NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

2018 Workshop on Autonomy for Future NASA Science Missions: Venus Design Reference Mission Reports

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Introduction

Autonomy is changing our world; commercial enterprises and academic institutions are developing and deploying drones, robots, self-driving vehicles and other autonomous capabilities to great effect here on Earth. Autonomous technologies will also play a critical and enabling role in future NASA science missions, and the Agency requires a specific strategy to leverage these advances and infuse them into its missions. To address this need, NASA sponsored the 2018 Workshop on Autonomy for NASA Science Missions, held at Carnegie Mellon University, October 10-11, 2018.

The Workshop goals included:

- Identifying emerging autonomy technologies (10-15 years) that will:
  - Enable or enhance mission capabilities
  - Reduce risk
  - Reduce cost
- Identifying potential collaborations, partnerships, or linkages involving government, industry, and/or academia to enable these technologies

Capturing crosscutting autonomy technology requirements for future NASA missions
Over 90 individuals from industry, academia, and NASA participated in the workshop, which included presentations by keynote speakers, panel discussions, and small group discussions.

To provide structure for workshop discussions and post-workshop analysis, NASA established eight teams to examine the following Design Reference Mission (DRM) areas: Astrophysics, Earth Science, Heliophysics, Mars, Moon, Ocean Worlds, Small Bodies and Venus. Each DRM team was led by a scientist and a technologist, and team members consisted of workshop participants with relevant experience and interest. NASA asked each team to develop one or more mission scenarios that would be enabled by infusion of autonomous technology. The Agency provided guidance to support these team discussions; in particular, NASA urged the DRM teams to "think out of the box" and to consider bold missions that would be enabled by autonomous technology to provide valuable science results. Each DRM team developed mission scenarios that included defined science objectives, capability and technology needs, system requirements, and a concept of operations. Teams also identified gaps where autonomy technologies and other supporting technologies need to be developed and/or infused to enable each mission.

The DRM teams conducted small group discussions at the workshop and then presented a summary of their findings to all workshop attendees. Each DRM team continued to refine its mission scenarios after the workshop, creating both a full report and a summary report to document team findings. DRM teams also reported results at the December 2019 meeting of the American Geophysical Union.

This document contains the full report and summary report generated by the Venus DRM team. Full and summary reports generated by all eight DRM teams, plus a summary of workshop results are available online.

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Venus Design Reference Mission Report

Part I: Abstract

Venus and Earth began as twins. Their sizes, densities, and elemental building blocks are nearly identical, and they stand out as being considerably more massive than other terrestrial planetary bodies. Yet the current Venus that has been revealed through past exploration missions is hellishly hot, devoid of oceans, and bathed in a thick, reactive atmosphere. A less Earth-like environment is hard to imagine. Precisely because it began so like Earth, yet evolved to be so different, Venus is the planet most likely to cast new light on the conditions that determine whether a planet evolves habitable environments.
Missions for descending and landing on Venus are helped by the dense atmosphere—which simplifies both the initial descent and the terminal phases relative to comparable phases at Mars. However, Venus's surface pressure and temperature are 92 bars and 450 °C, respectively, which adds additional design constraints on any system that will operate on or near the planet's surface.

Missions operating high (~55 km) in the Venus atmosphere can experience a benign environment in terms of temperature and pressure, but are exposed to the harsh, chemically reactive environment that is maintained in the sulfuric-acid clouds.

The Venus team delineated two Design Reference Mission (DRM) scenarios—the second building on the success of the first—that will help uncover Venus's early evolution, including possible habitability, as well as help NASA understand the evolutionary paths of other Earth-sized terrestrial planets and exoplanets. In addition, these DRM scenarios will help NASA understand the atmospheric dynamics, composition, and climate history of Venus. They will also uncover how physical and chemical processes interact to shape the modern surface of Venus. The first DRM scenario is based on a 5–14-year vision and is the foundation for the second DRM. The second DRM scenario, which requires additional autonomy, is much more ambitious and is envisioned for 2033-2042.

Design Reference Mission Scenarios

We suggest two Design Reference Mission (DRM) scenarios that autonomy would enable:

- **An Orbiter with Multiple Autonomous Assets**. A near-term (2023-2032) DRM scenario would characterize the interior, surface, and atmosphere of Venus while demonstrating increasing autonomy. This DRM scenario consists of a larger, more-capable orbiter with a limited number of associated small spacecraft, an aerial vehicle, dropsondes, and a lander system.

- **A Networked System of Multiple Autonomous Assets.** Targeted for 2033-2042, this DRM scenario uses networked lander-systems and/or orbiter(s) to detect seismic events. This more ambitious scenario consists of an orbiter with a fleet of small spacecraft, an aerial vehicle or two, dropsondes, and lander vehicles. The orbiter would detect volatiles from volcanically produced hotspots and/or seismic waves, while an aerial platform confirms the seismic event and releases dropsondes to measure the chemistry of the volcanic plume.

Critical Autonomous Technologies

The critical autonomous technologies needed to achieve both the **near-term and medium-term** DRM scenario are **situation and self-awareness**, **reasoning and acting**, **collaboration and interaction**, and **engineering and integrity**. These autonomous technologies include:

- Sensing and Perception
- State Estimation and Monitoring
- Knowledge and Model Building
- Event and Trend Identification
- Anomaly Detection
- Mission Planning and Scheduling
- Activity and Resource Planning and Scheduling
- Execution and Control
- Fault Response, Diagnosis and Prognosis
- Learning and Adapting
- Architecture and Design

The above autonomous technologies will enable the following capabilities:

- Networking
- Autonomous navigation
- Techniques for measuring attitude
- A network of landers and orbiter(s) to detect the event
- An orbiter to detect volcanic events and/or seismic waves
- An aerial platform to confirm a seismic event and release dropsondes to measure chemistry of volcanic plume

Supporting technologies that are needed for both of these scenarios are:

- Flight hardware and sensors that can operate under harsh conditions—including long-lived electronics (processors and memory) that can operate in harsh pressure, temperature, and chemical environments and/or long-lived cooling systems.
- Large infrared arrays (2000 × 2000 pixels) for 4.3-micron imaging, a capable array processor, and radiators to maintain the temperature of the detector arrays.

Findings

The Venus DRM team finds that the following actions and activities would facilitate implementation of the DRM scenarios described above.

- Institute a call for autonomy research using the type of hardware needed for multiple networked assets. This scenario would be very much like the Mars situation, and even Earth-sensor networks, except that the hardware has to be hardened and adapted to the temperature and pressure of Venus, where appropriate. Examples of the autonomous technologies needed include:
    1. Algorithms and models to detect, diagnose, and recover from hardware degradation under harsh Venus environmental conditions
    2. Sensors for dropsondes, landers, and aero-vehicles.
    3. Communication across multiple platforms (network topology)
    4. Demonstration of individual situational awareness and adaptability to enhance survivability and mission science
    5. Planning, scheduling, smart execution, and resource-management algorithms
- Continue and expand support for programs such High Operating Temperature Technology (HOTTech),
- Fund technology maturation of aero-vehicles
- Identify where joint sponsorship and dual-use development can be leveraged (e.g., the implementation of small platforms and autonomous systems) to result in new mission capabilities.

Part II: The Case for Venus

Venus and Earth began as twins. Their sizes, densities, and elemental building blocks are nearly identical (Figure 1), and they stand out as being considerably more massive than other terrestrial planetary bodies. As our infant Sun evolved, first Venus and then Earth had liquid water present on their surfaces for billions of years, likely with habitable conditions. Yet the Venus that has been revealed through past exploration missions is hellishly hot, devoid of oceans, and bathed in a thick, reactive atmosphere. A less Earth-like environment is hard to imagine. How, why, and when did Earth's and Venus's evolutionary paths diverge? What are the implications for understanding habitability and the potential for life on Venus- and Earth-sized objects throughout the universe?

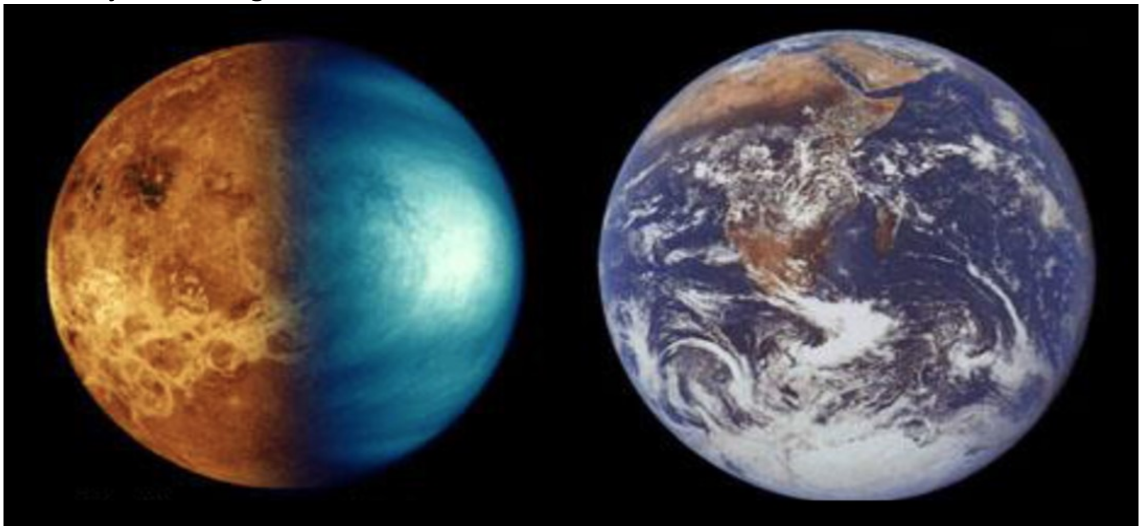

Figure 1: Venus and Earth compared. The left side of the Venus image is a radar image of the surface from the Magellan spacecraft. The right side is an optical image of the clouds from Galileo. The image of the Earth, centered on South Africa, was taken by Apollo 17.

These fundamental and unresolved questions drive the need for vigorous new exploration of Venus. The answers are central to understanding Venus in the context of terrestrial planets and their evolutionary processes. Precisely because it began so like Earth, yet evolved to be so different, Venus is the planet most likely to cast new light on the conditions that determine whether or not a planet evolves habitable environments. Current and future efforts to identify planetary systems beyond our solar system (e.g., the Kepler mission and the Transiting Exoplanet Survey Satellite) are ultimately aimed at finding Earth-size planets around Sun-size stars. For these discoveries, the Venus-Earth comparison is critical in assessing the likelihood that Earth-size *means* Earth-like and therefore *habitable*.

Previous Missions to Venus

More than 30 spacecraft have flown to Venus since Mariner 2 flew by the planet 50 years ago[1]. These missions have included flybys, orbiters, probes, short-lived landers, and balloons. All of the in situ surface missions occurred in the first 25 years and were sponsored by the U.S.S.R. Since then, the NASA Magellan orbital radar mission was completed in 1994, the European Space Agency's (ESA's) Venus Express operated at Venus from 2006–2014, and the Japan Aerospace Exploration Agency's (JAXA's) Akatsuki spacecraft has been in orbit since December 2015. The latter missions have ensured that limited Venus observational science from spacecraft has continued. But the absence of recent in situ missions and the aging/retirement of much of the Venus-focused workforce threatens to result in a loss of some of the technical capabilities important in Venus exploration; such expertise and capabilities are not easily reproduced. Although early successes provided a proof of principle that orbiters, probes, short-lived landers, and balloons can be successfully deployed at Venus, the lack of recent missions means that modern implementations of these concepts are yet to be tested.

Despite the dearth of recent U.S. missions, several assessments of Venus technologies and missions *have* been conducted, thereby expanding on the core concepts of previous missions. In 2006, NASA's solar system Exploration Roadmap included a Venus Mobile Explorer mission and an extensive discussion of the required technology for this mission. In April 2009, the Science and Technology Definition Team (STDT) for the Venus Flagship Mission assessed not only the new technology requirements for their mission concept, but also a greatly-enhanced science return mission with concomitant payload [2,3]. Studies of a Venus Climate Mission (VCM[4]) and a Venus Mobile Explorer (VME[5]) followed two years later under the auspices of the National Research Council (NRC) Planetary Science Decadal Survey. Subsequently, NASA has supported the Venera D mission study[6], which is being led by Russia. A number of detailed proposals for Venus missions have also been submitted to NASA's Discovery and New Frontiers programs but none, so far, have been selected. More recently, a series of studies was conducted in 2017–2018 related to small spacecraft, aerial platforms, surface platforms, and "Venus Bridge" approaches.

While there is a long history of Venus exploration, most notably by other countries, there has been no dedicated U.S. mission to Venus since Magellan ceased operations. NASA's science mission philosophy has been to orbit, land, and rove, but the lack of missions to accomplish the latter is reflective of the often incorrectly perceived challenges associated with Venus exploration. Specifically, the Venus environment raises varied issues for robotic exploration missions:

1. The orbital thermal environment is stressful as a result of the high solar reflection from the Venusian clouds and Venus's close proximity to the Sun, but it is a much-less-challenging orbital environment than that found around Mercury.
2. During planetary atmospheric entry, the velocity and thermal conditions are

more severe than for entry at Earth or Mars with conventional aeroshells (but less than for a Jupiter entry). A novel 3D-woven thermal protection system from the NASA-funded Heatshield for Extreme Entry Environment Technology (HEEET) project is now mature enough to mitigate this risk.

3. Once in the atmosphere, missions operating high (~55 km) in the atmosphere can experience a benign environment in terms of temperature and pressure, but are exposed to the harsh, chemically reactive conditions that are maintained in the sulfuric acid clouds.
4. Descent and landing on Venus are enabled by the dense atmosphere, which simplifies both the initial descent and the terminal phases relative to comparable phases at Mars. Surface pressure and temperature are 92 bars and 450 °C, respectively, which adds additional design constraints on any system that will operate on or near the planet's surface.
5. Surface operations using conventional electronics and passive thermal-control systems are limited to a few hours. Long-duration missions require components and packaging that will function at Venus's ambient pressure and temperature and/or have active thermal control systems. Current power and communication systems' technologies will not function well, or for long periods of time, under the surface conditions.

Improvements in miniaturization and harsh-environment technologies in a wide variety of subsystems already have the potential for enabling a new class of missions. A common theme is that these technological advancements allow small platforms of a variety of types to provide valuable science. Spacecraft orbiters—as well as aerial and lander systems—with significant capabilities are becoming available in smaller packages. Such technologies can provide valuable Venus science at reduced cost and complexity and may be launched into orbit as auxiliary payloads. Aerial platforms now have new capabilities beyond those previously flown in larger balloon missions, often leveraging reduced size or alternate methods to exploring the atmosphere. Most aerial vehicle concepts would be propelled around Venus in the super-rotating flow, but would have the ability to control altitude and to modify the trajectory to pass directly over surface features of special interest. Less-mature but groundbreaking technological advancements in high-temperature electronics developed through the NASA High Operating Temperature Technology (HOTTech) Program now enable small, long-lived lander systems, which could extend operational lifetimes on the Venus surface to 60 days or more.

Often overlooked, but critical to advancing exploration, is autonomous operation of the various elements comprising future missions. Increasing autonomous decision-making capabilities can change the way new missions are conducted and increase scientific discoveries. These advances are the core of this DRM activity.

Why is Autonomy Enabling for Venus Missions?

Significant aspects of Venus exploration are challenged by limited time or capability for human-in-the-loop interactions during the mission. Machine-based intelligence can optimize science return by providing operation independent of human intervention. The use of machine-based intelligence can vary from the use of automated systems carrying out a set sequence of actions to increasingly autonomous systems with the capability for situational awareness, decision making, and response. Automated and autonomous systems have been used in planetary exploration for years. These advanced systems are steadily increasing in capability and applicability with the potential to significantly impact future Venus exploration. Autonomous capabilities are *required* when there are changes in the environment or the spacecraft, those changes are not predictable, and the time needed to respond to those changes is shorter than ground-based operators can provide. Autonomous capabilities also are needed when the mission is short-lived and closing the loop onboard is required to meet lifetime requirements. Thus, in the short term, with landers lasting hours, dropsondes penetrating the atmosphere, and balloons circumnavigating Venus, coordination of assets is key to a successful mission. In the longer term, multiple aerial vehicles, dropsondes, and long-lived landers coordinating with an orbiter will provide unprecedented opportunistic scientific discoveries.

Examples of autonomous technologies for Venus orbital, atmospheric, and lander missions respectively include: 1) identification of a desired surface target for image navigation and reduction of data volume; 2) altitude and mission control of a Venus balloon, including optimization of atmospheric sampling, power handling and conservation, and altitude adjustment for characterization of atmospheric flow streams; and 3) lander operation on the surface over an ~ 2+ hour span to carry out the maximum number of experiments with on-site data quality evaluation, validation, and repeat of experiments as needed.

For more complex missions with multiple vehicles, autonomous systems enable the collection and correlation of data from the same phenomena observed from different vantage points to potentially identify instantaneous events—such as erupting volcanoes and Venus-quakes. Monitoring such events over time is needed to discern patterns. Leveraging advances in automation and autonomy can significantly broaden future Venus scientific discoveries.

Why is Venus a suitable target for advancing autonomy?

A number of different scenarios for Venus missions demand autonomy; these include, but are not restricted to:

- Constrained communications with Earth and between assets on Venus.
- Time-critical decisions involving events such as lifetime constraints, Venus-quakes and volcanic eruptions.
- Internally data-heavy decision processes such as terrain relative navigation (TRN), onboard data analysis.
- Distributed processing of complex computations, where computation power on each of the elements is uneven—with some having sophisticated, and others rudimentary, computers.
- System and mission architecture to support independent decision-making as well

as distributed decision-making across multiple assets.

- Situational complexity that exceeds the limits of useful human input, such as responding to surface events or changing atmospheric conditions. Aerial assets are moving 5,600 km/day, often out of Earth view.

Autonomous capabilities that will enable autonomous exploration of Venus include:

- Algorithms and models to detect, diagnose, and recover from hardware degradation under Venus conditions.
- Venus terrain-relative navigation, hazard avoidance, and station keeping, as well as the capability to deploy to a different location.
- Control algorithms/models for dropsonde transit through dense, rapidly moving atmosphere.
- Intelligent sensors and controllers for dropsondes.
- Communication across multiple platforms to share common mental models (network topology).
- Coordination of rapid responses to varying conditions and inputs.
- Developing situational awareness and adaptability to enhance survivability.
- Planning, scheduling, smart execution, and resource management algorithms.
- High bandwidth, high-speed computers.
- Image analysis methods enabling selection of high science-value targets

These capabilities provide a method to address Venus science questions related to Venus's early evolution (including possible habitability) and the evolutionary paths of Earth-sized terrestrial exoplanets; the atmospheric dynamics, composition, and climate history on Venus; and how physical and chemical processes interact to shape the modern surface of Venus.

Part III: Design Reference Missions

The Venus team developed two DRM scenarios that could uncover Venus's early evolution—including possible habitability—as well as help NASA understand the evolutionary paths of other Earth-sized terrestrial planets and exoplanets. More specifically, these DRMs will help NASA understand the atmospheric dynamics, composition, and climate history on Venus. They will also reveal how physical and chemical processes interact to shape the modern surface of Venus. Injecting autonomous elements increases science return and reduces overall mission risk, given the nature of space vehicles and Venus's harsh environment. The first DRM will test synchronization of assets and enhance current science objectives while enabling future, more complex missions. The atmospheric science to be obtained is enabled by small spacecraft and dropsondes. The second DRM builds from the first with multiple coordinated space vehicles acting in concert to provide instantaneous response to scientific events.

DRM Scenario 1: An Orbiter with Multiple Autonomous Assets

Description: SURVIVE, DETECT, COMMUNICATE!

This DRM scenario would characterize the interior, surface, and atmosphere of Venus while demonstrating increasing autonomy, with a targeted time frame of 2023-2032 (See Figure 2).

The Concept of Operations

The concept of operations for this DRM scenario consists of a larger, more capable orbiter with a limited number of associated small spacecraft; an aerial vehicle; dropsondes; and a lander system. The combined platforms will characterize the Venus interior, surface, and atmosphere while demonstrating increasing autonomy. The role for each includes:

1. **Orbiter and small spacecraft**: Acquire gravity, topography (radar), and spectral-imaging data to constrain the landing site and create a geological map
2. **Aerial vehicle:** Test control of flight/altitude mobility of an aerial vehicle at 50-60-km altitude and examine the ultraviolet absorber
3. **Dropsondes:** Acquire data on pressure, temperature, isotopic species, chemistry, and wind velocity in atmosphere
4. **Lander system:** Detect rock types and mineralogy, analyze atmosphere, obtain images, and test drilling

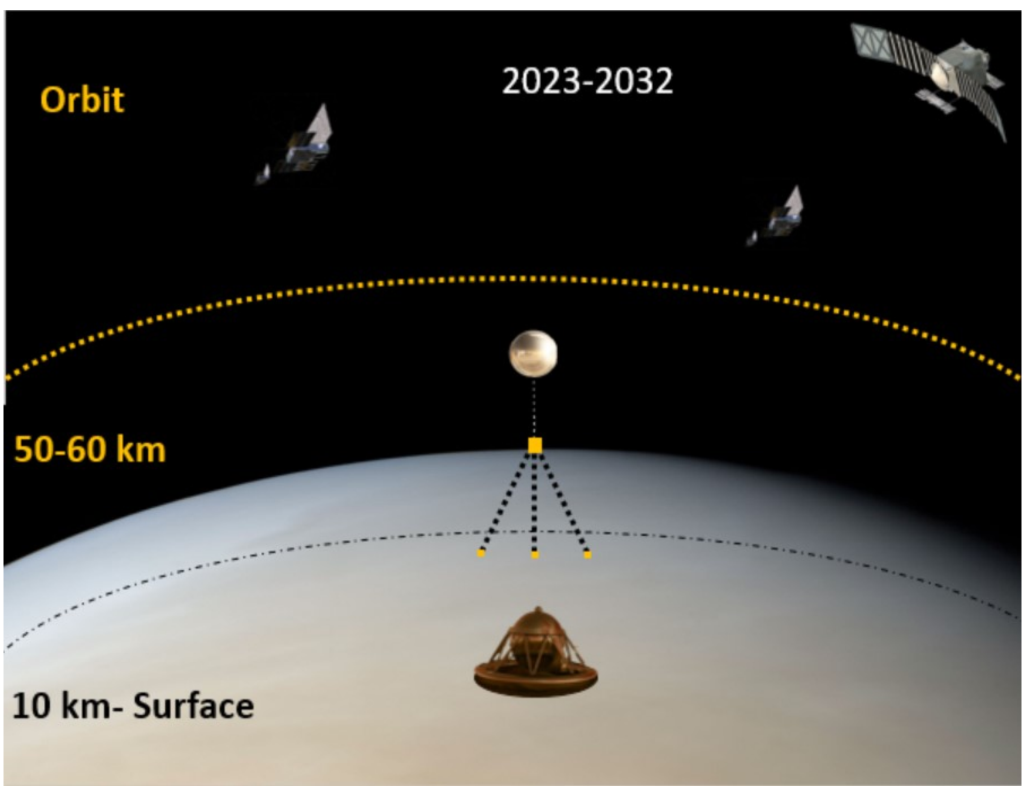

Figure 2. DRM 1 Concept Overview

Assumptions

- Each platform stands alone as a science mission if any individual element fails.
- Automatic positioning of orbiter and processing of data onboard
- Radio tracking on the orbiter allows the aerial vehicle to be localized when it is on the side of Venus away from Earth.
- Aerial vehicle can use local information and small spacecraft communications to determine location, but needs to navigate without the ground in the loop during the periodic small-spacecraft communications outages.
- Two to three dropsondes with sensors and communications onboard will collect visual imaging data once they are the region within 10 km of the surface where physical and chemical conditions are interesting and visual imaging is feasible.
- Situational awareness in this case is required by each agent to understand its own environment, though not the placement of other agents.
- Pinpoint landing is not feasible in this time frame, but refinement of atmospheric models and atmospheric characterization may make it feasible for subsequent missions.
- Venus's gravity model is not currently well known, but precision tracking of the aerial platform may permit refinement of the gravity field along its trajectory.
- Not all platforms will have high-performance computing capability, especially the landed vehicle, which will likely have a limited capability.

Autonomy Capabilities Needed to Characterize the Interior, Surface, and Atmosphere of Venus

The use of autonomy is enabling for both DRM scenarios. The harsh environmental constraints causing the short lifetime of hardware plus the rapid in situ response times needed in response to transient events will require coordination and communication across the agents. These agents cannot be 'operated in real-time' from the ground. Injecting autonomous elements into this mission concept will enable necessary science. Many of the autonomous capabilities developed such as fail-operational algorithms and structured system-level autonomy software architectures will also reduce risk. At least one vehicle should have a capable high-speed, high-bandwidth computer.

Networking Capability. The primary goal of science missions is to return data back to Earth. A network capability supports multiple assets to collect and transmit the data without requiring every asset to have direct-to-Earth communications capability. It also provides the ability to share navigation information across multiple vehicles for localization at Venus. This interconnected and coordinated network is comprised of a lander, orbiter, aerial vehicle, dropsonde, and small spacecraft. As such, this network capability would be both enabling and enhancing. It would enhance the science objectives by demonstrating autonomous systems' technologies in harsh environments and enable future, more complex missions. The atmospheric science to be obtained would also be enabled by small spacecraft and dropsonde(s) networked with a lander system, aerial vehicle, and orbiter.

Using NASA's Autonomous Systems Capability Leadership Team (AS-CLT) Taxonomy document as a guide (recognized AS-CLT technologies are *italicized*), the autonomous technologies needed for this capability are:

- Algorithms and models to detect, diagnose, and recover from hardware degradation under Venus conditions
  - *1.2 State Estimation and Monitoring*
  - *1.3 Knowledge and Model Building*
  - *1.5 Event and Trend Identification*
  - *1.6 Anomaly Detection*
  - *2.5 Fault Diagnosis and Prognosis*
  - *2.6 Fault Response*
- Sensors and controllers for dropsondes
  - *1.1 Sensing and Perception*
- Communication across multiple platforms (network topology)
  - *3.1 Joint Knowledge and Understanding*
- Demonstrate individual situational awareness and adaptability to enhance survivability
  - *1.2 State Estimation and Monitoring*
  - *1.3 Knowledge and Model Building*
  - *2.7 Learning and Adapting*
- Planning, scheduling, smart execution, and resource management algorithms
  - *2.1 Mission Planning and Scheduling*
  - *2.2 Activity and Resource Planning and Scheduling*
  - *2.4 Execution and Control*
- System and software autonomy architectures to support multi-agent collaboration and interaction
  - *4.5 Architecture and Design*

Other technologies that are needed to support autonomous-networking capability include at least one vehicle with a capable high-bandwidth, high-speed computer; flight hardware; and sensors that can operate under Venus's harsh conditions. This requirement includes long-lived electronics (processors and memory) that can operate in harsh pressure, temperature, and chemical environments. Also needed are technologies to support a multi-platform communications and navigation infrastructure for Venus, variable-altitude mobility systems, and theoretical environmental models of Venus's near-surface conditions (<10 km).

Autonomous Navigation. Autonomous navigation of the aerial vehicle orbiting Venus both enables and enhances science goals. Atmospheric science would be enabled by small spacecraft and dropsonde(s) networked with a lander system, aerial vehicle, and orbiter. This capability would enhance science objectives by expanding autonomous systems' technologies into harsh environments to enable future, more complex missions.

Autonomous technologies needed for this capability are (see above for references to AS-CLT Taxonomy document):

- Systems and software autonomy architecture to support autonomous navigation
- Algorithms and models to detect, diagnose and recover from hardware degradation under Venus conditions
- Sensors and controllers for dropsondes
- Communication across multiple platforms (network topology)
- Individual situational awareness and adaptability to enhance survivability
- Planning, scheduling, smart execution, and resource management algorithms
- Reasoning and Acting
    - Mission Planning and Scheduling
    - Motion Planning

Other technologies required to support autonomous navigation include flight hardware, long-lived electronics (processors and memory), and sensors that can operate under harsh Venus pressure, temperature, and chemical environments and/or long-lived cooling systems to house more moderate temperature and pressure electronics. Also needed would be the technology to create communications and navigation infrastructure for Venus and variable-altitude mobility systems that could survive 50-60-km atmospheric conditions.

Techniques for Measuring Attitude. The attitude of a lander or aerial platform within the Venus atmosphere is difficult to determine because scattering by clouds blocks the views of celestial references (the Sun and stars) and Venus has no permanent magnetic field that could help establish direction. An attitude-determination capability using inertial or radio tracking methods would be both enabling and enhancing. A method for performing inertial or radio tracking would also be useful for determining the position of any vehicles. Both attitude and relative-position data are needed to command a second vehicle based on measurements from another vehicle during the mission. This capability would further demonstrate autonomous systems' technologies in harsh environments and enable future missions. Atmospheric science would be obtained by small spacecraft and dropsonde(s).

Autonomous technologies needed for this capability are (see above for references to AS-CLT Taxonomy document):

- Algorithms and models to detect, diagnose, and recover from hardware degradation under Venus conditions

- Sensors and controllers for dropsondes
- Communication across multiple platforms (network topology)
- Demonstrate individual situational awareness and adaptability to enhance survivability
- Planning, scheduling, smart execution, and resource management algorithms
- Systems and software autonomy architecture to support autonomous navigation
- Other engineering and integrity techniques
    - *4.1 Verification and Validation*
    - *4.2 Test and Evaluation*
    - *4.3 Operational Assurance*
    - *4.4 Modeling and Simulation*

Other supporting technologies that are needed for autonomous attitude determination include flight hardware and sensors that can operate under harsh conditions, including long-lived electronics (processors and memory) that can operate in harsh pressure, temperature, and chemical environments and/or long-lived cooling systems.

DRM Scenario 2: A Networked System of Multiple Autonomous Assets

Description: DESIGN FOR AUTONOMY: SURVIVE, DETECT, COMMUNICATE, COORDINATE, AND RESPOND!

This DRM scenario would consist of networked lander systems and/or orbiter(s) to detect seismic events. The orbiter would detect volatiles from volcanically produced hotspots and/or seismic waves, while an aerial platform confirms the seismic event and releases dropsondes to measure the chemistry of the volcanic plume (See Figure 3). We envision this mission could occur in the 2033-2042 timeframe.

The Concept of Operations

The concept of operations for this more ambitious DRM consists of an orbiter with a fleet of small spacecraft, an aerial vehicle or two, dropsondes, and lander vehicles. The orbiter or small spacecraft will view the entire planet at a resolution of 2 km, acquiring infrared images at 4.3 microns every 0.5 seconds. A large seismic event would produce an infrared enhancement directly over the epicenter when the infrasound wave reaches the upper stratosphere. The infrared signal will then appear to propagate away from the epicenter at the velocity of a surface (Rayleigh) wave in the crust of Venus. An onboard analysis system will generate predictions of when seismic waves originating from the event including body waves (P and S) as well as surface waves will arrive at surface stations and aerial platforms. The constellation's autonomous system will report key parameters of the event to operators on Earth and to the other assets.

Active volcanic events produce thermal enhancements in infrared orbital images of the surface, but these will be detected by measuring the time variation of the infrared signal. Orbital imaging is limited in resolution to 50 km because of scattering in the Venus clouds. An aerial platform will be maneuvered so that it passes directly over the hot spot and obtains images at meter-scale resolution from the base of the clouds. Dropsondes will be deployed from the platform after confirmation of a hot spot and will be directed to the target by terrain-relative navigation. These dropsondes will observe the target with sub-meter-scale infrared imaging and with chemical sensors to establish the composition of the plume.

The orbiter and small spacecraft will target locations of interest across the planet. They will also provide communications and computational infrastructure to allow coordination across the different vehicle platforms. This DRM will need at least three or four high-altitude (10,000 km) satellites, which could be small spacecraft, to provide positional accuracy.

The aerial vehicle(s) will have controlled flight and altitude mobility for exploring Venus's atmosphere from 20–70 km with coordinated flight between vehicles. These vehicles can deploy dropsondes and atmospheric probes/small landers for atmospheric profiling or targeted surface investigations.

The lander system(s) will provide geological and geophysical data, as well as pressure, temperature, and atmospheric chemistry data on the surface (SO_2, H_2S, etc.). Multiple landers will be of various sizes and complexity and have varying degrees of processing capabilities, depending on lander types (cooled enclosure versus in situ operation). In the longer term, it is envisaged that the long-lived landers will have high-temperature electronics that can survive surface conditions for multiple Earth weeks.

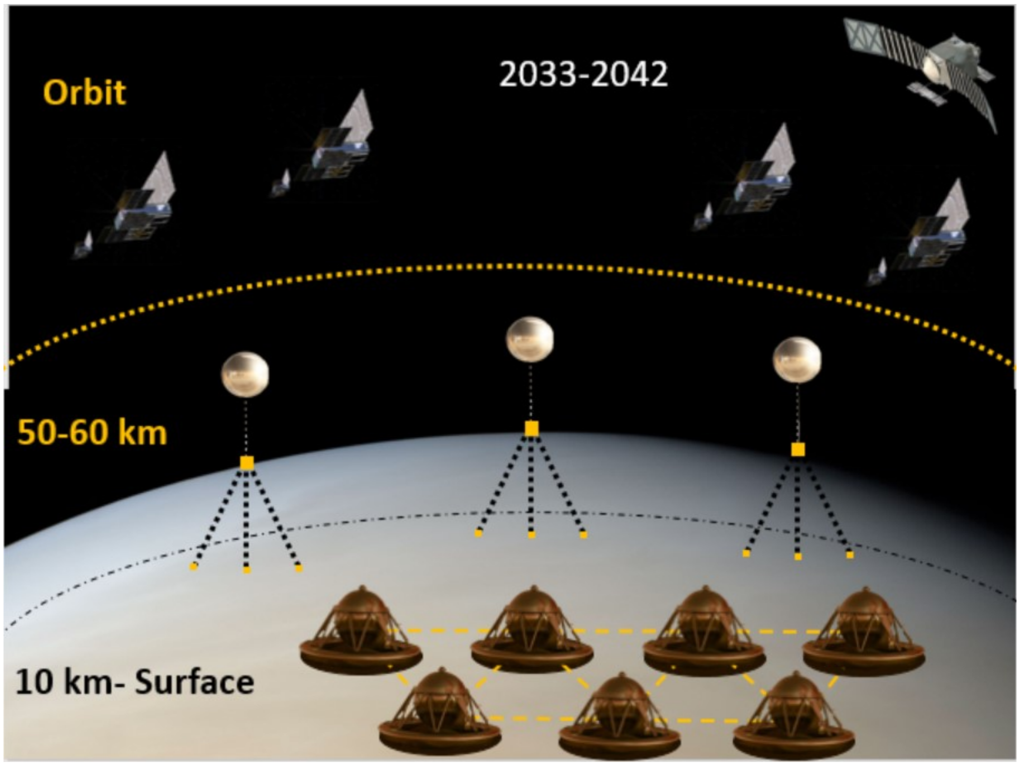

Figure 3: DRM 2 Concept Overview

Assumptions

- Small spacecraft are for communications and navigation for the planetary vehicles; the orbiter will relay communications back to Earth.
- Aerial vehicles will have the capability to reach the location of an event either by flying there directly against the super-rotating flow, if necessary, or maneuvering in-latitude to be carried over the target in the super-rotating flow.
- The orbiter and small spacecraft will have to be low enough to collect data on the events (e.g., 'sniff') but high enough to see large areas at once (the signal they are looking for is a thermal signal—a few-degrees temperature variation).
- Aerial platforms will have coordinated flight, communicating with each other through the orbiters, possibly directly, if communication links can be supported.
- Long-lived landers: configuration depends on whether cooling is available.
- Lander chemical information is related to proximity to volcanic eruption.
- Aerial platforms will confirm seismic events and reconfigure flight profiles to try to get closer.
- A matrix of vehicles surrounds the event, then drops the dropsondes; orbital platforms confirm the event and guide the aerial platforms to look for correlated events elsewhere on the planet.
- The lander network will be placed over different geological areas.
- During dropsonde descent, data is sent at a high rate to the aerial platforms that

deployed the dropsonde. The aerial platform stores and forwards the data acquired by the dropsonde to an orbiter for return to Earth.

- Dropsondes that are designed to reach the surface are guided to desired locations using a combination of inertial and terrain-relative navigation.
- A probe that is 2–5 kg can survive to the surface.
- TRN is possible using infrared emission from the surface from below the clouds but only on the nightside. Dayside imaging is only feasible within 10 km of the surface of Venus.
- TRN onboard, to pinpoint the volcano or earthquake epicenter using (e.g., usable spectrum not blocked by CO_2) images from less than 10 km, and beacons on landers/orbiters
- Dropsondes should be targeted to a volcanic crater.
- Dropsondes could be designed to also be landers and survive for a period of time on the surface.

Autonomy Capabilities Needed to Investigate a Venus Volcanic Eruption or Seismic Event

The harsh environmental constraints causing the short lifetime of hardware plus the rapid in situ response times needed in response to transient events will require coordination and communication across the agents. These agents cannot be 'operated in real-time' from the ground. Injecting autonomous elements into this mission concept will enable necessary science. Many of the autonomous capabilities developed such as fail-operational algorithms and structured system-level autonomy software architectures will also reduce risk. At least one vehicle should have a capable high-speed, high-bandwidth computer.

A Network of Landers and Orbiter(s) to Detect the Event. Both active volcanic events and seismic events will produce subtle changes that can be detected from the ground and orbit by various types of sensors. Active volcanic events will produce a thermal enhancement and, potentially, a release of volatiles into the atmosphere that would be visible in infrared orbital images of the surface, but these events will be detected by measuring the time variation of the infrared signal. Orbital imaging is limited in resolution to 50 km because of scattering in the Venusian clouds. However, smaller events can be detected because the imaging sensors are sensitive to very small changes in the average temperature over each resolution element.

Using NASA's AS-CLT Taxonomy document as a guide (recognized AS-CLT technologies are *italicized*), the autonomous technologies needed for this capability are:

- Algorithms and models to detect, diagnose and recover from hardware degradation under Venus conditions
- Venus terrain-relative navigation and hazard avoidance, station-keeping capability
- Control algorithms/models for dropsonde transit through dense, rapidly-moving atmosphere

- Sensors and controllers for dropsondes
- Communication techniques across multiple platforms to share common mental models (network topology)
- Collaboration and coordination of rapid response to varying conditions and inputs
    - *3.1 Joint Knowledge and understanding*
    - *3.2 Behavior and Intent prediction*
    - *3.3 Goal and task negotiation*
    - *3.4 Operational Trust Building*
- Situational awareness and adaptability to enhance survivability
- Planning, scheduling, smart execution, and resource management algorithms

Other technologies that are needed to support a network of landers and orbiters include flight hardware and sensors/instruments that can operate under harsh conditions and/or long-lived cooling systems. This requirement includes long-lived electronics (processors and memory) that can operate in harsh environments (pressure, temperature, chemical). Note that the computing power of each of the space vehicles will vary considerably and that aspect will be taken into account as the network is designed and built up. Other required technologies include creating a communications and navigation infrastructure for Venus, variable-altitude mobility systems, and theoretical environmental models of Venus near-surface conditions (<10 km).

An Orbiter to Detect Volcanic Events and/or Seismic Waves. It is important to determine both the rate and volatile content of the volcanic activity on Venus. The Magellan radar mission revealed a surface covered by volcanic features, where the number of small volcanoes has been estimated to be more than 900,000. These volcanoes may well be responsible for a much larger proportion of the heat flow from Venus's interior than is the case on Earth. An imaging near-infrared multispectral radiometer will be able to characterize the temperature changes associated with volcanic activity, while also characterizing the composition of volcanic flows.

The autonomous technologies needed to detect a seismic event are:

- Pattern-recognition techniques that enable the infrared signal to be discriminated from noise. These techniques use both the spatial nature of the pattern and the velocity with which it propagates from the epicenter. Following the recognition of an event, the algorithms need to predict the arrival times of seismic waves at aerial and landed assets to optimize the chance of localization and observation.

An Aerial Platform to Confirm a Seismic Event and Release Dropsondes to Measure Chemistry of Volcanic Plume. Venus quakes will produce strong infrasonic signals that can be detected as pressure waves at altitudes in the Venus atmosphere where long-duration observations are possible with existing technology. Infrasonic pressure signals emanate either directly above the epicenter of a seismic event or from the surface. Two or more micro-barometers deployed on a tether beneath a balloon can discriminate pressure variations resulting from an upwardly propagating Rayleigh wave from the surface, as demonstrated on Earth. The platform would circumnavigate Venus every few days enabling a survey of Venus quakes of magnitude ≥3.

The autonomous technologies needed for this capability are:

- Signal processing methods that integrate pressure disturbances measured at the platform and then integrate them with measurements of inertial disturbances and tracking data, and then correlate them with the expected form of the seismic signal.

Other supporting technologies needed include variable-altitude balloon systems and flight hardware and sensors that can operate on balloons, especially if they drop to below 55 km where the environment becomes more extreme. If complemented by seismometers on the surface then this DRM scenario also requires long-lived seismometers that can operate in harsh environments (pressure, temperature, chemical) and/or long-lived cooling systems, and long-lived electronics (processors and memory) and power systems that can survive the surface environment. Other supporting technologies needed include a communications and navigation infrastructure for Venus and theoretical environmental models of Venus's near-surface conditions (<10 km). Dropsondes are technologically possible, but must be engineered to last in the harsh environments below 55 km and on the surface if the dropsonde is to survive to take chemical or seismic measurements.

The Relevant Research and Development Projects for these DRM Scenarios

The Venus community has been actively studying many of the necessary elements for this project. The Venus Exploration Analysis Group (VEXAG) has compiled an updated Scientific Goals, Objectives and Investigations (GOI) document from which the Venus Roadmap and Technology Plan are derived. The latter two provide an estimate of the technology readiness of systems and subsystem technologies. Current technology research is being done on the Long-Lived In-situ Solar System Explorer (LLISSE)[7], the long-lived surface platform, which is currently being developed to the Engineering Model level. Aerial platforms for the scientific exploration of Venus[8,9] have also been studied and reported in the Aerial Platform Report, which describes the breadth of planetary aero-vehicles[10, 11, 12, 13], their technical maturity, and the scientific applicability of each. High operating temperature technology is being developed under the HOTTech program, including:

- Low-intensity, high-temperature solar cells[26]
- High-temperature memory[27]
- High-temperature microprocessors[28, 29]

In addition, examples of both research and mission autonomy including overall autonomy[14] and science tasks include:

- Lander autonomous target selection or sample selection Autonomous Exploration for Gathering Increased Science (AEGIS) (also for aerial target

selection)[15]
- Overall science autonomy[16]

Work has been done over the last decade to further autonomy in bodies with atmospheres:
- Aerial event detection and response[17]
- Data reduction from an aerial platform[18]
- System-wide resource planning on a surface or aerial platform[19,20]
- Autonomous navigation on planetary bodies with atmospheres, including vehicles used for winged flight[21, 22, 23, 24, 25]

The Potential Challenges, Risks, or Questions for these DRM Scenarios

Scenarios that demand autonomy include (but are not restricted to):
- Constrained communications with Earth and among assets on Venus
- Time-critical decisions involving events such as lifetime constraints, Venus quakes, and volcanic eruptions
- Internally data-heavy decision processes such as TRN, onboard data analysis, and distributed processing
- System architecture simplification where the decision making could occur at a central point, relying on data from all the available sensors across all of the vehicles. If one of the vehicles is not available, the authority for decision making could transfer to a secondary vehicle. This scenario could be described as a hierarchical approach to decision making
- Situational complexity that exceeds the limits of useful human input such as responding to surface events or changing atmospheric conditions. Aerial assets are moving 5,600 km/day, making real-time Earth communications difficult

Injecting autonomous elements into this mission concept will demonstrate science capabilities, reducing risk overall once the technologies are proven. However, the capabilities will require substantial investments; and more importantly, they will require a cultural change to train project teams, modernize space vehicles, and incorporate autonomy. Multiple technology demonstrations will be required to ensure that autonomous technologies are verified and validated. Ground operational tools will also need to be developed to deal with space vehicles in unknown 'states.' This second DRM scenario will stretch the limits of autonomy by testing synchronization of multiple space vehicles in an extreme environment.

Part IV: Findings

The Venus DRM team finds that the following actions and activities would facilitate implementation of the DRM scenarios described above.

- Institute a call for autonomy research that uses the type of hardware needed for multiple networked assets. This scenario would be very much like the Mars situation, and even Earth-sensor networks, except that the hardware has to be hardened and adapted to the temperature and pressure of Venus, where appropriate. Examples of the autonomous technologies needed include:
    1. Algorithms and models to detect, diagnose and recover from hardware degradation under harsh Venus environmental conditions
    2. Sensors for dropsondes, landers and aero-vehicles.
    3. Communication across multiple platforms (network topology)
    4. Demonstration of individual situational awareness and adaptability to enhance survivability and mission science
    5. Planning, scheduling, smart execution and resource-management algorithms
- Continue and expand support for programs such as HOTTech
- Fund technology maturation of aero-vehicles
- Identify where joint sponsorship and dual-use development can be leveraged, (e.g., the implementation of small platforms and autonomous systems), that would result in new mission capabilities.

There may be a timing issue because the orbital assets are moving so quickly (much faster than on Mars). However, an opportunity exists to test out the autonomy technologies around Earth before tackling the harder problem of doing so around Mars or Venus.

Part V: Venus DRM Team

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Venus Design Reference Mission Report Summary

How, why, and when did Earth’s and Venus’s evolutionary paths diverge? What are the implications for present-day Earth? The answers are central to understanding Venus in the context of terrestrial planets and their evolutionary processes. These fundamental and unresolved questions drive the need for vigorous new exploration of Venus.

Significant aspects of Venus exploration are challenged by limited time or the limited capability for human-in-the-loop interactions during the mission. Machine-based intelligence can optimize the science return by enabling operation independent of human intervention. The use of machine-based intelligence can vary from the use of automated systems carrying out a set sequence of actions to increasingly autonomous systems with the capability for situational awareness, decision-making, and response.

Autonomy is mission-enabling for the following reasons:

- The harsh environmental constraints (~460C, ~90 bars, and chemically reactive environment) limiting the operating lifetime of mission assets, plus the rapid response times needed in situ, require coordination and communication across the various mission agents. These activities cannot be “joy-sticked” from the ground.

- Injecting autonomous elements into this mission concept will enable necessary science, potentially at the cost of managing additional risk and safety. However, many of the autonomous capabilities developed will also reduce risk.

The Venus DRM Team suggests two autonomous DRM scenarios.

DRM Scenario: An Orbiter with Multiple Autonomous Assets

This near-term mission will characterize Venus's interior, surface, and atmosphere with a large, capable orbiter; a limited number of small spacecraft; an aerial vehicle; dropsondes; and a lander system.

This DRM scenario requires a level of autonomy that is not currently available. Advancements in autonomy technology are required for this mission scenario to perform the following:

Networking Capability: The mission requires a lander system to be networked with an orbiter, aerial vehicle, dropsonde, and small spacecraft. These multiple platforms will need to be situationally aware, adapt to enhance their survivability, and communicate and collaborate with one another under harsh conditions in the Venus environment.

Autonomous Navigation: The orbiter, aerial vehicle, dropsonde, and small spacecraft must be aware of their respective surroundings and able to navigate autonomously, including implementation of terrain-relative navigation and onboard data analysis.

Techniques for Measuring Attitude: The attitude of a lander or aerial platform within the Venus atmosphere is difficult to determine because scattering by clouds blocks the views of celestial references (the Sun and stars) and Venus has no permanent magnetic field that could help establish direction. An autonomous attitude-determination capability using inertial or radio-tracking methods will be both enabling and enhancing. A method for performing attitude determination via inertial or radio tracking will also be useful for determining the position of any vehicle.

To enable autonomy in this DRM scenario, advancements in the following supporting technology areas are required:

- At least one vehicle with a capable high-bandwidth, high-speed computer
- Flight hardware, long-lived electronics (processors and memory), and sensors that can operate under Venus's harsh conditions or long-lived cooling systems to house electronics that can survive more moderate temperature and pressure conditions
- Technology to create communications and navigation infrastructure for Venus and variable-altitude mobility systems that could survive atmospheric conditions at altitudes of 50-60-km

DRM Scenario: A Networked System of Multiple Autonomous Assets

In this mission, the orbiter(s) will detect volatiles from volcanically produced hotspots and/or seismic waves, while an aerial platform confirms the seismic event and releases dropsondes to measure the chemistry of the volcanic plume. This more ambitious DRM consists of an orbiter with a fleet of small spacecraft, an aerial vehicle or two, dropsondes, and lander vehicles.

This DRM scenario will require a level of autonomy that is not currently available. In addition to the autonomy technology advancements required by the previously described DRM scenario (Orbiter with Multiple Autonomous Assets), additional advancements in autonomy technology are required for this mission scenario to perform the following:

Event Detection: Both active volcanic events and seismic events will produce subtle changes that can be detected from the ground and orbit, and by various types of sensors. It is also important to determine both the rate and volatile content of the volcanic activity on Venus. This capability could be accomplished autonomously by a network of landers and orbiter(s) that detect the event, as well as an orbiter that detects volcanic events and/or seismic waves

Event Confirmation with Coordinated Dropsonde Release: Venus quakes will produce strong infrasonic signals that can be detected as pressure waves using existing technology at altitudes in the Venus atmosphere where long-duration observations are possible. This capability could be accomplished autonomously by a platform that circumnavigates Venus every few days to confirm a seismic event and releases dropsondes to measure the chemistry of a volcanic plume.

To enable autonomy in this DRM scenario, advancements in the following supporting technology areas are required in addition to those listed for the previously described DRM scenario (Orbiter with Multiple Autonomous Assets):

- Technology to create a communications and navigation infrastructure for Venus and the variable-altitude mobility systems and theoretical environmental models of Venus's near-surface conditions (<10 km)
- Variable-altitude balloon systems and flight hardware and sensors that can operate on balloons, especially if they drop below 55 km, where the Venus environment becomes more extreme

The key takeaway and the next steps to consider for future Venus missions include a call for autonomy research that uses the type of hardware needed for multiple networked assets. This hardware would be very much like that deployed at Mars, and even hardware used for Earth-sensor networks, except that the hardware must be hardened and adapted to the temperature and pressure conditions of Venus, where appropriate.

Findings

The Venus DRM team finds that the following actions and activities would facilitate implementation of the DRM scenarios described above:

1. Develop 'fail-operational' algorithms and models to handle hardware degradation under harsh Venus environmental conditions
2. Develop engineering and science sensors to enable autonomy for orbiters, dropsondes, landers, and aero-vehicles
3. Develop methods to communicate across multiple platforms (network topology)
4. Demonstrate individual agent situational awareness and adaptability to enhance survivability and mission science
5. Develop planning, scheduling, smart execution, and resource-management algorithms
6. Continue and expand support for programs such as the High Operating Temperature Technology (HOTTech) Program
7. Fund technology maturation of aero-vehicles
8. Identify where joint sponsorship and dual-use development can be leveraged (e.g., the implementation of small platforms and autonomous systems) to result in new mission capabilities