planets, but Major Challenges

| | Mission Mode | Far-Term Missions: Advanced Orbiter /Smallsat Networks | Aerial Platforms Altitude Control | Lander - Cooled, Long Duration | Lander Network- Long Duration | Mobile Surface | Sample Return Clouds | Sample Return Surface |
|---|---|---|---|---|---|---|---|---|
| System Technologies | Aerocapture | | | | | | | |
| System Technologies | Entry ↑ | | | | | | | |
| System Technologies | Descent and Deployment ↑ | | | | | | | |
| System Technologies | Landing | | | | | | | |
| System Technologies | Flight ↑ | | | | | | | |
| System Technologies | Landers ↑ | | | | | | | |
| System Technologies | Mobility | | | | | | | |
| System Technologies | Ascent Vehicle | | | | | | | |
| System Technologies | Small Platforms ↑ | | | | | | | |
| System Technologies | Automation and Autonomy ↑ | | | | | | | |
| Subsystem Technologies | Energy Storage- Batteries ↑ | | | | | | | |
| Subsystem Technologies | Energy Generation- Solar ↑ | | | | | | | |
| Subsystem Technologies | Energy Generation - Radioisotope Power | | | | | | | |
| Subsystem Technologies | Energy Generation-Alternative Sources | | | | | | | |
| Subsystem Technologies | Thermal Control - Passive | | | | | | | |
| Subsystem Technologies | Thermal Control - Active | | | | | | | |
| Subsystem Technologies | High temperature mechanisms ↑ | | | | | | | |
| Subsystem Technologies | Moderate temperature electronics ↑ | | | | | | | |
| Subsystem Technologies | High temperature electronics ↑ | | | | | | | |
| Subsystem Technologies | Communications | | | | | | | |
| Subsystem Technologies | Guidance, Navigation, and Control | | | | | | | |
| Instrument | Remote Sensing - Active | | | | | | | |
| Instrument | Remote Sensing - Passive | | | | | | | |
| Instrument | In-Situ Aerial Platform and Probe | | | | | | | |
| Instrument | *In Situ* Surface - High Temperature Sensors | | | | | | | |
| Instrument | *In Situ* Surface - Long Duration Mobile Lab | | | | | | | |

# Venus Surface Platform Study
# On-Going
# Leads: T. Kremic and M. Amato

# Venus Surface Platform Study
# Lander Characteristics



# Venus Surface Platform Study
# Capability to Science Links

| Interior | Time | Smarts | Mobility | MSM |
|---|---|---|---|---|
| Structure | H | | | H |
| Composition | H | S | | S |
| Dynamics | H | | | H |
| Heat Escape | S | | | S |

| Surface | Time | Smarts | Mobility | MSM |
|---|---|---|---|---|
| Composition | | S | | S |
| Dynamics (Eruptions, flows, … | H | | H | |
| Diversity (Spacial) | H | S | H | S |
| Morphology | H | S | S | H |
| Age | S | H | S | S |
| Geologic Record (Layers, craters,..) | H | H | H | H |

| Interactions | Time | Smarts | Mobility | MSM |
|---|---|---|---|---|
| Gas and Surface Composition | H | H | | H |
| Winds | H | | | H |
| Reactions | H | H | | S |
| Momentum Exchange | H | | S | H |

An "H" in a field signifies that the capability is highly impactful in understanding that aspect of the science. A "S" in a field signifies somewhat impactful.

# Technology To Capability Links

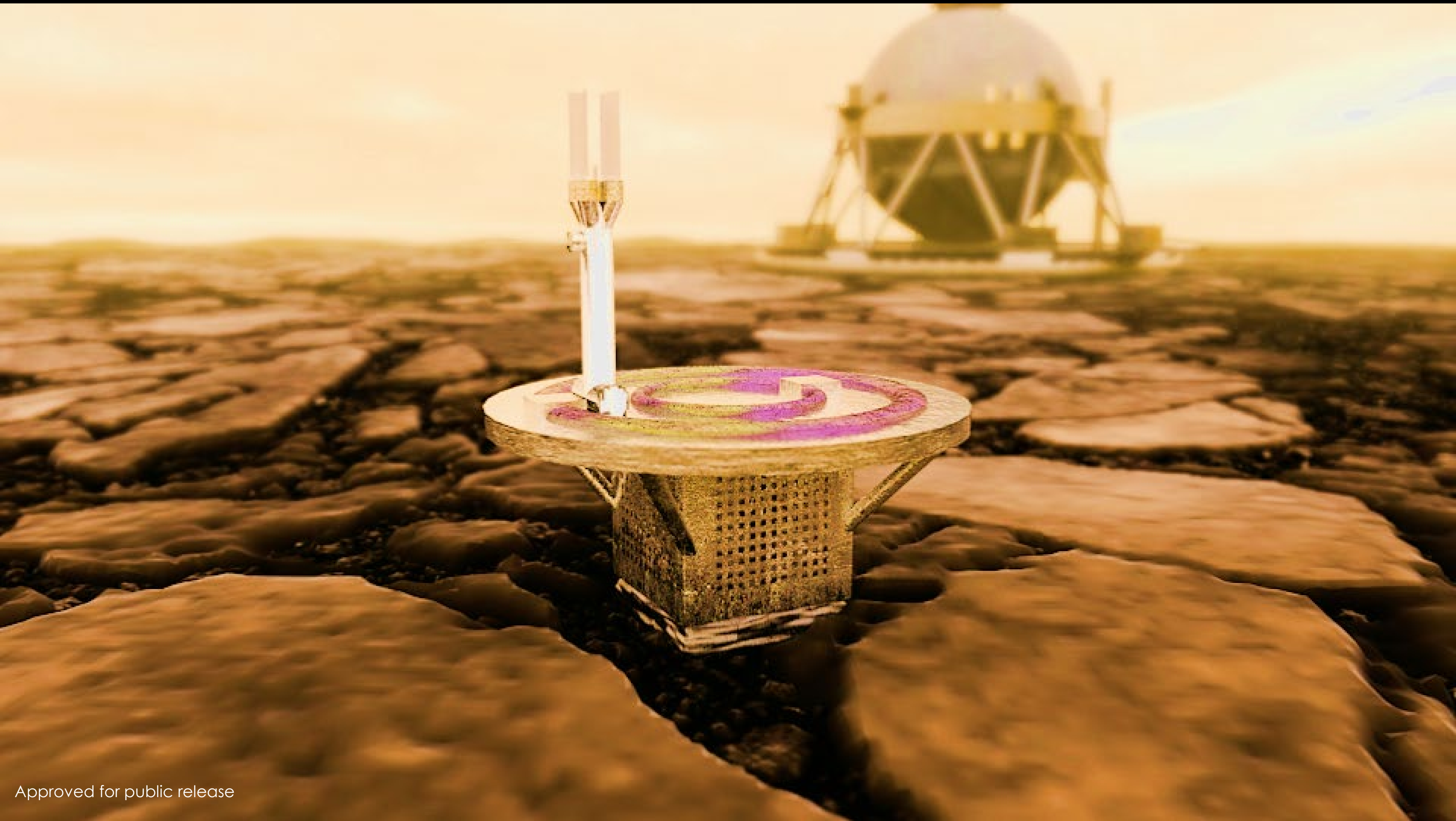
| | Capability | | |
|---|---|---|---|
| **Technology** | Time | Smarts | Mobility |
| **Power (L – low, 10's of watts or less)** | H | H | |
| **Power (H - high, 100's of watts )** | | | H |
| **Cooling (Needs Power H )** | S | H | |
| **High Temp Electronics / Memory** | H | H | H |
| **Mechanisms (Drills, Wheels, …)** | S | S | H |
| **Autonomous Ops, Nav** | S | H | H |
| **SOA Instruments** | H | H | H |

An "H" in a field signifies that the capability is highly impactful in understanding that aspect of the science. A "S" in a field signifies somewhat impactful.

# Long Lived Surface Platforms Development
# LLISSE,  SAEVe, HOTTech, etc.

# LONG-LIVED IN-SITU SOLAR SYSTEM EXPLORER (LLISSE)

**PI** TIBOR KREMIC, NASA GLENN



# LONG-LIVED IN-SITU SOLAR SYSTEM EXPLORER (LLISSE)

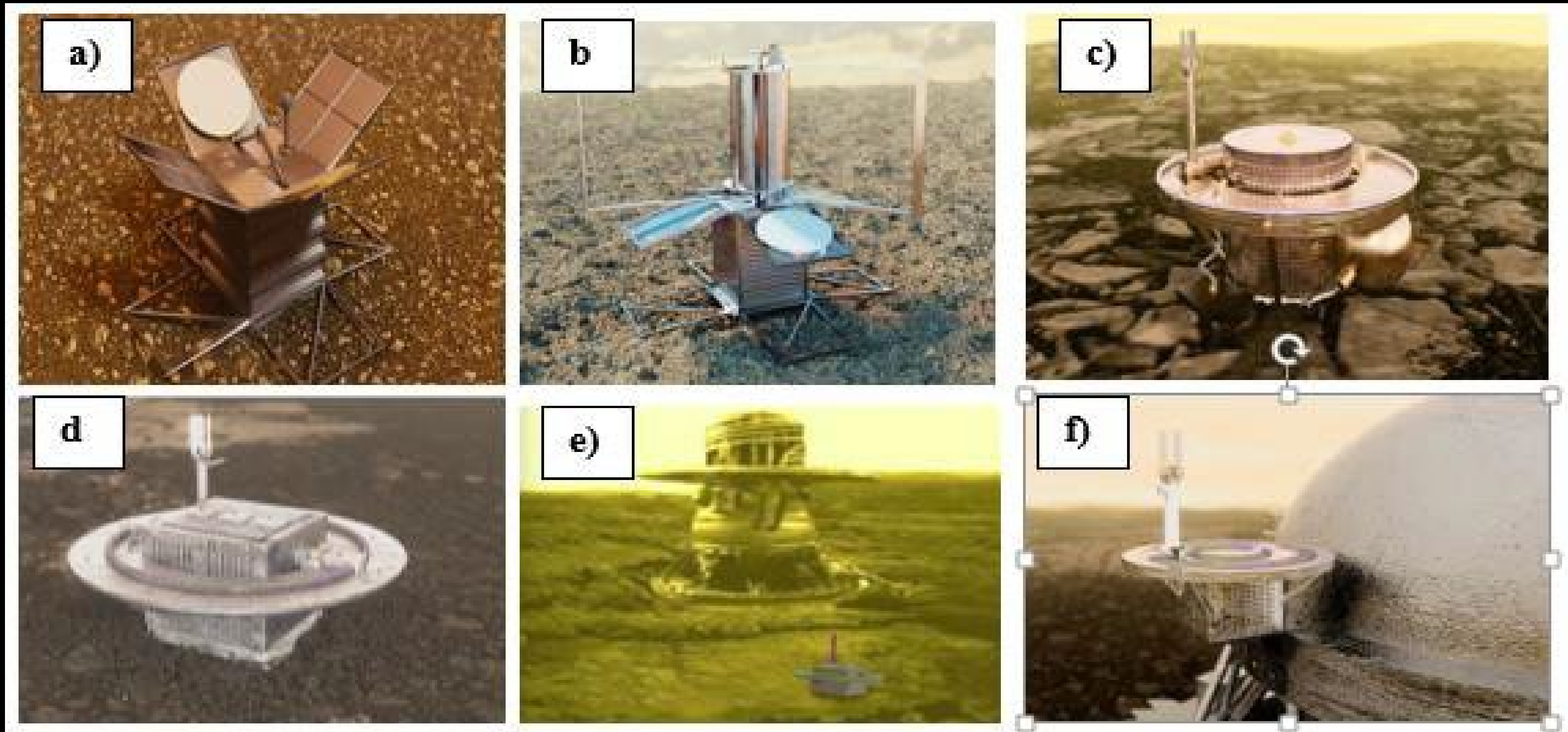
- LLISSE is a small and “independent” probe for Venus surface applications
- LLISSE acquires and transmits simple but important science
- Three key elements leveraged
  - Recent developments in high temperature electronics
  - Focused, low data volume measurements
  - Novel operations scheme

Operations Goals:

- Operate for a minimum ½ Venus solar day – capture one day/night transition
- Take / transmit measurements periodically – timed for science need and to maximize transfer to orbiter / data relay

# LLISSE

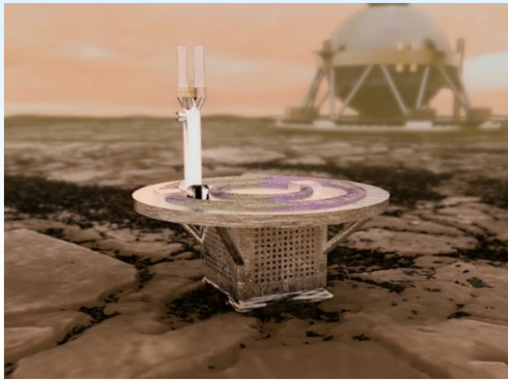
## An Approach to achieve a class of long-lived landers for Venus




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.

# LLISSE Intelligent Systems Introduction

- **LLISSE is a Complete, Compact, Stand-alone System Intended For Extended Operation On The Venus Surface**
- Intelligent Systems in the LLISSE Project Develops Three Core High Technologies for LLISSE Operation
  - ➢ Electronics for sensor control and monitoring, signal conditioning, data processing, and power management without use of an environmentally controlled enclosure.
  - ➢ Sensor systems for acquiring temporal meteorological and key atmospheric species data, momentum exchange between surface and atmosphere, and the rate of solar energy deposition.
  - ➢ Communications for data transfer from the Venus surface to an orbiter including circuit and antenna design. Determination of lander orientation.



**Version of LLISSE in development ~10 kg and ~60 days life**

# HOTTech Project Technology Areas

| | Technology Area | HOTTech Tasks | PI | Organization |
|---|---|---|---|---|
| 1 | Packaging | 500°C Capable, Weather-Resistant Electronics Packaging for Extreme Environment Exploration | Simon Ang | University of Arkansas |
| 2 | Clocks & Oscillators | Passively Compensated Low-Power Chip-Scale Clocks for Wireless Communication in Harsh Environments | Debbie Senesky | Stanford University |
| 3 | GaN Electronics | High Temperature GaN Microprocessor for Space Applications | Yuji Zhao | Arizona State University |
| 4 | Computer Memory | High Temperature Memory Electronics for Long-Lived Venus Missions | Phil Neudeck | NASA GRC |
| 5 | Diamond Electronics | High Temperature Diamond Electronics for Actuators and Sensors | Bob Nemanich | Arizona State University |
| 6 | Vacuum Electronics | Field Emission Vacuum Electronic Devices for Operation above 500 degrees Celsius | Leora Peltz | Boeing Corp. |
| 7 | ASICs & Sensors | SiC Electronics To Enable Long-Lived Chemical Sensor Measurements at the Venus Surface | Darby Makel | Makel Engineering, Inc |
| 8 | Primary Batteries | High Temperature-resilient And Long-Life (HiTALL) Primary Batteries for Venus and Mercury Surface Missions | Ratnakumar Bugga | NASA JPL |
| 9 | Rechargeable Batteries | High Energy, Long Cycle Life, and Extreme Temperature Lithium-Sulfur Battery for Venus Missions | Jitendra Kumar | University of Dayton |
| 10 | Solar Power | Low Intensity High Temperature (LIHT) Solar Cells for Venus Exploration Mission | Jonathan Grandidier | NASA JPL |
| 11 | Power Generation | Hot Operating Temperature Lithium combustion IN situ Energy and Power System (HOTLINE Power System) | Michael Paul | JHU/APL |
| 12 | Electric Motors | Development of a TRL6 Electric Motor and Position Sensor for Venus | Kris Zacny | Honeybee Robotics, Inc. |

# HOTTech-2 Projects



| Title | PI Information | | |
| --- | --- | --- | --- |
| | First Name | Last Name | Organization |
| Venus Surface Solar Array | Joel | Schwartz | Jet Propulsion Laboratory |
| Non-Volatile, Low Power, and High Density SiC Memory For Future Venus Missions | Phil | Neudeck | NASA Glenn Research Center |
| High-Temperature MEMS based Venus Seismometer | Tibor | Kremic | NASA Glenn Research Center |
| High Temperature UV near field Imager | Emad | Andarawis | GE Research |
| A High Temperature Transmitter for Venus Surface Environment | Laurence | Sadwick | InnoSys, Inc. |
| Advanced Co-Based Nanocrystalline Soft Magnetics for Extreme Temperature Inductor Applications | Paul | Ohodnicki | University of Pittsburgh |
| A Venus Durable Actuator and Electronics System | Erik | Mumm | Honeybee Robotics Spacecraft Mechanisms Corporation |

https://www1.grc.nasa.gov/space/pesto/space-vehicle-technologies-current/high-operating-temperature-technology-hottech/

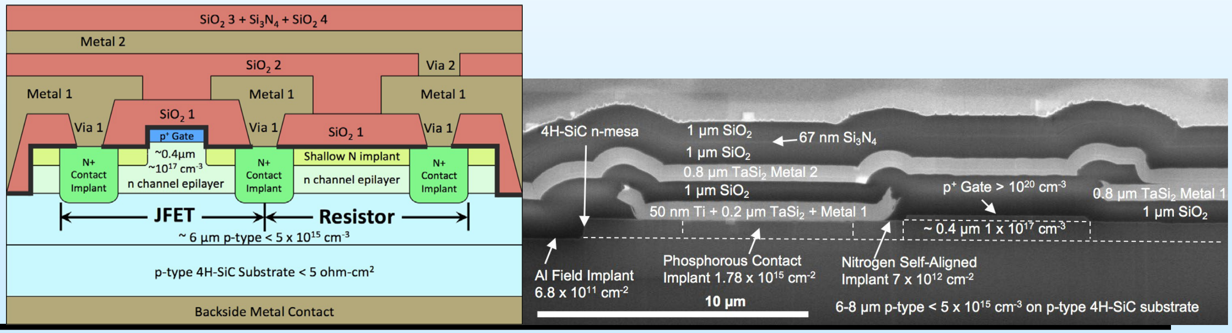
# Electronics

# High Temperature Electronics Advancements

## R&D 100 Award 2018

- *Unique capabilities have produced the World's First Microcircuits at moderate complexity (Medium Level Integration) that have the potential for long-lived operation at 500˚C*
- **Circuits contain 10's to ~1000 of Junction Field Effect Transistors (JFETs); An order of magnitude beyond a few JFETs previously demonstrated**
- **Enables a wide range of sensing and control applications *at High Temperatures***
  - **In-package signal conditioning for smart sensors**
  - **Signal amplification and local processing**
  - **Wireless transmission of data**
- **A tool-box of signal conditioning, processing, and communications circuits are being developed and demonstrated**

Cross-sectional illustrations of NASA Glenn 4H-SiC JFET-R devices with two levels of interconnect. (a) Simplified device structure drawing. (b) Scanning electron micrograph of Generation 10 JFET source and gate region

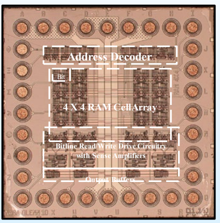


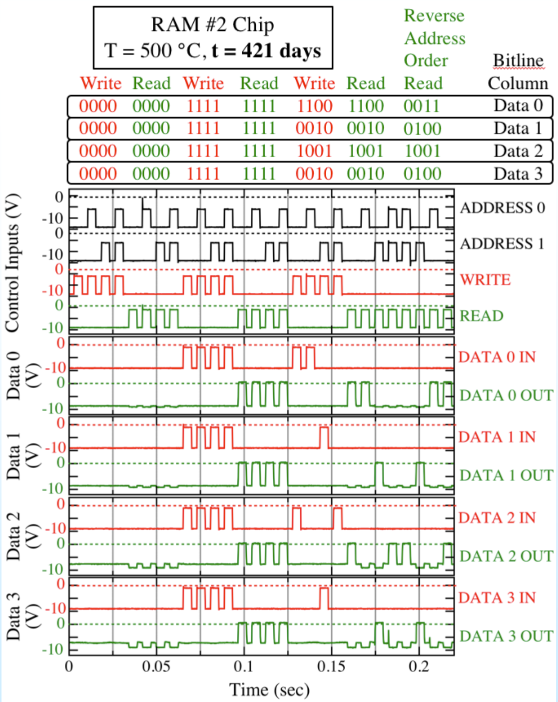
# NASA GRC Electronics Development

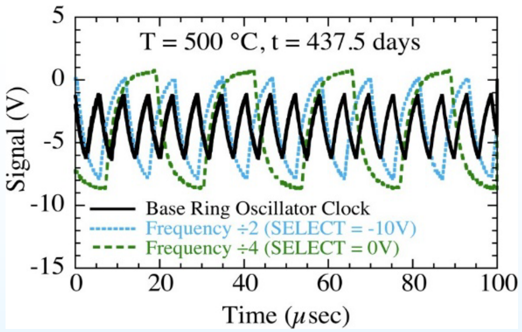
## 2017 NASA Glenn SiC JFET IC "Version 10"
## 1+ year of operation in Earth air oven at 500 ° C Achieved

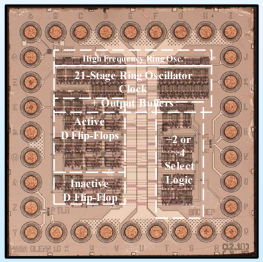
**Version 10 ICs** continue to **set high temperature durability world records in T ≥ 500 °C Earth-atmosphere oven testing.**

Complex ICs Operating more that 1 Year at 500 °C[1]

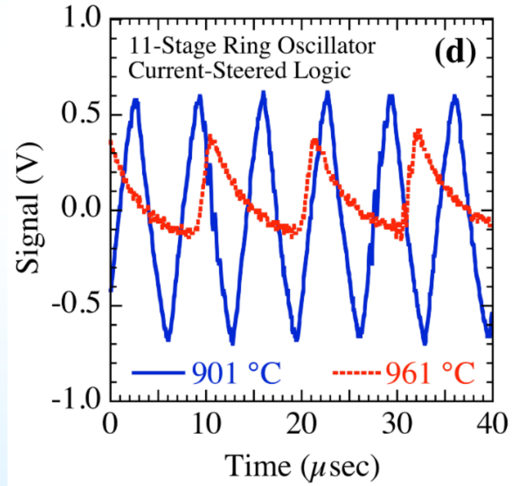





ICs Operating at World Record 961 °C[2]



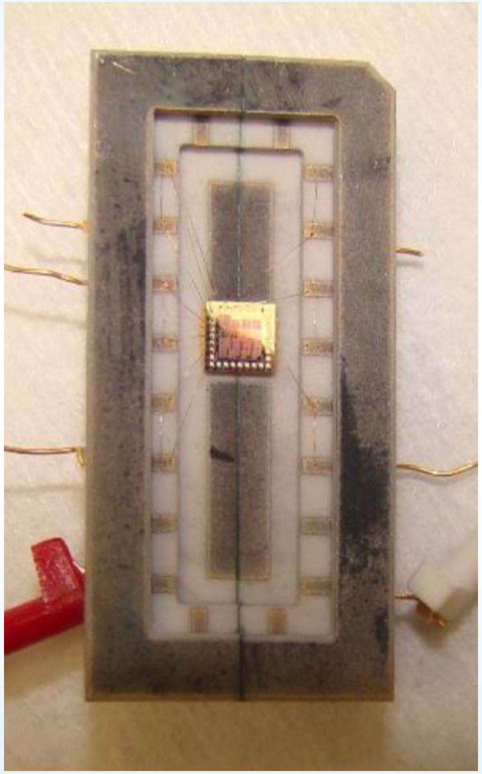

[1] 2018 Int. Conf. High Temperature Electronics p. 71
[2] IEEE Electron Device Letters vo. 38 p. 1082 (2017).

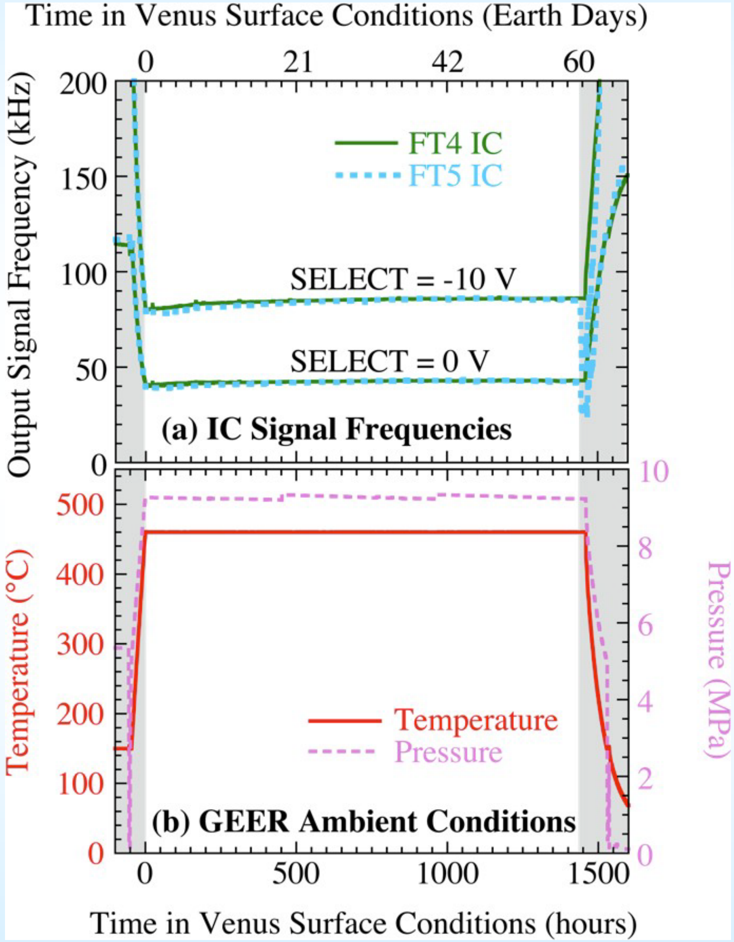
# 60-Day Venus Environment IC Test (in GEER)[1,2]

Two IC Version 10 ÷2/÷4 Clock ICs (175 JFETs/chip) successfully operated in GEER Venus surface conditions for 60 days duration.

Before GEER

After 60 days GEER





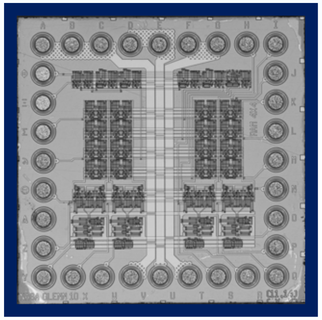

[1]Neudeck et al., IEEE J. Electron Devices Soc., vol. 1, p. 100 (2018).

[2]Chen et al., Proc. 2018 Int. High Temperature Electronics Conf.

# NASA Glenn SiC JFET IC Technology Progress

## “Learn by doing” fabricating and testing **successive upscaled generations** of prototype IC wafers/chips.

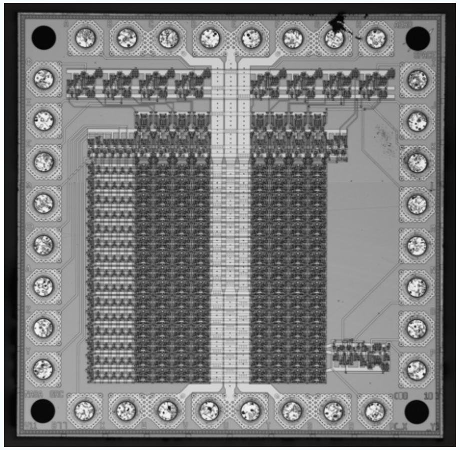
**“IC Gen. 10” (2017)**
(16-bit RAM, 195 SiC JFETs)
2 prototype 75 mm diameter SiC epi-wafers
6 µm gate length, 6 µm resistor width
3 mm x 3 mm, 32 I/O Bond Pads



**Key IC Version 10 Accomplishments***

- **400+ days stable 500 °C electrical operation**
- **60 days stable Venus surface environment electrical operation**
- 961 °C electrical operation (short-term)
- -190 °C cryogenic electrical operation
- Radiation immunity through 7 Mrad(Si) ionizing dose and 86 MeV-$cm^2$/mg heavy ions (25 °C)

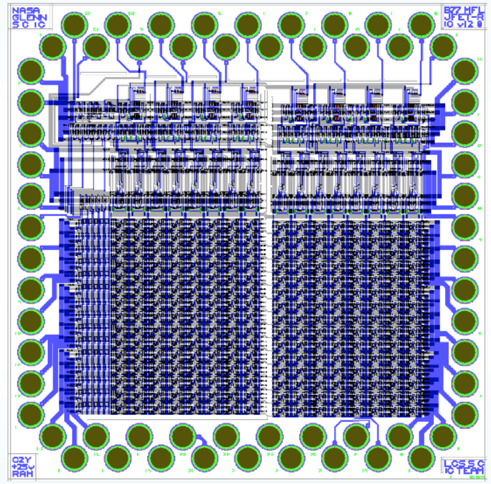
**“IC Gen. 11” (2018)**
(120-bit RAM, ~ 1000 SiC JFETs)
4 prototype 75 mm diameter SiC epi-wafers
6 µm gate length, 3 µm resistor width
4.65 mm x 4.65 mm, 32 I/O Bond Pads



**Key IC Version 11 Accomplishments**

- **5-fold reduction in logic gate power**
- **First ICs designed for LLISSE**
- 500 °C 8-bit Analog to Digital converter
- Few days 500 °C ~1 kbit ROM operation

**“IC Gen. 12” (2022)**
(248-bit RAM, ~ 2000 SiC JFETs)
6 prototype 100 mm diameter SiC epi-wafers
3 µm gate length, 2 µm resistor width
5 mm x 5 mm, 62 I/O Bond Pads



Wafer fabrication in progress

*Published results, see https://www1.grc.nasa.gov/research-and-engineering/silicon-carbide-electronics-and-sensors/technical-publications/

# Example Sensors/Instruments

# LLISSE Sensors Summary

## Broad Array Of Sensor Technology For Venus Applications Leveraged From Aeronautics Development

- Long History Of Active Development of Harsh Environment Smart Sensors Systems For Engine Test Stand, Health Management, and Intelligent Engines
- Multiple Demonstrations/Applications e.g., Including On-wing Engine Testing

## Development Approach

- Miniaturized Sensor Systems Produced By Microfabrication Techniques and High Temperature Compatible Materials
- Parallel Development Of Multiple Sensor Types
  - Multiple Chemical Species
  - Temperature
  - Wind (3 Directions)
  - Pressure
  - Radiance
- Each Sensor Has Targeted Specifications and Associated Electronics Requirements

## Status

- Several Sensors Have Reached High Levels of Maturity For This Application
- Integration of Multiple Sensor Types with SiC Electronics Demonstrated

Courtesy of D. Makel, Makel Engineering, Inc.

**SiC Electronics Combined With Chemical Sensor for GEER Testing**

**High Temperature Pressure Sensor**

# LLISSE Chemical Sensors Status

## Chemical Sensors Summary

**Background:** ***Sensor Array Developed Under Completed NASA Phase I and Phase II SBIR***

- Demonstrated Measurement of Key Species Including $SO_2$, $H_2O$, OCS, CO, HCl, and HF Under Relevant Conditions
- Sensors are selective to targeted species with minimal cross sensitivity to other species in Venus atmosphere

**Status:** ***Development of Chemical Sensors*** *(including GRC sensors)* ***Integrated with NASA GRC SiC Electronics On-Going in HOTTech project***

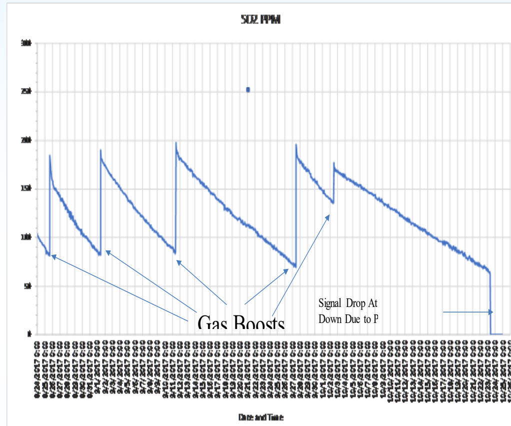
Four Chemical Microsensors ($SO_2$, CO, OCS, HF) Tested for 60 days in Venus Simulated Conditions in GEER

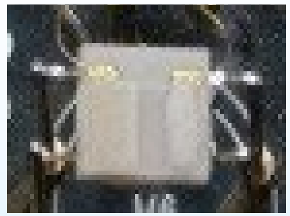
- All 4 Sensors Operated Nominally During 60 Day Test
- First Demonstration of In-Situ $SO_2$ Tracking in GEER for Extended Periods

- HF Sensor Integrated With Signal Transduction/Amplification SiC Electronics Monitored HF Boosts in GEER 10 Day Test

**TRL Summary:** Four chemical sensors successfully tested in Venus conditions for 60 days with SO2 sensor tracking concentration changes and consistent with gas chromatograph readings. HF sensor with SiC electronics responded to concentration changes in 12 day testing.

**$SO_2$ Sensor Operation in GEER for 60 Days in Venus Simulated Conditions**



**$SO_2$ MicroSensor**

# Venus In Situ Surface Imager (VISSI)

PI: Jeffrey Balcerski, Ohio Aerospace Institute

**Target Application:** Venus surface – long duration

**Science:**
- Obtain high resolution digital images of the surface of Venus at multiple scales
- Resolve geologic features near landing site at a resolution of 1 mm/px at 1 m
- Observe transient phenomena (i.e. active sediment transport) over the period of days to weeks
- Resolve basic rock and mineral types via optical filters

**Objectives:**
- Develop imaging array of high-temperature photodiodes sensitive to visible spectrum
- Develop high-temperature electronics to produce transmit-ready digital image data
- Identify and integrate appropriate optical lenses and filters
- Test and demonstrate the operation of all components at Venus surface conditions for extended time (days to weeks)

**CoIs:** Gary Hunter, Geoffrey Landis, Phillip Abel – NASA Glenn Research Center; Martha Gilmore – Wesleyan University


Figure Caption: A new generation imager for the surface of Venus.

**Planned Key Milestones (Tentative Based on Facility Availability/Pre COVID):**
- 4Q FY19: Performance requirements for VISSI
- 3Q FY20: Demonstrate Photodiode and Amplification at 500ºC
- 3QFY20: Demonstrate Photodiode for 60 days at 500ºC
- 2Q FY21: First generation VISSI electronics evaluated at 500ºC
- 4Q FY21: Integrated photodiode array and electronics providing image at 500ºC
- 3QFY22: Image produced at 500ºC
- 4Q FY22: VISSI proof-of-concept demonstration in Venus simulated conditions

**TRL 3 to 4**

# High-Temperature MEMS based seismometer

HOTTech – High Operating Temperature Technology

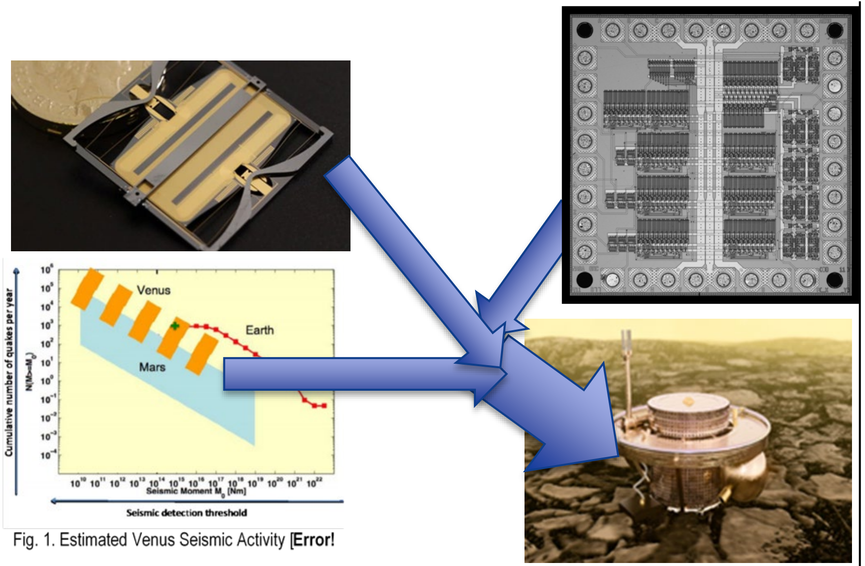



Fig. 1. Estimated Venus Seismic Activity [Error!

## Team Member(s)/Institution(s)


| | |
|---|---|
| T. Kremic / PI | NASA Glenn Research Center (GRC) |
| D. Spry / CO-I | GRC |
| M. Krasowski / CO-I | GRC |
| R. Herrick /Science PI | Univ. of Alaska/Fairbanks (UAF) |
| Michael West / CO-I | UAF |
| T. Pike / Collaborator | Imperial College of London |


### Technology Overview/Description

Overall objective:

Leverage existing MEMS seismic sensor, recent developments in high-temperature electronics and sensors, terrestrial analogues and Venus seismicity studies, and an expert team to design and mature a MEMS based seismometer suitable for use on long-duration Venus landers, like SAEVe.

Accomplishing this involves:

- Assessing / modifying existing MEMS seismic sensors that may be suitable for Venus applications
- Developing driving/interfacing electronics to support required operations and interfaces of a notional lander
- Design and fabricate a 1-axis instrument (but readily scalable to 3 axis) and verify performance via tests and analysis. Iterate.
- Mature instrument and demonstrate performance of breadboard system in Venus surface conditions against model-based predictions and reach a TRL of 4 or greater

## Technology Goals

1. Develop science-based requirements for a Venus seismometer that consider the Venus unique operations circumstances
2. Assess MEMS seismic sensors, modify as required, and fabricate and test under Venus conditions
3. Analysis and the sensor / electronics system and design, fabricate and test a 1 axis system that meets requirements and is consistent with expected Venus mission applications
4. Demonstrate operations of breadboard 1 axis instrument in Venus conditions

**Starting TRL: 2** **Ending TRL: 4**

# Communications

# LLISSE Communications Summary

## History of Cutting Edge Development in High Temperature Wireless Communications

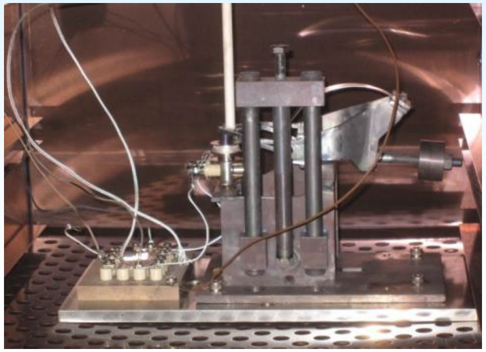
- Wireless Signal Spectra For High Temperature Seismometer Sensor Displacements Demonstrated (2012)
- Demonstrated Wireless Pressure Sensor At 475ºC  Including Pressure Sensor, SiC Circuitry, and Wireless Circuit (2013)

## Development Approach

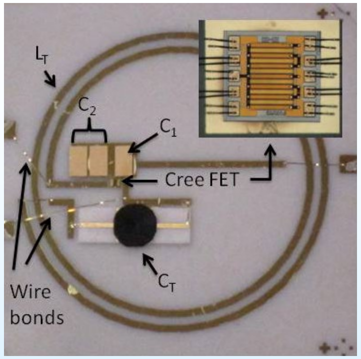
- Activities Include Venus Relevant Development Of Antennas, Transmitters, and Other Components
- Increasing Capabilities and Complexity of High Temperature Electronics Circuits Increases Communication System Capabilities
- Targeted Operation of Communication System from 100 to 150 MHz.

## Status

- Development of Circuit Hardware Architecture for Higher Frequency Communications Systems On-going
- Baseline LLISSE Antenna Materials and Design Approach Identified And Initial Material Testing In Venus Simulated Conditions Begun
- Proof-of-concept Demonstration of Ability to Determine Orientation of the Lander from the Communication System Achieved
- Propagation studies conducted in GEER at higher frequencies; transmission with limited losses observed.



**Wireless seismometer and circuit in an oven at 500ºC**

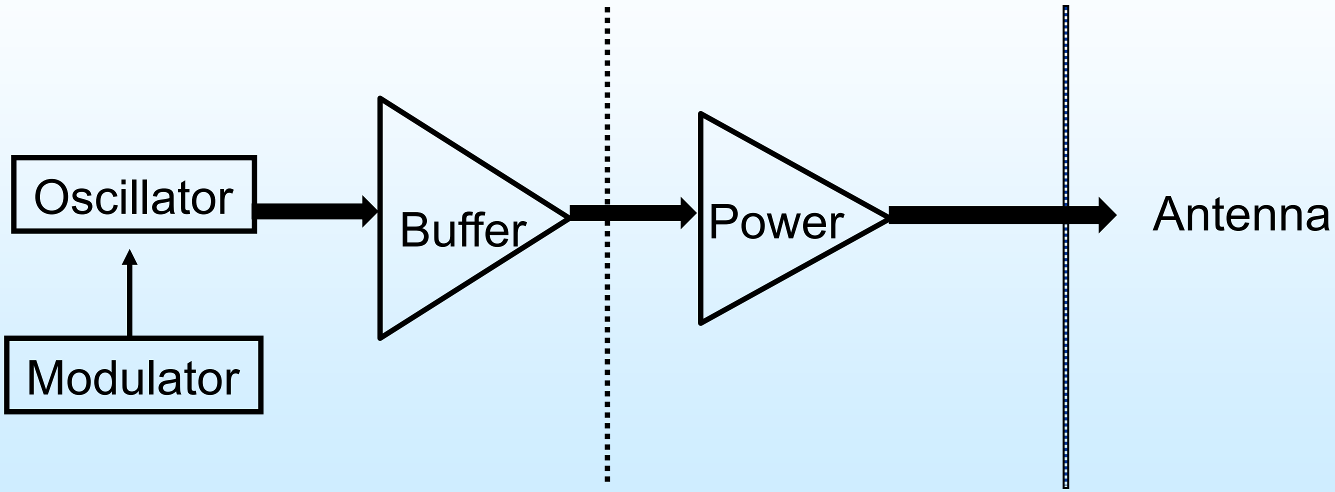



**Wireless Pressure Sensing Circuit**

# LLISSE Communications Status

## Baseline Communications Approach

- Communications System Includes: Active Circuits, Passives, Antenna
- Targeted 100 MHz Frequency Range; Relevant for Venus Surface Operations
- Communication System Dependent on SiC Circuit Advancements
  - First SiC-based Communication Circuit Designed To Operate On A Long-lived Venus Lander Based on SiC JFET technology Demonstrated
- Final Communications System at 100 MHz Will Be Based on BJT (Not JFET) Transistors
- Antenna Materials Must Be Both Resilient to Venus Surface Conditions and Have High Permittivity



# Power

# LLISSE Power

**Performance Summary**

Voltage (max./min.): +25 V/ 0.0/-25 V
Current: 0.2 with pulses up to 12A
Life: 60 Earth days
Temperature: + 465$^{0}$C
Environment: Venus Surface @ 90 Bar

**Configuration**

Volume: 1.07 liters
Weight: 2.83 kg
2.39 Ampere-Hours
95.6 Watt-Hours @ 40 V
89 Watt-Hour/liter

1/6 Scale Battery


Test Hardware S/N 002-005 cells;
S/N 006 & 007 Batteries

# SUMMARY AND FUTURE PROPECTS

- **Venus Surface Exploration Has Unique Technical Challenges Due To The Extreme Environment**
- **Venus Technology Plan: More complex missions are envisioned as a range of technologies mature**
- **The Combination of Smarts, Mobility, and Extended Life is Enabling for Surface Lander Platforms**
  - **Impact On Both Science Delivered and Mission Capabilities**
- **A Range Of Harsh Environment Technologies Are In Development To Enable Long Life Surface Missions in e.g., LLISSE and HOTTech**
  - **Electronics, Packaging, Communications, Power, Actuation**
  - **HOTTech 2016 Awarded 12 Awards**
  - **HOTTech 2021 Awarded 7 Awards**
- **Recent Advances Have Been Significant And The Prospect Of Long-lived Missions On The Venus Surface Is Becoming Increasingly Viable**

# Backup

# Venus Technolgy Plan Team Members

Gary Hunter, NASA Glenn (Chair)

Jeffery Balcerski, Ohio Aerospace Institute/NASA Glenn

Samuel Clegg, Los Alamos National Laboratory

James Cutts, NASA JPL

Candace Gray, New Mexico State University

Noam Izenberg, Applied Physics Lab

Natasha Johnson, NASA Goddard

Tibor Kremic, NASA Glenn

Larry Matthies, NASA JPL

Joseph O'Rourke, Arizona State University

Ethiraj Venkatapathy, NASA Ames

# Technology Framework

| | Technology Area | Time Frame | Assessment |
|---|---|---|---|
| System Technologies | Aerobraking | N, M | Aerobraking is a mature technology and autonomous aerobraking can reduce the cost and risk while improve the time to achieve the desired orbit. |
| | Aerocapture | N, M | A large gap in aerocapture has been met with a nearly mature HEEET technology. ADEPT with a sounding rocket sub-orbital flight test requires minimal additional development for enabling small and cube-sat missions to Venus. |
| | Entry (Upper Atmosphere) | N,M | ADEPT with a sounding rocket sub-orbital flight test requires minimal additional development for enabling small and cube-sat missions to Venus. |
| | Descent and Deployment | M,F | Control descent of probes, drop-sondes, and aerial platforms in development for future use in atmospheric profiling. Incorporating guidance, with improved navigation, could enable more accurate targeting for these systems. |
| | Entry, Descent, and Landing (EDL) Modeling & Simulation | N,M, F | Updates are needed for multiple modeling systems, including modeling for descent GNC pin-point landing and hazard avoidance. |
| | Aerial Platforms | N,M, F | Technology for near-term missions is mature. Technology investments are needed including new science instrumentation and modeling tools to characterize the behavior of vehicles in the Venus environment. However, there are no technological show stoppers to impede the development of these capabilities. |
| | Landed Platforms | N,M,F | Three classes of landed platform will be needed of increasing technical challenge: short duration containing analytical instruments (near term, current technology), long duration with sensors (mid term) and long durations with a complex instrument suite (far term). Significant advances have been made to enable longer term surface platforms. |
| | Mobile Platforms | F | Mobile systems would require a range of subsystems technology to allow, e.g., motion, power, cooling, and actuation, for extended periods. These are major challenges for mobile systems on the surface, but achieving these objectives with floating platforms may be more viable but also challenging. |
| | Ascent Vehicles | F | Ascent vehicles are only needed for Venus sample return. This is a very immature technology and much more demanding than for Mars surface sample return. Some concepts for Venus Surface sample return require the Venus Ascent Vehicle to descend to the surface. Atmospheric return missions are more feasible but significant challenges remain. |
| | Small Platfroms | N, M, F | SmallSat, CubeSat and other small platform technology can make important contributions to Venus exploration. The development of small platform concepts as an addition to larger missions, as well as a new mission type or mission augmentation, is an integral part of a complete multistage Venus exploration program. |
| | Automation and Autonomy | M, F | Increasing capabilities for automation and autonomous decision-making combined with increasing computing power can change the way missions are conducted. Efforts to transition automation and autonomous technologies to Venus specific applications would enhance science delivered and mission success. |